

Assessment of Appalachian Basin Oil and Gas Resources: Devonian Gas Shales of the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System

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Chapter G.9 of

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Distribution, Geologic Framework, and Geochemical Character**

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Conversion Factors

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square inch (in ²)	6.452	square centimeter (cm ²)
square mile (mi ²)	2.590	square kilometer (km ²)
Volume		
barrel (bbl; 42 U.S. gallons)	0.1590	cubic meter (m ³)
cubic foot (ft ³)	0.02832	cubic meter (m ³)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
Pressure		
pound per square inch (lb/in ²)	6.895	kilopascal (kPa)

Horizontal coordinate information is referenced to the North American Datum of 1927.

Assessment of Appalachian Basin Oil and Gas Resources: Devonian Gas Shales of the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System

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Abstract

This report presents the results of a U.S. Geological Survey (USGS) assessment of the technically recoverable undiscovered natural gas resources in Devonian shale in the Appalachian Basin Petroleum Province of the eastern United States. These results are part of the USGS assessment in 2002 of the technically recoverable undiscovered oil and gas resources of the province. This report does not use the results of a 2011 USGS assessment of the Devonian Marcellus Shale because the area considered in the 2011 assessment is much greater than the area of the Marcellus Shale described in this report. The USGS assessment in 2002 was based on the identification of six total petroleum systems, which include strata that range in age from Cambrian to Pennsylvanian. The Devonian gas shales described in this report are within the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System, which extends generally from New York to Tennessee. This total petroleum system is divided into ten assessment units (plays), four of which are classified as conventional and six as continuous. The Devonian shales described in this report make up four of these continuous assessment units. The assessment results are reported as fully risked fractiles (F95, F50, F5, and the mean); the fractiles indicate the probability of recovery of the assessment amount. The products reported are oil, gas, and natural gas liquids. The mean estimates for technically recoverable undiscovered hydrocarbons in the four gas shale assessment units are 12,195.53 billion cubic feet (12.20 trillion cubic feet) of gas and 158.91 million barrels of natural gas liquids.

Introduction

This report is part of the U.S. Geological Survey (USGS) Appalachian basin coal and petroleum resources framework study. The study area includes resources in strata traditionally assigned to both the Appalachian basin and the Black

Warrior basin. For energy assessment purposes, however, the Appalachian and Black Warrior basins are merged because the resources can be continuous from one basin to the other. The boundary of the structural Appalachian basin differs from that of the Appalachian Basin Petroleum Province (067), which was defined for the USGS 1995 National Oil and Gas Assessment (Gautier and others, 1998); in that assessment, the Black Warrior Basin Province (065) also was separately defined and assessed.

The 2002 U.S. Geological Survey assessment of the technically recoverable undiscovered oil and gas resources in the Appalachian Basin Petroleum Province of the United States identified six total petroleum systems (Milici and others, 2003). One of these petroleum systems is the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System (TPS), which consists of Devonian shale petroleum source rocks and various reservoir intervals in Middle and Upper Paleozoic strata. The reservoir intervals of this TPS were assigned to 10 assessment units, four of which are Devonian gas shale units. This report presents a summary of these four gas shale units, using the 2002 assessment results reported by Milici and others (2003) and additional descriptions and interpretations reported by Milici and Swezey (2006). This report does not use the results of a 2011 USGS assessment of the Devonian Marcellus Shale (Coleman and others, 2011) because the area considered in the 2011 assessment is much greater than the area of the Marcellus Shale Assessment Unit (AU) described in this report.

The first well drilled specifically for natural gas in the United States was operated by William A. Hart in 1821, in the village of Fredonia, Chautauqua County, New York (Weeks, 1886). The well was drilled into the Devonian Dunkirk Shale Member of the Perrysburg Formation, produced gas from depths of 30 to 70 feet (ft), and supplied gas to Fredonia for several years (de Witt, 1997). The modern petroleum industry had its beginnings in the Appalachian Basin Petroleum Province on August 27, 1859, when Colonel Edwin L. Drake (Seneca Oil Company) produced oil from a well drilled to a depth of 69.5 ft on Oil Creek, near Titusville in northwestern Pennsylvania (fig. 1). The well was located near surface seeps where oil had been collected and used locally, first by Native

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Americans and then by early settlers. The production was from a relatively thin bed of sandstone in the Upper Devonian Riceville Formation (Carter and Flaherty, 2011). The well reportedly produced at least 10 barrels of oil per day for a year and was the first oil produced commercially from a well drilled in the United States. The success of the well ignited an “industrial explosion” that spread rapidly throughout the region and into other areas of the country. A brief history of the Drake well and oil development in the Titusville area was compiled by the U.S. Department of the Interior (1976). Drake did not realize it at the time, but he had discovered the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System, which is the foremost petroleum system in the Appalachian Basin Petroleum Province (figs. 2, 3).

The Devonian Shale-Middle and Upper Paleozoic TPS contains some of the more productive petroleum source rocks and reservoirs in the Appalachian Basin Petroleum Province (fig. 2). The regional stratigraphy and geologic framework of the Devonian System in the Appalachian Basin Petroleum Province and depositional models for these strata have been described by numerous writers (for example, Oliver and others, 1967, 1971; Piotrowski and Krajewski, 1977; Piotrowski and Harper, 1979; Etensohn, 1985a,b; Lundegard and others, 1985; Sevon, 1985; Bjerstedt, 1986; Dennison and others, 1986, 1996; Kammer and Bjerstedt, 1986; Bjerstedt and Kammer, 1988; Boswell and Donaldson, 1988; Boswell and Jewell, 1988; Denkler and Harris, 1988; Hasson and Dennison, 1988; Milici and de Witt, 1988; Woodrow and others, 1988; de Witt and others, 1993; Boswell, 1996; Boswell, Heim, and others, 1996; Boswell, Thomas, and others, 1996; Donaldson and others, 1996; Matchen and Vargo, 1996; Milici, 1996a,c; Tomastik, 1996; Van Tyne, 1996; Vargo and Matchen, 1996; Faill, 1997; Harper, 1999; Swezey, 2002; Filer, 2003; Etensohn, 2008).

Stratigraphy

The Devonian through Lower Mississippian strata in the Appalachian Basin Petroleum Province may be divided into the following two groups: (1) Lower Devonian predominantly carbonate strata; and (2) Middle Devonian through Lower Mississippian predominantly siliciclastic strata (figs. 3, 4). Most of the Lower Devonian carbonate strata (for example, the Helderberg Group) are interpreted as pre-orogenic stable-shelf sediments, whereas most of the Middle Devonian through Lower Mississippian siliciclastic strata are interpreted as syn- to post-orogenic turbidite and deltaic sediments that accumulated in a foreland basin in association with the Acadian orogeny.

A regional unconformity is present throughout the basin immediately below the Upper Devonian Berea Sandstone and equivalent strata. This regional unconformity is referred to as the Kaskaskia I–Kaskaskia II unconformity (Sloss, 1988; Swezey, 2002). In some older publications, some Middle

Devonian through Upper Devonian siliciclastic strata (for example, the Needmore Shale through Hampshire Formation; fig. 4) below the Kaskaskia I–Kaskaskia II unconformity are informally referred to as the “Catskill delta” and some Upper Devonian through Lower Mississippian siliciclastic strata (for example, the Price Formation, Rockwell Formation, and Purslane Sandstone; fig. 4) above the Kaskaskia I–Kaskaskia II unconformity are sometimes informally referred to as the “Price-Rockwell delta.” The Lower Mississippian siliciclastic strata are overlain by Mississippian carbonate strata (for example, the Greenbrier Limestone; fig. 4) that are interpreted as stable-shelf sediments that accumulated before the Alleghenian orogeny began.

Middle Devonian Through Upper Devonian Siliciclastic Strata Below the Kaskaskia I–Kaskaskia II Unconformity

The Middle Devonian through Upper Devonian siliciclastic strata below the Kaskaskia I–Kaskaskia II unconformity consist of a coarsening-upward sequence that is thickest (up to 12,000 ft) in eastern Pennsylvania (fig. 5). The strata thin westward across the basin into central Ohio, where they are about 400 ft thick, and southwestward to Tennessee, where Middle Devonian strata are absent and the Upper Devonian to Lower Mississippian strata are approximately 8 ft thick (Hayes, 1891). The geographic extent of the Devonian strata and a generalized cross section along the depositional strike of these strata are shown in figures 6 and 7 (Oliver and others, 1967; de Witt and others, 1975).

From west to east, the Middle to Upper Devonian siliciclastic strata below the Kaskaskia I–Kaskaskia II unconformity consist of several distinct lithologic units that extend widely across the basin (Boswell and Donaldson, 1988). Black mudstone (interpreted as distal marine deposits) in the western part of the basin grades laterally eastward and vertically into gray and green, silty shale and then into mudstone and fine-grained sandstone (interpreted as distal-shelf turbidite deposits). These strata grade farther eastward into coarser-grained sandstone (interpreted as shallow-marine-shelf deposits that grade eastward into paralic to fluvial-deltaic deposits). The section is capped by red beds (interpreted as fluvial deposits and paleosols). The cross section (fig. 7) illustrates the overall coarsening-upward nature of the strata, with black mudstone at the base grading upward into red beds.

Harper (1999, table 7–1, figure 7–15) described and illustrated five facies (Facies I through V) of the Middle to Upper Devonian siliciclastic strata below the Kaskaskia I–Kaskaskia II unconformity in Pennsylvania and Ohio (fig. 8). Facies I consists of “dark-gray to black, somewhat calcareous, pyritic, sparsely fossiliferous shales” (Harper, 1999, table 7–1) that are interpreted as distal marine muds that accumulated under anoxic conditions (Etensohn, 1985a). Facies I includes at least eight repetitive lithologic sequences, each represented

by tongues of black shale that are intercalated with coarser-grained siliciclastic strata (figs. 8, 9). This facies is represented by the Middle Devonian Marcellus Shale in Pennsylvania and Ohio and the Lower Mississippian Sunbury Shale in Ohio. Facies II consists of sparsely fossiliferous “interbedded dark-gray shales and thin-bedded, light- to medium-gray siltstones” (Harper, 1999, table 7–1) that are interpreted as turbidite deposits that accumulated on a delta-fed submarine ramp (Lundegard and others, 1985). This facies is represented by the Brallier Formation. Facies III consists of “light- to dark-colored greenish, brownish, purplish, or reddish, highly fossiliferous shales, siltstones, and fine-grained sandstones” that are interpreted as “shallow marine open shelf” deposits (Harper, 1999, table 7–1). This facies is represented by the Upper Devonian Chadakoin Formation, Oswayo Formation, and Riceville Shale in western Pennsylvania (fig. 4). Facies IV consists of “interbedded silty, micaceous mudrocks and fine- to coarse-grained, thin- to thick-bedded siltstones, sandstones, and conglomerates” as well as beds of limestone (Harper, 1999, table 7–1). This facies is interpreted as a mixture of fluvial-deltaic and linear shoreline deposits that are interspersed with open-marine carbonate deposits, which accumulated during episodes of eustatic sea-level rise. This facies is represented by the Elk, Bradford, and Venango Groups in Pennsylvania (equivalent to the Upper Devonian Sherr and Foreknobs Formations of the Greenland Gap Group in West Virginia and Maryland). Facies V consists of gray to red siliciclastic strata that are interpreted as “mixed continental, fluvial-deltaic, and marginal marine” deposits (Harper, 1999, table 7–1). This facies is represented by the Upper Devonian Catskill Formation in Pennsylvania (equivalent to the Hampshire Formation in West Virginia, Virginia, and Maryland).

In much of the basin, the Middle Devonian through Upper Devonian siliciclastic strata below the Kaskaskia I–Kaskaskia II unconformity are divided into a lower unit of siliciclastic strata (the Hamilton Group and equivalent strata), a middle unit of limestone (the Middle Devonian Tully Limestone) that is capped by a regional unconformity, and an upper unit of siliciclastic strata (the Middle to Upper Devonian Genesee Formation and Harrell Shale, and the Upper Devonian Sonyea Formation, West Falls Formation, Java Formation, Perrysburg Formation, and Ohio Shale). In some areas, the Tully Limestone is absent and only the regional unconformity separates the lower siliciclastic strata from the upper siliciclastic strata.

Hamilton Group and Equivalent Strata

The Hamilton Group includes the Marcellus Shale and Mahantango Formation in West Virginia and the Marcellus, Skaneateles, Ludlowville, and Moscow Shales in New York. The group term is not used in Ohio, Maryland, or Pennsylvania, although the Marcellus Shale is present in those States (fig. 4). The Marcellus Shale is best developed in central Pennsylvania, where it is up to 200 ft thick (de Witt and others,

1993). To the south and west, the Marcellus Shale grades upward into silty shale of the Mahantango Formation, which in turn grades laterally into the Millboro Shale in Virginia (fig. 4). The Millboro Shale is about 1,500 ft thick in western Virginia (Woodrow and others, 1988), where it includes all strata from the top of the Tioga Ash Bed to the base of the Brallier Formation (Hasson and Dennison, 1988). In Ohio, the Marcellus Shale is replaced by the Delaware Limestone to the west, and the Mahantango Formation is replaced by the Plum Brook Shale, Prout Limestone, and lower part of the Olentangy Shale (fig. 4). In central Pennsylvania and eastern New York, the Marcellus Shale and Mahantango Formation grade laterally into thin limestone and (or) fossiliferous sandstone and shale (Woodrow and others, 1988).

Tully Limestone and the Acadian Unconformity

The Hamilton Group and equivalent strata are overlain by the uppermost Middle Devonian Tully Limestone (figs. 7, 9), which is capped by the regional Acadian unconformity (Sloss, 1988; Swezey, 2002). The Tully Limestone extends from west-central New York to northern West Virginia. In general, the formation is a cobbly weathering, fossiliferous, silty limestone. The Tully Limestone is as much as 200 ft thick in north-central Pennsylvania (de Witt and others, 1993), but thins and is replaced by a zone of pyrite nodules and pyritized fossils in western New York (Woodrow and others, 1988; Sessa, 2003).

In eastern Kentucky and Ohio, the Tully Limestone is absent, but the major regional Acadian unconformity is present. In central Tennessee and south-central Kentucky around the edges of the Nashville dome (fig. 6), the unconformity cuts so deeply into the section that Upper Devonian strata overlie strata as old as Ordovician (de Witt and others, 1993; J.A. Drahovzal, written commun, *as cited in* Wickstrom, 1996). Baranoski and others (1996) and Nuttall (1996) describe a similar situation on the Cincinnati arch (fig. 6).

Post-Acadian Unconformity Siliciclastic Strata

The Devonian regional Acadian unconformity is overlain by several shale units of Devonian and Early Mississippian age (de Witt and others, 1993). These Upper Devonian shale units include the Renwick Shale Member and Genesee Shale Member of the Genesee Formation, the Burket Member of the Harrell Shale, the Middlesex Shale Member of the Sonyea Formation, the Rhinestreet Shale Member of the West Falls Formation, the Pipe Creek Shale Member of the Java Formation, the Dunkirk Shale Member and Hume Shale Member of the Perrysburg Formation, and the Huron Member and Cleveland Member of the Ohio Shale (figs. 4, 7, 9). The black shale units are almost all regionally extensive and are interbedded with gray and greenish-gray siltstone and fine-grained sandstone that contain relatively small amounts of organic matter (de Witt and others, 1993). Those shale units near the bottom and middle parts of the Devonian stratigraphic

section (Marcellus Shale through Rhinestreet Shale Member of the West Falls Formation) are located mainly in the eastern part of the basin, and those shale units in the middle and upper parts of the section (Ohio Shale) are located mainly in the western part of the basin and, in part, overlie the Cincinnati arch (de Witt and others, 1993). The beds of gas-bearing Middle Devonian black shale grade upward and eastward into coarser-grained siliciclastic strata of the Brallier Formation. Partial equivalents of the Brallier Formation include the Scherr and Foreknobs Formations of the Greenland Gap Group in West Virginia and Maryland (fig. 4) and the Trimmers Rock, Lock Haven, and Catskill Formations in eastern Pennsylvania (Harper, 1999, figure 7–4).

Upper Devonian Through Lower Mississippian Siliciclastic Strata Above the Kaskaskia I–Kaskaskia II Unconformity

A regional unconformity is present within the uppermost Devonian strata, in most places beneath the Upper Devonian Berea Sandstone (fig. 4). This unconformity is overlain by Upper Devonian through Lower Mississippian siliciclastic strata (for example, the Sunbury Shale, the Rockwell Formation, Purslane Sandstone, and Burgoon Sandstone; see figures 3 and 4). In southwestern Virginia and adjacent West Virginia, these Upper Devonian through Lower Mississippian siliciclastic strata above the Kaskaskia I–Kaskaskia II Unconformity include the upper part of the Devonian–Mississippian Chattanooga Shale and the overlying Lower Mississippian Price Formation (fig. 10). In outcrops in this area, the Chattanooga Shale consists of the following three members: (1) a lower black shale member, (2) a middle gray siltstone member, and (3) the Big Stone Gap Member (black shale). The upper 131 ft of the Big Stone Gap Member consist of gray and grayish-black shale and are equivalent to the Lower Mississippian Sunbury Shale (Filer and others, 1996). In the subsurface, the Sunbury Shale is a 110-ft-thick unit of grayish-black to gray shale, which is overlain by the Price Formation (Filer and others, 1996).

Devonian and Mississippian Shale Depositional Models

Numerous interpretations of depositional environments have been applied to the Devonian and Mississippian strata in the Appalachian basin. Some models interpret the black shale as deposits of black mud that was rich in organic matter and that accumulated in the distal parts of the foreland basin, perhaps during periods of marine transgression (Ettensohn and Barron, 1981, 1982; Ettensohn, 1985a,b; Kepferle, 1993; Leone and Smith, 2011). Dennison (1985) proposed a model where Middle Devonian sea-level transgressions generally resulted in the deposition of limestone, and Late Devonian

transgressions (after the deposition of the Tully Limestone) resulted in the deposition of black shale. He suggested that the following black shale units may have been deposited during periods of relative sea-level rise, as deltaic environments generally shifted eastward: (1) the Middle to Upper Devonian Geneseo Shale Member of the Genesee Formation, the Middle to Upper Devonian Harrell Shale, the Upper Devonian Rhinestreet Member of the West Falls Formation, and the Upper Devonian Pipe Creek Shale Member of the Java Formation; (2) the Famennian Dunkirk Shale Member of the Perrysburg Formation (Over, 2002); and (3) the unnamed lower black shale member and Big Stone Gap Member of the Upper Devonian to Lower Mississippian Chattanooga Shale (fig. 9).

Lundegard and others (1985) interpreted the Brallier Formation and overlying siliciclastic beds as having accumulated in the following five depositional environments: (1) delta front, (2) turbidite slope, (3) interlobe slope, (4) lobe margin, and (5) deep basin. Their paleocurrent map shows a consistent westward trend for the direction of transport of the Brallier sediments.

Boswell and Donaldson (1988) compared the sea-level curve of Johnson and others (1985) with the inferred positions of Late Devonian deltaic shorelines. They showed a correlation between sea level and late Late Devonian (Famennian) shoreline positions, but not between sea level and early Late Devonian (Frasnian) shoreline positions. From this comparison, they concluded that a global change in sea level, perhaps driven by glaciation in Gondwanaland, was an important factor for controlling Famennian sediment accumulation. During the Frasnian, however, the supply of sediments resulting from erosion during the Acadian orogeny may have overwhelmed the effects of glacially driven sea-level changes and could explain why there is no correlation between Frasnian shoreline positions and the Euramerican sea-level curve.

Many studies noted that Devonian and Mississippian black shale in the Appalachian basin displays an apparently cyclical nature. Ettensohn (1985a,b), for example, described five depositional cycles of finer-grained to coarser-grained rock within the Devonian siliciclastic strata. Each cycle is interpreted to have begun with a period of rapid subsidence in the basin, when black shale in the lower part of a cycle accumulated during a period of relative sea-level rise. This initial basin subsidence occurred in conjunction with (or was followed closely by) a period of tectonic uplift. According to this model, the coarser-grained clastic strata in the upper part of each cycle accumulated during a second period of subsidence, which followed the main tectonic event. Each of the following five black shale units described by Ettensohn (1985a,b) comprise the base of a cycle: (1) the Middle Devonian Marcellus Shale and the Mahantango Shale, (2) the Middle Devonian Geneseo Shale Member of the Genesee Formation and Burket Member of the Harrell Shale, (3) the Upper Devonian Middlesex Shale Member of the Sonyea Formation, (4) the Upper Devonian Rhinestreet Shale Member of the West Falls Formation, and (5) the Upper Devonian Dunkirk Shale Member of the Perrysburg Formation (fig. 4). Each of the black shale units

and the immediately overlying beds of coarser-grained strata constitute one cycle.

Cyclical patterns were also noted by Kepferle (1993), Filer (1994), and Schieber (1998). For example, Kepferle (1993) cited evidence for four to eight transgressive and regressive events in the Appalachian basin during the Devonian and Mississippian. Filer (1994) proposed that there are seven or more basinwide third-order cycles of organic-matter-rich black shale (including the Marcellus Shale and associated strata) intercalated generally with coarser-grained strata that contain much less organic material. Schieber (1998) recognized numerous extensive unconformities within the Upper Devonian to Lower Mississippian Chattanooga Shale in central Tennessee and adjacent Kentucky. He interpreted these unconformities as subtle sequence boundaries that reflect a temporary lowering of sea level, and he used these unconformities to divide the Chattanooga Shale into 14 regional sequences.

More recently, Filer (2002) described 11 cyclic lithologies in an interval of Upper Devonian strata from the upper part of the Rhinestreet Shale Member of the West Falls Formation to the Dunkirk Shale Member of the Perrysburg Formation in New York. These cycles were correlated through equivalent strata (parts of the Brallier Formation, Greenland Gap Group, Ohio Shale, and lower black shale member of the Chattanooga Shale) in a region that extends 435 miles (mi) or more along the length of the Appalachian Basin Petroleum Province from New York southwestward through Pennsylvania, Ohio, and West Virginia to eastern Kentucky and Tennessee and southwestern Virginia. In the western (distal) part of the basin, each of these cycles consists of dark, organic-matter-rich shale at the base that grades upward into lighter-colored shale that contains less organic material. In the eastern (proximal) part of the basin, each of these cycles consists of relatively thin shale beds at the base that grade upward into relatively thick beds of siltstone and sandstone. In general, the cycles range from 2 to 3 ft thick in the western part of the basin to as much as 230 ft thick in the eastern part of the basin. Filer (2002) concluded that these basinwide high-frequency cycles were affected by glacially induced sea-level changes.

Petroleum Geology

Several estimates of undiscovered hydrocarbon resources of the Appalachian Basin Petroleum Province have been published. In 1995, for example, the USGS published assessments of the undiscovered hydrocarbon resources in Devonian shale in the Appalachian Basin Petroleum Province (Gautier and others, 1995). Briggs and Tatlock (1999) estimated the undiscovered recoverable natural gas resources in Pennsylvania. The 2002 USGS assessment (Milici and others, 2003) differs from these earlier assessments in that it was based on the concept of total petroleum systems, which considers source rocks, maturation, migration, reservoir rocks, and reservoir seals (Magoon and Dow, 1994).

Assessment Model

For assessment purposes, oil and gas reservoirs are commonly divided into the following two distinct types: conventional and continuous (unconventional). Conventional resources are characterized by discrete structural, stratigraphic, or combination traps in which water and oil and natural gas are separated into layers by their immiscibility and relative buoyancies. In contrast, continuous accumulations are accumulations of hydrocarbons (generally gas) that are not segregated into discrete fields with well-defined fluid contacts. Instead, continuous accumulations produce hydrocarbons, if only in small and potentially noneconomic amounts, wherever they are drilled. Such continuous reservoirs include coal (as coalbed methane), shale that is rich in organic material, and low-porosity (tight) sandstone (Schmoker, 1999, 2002). In the Appalachian Basin Petroleum Province, continuous accumulations commonly consist of multiple coal beds, sandstone beds, or shale beds that are amalgamated into larger stratigraphic units in which multiple zones may be drilled, perforated, and completed within a single well.

Thermal Maturity Data

For the 2002 USGS assessment of the Devonian Shale-Middle and Upper Paleozoic TPS, thermal maturity data were obtained by vitrinite-reflectance (Milici and Swezey, 2006). These data were obtained from the following shale units in the lower part of the Devonian siliciclastic section: (1) the Marcellus Shale in the eastern part of the Appalachian Basin Petroleum Province, and (2) the slightly younger basal shale units to the west where the Marcellus Shale has pinched out. The vitrinite in samples of these shale units consisted of dispersed fragments of organic matter within a shale and siltstone matrix. Shale samples were collected under the direction of Robert T. Ryder (USGS) in cooperation with staff from the State geological surveys, and were analyzed by Humble Geochemical Services, Humble, Texas. The analyses of these data, as well as the vitrinite-reflectance isolines and the limits of oil generation and preservation in Devonian shale shown in figure 11, are taken from Weary and others (2000, 2001), Repetski and others (2002, 2005, 2008), and John R. Repetski (USGS, oral commun., 2008). Vitrinite-reflectance data are expressed as percentages (%R_o) of light reflected back from a sample that is illuminated when compared with material that provides 100 percent reflectance (such as a mirror). In general, 0.6 %R_o is regarded as the approximate lower limit of thermal maturity for oil generation, and 2.0 %R_o is the approximate upper limit for oil preservation (Tissot and Welte, 1984; Taylor and others, 1998). Additional data on thermal maturity of Devonian shale may be found in East and others (2012).

During the 2002 USGS assessment, estimates of vitrinite-reflectance values from Devonian dispersed vitrinite in Ohio, northwestern Pennsylvania, and New York may have been lower than the true vitrinite-reflection values because of a phenomenon described by Lo (1993) as “vitrinite reflectance

suppression.” Recent work by Rowan, Ryder, Repetski and others (2004); Rowan, Ryder, Swezey and others (2004); Rowan (2006); and Ruppert and others (2010) has determined that the vitrinite-reflectance values obtained from Pennsylvanian coal beds are, in general, equal to or greater than the values obtained from dispersed vitrinite in underlying Devonian shale, especially in the western part of the basin. Thermal or burial history models constructed along Appalachian Basin Petroleum Province cross section *E–E'* (fig. 12) of Ryder and others (2008) have determined that the 0.6-% R_o isoline in Devonian shale may well lie 20 to 60 miles to the west of the line determined from dispersed vitrinite (Rowan, Ryder, Repetski and others, 2004; Rowan, Ryder, Swezey and others, 2004; Rowan, 2006; Ruppert and others, 2008). Indeed, vitrinite-reflection data obtained after the 2002 assessment, as well as older data corrected for vitrinite suppression (Repetski and others, 2008), have shown that the 0.6-% R_o isoline could lie along the westernmost occurrence of the Devonian shale (fig. 13). Thus, much of the oil in the Devonian shale of central Ohio may have been generated in place, with little or no lateral migration from source rocks to the east.

Since the 2002 USGS assessment, basin modeling by Elisabeth L. Rowan (USGS, written commun., December 2004; Rowan, 2006) has indicated that the base of the Devonian shale entered the oil window during the Early Devonian at about 275 million years ago (Ma) in central Ohio and at about 340 Ma (Early Pennsylvanian) in west-central West Virginia. Near the Ohio-West Virginia border, basal Devonian shale entered the oil window at about 330 Ma (Middle Mississippian) and entered the gas window at about 230 Ma (Middle Triassic).

Petroleum System Data

Petroleum system data for the Devonian Shale-Middle and Upper Paleozoic TPS include descriptions of petroleum source rocks, petroleum generation, petroleum migration, reservoir rocks, and reservoir seals (fig. 14). The petroleum source rocks are Middle and Upper Devonian and Lower Mississippian shale. The total organic carbon (TOC) content (in weight percent) of Devonian black shale of the Appalachian Basin Petroleum Province ranges widely from less than 1 percent to about 12 percent, but locally it can be as high as 27 percent (Zielinski and McIver, 1982). Hydrocarbon generation occurred from Early Devonian to Early Triassic, and hydrocarbon migration and accumulation occurred during hydrocarbon generation and shortly thereafter. The reservoirs range in age from Ordovician (strata in the Cumberland saddle region, which is located outside of the Appalachian Basin Petroleum Province in Kentucky and Tennessee; fig. 6) to Mississippian (strata in the Appalachian Plateau; fig. 6). Local seals include siltstone and shale throughout the section. Stratigraphic traps occur in sandstone and limestone throughout the section (de Witt and others, 1979). Some structural traps may have formed by extensional deformation during the late Precambrian and early Paleozoic formation of the Rome trough, but most

structural traps formed by compression during the late Paleozoic Alleghanian orogeny, when the eastern part of the basin was folded and faulted.

The critical moment, which is considered to be the time when a large volume of the source rocks reaches thermal maturity and when large amounts of petroleum are generated and expelled from their source rocks, occurred during the Early Permian. During the critical moment, the source rocks and carrier beds were sufficiently fractured to facilitate migration and accumulation of liquid and gaseous hydrocarbons in porous reservoirs within available stratigraphic and structural traps. The residual hydrocarbons that remain within the source rocks after the critical moment constitute the continuous accumulations that are the subject of this paper.

In the Appalachian Basin Petroleum Province, methane and smaller amounts of other gases occur within Devonian shale in fractures of various sizes and (or) are adsorbed onto the surfaces of the large amounts of organic matter (de Witt and others, 1993). Charpentier and others (1993) classified these modes of occurrence as domains that contain macrofracture gas, microfracture gas, and sorbed gas. During production of these gases, the reservoir pressure is initially reduced as fractures are drained of formation waters, if present. Subsequently, as gas is produced from the fractures, additional gas is desorbed from the organic matter into microfractures and then into macrofractures on the way to the well bore. These processes are similar to the desorption and production of methane from coal beds (for a summary, see Markowski, 2001). Bustin and others (2006), however, demonstrated that the application of coalbed-methane-desorption techniques to most overmature gas shale units resulted in an overestimation of the adsorbed gas content and an underestimation of the free gas capacity of the shale. Instead, the use of production isotherms may result in a better estimation of the total reservoir capacity of gas in shale reservoirs.

Devonian Gas Shale Assessment Units

Most of the undiscovered petroleum resources in the Appalachian Basin Petroleum Province occur either within Devonian black shale as continuous autogenic (self-sourced) reservoirs (Milici, 1993) or within overlying and intertonguing Devonian siltstone and sandstone reservoirs (Schmoker, 1999, 2002). Of the 10 assessment units identified in the Devonian Shale-Middle and Upper Paleozoic TPS, 4 are conventional and 6 are continuous (table 1). This chapter focuses on the 4 continuous Devonian shale assessment units, which are named the Greater Big Sandy Assessment Unit (AU), the Northwestern Ohio Shale AU, the Devonian Siltstone and Shale AU, and the Marcellus Shale AU (fig. 15). The petroleum geology of these assessment units is summarized in Boswell (1996), Milici (1996a), and Milici and Swezey (2006). In addition, gas data were compiled from Roen and Kepferle (1993), Roen and Walker (1996), and the U.S. Department of Energy Eastern Gas Shales Project (U.S. Department of Energy, National Energy Technology Laboratory, 2007).

Greater Big Sandy Assessment Unit

The Greater Big Sandy Assessment Unit (AU) is a Devonian shale interval in parts of eastern Kentucky and adjacent regions in Tennessee, Virginia, and West Virginia. This assessment unit is located east of the 0.6-%R_o Devonian thermal maturity isoline, which is based on dispersed vitrinite (fig. 16). Thus defined, the Greater Big Sandy AU is stratigraphically gradational with the Devonian Siltstone and Shale AU to the east and with the Northwestern Ohio Shale AU to the west. Gas and natural gas liquids have been produced from this area at depths that range from about 1,700 to 5,595 ft (Boswell, 1996).

The thickness of the assessment unit decreases from about 2,500 ft in the northeastern part of the area to about 100 ft in the southwestern part (figs. 17, 18). The thickness of coarser-grained siliciclastic strata generally increases relative to the total thickness of black shale and is also concurrent with the overall increase in thickness of strata to the northeast. The depositional strike is generally north to south and follows the general thickness trends of the assessment unit (fig. 16).

Stratigraphy.—The Greater Big Sandy AU consists of several beds of black shale that are interbedded with beds of gray and greenish-gray shale, siltstone, and fine-grained sandstone. The assessment unit includes all of the strata from the base of the Devonian Rhinestreet Shale Member of the West Falls Formation (or the base of the Marcellus Shale, where present) to the top of the Mississippian Sunbury Shale (figs. 17, 18). The Marcellus Shale occurs beneath the Rhinestreet Shale Member in a small area in the northeastern part of the assessment unit (fig. 17). The major black shale units in the assessment unit include the Rhinestreet Shale Member of the West Falls Formation, the lower and upper parts of the Huron Member of the Ohio Shale, and the Cleveland Member of the Ohio Shale. In addition, the relatively thin Pipe Creek Shale Member of the Java Formation may be productive in places. In general, the upper part of the Huron Member of the Ohio Shale grades into gray or greenish-gray shale, siltstone, and fine-grained sandstone to the east across the assessment unit and, together with Cleveland Member of the Ohio Shale, pinches out to the northeast.

Structure.—The relation of the Greater Big Sandy AU to the regional geologic structure is shown in figure 20. In general, this assessment unit extends northeastward from the Pine Mountain block in Kentucky and Virginia to the western side of the Rome trough in Kentucky and southern West Virginia (Shumaker, 1980). In their study of play 8 (Western Rome Trough; fig. 19), Charpentier and others (1993) related the fracture porosity in the Big Sandy gas field and adjacent areas to late Paleozoic vertical movements of normal faults associated with the Rome trough. Shumaker (1980), however, proposed that a limited décollement in the Devonian black shale was responsible for the development of a “porous fracture facies” within these rocks. Indeed, Charpentier and others (1993) described a “blowout zone” that occurred in Devonian shale beneath the Pine Mountain block (play 10

in figs. 19, 20), where drilling intersected the subhorizontal décollement of the Pine Mountain thrust fault within Devonian shale (Young, 1957).

Where they are of limited extent, décollements apparently enhance fracture development within black shale. In contrast, where deformation is extreme in fractured shale, relatively small pockets of gas under high pressure may be released with explosive intensity (Young, 1957). Charpentier and others (1993) proposed a region (play 9, Tug Fork; fig. 19) that was intermediate between the areas of limited décollement and the relatively larger décollement in which increased fracture porosity in Devonian shale was caused by both vertical movement along the Rome trough border faults and deformation related to thrusting. Shumaker (1993) studied the Midway-Extra and Cottageville fields (fig. 21) in the northern part of the Greater Big Sandy AU in West Virginia and concluded that (1) the fracture porosity induced by a décollement in the black shale was enhanced near or above low-relief basement structures, and (2) this “fracture permeability formed during Alleghanian detached deformation when the lower Huron shale was overpressured” (Shumaker, 1993, p. K17–K18).

In addition to the work by Shumaker (1980, 1993), the relation between limited décollements and the generation of extensional and contractional fracture porosity in the Appalachian region was described in detail by Harris and Milici (1977), Milici (1980), Milici and Statler (1980), and Milici and Gathright (1983). These studies confirm the observation that organic-rich (and perhaps overpressured) strata such as coal or shale (Shumaker, 1980, 1993) serve to localize bedding décollements with an associated array of extensional fractures.

Petroleum source rocks.—The petroleum source rocks for the Greater Big Sandy AU are thought to be the Devonian shale. The mass of organic carbon per unit of area in the stratigraphic section generally exceeds 1.8 pounds per square inch (lb/in²) of surface area (Schmoker, 1993). For the Greater Big Sandy AU, Streib (1981) reported that the total organic carbon (TOC) content of 5 samples from the Cleveland Member of the Ohio Shale in the Greater Big Sandy Assessment Unit averaged 3.89 percent (table 3).

Thermal maturity.—Devonian shale in most of the Greater Big Sandy AU has dispersed vitrinite-reflectance values within the range of 0.6 to 1.0 %R_o (fig. 16), which is within the thermal maturity window for oil generation (Repetski and others, 2008). In the eastern part of the assessment unit, however, vitrinite-reflectance values attain a maximum of about 1.5 %R_o (fig. 16), which is within the thermal maturity window for gas generation (Repetski and others, 2008). The kerogen types in the Greater Big Sandy AU are expected to be mixed types I, II, and III (Maynard, 1981; Zielinski and McIver, 1982). The model-predicted vitrinite reflectance values (Rowan, Ryder, Repetski and others, 2004; Rowan, Ryder, Swezey and others, 2004; Rowan, 2006) indicate that the basal Devonian shale in the northern part of the assessment unit entered the oil window at approximately 330 to 325 Ma (Mississippian) and entered the gas window

at approximately 230 Ma (Triassic). In comparison, the upper part of the Ohio Shale appears to have entered the oil window at approximately 260 Ma (Permian).

Reservoir and production data.—In the Greater Big Sandy AU, gas has been produced from the Marcellus Shale, the Rhinestreet Shale Member of the West Falls Formation, the Huron and Cleveland Members of the Ohio Shale, and the Sunbury Shale (fig. 8). Reservoir depths range from approximately 1,700 ft to nearly 6,000 ft (Boswell, 1996). The reservoir is extremely underpressured and has very low permeability values of <0.0001 millidarcies (Kendrick, 2009; Wrightstone, 2009). Log-derived porosity values in the Big Sandy field range from 1.5 to 11 percent, with an average of 4.3 percent (Boswell, 1996). The better gas shale reservoirs within the AU are characterized by pervasive gas-filled micropores in laminated black shale, siltstone, and fine-grained sandstone that contain networks of natural fractures (Patchen and Hohn, 1993).

The database that accompanies Roen and Walker (1996) lists 61 named fields that lie within the boundaries of the Greater Big Sandy AU (fig. 21). Several of these fields are located near or on the boundaries of adjacent assessment units. Although these fields are administrative entities for State regulatory agencies, the fields are part of the continuous accumulation that constitutes the Greater Big Sandy AU. In these fields, the average completion thicknesses range generally from 189 to 980 ft, with the greatest average thickness completed from the Fourmile-Branchland field in West Virginia. Cumulative production data (as of September 30, 1996) are not available for all of the fields, but the available data indicate that at least 3.7 trillion cubic feet (TCF) of gas have been produced from named fields in the Greater Big Sandy AU, and about 2.5 TCF of gas have been produced from the Big Sandy gas field alone. Although much of the gas production from the Big Sandy field (and from many other fields) is commingled with production from other stratigraphic units, most of the gas is apparently produced from the Devonian shale.

Several published estimates of gas resources in the area of the Greater Big Sandy AU exist, although they did not use the same methodology that was used in the 2002 USGS assessment. For example, Kuuskraa and Wicks (1984) and Kuuskraa and others (1985) estimated the gas-in-place resources in the Cleveland and Huron Members of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation (within the area of the Greater Big Sandy Assessment Unit) at about 60 TCF. Charpentier and others (1993), however, estimated the mean gas-in-place resources in the approximate area of the assessment unit at about 76 TCF (table 2, fig. 19). The difference between these two estimates may be the result of the relatively low values for the estimated gas-in-place resources that Kuuskraa and others (1985) assigned to the counties in the western part of the assessment unit (their Setting II) (fig. 22), which is the area associated with the Western Rome Trough (play 8 of Charpentier and others, 1993). In addition, the estimated gas-in-place resources that Kuuskraa and Wicks (1984) and Kuuskraa and others (1985) assigned to

all stratigraphic intervals are more than double the estimated gas-in-place resources that they assigned to the target intervals in their Setting I (fig. 22).

In the database that accompanies Roen and Walker (1996), the original gas-in-place resources for the Big Sandy field were estimated at approximately 20 TCF. In this database, the original gas reserves for this field were estimated as 3.4 TCF, the gas produced was estimated as 2.5 TCF, and the remaining reserves were estimated as approximately 900 BCF. Using data from Roen and Walker (1996), the distribution (by thirds) of estimated ultimate recovery (EUR) values of gas per well calculated for shale gas wells in this assessment unit in eastern Kentucky is illustrated in figure 23. At the median, the early third of the wells attained an EUR of about 73 million cubic feet (MMCF), the middle third attained about 105 MMCF, and the late third attained about 90 MMCF.

USGS assessment results.—For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian Basin Petroleum Province, the USGS estimated a range of 3,877.33 to 9,562.42 BCF of gas and 34.06 to 104.50 million barrels (MMB) of natural gas liquids in the Greater Big Sandy AU. The mean values for these estimates are 6,322.67 BCF of gas and 63.23 MMB of natural gas liquids in the Greater Big Sandy AU (Milici and others, 2003).

Northwestern Ohio Shale Assessment Unit

The Northwestern Ohio Shale Assessment Unit (AU) is a Devonian shale interval that occupies an area in eastern Kentucky, east-central Ohio, western Pennsylvania, and western New York (figs. 12, 15). This assessment unit is located to the west of the 0.6-% R_o Devonian thermal maturity isoline (based on dispersed vitrinite). The Northwestern Ohio Shale AU is stratigraphically gradational with the Greater Big Sandy AU to the southeast and with the Devonian Siltstone and Shale AU to the northeast (fig. 15).

The thickness of Devonian strata in the assessment unit ranges from about 25 ft in southern Kentucky and adjacent Tennessee to about 4,000 ft in the northern panhandle of West Virginia (fig. 5). The thickest accumulation of black shale, however, extends northward from easternmost Kentucky through Ohio (fig. 15), where the net thickness of black shale ranges generally from 200 to 400 ft. In general, the Northwestern Ohio Shale AU (fig. 15) contains much of the thicker accumulations of black shale in the Devonian strata.

Stratigraphy.—The Northwestern Ohio Shale AU includes all of the shale strata from the base of the Rhinestreet Shale Member of the West Falls Formation to the top of the Sunbury Shale (figs. 24, 25, 26). The major black shale units in the assessment unit are the Rhinestreet Shale Member of the West Falls Formation and the Huron Member of the Ohio Shale. The Pipe Creek Shale Member of the Java Formation, the Cleveland Member of the Ohio Shale, and the Sunbury Shale are relatively thin, but may produce gas in places. Beds of black shale in the upper part of the Huron Member and the

Cleveland Member of the Ohio Shale grade eastward across the assessment unit area into gray and greenish-gray shale, siltstone, and fine-grained sandstone of the Chagrin Shale (figs. 25, 26).

Structure.—The relation of producing areas in the Northwestern Ohio Shale AU to geologic structure is shown in figure 27. Although the assessment unit was assessed as a continuous accumulation, the commercial production of hydrocarbons depends largely on the local development of fracture-generated porosity and permeability within the shale. In some places within the assessment unit, gas is produced with oil, but in other places natural gas is the only hydrocarbon produced. In yet other places (such as the Cumberland saddle region of south-central Kentucky and adjacent Tennessee, along the Cambridge structural discontinuity in central Ohio, and in northwestern Pennsylvania), gas is produced together with oil. The chief gas-producing areas in the Northwestern Ohio Shale AU are (1) adjacent to the Greater Big Sandy AU in eastern Kentucky, (2) along the northwestern edge of the Rome trough in southern Ohio, (3) along the Waverly arch in Ohio, and (4) the Lake Shore fields along the southern shore of Lake Erie in northern Ohio, Pennsylvania, and western New York (fig. 27). Gas production along the western margin of the Rome trough in southeastern Ohio may have been enhanced by fracture porosity related to late-stage movement along the western boundary fault (Charpentier and others, 1993).

When compared with the other Devonian shale assessment units, a structural interpretation of the Northwestern Ohio Shale AU is relatively simple. Glacial loading and rebound that were caused by the incursion and melting of continental ice sheets during the Pleistocene appear to have enhanced fracture porosity and permeability in the northwestern and northern parts of the assessment unit, especially in the Lake Shore fields (fig. 27) where fractures extend to depths of 1,000 to 1,500 ft (Charpentier and others, 1993). To the east, in the panhandle of northwestern Pennsylvania and in western New York, beds of relatively brittle siltstone are intercalated with beds of Devonian black shale and are broken by an extensive network of fractures that also appears to have formed in response to several episodes of glacial loading and crustal rebound. The combination of natural fractures and thin, broken beds of siltstone interbedded with the thick beds of black shale has enhanced gas production from Devonian shale in this area (Charpentier and others, 1993).

East of the Cambridge structural discontinuity, a relatively large area in eastern Ohio, western Pennsylvania, and northern West Virginia is underlain by evaporite beds in the Silurian Salina Group. The evaporite beds contain a widespread subhorizontal bedding-parallel fault that exhibits only a relatively small amount of displacement (Frey, 1973). In the region to the east of the Northwestern Ohio Shale AU, this fault is a décollement that has had sufficient movement on it to generate numerous blind splay thrust faults and a series of relatively low relief, subparallel, superficial anticlines within hanging-wall strata. The folding is a reflection of the amount of shortening that has taken place in the strata overlying

the décollement in the Salina Group (fig. 27). This décollement has been recognized as far west as the Bass Islands trend (fig. 27) in southwestern New York (Beinkafner, 1983; Patenaude and others, 1986; Van Tyne, 1996). Nevertheless, an extension of the décollement within evaporite beds in the Salina Group westward into Ohio to the vicinity of the Cambridge structural discontinuity is speculative. Fractures in Devonian strata that are related to movement along the Salina décollement may be present along the northeastern margin of the Northwestern Ohio Shale AU, generally from southeastern Ohio, through the panhandle of West Virginia, to the Bass Islands trend (fig. 27) in southwestern New York (Charpentier and others, 1993; Shumaker, 1996, fig. 6).

Petroleum source rocks.—The petroleum source rocks for the Northwestern Ohio Shale AU are thought to be the Devonian shale. The greatest thickness of Devonian black shale extends from the Greater Big Sandy AU in eastern Kentucky northward into eastern Ohio, where the cumulative thickness of potential source rocks locally exceeds 400 ft (fig. 15; de Witt and others, 1993, fig. 2). Kerogen types in this area are generally derived from marine biota, especially algae (*Tasmanites*), and are commonly type I and II kerogens, which are prone to generate oil as well as natural gas (Maynard, 1981; Zielinski and McIver, 1982). Although vitrinite-reflectance data from dispersed organic matter in the Devonian shale indicate that this area is thermally immature to marginally mature with respect to oil generation (figs. 11, 13), oil is found in wells scattered throughout much of the assessment unit (figs. 27, 28). Streib (1981) reported that the total organic carbon (TOC) content of 6 samples from the Cleveland Member of the Ohio Shale averaged about 7.46 percent in Gallia County, Ohio (table 3).

Thermal maturity.—Devonian shale in most of the Northwestern Ohio Shale AU has dispersed vitrinite values within the range of 0.6 to 0.79 %R_o (figs. 12, 13), which is within the thermal maturity window for oil generation (Repetski and others, 2008). On the basis of the burial history curve for the Amerada No. 1 Ullman well in Noble County, Ohio (figs. 24, 29), the lower part of the Devonian shale in the eastern part of the Northwestern Ohio Shale AU appears to have entered the oil window sometime during the Middle Triassic (Ryder and others, 1998), but subsequent work on the Ullman well indicates that basal Devonian shale in southeastern Ohio entered the oil window during the Mississippian and entered the gas window during the latest Permian or earliest Triassic (Rowan, Ryder, Repetski, and others, 2004; Rowan, Ryder, Swezey and others, 2004; Rowan, 2006). In this area, the top of the Devonian shale entered the oil window during the latest Permian or earliest Triassic, but remained immature with regard to thermal generation of natural gas. The western part of the Northwestern Ohio Shale AU in Ohio may be generally immature with respect to the generation of hydrocarbons (Repetski and others, 2008).

Reservoir and production data.—In the Northwestern Ohio Shale AU, the stratigraphic names and reservoir data vary from State to State. In much of Ohio, the Devonian shale

source rocks and reservoirs consist predominantly of the Huron and Cleveland Members of the Ohio Shale (figs. 25, 26). In western New York, the producing units are the Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Member of the West Falls Formation, and the Marcellus Shale (fig. 9). The available gas field data (fig. 29) show that the average thickness completed (by field) ranges up to 352 ft in northeastern Kentucky (Naples field), up to 600 ft in eastern Ohio (Brookville field), and up to 378 ft in western West Virginia (Apple Grove field). The depths to the producing reservoirs range generally from about 365 ft in north-central Ohio (Lewin and Associates, 1983) to 2,300 ft in southern Ohio and to 4,000 ft or more in western West Virginia and adjacent Kentucky. The average log-derived porosity values range from about 3 to 14 percent in the Newton field in central Ohio, and up to 16 percent in the Darlington field in western Pennsylvania (Roan and Walker, 1996). Maximum porosity values of 8 and 9 percent have been reported for other fields (Boswell, 1996). Lewin and Associates (1983) used nominal values of 1 percent for shale matrix porosity and 5×10^{-6} millidarcies for shale matrix permeability. Soeder and others (1986) observed that shale samples from wells in the lower part of the Huron Member of the Ohio Shale in southeastern Ohio and northwestern West Virginia contain liquid petroleum in their pores. As a result, the ratio of matrix permeability to gas is very low (in the range of tens of nanodarcies), and gas-filled porosity is generally less than 0.1 percent (Soeder and others, 1986).

The database that accompanies Roan and Walker (1996) lists 49 named gas fields within the boundaries of the Northwestern Ohio Shale AU (fig. 28). Although these fields are administrative entities for State regulatory agencies, the fields are part of the continuous accumulation that constitutes the Northwestern Ohio Shale AU. Cumulative production data are generally not available from these fields, and much of the gas production from the Northwestern Ohio Shale AU is commingled with production from other stratigraphic units.

Several published estimates of gas resources in the area of the Northwestern Ohio Shale Assessment Unit exist, although they did not use the same methodology that was used in the 2002 USGS assessment. For example, Lewin and Associates (1983), Kuuskraa and Wicks (1984), and Kuuskraa and others (1985) portioned areas of Ohio, West Virginia, and Kentucky into different geological settings (fig. 30), and they estimated the gas-in-place resources in the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation (within the area of the Northwestern Ohio Shale Assessment Unit) to be about 112 TCF. Charpentier and others (1993), however, estimated the mean gas-in-place resources in the approximate area of the assessment unit to be about 245 TCF (table 2, fig. 19).

Using data from Roan and Walker (1996), the distribution (by thirds) of estimated ultimate recovery (EUR) values of gas per well calculated for shale gas wells in the Northwestern Ohio Shale AU is shown in figure 31. At the median, the early third of the wells attained an EUR of about 37 MMCF,

the middle third attained about 48 MMCF, and the late third attained about 40 MMCF.

USGS assessment results.—For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian Basin Petroleum Province, the USGS estimated a range from 1,453.59 to 4,338.99 BCF of gas and from 25.95 to 93.32 million barrels (MMB) of natural gas liquids in the Northwestern Ohio Shale AU. The mean values for these estimates are 2,654.07 BCF of gas and 53.08 MMB of natural gas liquids in the Northwestern Ohio Shale AU (Milici and others, 2003).

Devonian Siltstone and Shale Assessment Unit

The Devonian Siltstone and Shale Assessment Unit (AU) extends across the Appalachian Basin Petroleum Province from western New York through western Pennsylvania and central West Virginia into southwestern Virginia (figs. 15, 32). This assessment unit follows the depositional strike throughout much of the basin, except at its northern end in New York. The western boundary of the assessment unit lies along the 0.6-% R_0 Devonian thermal isoline in New York, Pennsylvania, and Ohio (fig. 12, 15). To the south in West Virginia and Virginia, the western boundary of the assessment unit lies along the eastern margin of the Greater Big Sandy AU. This assessment unit is generally coincident with much of the area occupied by play D_{bg} (Upper Devonian fractured black and gray shales and siltstones) of Milici (1996a), and the geology of the region is described in more detail there. The Devonian Siltstone and Shale AU is geographically intermediate between shale of the Greater Big Sandy AU and the Northwestern Ohio Shale AU on the west and coarser-grained strata of the Catskill Sandstones and Siltstones AU on the east (Filer, 1985; Boswell, Heim, and others, 1996a; Boswell, Thomas, and others, 1996b; Donaldson and others, 1996). The Devonian Siltstone and Shale AU includes the “emerging area” of Patchen and Hohn (1993) in northwestern West Virginia.

The overall thickness of the Devonian section in the area of the assessment unit ranges from 1,000 ft or less in western New York to 6,000 ft in central Pennsylvania. The thickness of the Devonian strata in the assessment unit thin farther to the south to less than 1,000 ft in southwestern Virginia (fig. 32). The net thickness of the black shale in the assessment unit ranges from less than 100 ft in West Virginia to a little more than 500 ft in southwestern New York and adjacent Pennsylvania (fig. 16).

Stratigraphy.—The Devonian Siltstone and Shale AU generally lies between the eastern limit of the upper black shale tongue of the Huron Member of the Ohio Shale and the eastern limit of the Rhinestreet Shale Member of the West Falls Formation (fig. 4). The Devonian Siltstone and Shale AU consists of dark-gray to black shale that is interbedded with gray and greenish-gray shale and siltstone (de Witt and others, 1993). The assessment unit includes all of the strata from the

base of the Hamilton Group (Marcellus Shale) to the top of the Sunbury Shale. The major black shale units in the assessment unit are the Marcellus Shale at the base, the Pipe Creek Shale Member of the Java Formation, the lower part of the Huron Member of the Ohio Shale, and the Dunkirk Shale Member of the Perrysburg Formation (figs. 4, 25, 26).

Structure.—The relation of producing areas in the Devonian Siltstone and Shale AU to geologic structure is shown in figure 33. Much of the assessment unit is deformed to some extent by a limited décollement in Devonian shale in the area south of the Rome trough in southern West Virginia and southwestern Virginia. North of the trough, in northwestern Pennsylvania, a limited décollement within evaporite beds of the Silurian Salina Group has resulted in shortening and folding of the hanging wall into a series of relatively low amplitude folds (fig. 27). The coincidence of a subhorizontal décollement within the black shale, the fractured superficial anticlines that were formed by splay faults from the décollement in the underlying Silurian evaporite beds (Filer, 1985; Sweeney, 1986), and perhaps any late-stage movement on steeply dipping faults associated with the Rome trough (Caramanica, 1988) appear to have increased the fracture porosity within the assessment unit, especially where siltstone and fine-grained sandstone are intercalated with black shale. In the “emerging area” of Patchen and Hohn (1993) in northwestern West Virginia, the two main plays are the Huron Member of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation. The fracture porosity within these shale units appears to be related to folds that were formed by a limited décollement in the underlying Silurian evaporite beds (Shumaker, 1993).

Petroleum source rocks.—The petroleum source rocks for the Devonian Siltstone and Shale AU are thought to be the Devonian shale. Except in southwestern New York and western Pennsylvania, the Devonian Siltstone and Shale AU lies along the eastern margin of thick shale, where the net thickness of black shale ranges from about 100 ft to as much as 250 ft. In northern Pennsylvania, however, the net thickness of black shale is 500 ft or more (fig. 15). Because the assessment unit is located in the center of the basin and presumably was close to the source of terrigenous clastic sediments, the Devonian Siltstone and Shale AU should contain greater proportions of type III kerogen than the assessment units to the west (Maynard, 1981; Zielinski and McIver, 1982). The geochemical characteristics of samples from the Devonian Siltstone and Shale AU are listed in table 3 (Streib, 1981). Streib (1981) reported that the total organic carbon (TOC) content of one sample from the Marcellus Shale in a well in Wetzell County, West Virginia, was 6.19 percent (table 3).

Thermal maturity.—On the basis of dispersed vitrinite-reflectance data, the Devonian shale in the Devonian Siltstone and Shale AU is located to the east of the 0.6-% R_o thermal isoline (fig. 11). The assessment unit, therefore, is thermally mature with respect to the generation of hydrocarbons. To the east, the assessment unit reaches the 2.0-% R_o isoline (the

eastern limit of oil preservation) in western Pennsylvania and the 4.0-% R_o isoline in southern West Virginia (figs. 11, 12). Oil is commonly produced with gas in much of the assessment unit area because of the increased fracture porosity in the interbedded siltstones of the Devonian Siltstone and Shale AU (fig. 32). Where thermal maturity is the greatest in central Pennsylvania and in the southern part of the assessment unit, however, gas is the primarily produced hydrocarbon.

Model-predicted vitrinite-reflection values from three wells in the Devonian Siltstone and Shale AU in western West Virginia indicate that the base of the Devonian shale entered the oil window during the Pennsylvanian and entered the gas window during the Permian (Rowan, Ryder, Repetski, and others, 2004; Rowan, Ryder, Swezey, and others, 2004; Rowan, 2006). Calculated vitrinite-reflectance values for these wells (the No. 1 Gainer-Lee, the No. 1 McCoy, and the No. 1 Deem wells) are based on vitrinite-reflectance values from Pennsylvanian coal beds and are significantly greater than the values determined from dispersed vitrinite in the basal Devonian shale (fig. 12). For example, the calculated vitrinite-reflectance value for the No. 1 Gainer-Lee well is 2.17 % R_o , which is significantly greater than the 1.5-% R_o value to the east that was determined from vitrinite dispersed in the shale.

Reservoir and production data.—In the Devonian Siltstone and Shale AU, the principal gas-producing units are the Rhinestreet Shale Member of the West Falls Formation, the lower part of the Huron Member of the Ohio Shale, and (to a lesser extent) the Marcellus Shale (figs. 25, 26). Completion intervals range generally from 10 to nearly 1,600 ft, final open flow rates range from 30 to 1,500 thousand cubic feet (MCF) per day, and initial reservoir pressures range from 125 to 2,529 lb/in². Although the data are limited, log-derived porosity values are as high as 8 percent (see database that accompanies Roen and Walker, 1996). Drilling depths range from several hundred feet or more in New York to about 5,000 ft in West Virginia.

The database that accompanies Roen and Walker (1996) lists 68 named gas fields within the boundaries of the Devonian Siltstone and Shale AU (fig. 34). Of the few fields for which data are available, the average thickness completed was greatest at 1,590 ft in the Blue Creek field in Kanawha County, West Virginia (fig. 34). Although oil and gas exploration has occurred over much of the assessment unit (fig. 32), exploration has been concentrated in west-central West Virginia, which is the “emerging area” of Patchen and Hohn (1993). Patchen and Hohn (1993, p. L26) concluded “. . . that the overall emerging area of Devonian shale oil and gas production has been overpromoted and will prove to be non-commercial to many operators and investors.” Subsequently, Douglas Patchen (West Virginia Geological and Economic Survey, written commun., 2005) indicated that production from wells drilled more recently has improved since their 1993 publication. In addition, production from many of the newer shale-gas wells is commingled with production from Devonian sandstone reservoirs.

Several published estimates of gas resources in the area of the Devonian Siltstone and Shale AU exist, although they did not use the same methodology that was used in the 2002 USGS assessment. For example, Tetra Tech, Inc. (1981) estimated 482 TCF (black shale thickness determined from log data) to 790 TCF (black shale thickness determined from sample data) of gas-in-place resources in the approximate area of the assessment unit in Pennsylvania, with relatively favorable areas for shale gas occurring in the Rhinestreet Shale Member of the West Falls Formation and the Dunkirk Shale Member of the Perrysburg Formation in northeastern Pennsylvania and in the Marcellus Shale in west-central Pennsylvania (fig. 35). Lewin and Associates (1983) estimated that the Devonian shale in the approximate area of the assessment unit in Ohio contained 3.5 TCF (figure 35), and Kuuskraa and Wicks (1984) estimated that the Devonian shale in the approximate area of the assessment unit in West Virginia contained 53.4 TCF (figure 35). Charpentier and others (1993) estimated the mean gas-in-place resources in the approximate area of the assessment unit to be about 228 TCF (fig. 19, table 2).

Using data from Roen and Walker (1996), the distribution (by thirds) of estimated ultimate recovery (EUR) values of gas per well calculated for shale gas wells in this assessment unit is shown in figure 36. At the median, the early third of the wells attained an EUR of about 55 MMCF, the middle third attained about 33 MMCF, and the late third attained about 30 MMCF.

USGS assessment results.—For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian Basin Petroleum Province, the USGS estimated a range from 829.34 to 1,925.18 BCF of gas and from 4.50 to 23.14 MMB of natural gas liquids in the Devonian Siltstone and Shale AU. The mean values for these estimates are 1,293.61 BCF of gas and 31.05 MMB of natural gas liquids in the Devonian Siltstone and Shale AU (Milici and others, 2003).

Marcellus Shale Assessment Unit

The Marcellus Shale Assessment Unit (AU) extends southward from central Pennsylvania, southwestern New York, and eastern Ohio through West Virginia to southwestern Virginia. This assessment unit lies generally to the east of the Devonian Siltstone and Shale AU, where the thickness of Marcellus Shale is greater than 50 ft (fig. 37).

Stratigraphy.—The Marcellus Shale AU includes the Hamilton Group (Marcellus Shale and Mahantango Formation) in much of the Appalachian basin and the Millboro Shale in Virginia (fig. 4). Although the Hamilton Group and the Millboro Shale may attain thicknesses of 1,000 ft and 1,500 ft, respectively, the net thickness of the black shale within these units ranges generally from less than 50 ft in Ohio and the western parts of New York, Pennsylvania, and northern West Virginia to about 200 ft in northeastern Pennsylvania (de Witt and others, 1993).

Structure.—The Marcellus Shale AU is underlain by a regional décollement in evaporite beds of the Silurian Salina Group (fig. 3) in the Appalachian Plateau region of Pennsylvania, northern West Virginia, and eastern Ohio (Frey, 1973). In this region, the Marcellus Shale is folded into numerous rootless folds, and interstratal slip during folding may have increased the fracture porosity within the shale.

Petroleum source rocks.—The petroleum source rocks for the Marcellus Shale AU are thought to be the Devonian shale. The total organic carbon (TOC) contents of samples from the Marcellus Shale (table 4) show that the organic richness of the Marcellus Shale decreases generally from New York southward to West Virginia (Weary and others, 2000, 2001; Repetski and others, 2002, 2005). These variations appear to reflect the overall paleogeography, with the higher TOC content in the more distal parts (New York) and the lower TOC content in the more proximal parts (West Virginia) of the siliciclastic depositional system. The TOC data presented in table 4 include samples of the Marcellus Shale that were collected from wells distributed across several of the assessment units. In general, the higher TOC values for the Marcellus Shale in New York occur in the Northwestern Ohio Shale AU and in counties that lie along the border of the Northwestern Ohio Shale AU and Devonian Siltstone and Shale AU (table 4). In New York, the TOC content of 19 samples of the Marcellus Shale averaged 4.3 percent (table 4), but only 8 of these 19 samples were collected within the area of the USGS Marcellus Shale Assessment Unit. In Pennsylvania, however, the TOC content of 36 samples averaged 3.61 percent (table 4), but only 23 of these 36 samples were collected from within the area of the USGS Marcellus Shale Assessment Unit. In West Virginia, the TOC content of 22 samples of the Marcellus Shale averaged 1.40 percent (table 4), but only 13 of these 22 samples were collected within the area of the USGS Marcellus Shale Assessment Unit.

Thermal maturity.—Devonian shale in much of the Marcellus Shale AU has dispersed vitrinite values of 1.5 to 3.0 %R_o (figs. 11, 12), which is within thermal maturity windows for gas generation (Repetski and others, 2008). In the Amerada No. 1 Ullman well, the maximum depth of burial of the Marcellus Shale ranges from about 7,000 to 10,000 ft (fig. 29). Because of its more eastward location and greater depth of burial, the Marcellus Shale probably attained thermal maturity earlier during the Paleozoic than did stratigraphically higher Devonian shale to the west.

Reservoir and production data.—The database that accompanies Roen and Walker (1996) lists only one field (Genegants field in New York) in the Marcellus Shale AU (fig. 34). Wells in this field have been drilled to 2,000 ft or more and may bottom in Lower Devonian limestone.

Several published estimates of gas resources in the area of the Marcellus Shale AU exist although they did not use the same methodology that was used in the 2002 USGS assessment. For example, Kuuskraa and Wicks (1984) estimated the gas-in-place resources in the Marcellus Shale in eastern West Virginia to be about 101 TCF. In comparison, Charpentier and

others (1993) estimated the mean gas-in-place resources in the Marcellus Shale in northern West Virginia, central Pennsylvania, and southwestern New York (in an area that is larger than the Marcellus Shale AU described in this publication) to be about 295 TCF (table 2). At a 10 percent recovery factor, these estimates would yield almost 30 TCF of gas.

USGS assessment results.—For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian Basin Petroleum Province, the USGS estimated a range from 821.83 to 3,667.59 BCF of gas and from 4.50 to 23.14 MMB of natural gas liquids in the Marcellus Shale AU. The mean values for these estimates are 1,925.18 BCF of gas 11.55 MMB of natural gas liquids in the Marcellus Shale AU (Milici and others, 2003). USGS oil and gas assessments of the Appalachian Basin Petroleum Province are based largely on previous well performance within the assessment units. At the time of the 2002 assessment, very little drilling had occurred within the Marcellus Shale AU. Accordingly, the Greater Big Sandy AU was used as a partial analog for assessing the Marcellus Shale AU.

The area of the Marcellus Shale AU, as it was assessed by the USGS in the 2002, does not encompass the entire extent of the Marcellus Shale geologic unit. Some of the mapped extent of the Marcellus Shale extends to the east of the Marcellus Shale AU and into the Devonian Siltstone and Shale AU. A vitrinite reflectance value of 2 %R_o is taken as the boundary between the two assessment units. Although large amounts of gas are produced from Devonian shale to the west of the 2-%R_o isoline, the thickness of the Marcellus Shale is less than 50 ft to the west of this isoline in western New York, western Pennsylvania, western West Virginia, and eastern Ohio. Residual oil in this area of lower thermal maturity may clog porosity and interfere with gas production. Accordingly, the most productive area (“sweet spot”) for the Marcellus Shale is thought to extend from south-central New York to southwesternmost Pennsylvania and then into adjacent West Virginia (fig. 37). In 2002, the USGS estimated that technically recoverable undiscovered gas resources in the Marcellus Shale AU ranged from a minimum of 0.83 TCF to a maximum of 3.67 TCF (Milici and others, 2003). In 2008, Engelder (*in Kane, 2008*) estimated that the Marcellus Shale contained 1,307 TCF of gas. Engelder’s study encompassed a larger area than the Marcellus Shale AU described in this publication and Engelder’s estimates were based largely on estimated gas-in-place resources that he calculated for that area. Engelder and Lash (2008) estimated that the Marcellus Shale might contain more than 500 TCF of gas-in-place resources, of which about 10 percent (50 TCF) might be recoverable. More recently, Engelder (2009) estimated that, after a 50-year decline, the estimated ultimate recovery (EUR) values from the Marcellus Shale would range from about 221 TCF (a 90 percent chance of at least this amount) to 867 TCF (a 10 percent chance of at least this amount), with a 50 percent probability that the Marcellus Shale would ultimately yield 489 TCF. In 2011, the USGS published a revised study of the Marcellus Shale (Coleman and others, 2011) that estimated that technically

recoverable undiscovered gas resources in the Marcellus Shale ranged from 43 to 144 TCF. This revised USGS estimate, however, considered an area that is much larger than the Marcellus Shale AU of the 2002 USGS assessment.

Summary

In 2002, the U.S. Geological Survey (USGS) conducted an assessment of the technically recoverable undiscovered oil and gas resources of the Appalachian Basin Petroleum Province in the eastern United States. This assessment identified six total petroleum systems, one of which is the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System (TPS). The oil and gas of this TPS are derived from Devonian shale, and the reservoir intervals encompass a variety of middle and upper Paleozoic strata. This TPS is divided into 10 assessment units (reservoir intervals), including the following four Devonian shale-gas assessment units: (1) the Greater Big Sandy AU, which is located primarily in eastern Kentucky; (2) the Northwestern Ohio Shale AU, which is located in eastern Kentucky, east-central Ohio, western Pennsylvania, and western New York; (3) the Devonian Siltstone and Shale AU, which extends across western New York through western Pennsylvania and central West Virginia into southwestern Virginia; and (4) the Marcellus Shale AU, which extends southward from central Pennsylvania, southwestern New York, and eastern Ohio through West Virginia to southwestern Virginia. These four AUs are composed of Devonian shale, siltstone, and fine-grained sandstone. They are considered to be continuous (unconventional) assessment units in which the shale is both the petroleum source rock and the reservoir interval. In the 2002 USGS assessment, the Greater Big Sandy AU was estimated to contain 3,877.33 to 9,562.42 billion cubic feet (BCF) of gas and 34.06 to 104.50 million barrels (MMB) of natural gas liquids. The Northwest Oil Shale AU was estimated to contain 1,453.59 to 4,338.99 BCF of gas and 25.95 to 93.32 MMB of natural gas liquids. The Devonian Siltstone and Shale AU was estimated to contain 829.34 to 1,894.48 BCF of gas and 17.35 to 50.08 MMB of natural gas liquids. The Marcellus Shale AU was estimated to contain 821.83 to 3,667.59 BCF of gas and 4.50 to 23.14 MMB of natural gas liquids.

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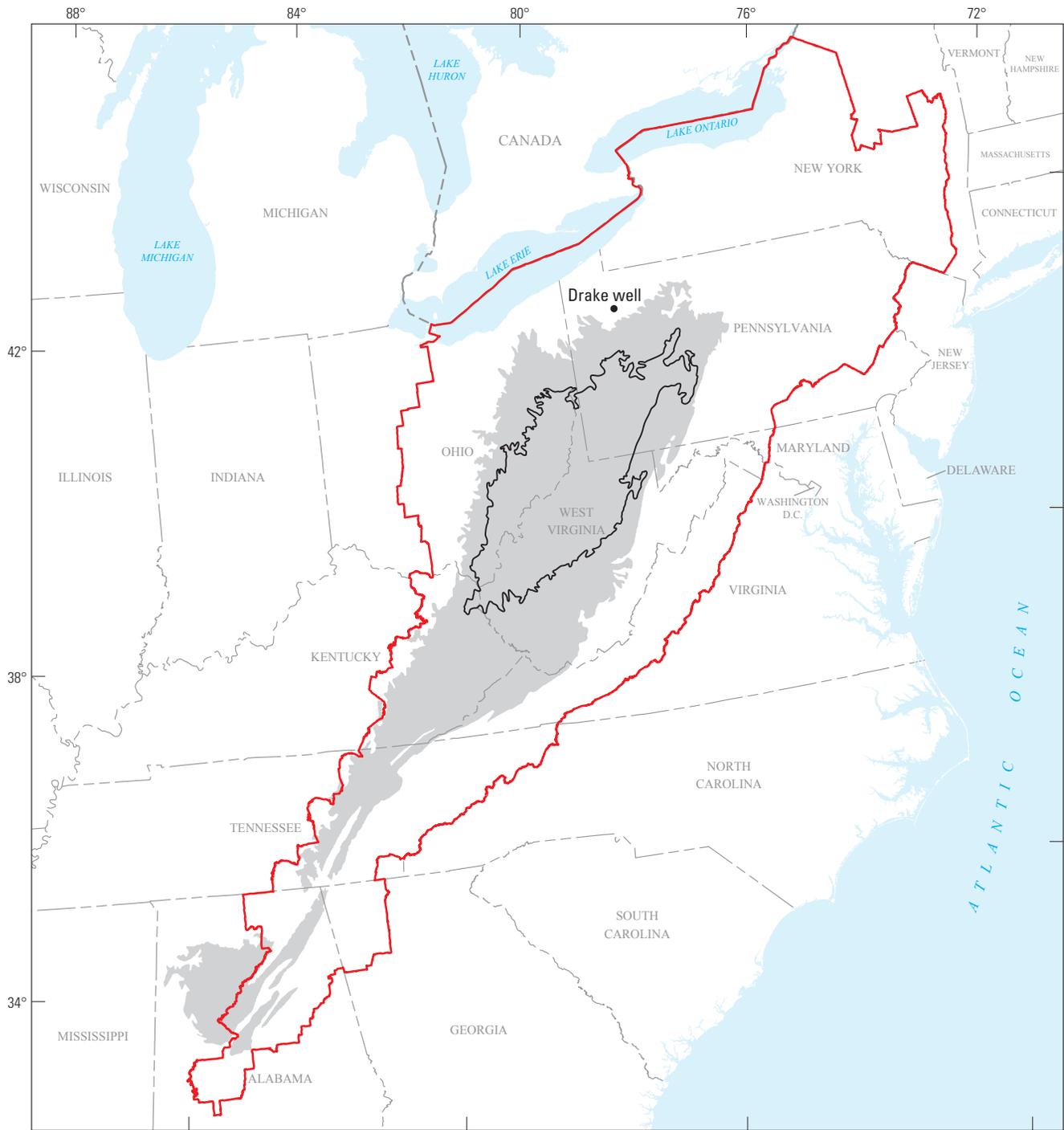
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Figures 1–37 and Tables 1–4

24 Coal and Petroleum Resources in the Appalachian Basin



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Area of Appalachian Plateau region**
- Boundary of Appalachian Basin Petroleum Province**
- Boundary of Dunkard subbasin**

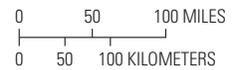
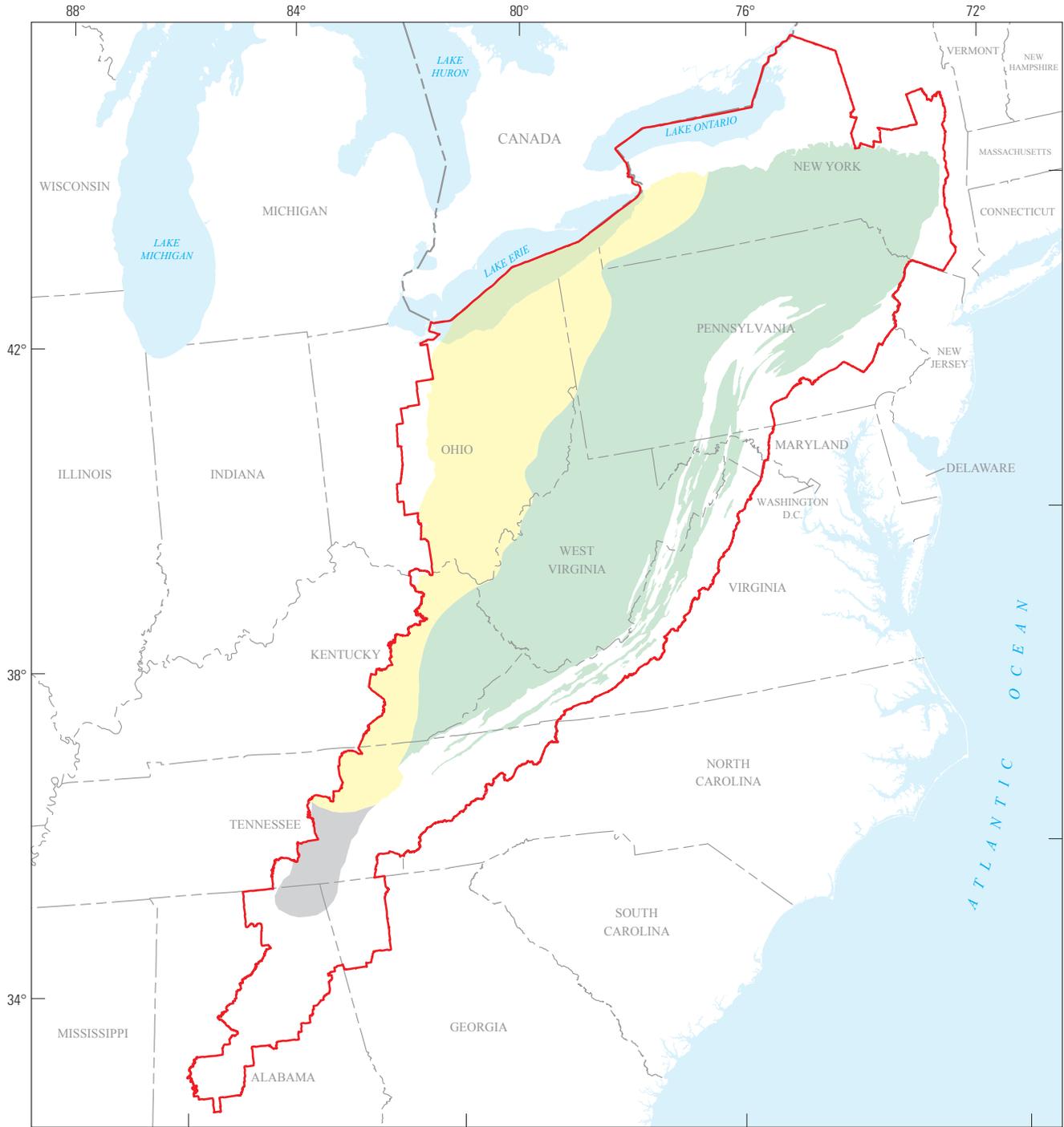


Figure 1 (facing page). Map showing the location of the Appalachian Basin Petroleum Province and the location of the Drake oil well. In 2002, the U.S. Geological Survey assessed the undiscovered oil and gas resources of the United States' portion of this province (Milici and others, 2003).

26 Coal and Petroleum Resources in the Appalachian Basin



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Devonian Shale-Middle and Upper Paleozoic Total Petroleum System**
- Area of thermally immature Devonian shale
 - Area of thermally mature Devonian shale
 - Unassessed area of Devonian shale
 - Boundary of Appalachian Basin Petroleum Province**



Figure 2 (facing page). Map showing the extent of the the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System (TPS) within the Appalachian Basin Petroleum Province. The green, yellow, and gray areas represent the extent of the Devonian and Lower Mississippian shale. The yellow area represents the extent of thermally immature source rocks, and the green area represents the extent of thermally mature source rocks. The mature source rocks (green) of this TPS are of Devonian age. The gray areas were not assessed. Additional data on thermal maturity of the Devonian shale may be found in East and others (2012).

ERATHEM SYSTEM (AND SERIES WHERE SHOWN)	STRATIGRAPHIC UNIT	RESERVOIR	ASSESSMENT UNIT TYPE	SOURCE ROCK	TOTAL PETROLEUM SYSTEM	
PERMIAN	Dunkard Group					
	PENNSYLVANIAN	Monongahela Group	Coal, sandstone	Continuous	Coal, black shale	Carboniferous Coal-bed Gas
		Conemaugh Group	Coal, sandstone	Continuous	Coal, black shale	
		Allegheny Group	Coal, sandstone	Continuous	Coal, black shale	
Pottsville Group		Coal, sandstone	Continuous	Coal, black shale		
MISSISSIPPIAN	UPPER	Mauch Chunk and Pennington Formation	Ravencliff and Maxon sandstones	Conventional		
		Greenbrier Limestone	Loyalhanna sandstone, "Big lime"	Conventional		
	LOWER	Pocono Formation	Big Injun, Squaw, and Weir sandstones	Conventional		
		Sunbury Shale	Sunbury Shale	Continuous	Sunbury Shale	
DEVONIAN	UPPER	Berea Sandstone	Berea Sandstone	Continuous	Sunbury Shale	
		Hampshire and Brallier Formations; Cleveland and Huron Members of Ohio Shale, and Rhinestreet Shale Member of West Falls Formation	Venango, Bradford, and Elk sandstones; black shale	Continuous	Upper Devonian black shale	
	Harrell Formation	Black shale	Continuous	Burket Member		
	MIDDLE	Hamilton Group	Black shale	Continuous	Marcellus Shale	
		Onondaga Group	Huntersville Chert and "Corniferous lime"	Conventional		
		Huntersville Chert	Huntersville Chert and "Corniferous lime"	Conventional		
	LOWER	Oriskany Sandstone	Oriskany Sandstone	Conventional		
SILURIAN	Helderberg Group					
	Bass Islands Dolomite					
	Salina Group		Regional seal			
	Lockport Dolomite	"Corniferous lime"				
	Clinton Group	Keefer or Big Six sandstone	Continuous			
	Medina Group	Tuscarora and Clinch Sandstones, "Clinton" sandstone, and Medina Group	Continuous			
ORDOVICIAN	Juniata and Bald Eagle Formations	Bald Eagle Sandstone				
	Reedsville Shale					
	Utica Shale	Utica Shale	Continuous	Utica Shale		
	Trenton Limestone	Trenton Limestone	Conventional	Trenton Limestone		
	Black River Limestone	Black River Limestone and Wells Creek dolomite	Conventional	Sevier and Blockhouse Shales		
	Beekmantown Group	Knox Dolomite	Conventional			
CAMBRIAN	Chepultepec and Copper Ridge Dolomites	Rose Run sandstone Knox Dolomite	Conventional			
	Conasauga Group			Conasauga Formation		
	Rome Formation	Rome Formation				
	Mount Simon Sandstone	Mount Simon Sandstone				

EXPLANATION

Predominant lithology of source or reservoir rock

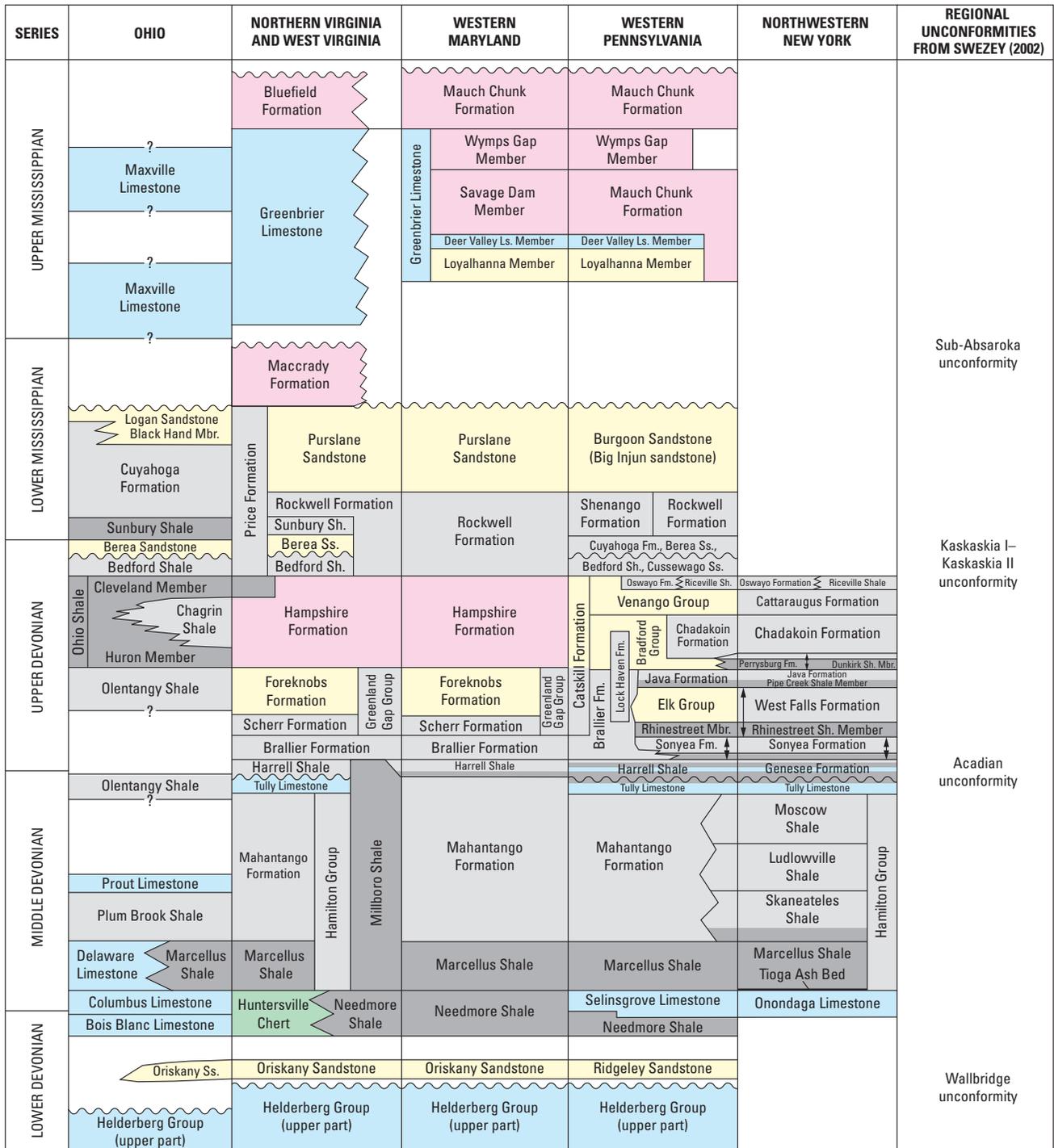
- Coal, black shale, and (or) sandstone
- Black shale and (or) coal
- Sandstone
- Limestone
- Dolomite

Devonian Shale-Middle and Upper Paleozoic

Utica-Lower Paleozoic

Conasauga-Rome/Conasauga

Figure 3. Chart showing the generalized stratigraphy of the Appalachian Basin Petroleum Province and total petroleum system data (adapted from de Witt and Milici, 1991, fig. 2).



EXPLANATION

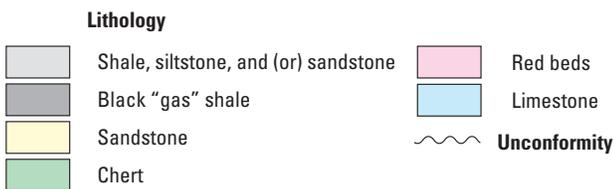
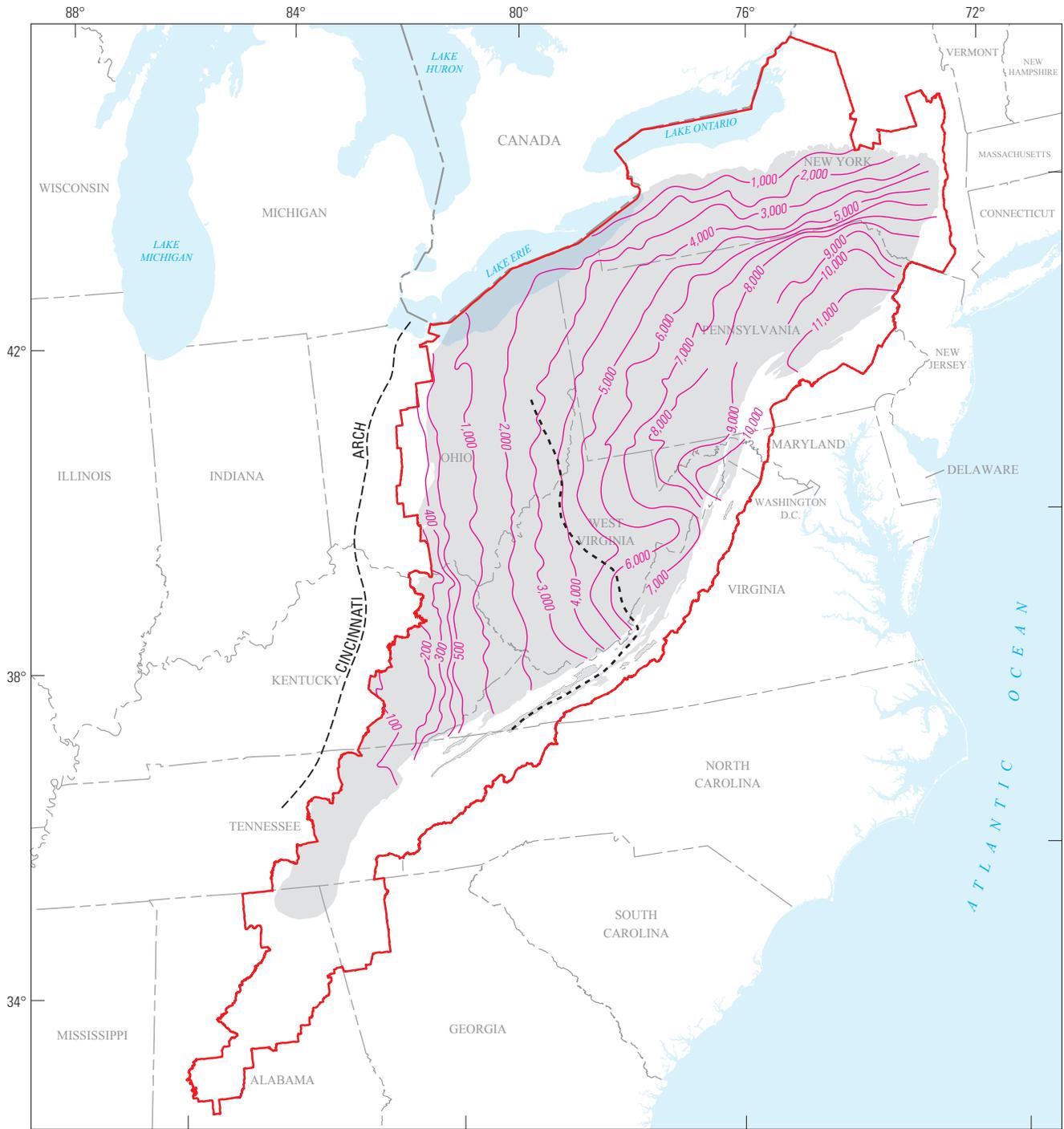


Figure 4. Chart showing generalized stratigraphic nomenclature for Lower Devonian through Upper Mississippian strata in the northern part of Appalachian Basin Petroleum Province (adapted from Patchen and others, 1985a,b; Bjerstedt and Kammer, 1988; Brezinski, 1989a,b, 1999; Filer and others, 1996; Matchen and Vargo, 1996; Milici, 1996c; Vargo and Matchen, 1996; Harper, 1999; Berg, 1999). Abbreviations are as follows: Fm., Formation; Gp., Group; Ls., Limestone; Mbr., Member; Sh., Shale; Ss., Sandstone; undiv., undivided.



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Devonian Shale-Middle and Upper Paleozoic Total Petroleum System**
- Isopach showing thickness of Devonian siliciclastic strata—Contour interval 1,000 feet (ft). West of 1,000-ft isopach line, contour interval is 100 ft**
- Approximate western limit of Upper Devonian through Lower Mississippian siliciclastic strata younger than Hampshire Formation—Adapted from Bjerstedt and Kammer (1988, fig. 13)**
- Approximate trace of Cincinnati arch**
- Boundary of Appalachian Basin Petroleum Province**



Figure 5. Map showing the extent of the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System and thickness of Devonian siliciclastic strata in the Appalachian Basin Petroleum Province (adapted from de Witt and others, 1975).

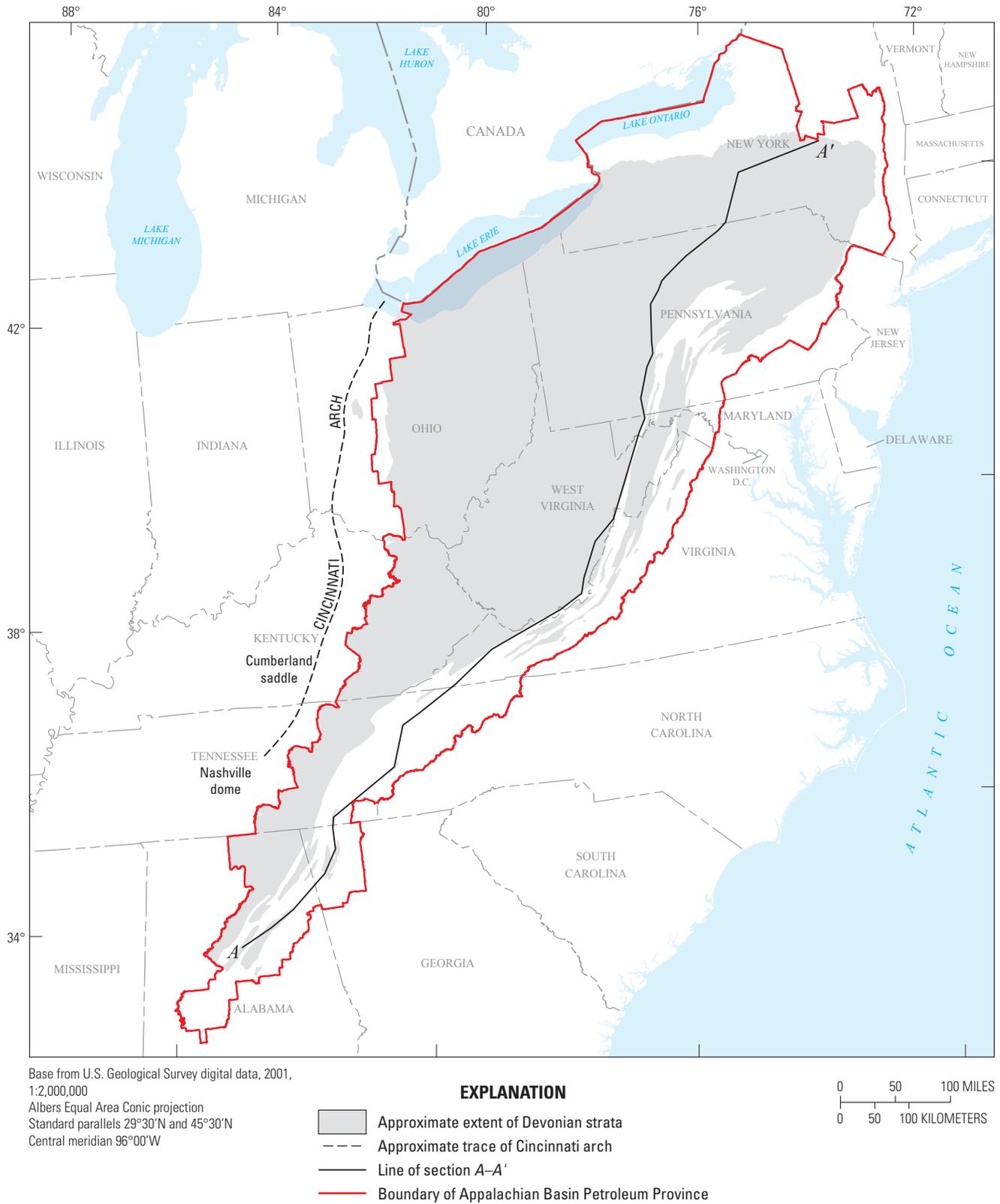


Figure 6. Map showing the extent of Devonian strata in the Appalachian Basin Petroleum Province (from Oliver and others, 1967) and the location of geologic cross section A–A' (fig. 7).

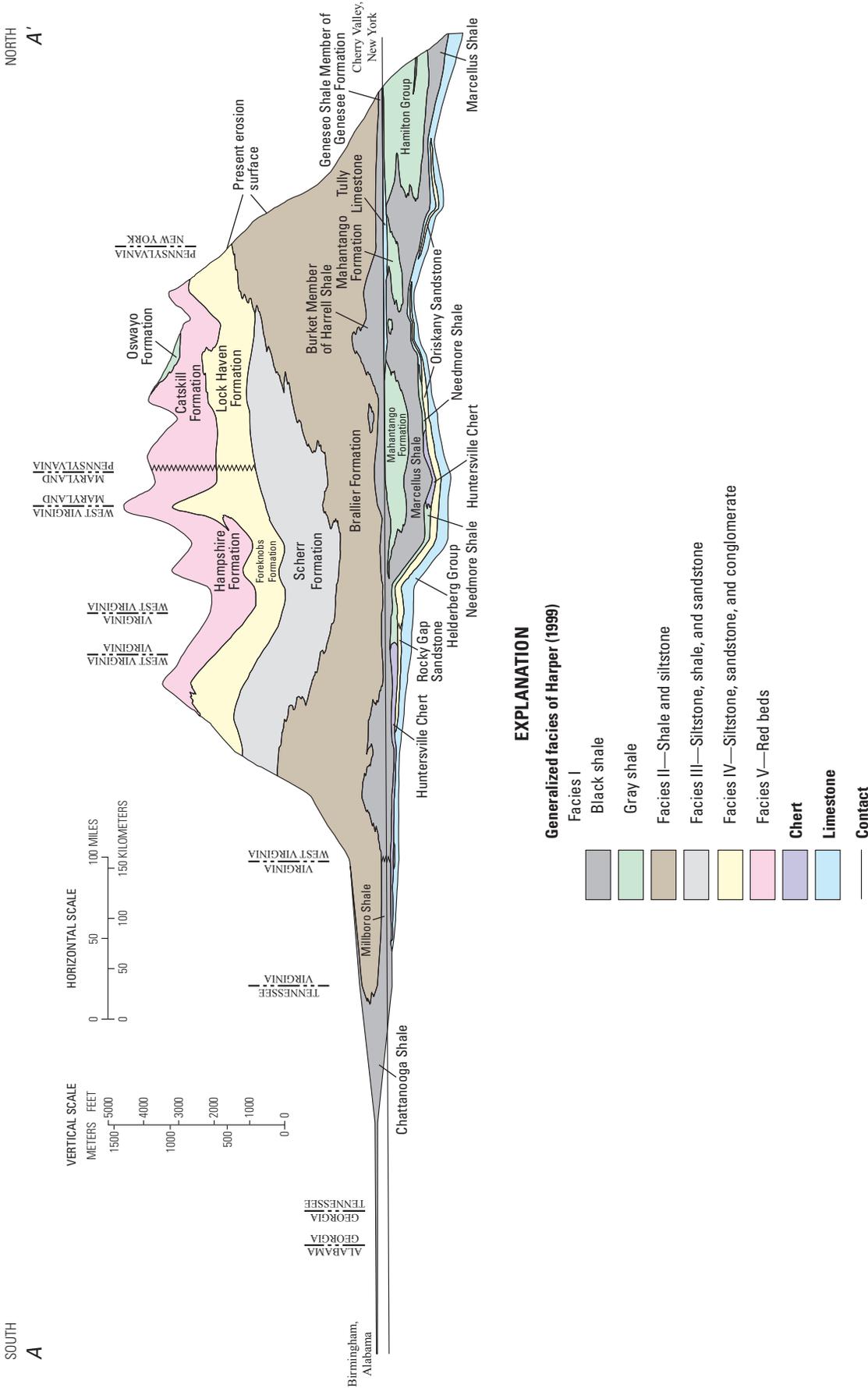


Figure 7. Geologic cross section of Devonian strata from New York to Alabama (after de Witt and others, 1975; modified from Oliver and others, 1967), showing generalized facies of Harper (1999). Datum is base of the Upper Devonian. Location of cross section is shown in figure 6.

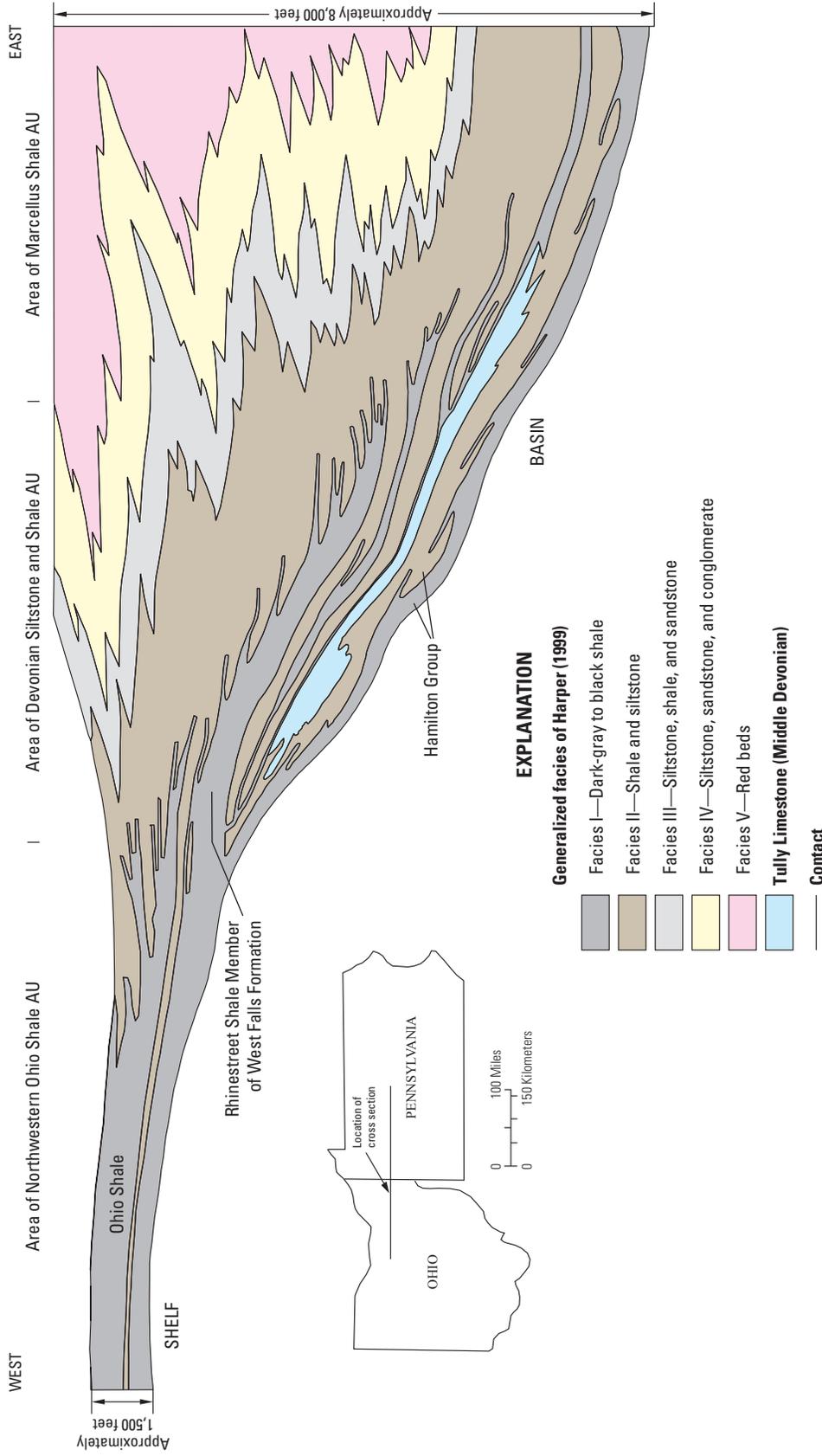


Figure 8. Generalized cross section of Devonian siliciclastic strata across eastern Ohio and western Pennsylvania (adapted from Harper, 1999). The five facies (Facies I through V) of Harper (1999) are shown. The lower part of the section, from the Hamilton Group to the Tully Limestone, is Middle Devonian, and the upper part of the section is Upper Devonian. AU, Assessment Unit.

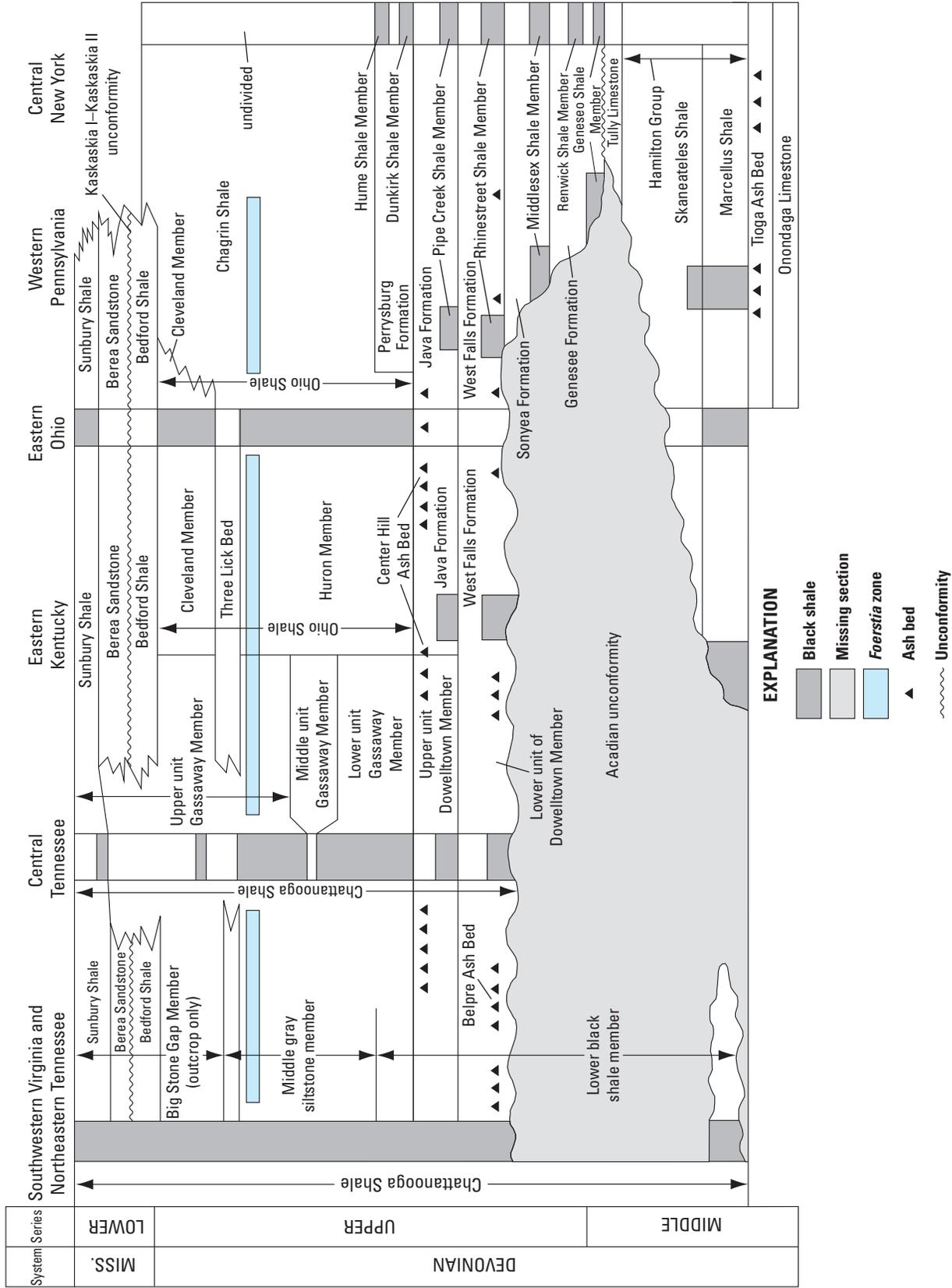


Figure 9. Chart showing the correlation of Devonian and Mississippian black shale units and some related strata in the Appalachian Basin Petroleum Province (modified from de Witt and others, 1993). Miss., Mississippian.

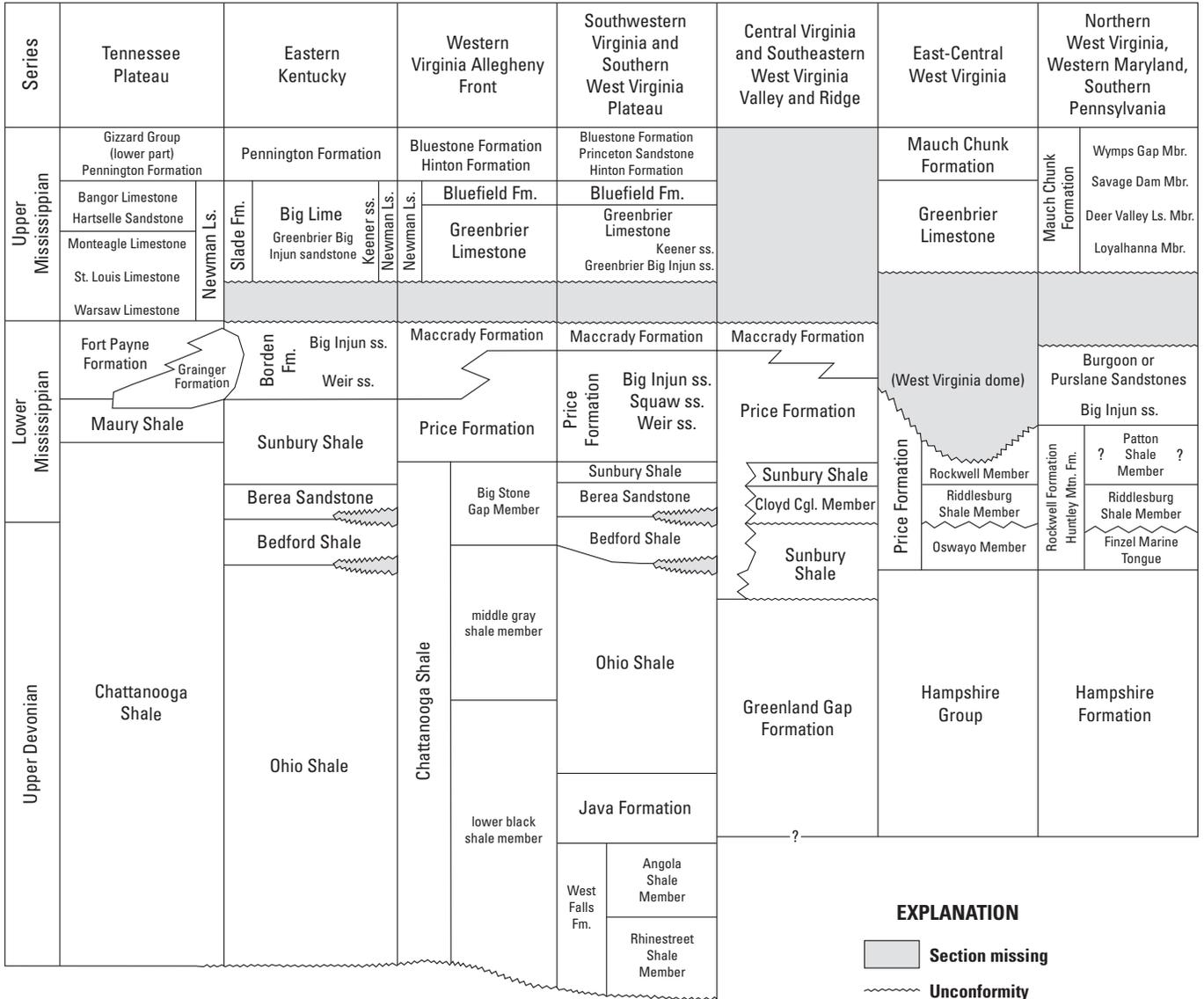


Figure 10. Chart showing stratigraphic nomenclature for the Upper Devonian through Upper Mississippian strata in the eastern part of the Appalachian Basin Petroleum Province (adapted from Patchen and others, 1985a,b; Bjerstedt and Kammer, 1988; Brezinski, 1989a,b, 1999; Filer and others, 1996; Matchen and Vargo, 1996; Milici, 1996c; Vargo and Matchen, 1996; Berg, 1999; Harper, 1999). Abbreviations are as follows: Cgl., Conglomerate; Fm., Formation; Ls., Limestone; Mbr., Member; Mtn., Mountain; ss., sandstone.

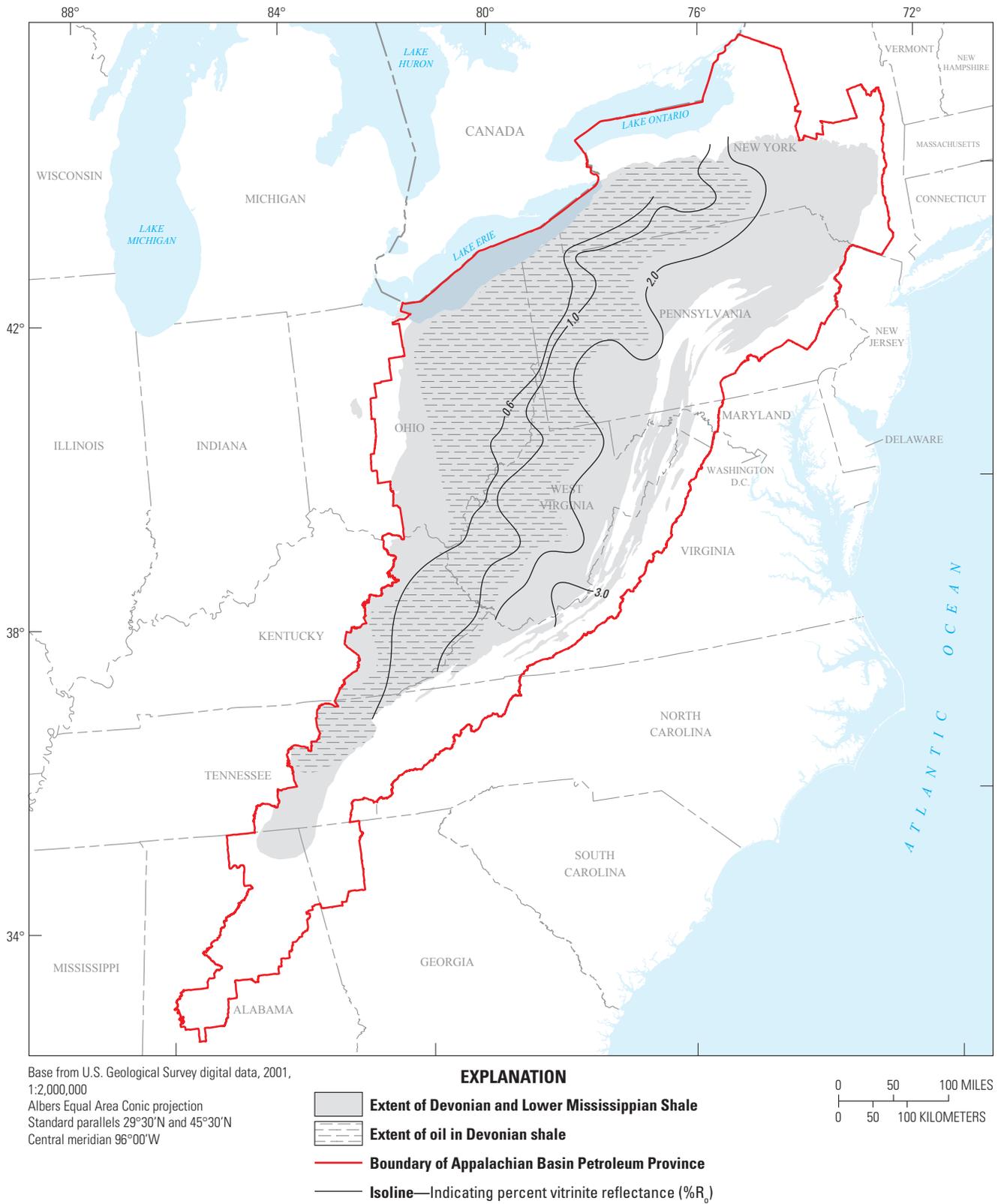


Figure 11. Map of the Appalachian Basin Petroleum Province, illustrating the extent of the Devonian and Lower Mississippian shale, the extent of oil in Devonian shale, and vitrinite-reflectance contours (Weary and others, 2000, 2001; Repetski and others, 2002, 2005; John R. Repetski, oral commun., 2008).

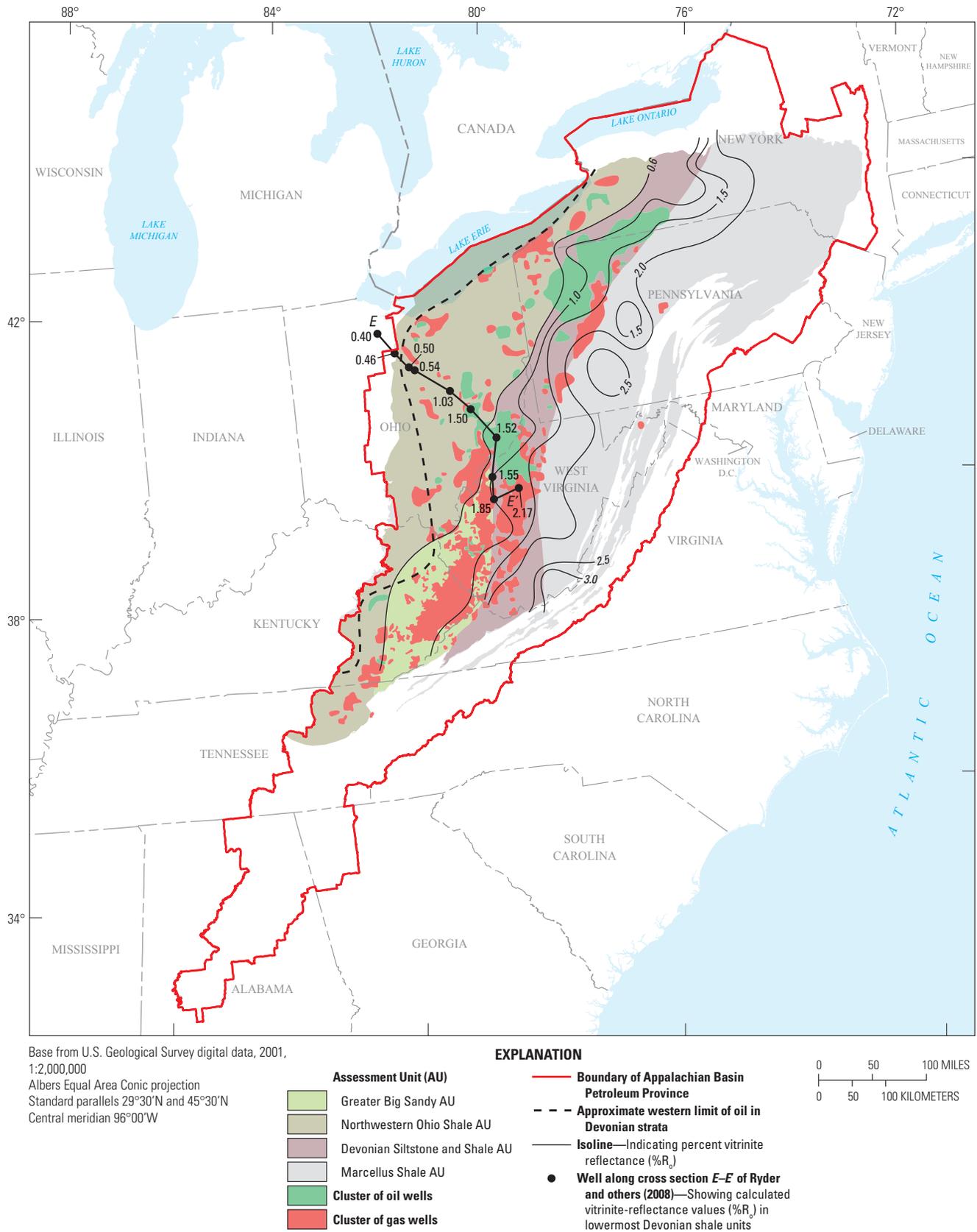
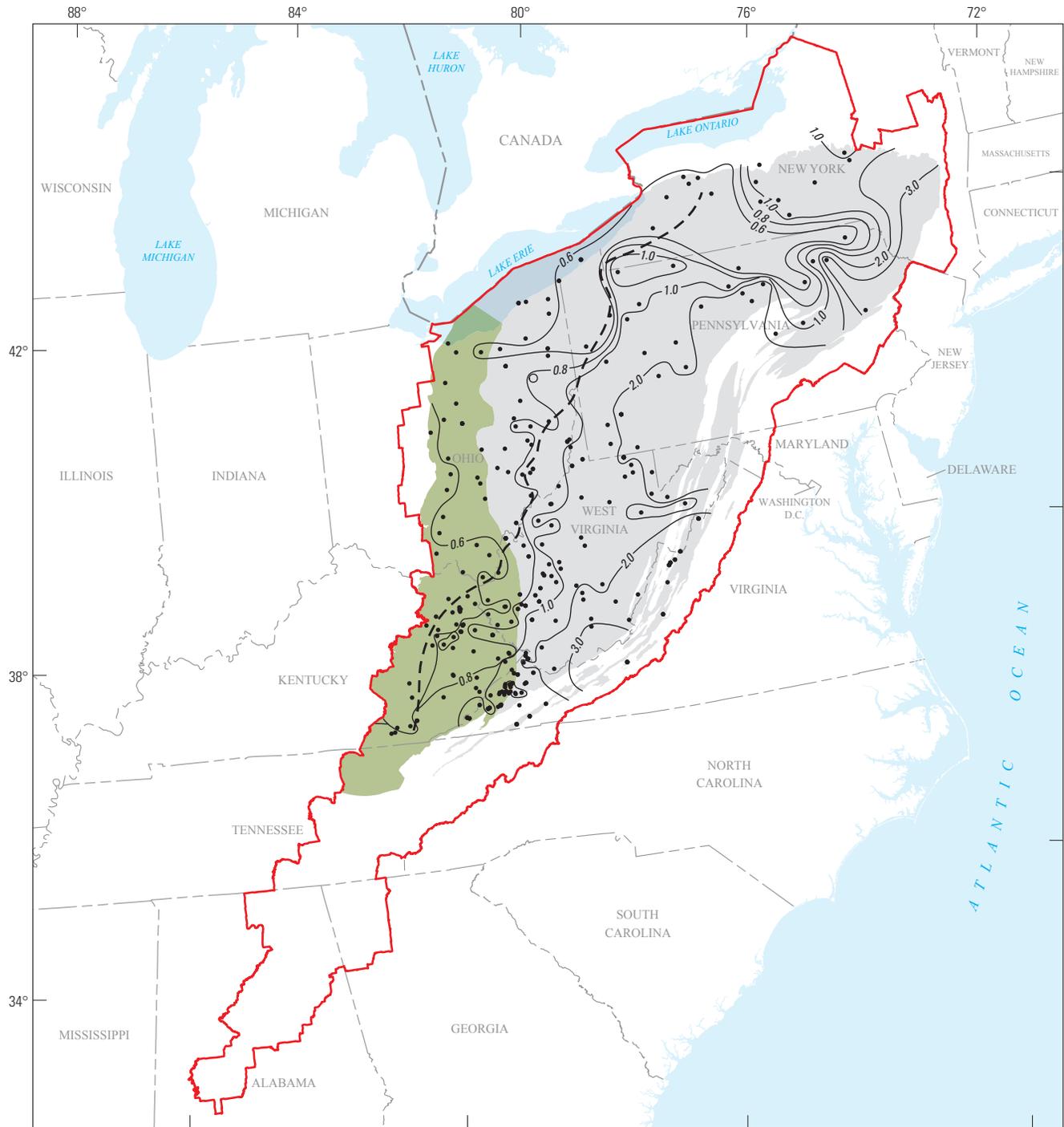


Figure 12. Map showing the four Devonian gas shale assessment units and the distribution of oil and gas wells within the assessment units. Map also shows the vitrinite-reflectance values calculated for wells along cross section E–E' (Rowan and others, 2004a,b) as well as vitrinite-reflectance isolines derived from dispersed vitrinite data (Weary and others, 2000, 2001; Repetski and others, 2002, 2005).



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Extent of Devonian shale beyond the area of the Marcellus Shale**
- Extent of Devonian Marcellus Shale (Devonian)—Includes areas beyond the extent of the Marcellus Shale Assessment Unit**
- Boundary of Appalachian Basin Petroleum Province**
- Isoline—Indicating percent vitrinite reflectance (%R₀)**
- 0.6-%R₀ isoline used in 2002 assessment by U.S. Geological Survey
- 0.6-%R₀ isoline based on data from Repetski and others (2008) and R.C. Milici (U.S. Geological Survey, unpub. data, 2002–2012)
- Location of vitrinite-reflectance sample**

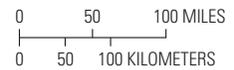
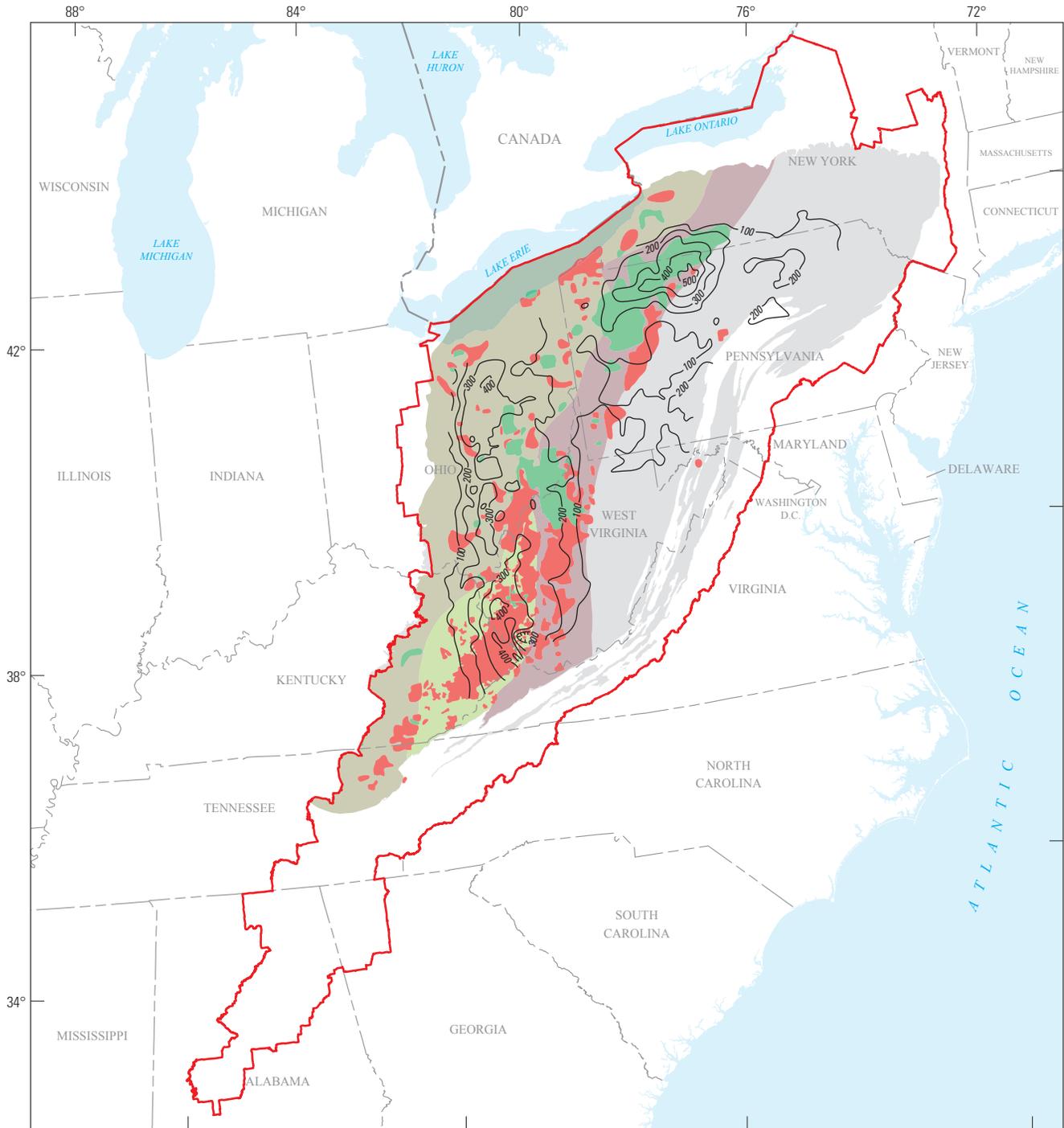


Figure 13 (facing page). Map showing the extent of the Devonian Marcellus Shale and Millboro Shale, and the extent of Devonian shale beyond the area of the Marcellus and Millboro Shales. Map also shows the 0.6-% R_o vitrinite-reflectance isoline used in the 2002 USGS assessment, and vitrinite-reflectance isolines based on data from Repetski and others (2008) and R.C. Milici (USGS, unpub. data, 2002–2012).

Figure 14 (facing page). Chart showing petroleum system events for the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System in the Appalachian Basin Petroleum Province. Time scale is from Harland and others (1990).

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Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

- Assessment Unit (AU)**
- Greater Big Sandy AU
 - Northwestern Ohio Shale AU
 - Devonian Siltstone and Shale AU
 - Marcellus Shale AU
- Cluster of oil wells**
- Cluster of gas wells

EXPLANATION

- Boundary of Appalachian Basin Petroleum Province**
- Isopach**—Showing net thickness of radioactive shale, in feet. Hachures indicate direction of thinning

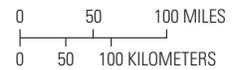
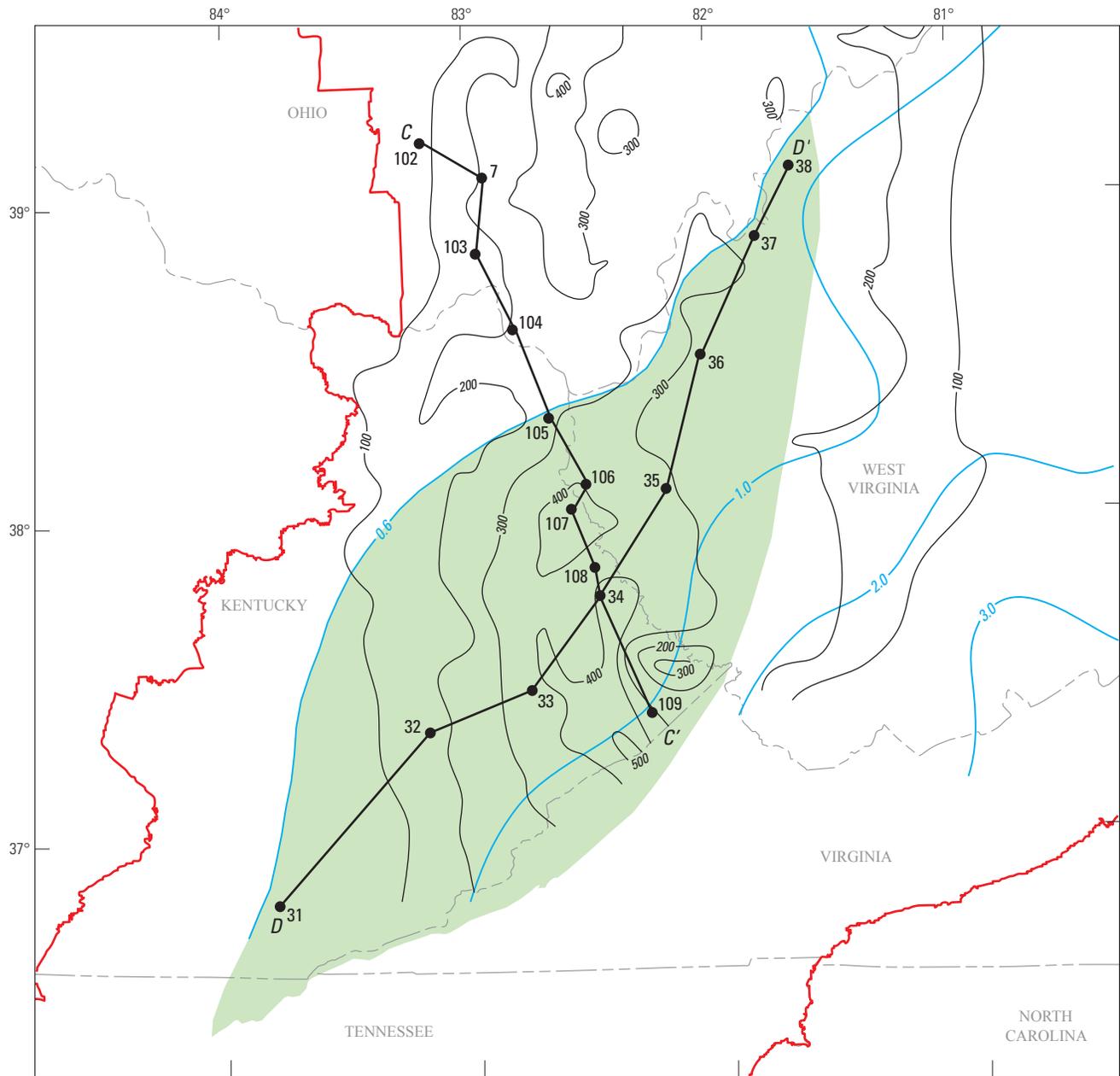


Figure 15 (facing page). Map of Devonian shale assessment units, showing net thickness of black shale and areas of closely spaced oil and gas wells. Net thickness (isopach) lines are from de Witt and others (1993, fig. 2).

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Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Extent of Greater Big Sandy Assessment Unit**
- Boundary of Appalachian Basin Petroleum Province**
- Isoline**—Indicating percent vitrinite reflectance (%R₀)
- Isopach**—Showing net thickness of radioactive shale, in feet
- Line of section, showing wells**—See figures 17 and 18

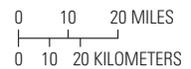


Figure 16 (facing page). Map showing the extent of the Greater Big Sandy Assessment Unit, thermal maturity isolines, and net thickness of black shale. Well numbers and lines of cross sections are from de Witt and others (1993). Cross sections *C–C'* and *D–D'* are shown on figures 17 and 18, respectively. See figure 15 for source of vitrinite-reflectance data.

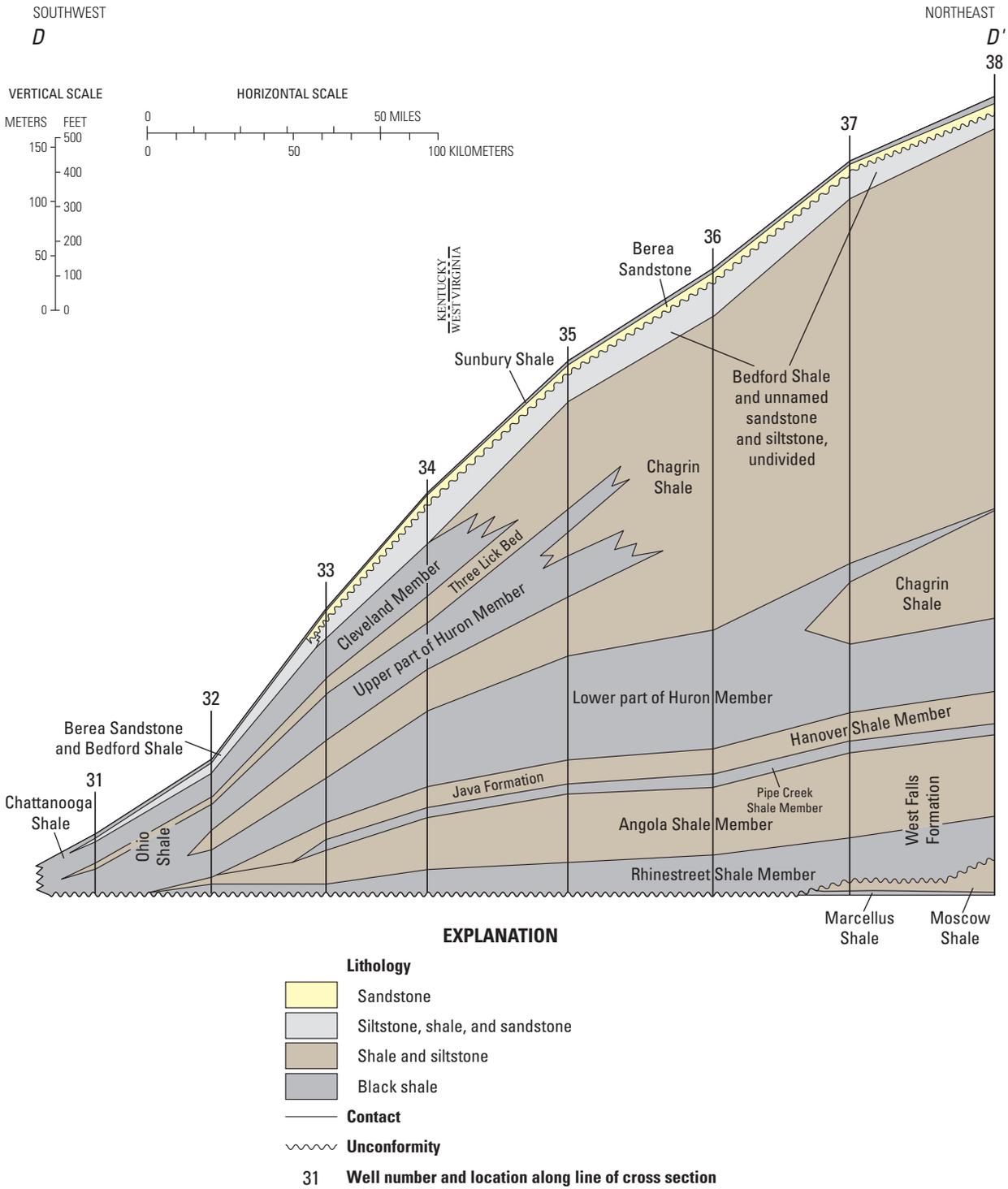


Figure 17. Stratigraphic cross section *D-D'*, showing Devonian and Lower Mississippian strata across the Greater Big Sandy Assessment Unit in eastern Kentucky and western West Virginia. Location of cross section is shown in figure 16 (after de Witt and others, 1993, pl. 3, section *B-B'*).

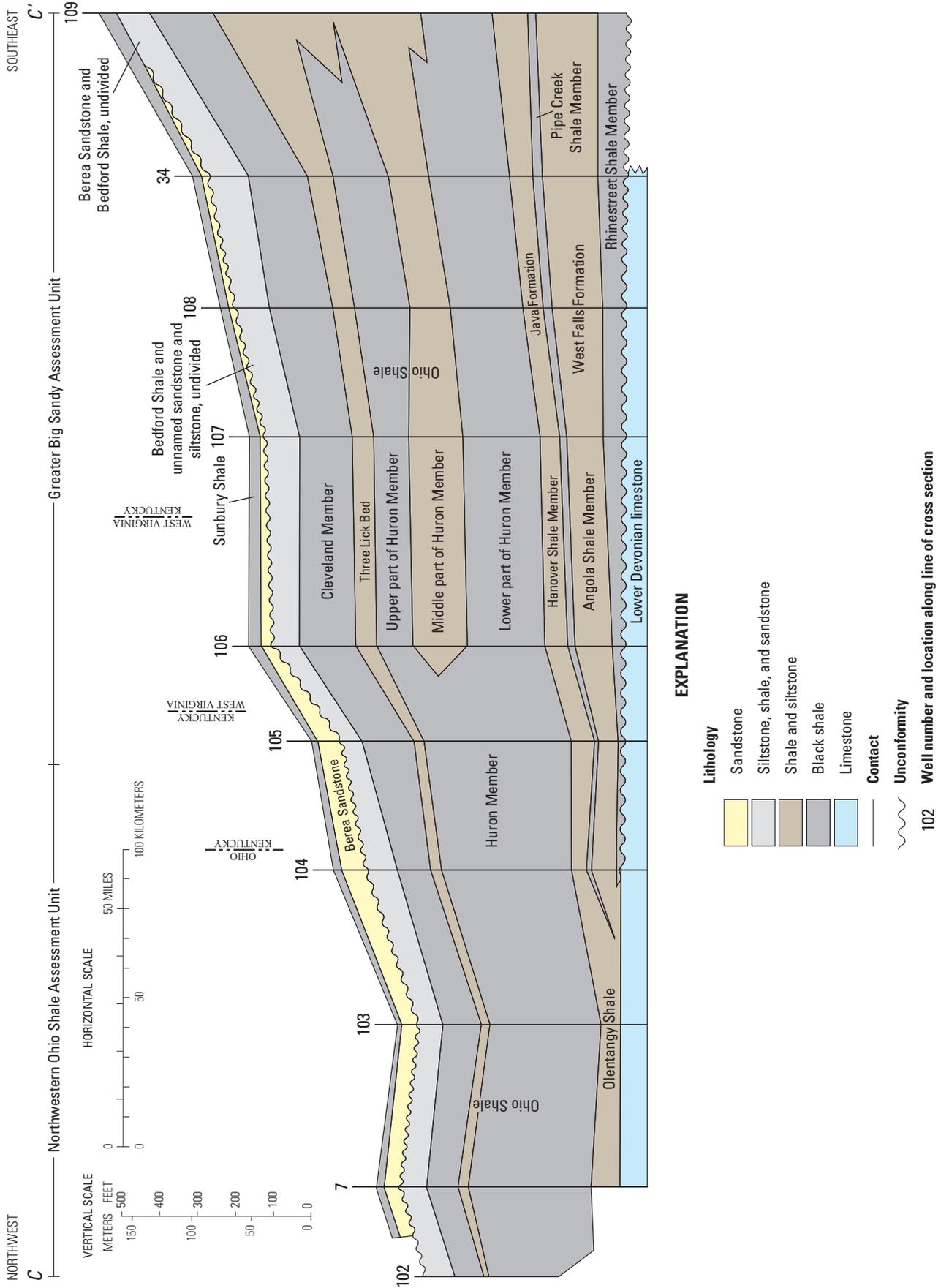
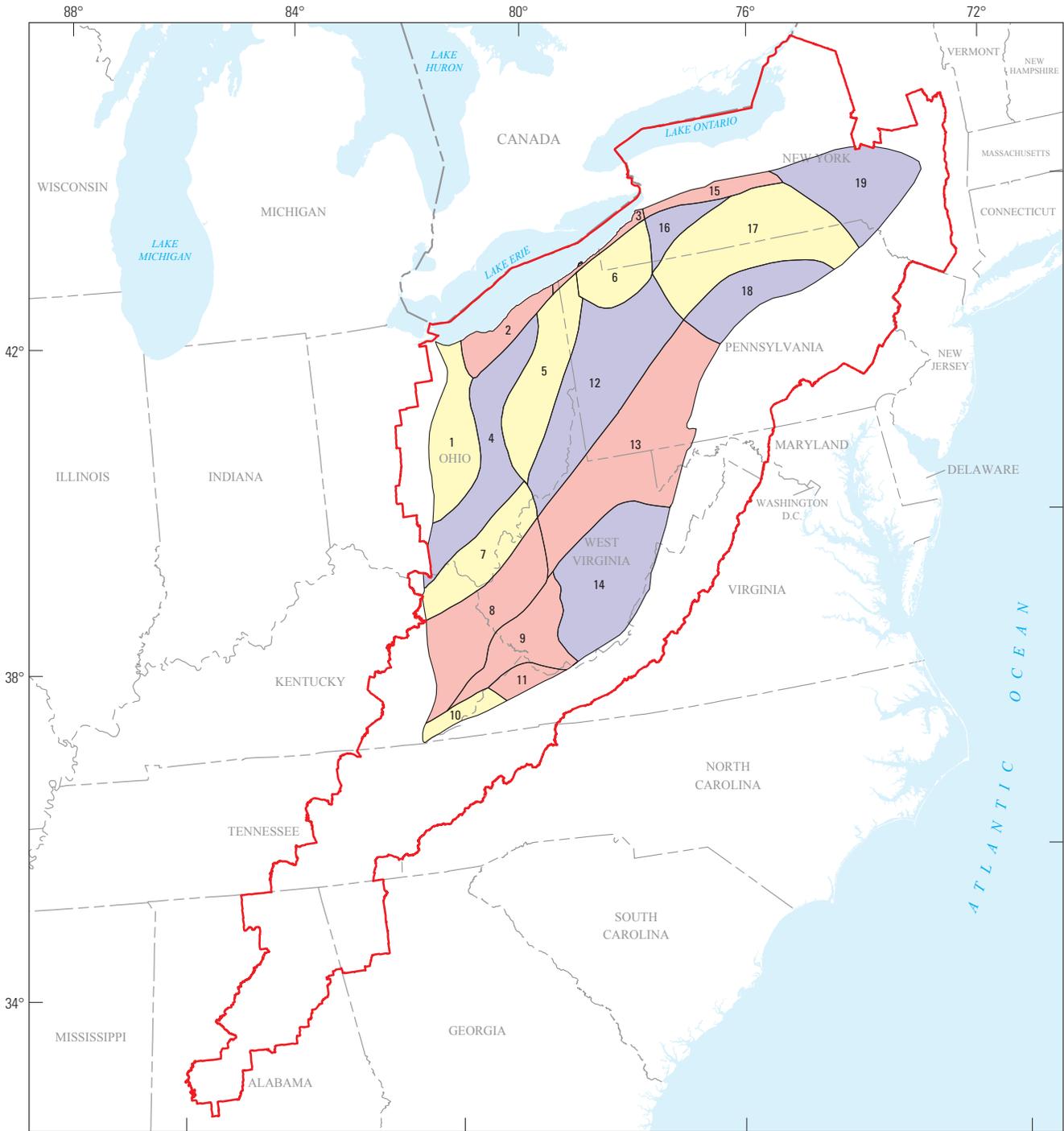


Figure 18. Stratigraphic cross section C-C', showing Devonian and Lower Mississippian strata across the Greater Big Sandy Assessment Unit in southern Ohio, eastern Kentucky, and West Virginia. Location of cross section is shown in figure 15 (after de Witt and others, 1993, pl. 9, section H-H').



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Shale gas recoverability estimates of Charpentier and others (1993)**
- Good
 - Moderate
 - Poor
- Boundary of Appalachian Basin Petroleum Province**

- Gas plays of Charpentier and others (1993)**
- | | |
|------------------------|------------------------|
| 1 North-Central Ohio | 11 Plateau Virginia |
| 2 Western Lake Erie | 12 Pittsburgh Basin |
| 3 Eastern Lake Erie | 13 Eastern Rome Trough |
| 4 Plateau Ohio | 14 New River |
| 5 Eastern Ohio | 15 Portage Escarpment |
| 6 Western Penn-York | 16 Cattaraugus Valley |
| 7 Southern Ohio Valley | 17 Penn-York Plateau |
| 8 Western Rome Trough | 18 Western Susquehanna |
| 9 Tug Fork | 19 Catskill |
| 10 Pine Mountain | |

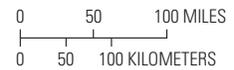


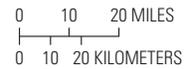
Figure 19 (facing page). Map showing the qualitative assessment of gas recoverability from Devonian shale within each gas play of the Appalachian Basin Petroleum Province (from Charpentier and others, 1993). Estimates of gas-in-place resources in these plays are given in table 2.



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Cluster of gas wells
- Extent of Greater Big Sandy Assessment Unit
- Crystalline rocks
- Boundary of Appalachian Basin Petroleum Province
- Faults**
- Normal fault—Bar and ball on downthrown block
- Strike-slip fault—Arrows show sense of relative movement
- Thrust fault—Teeth on upper plate
- Folds**
- Anticline
- Syncline



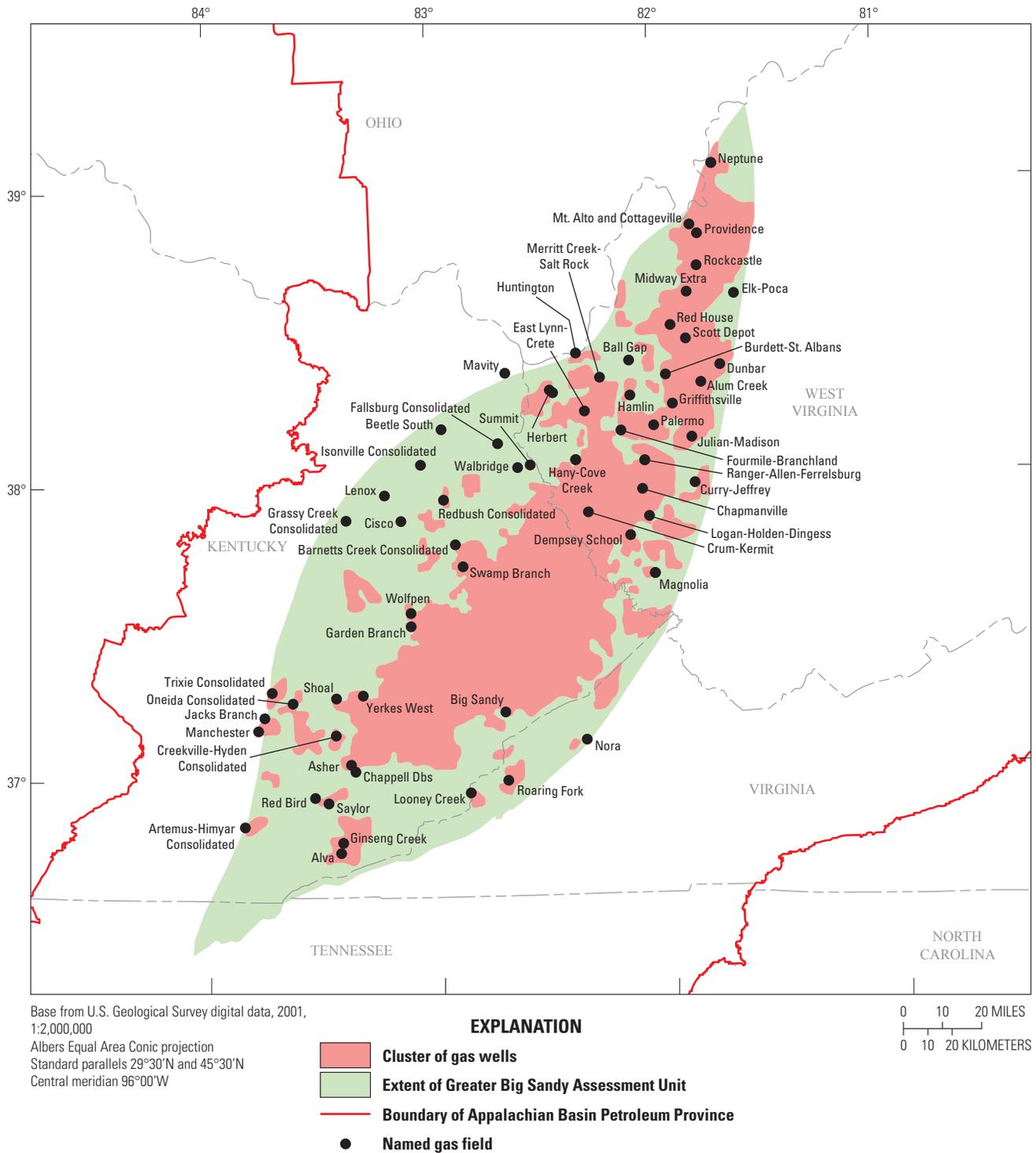
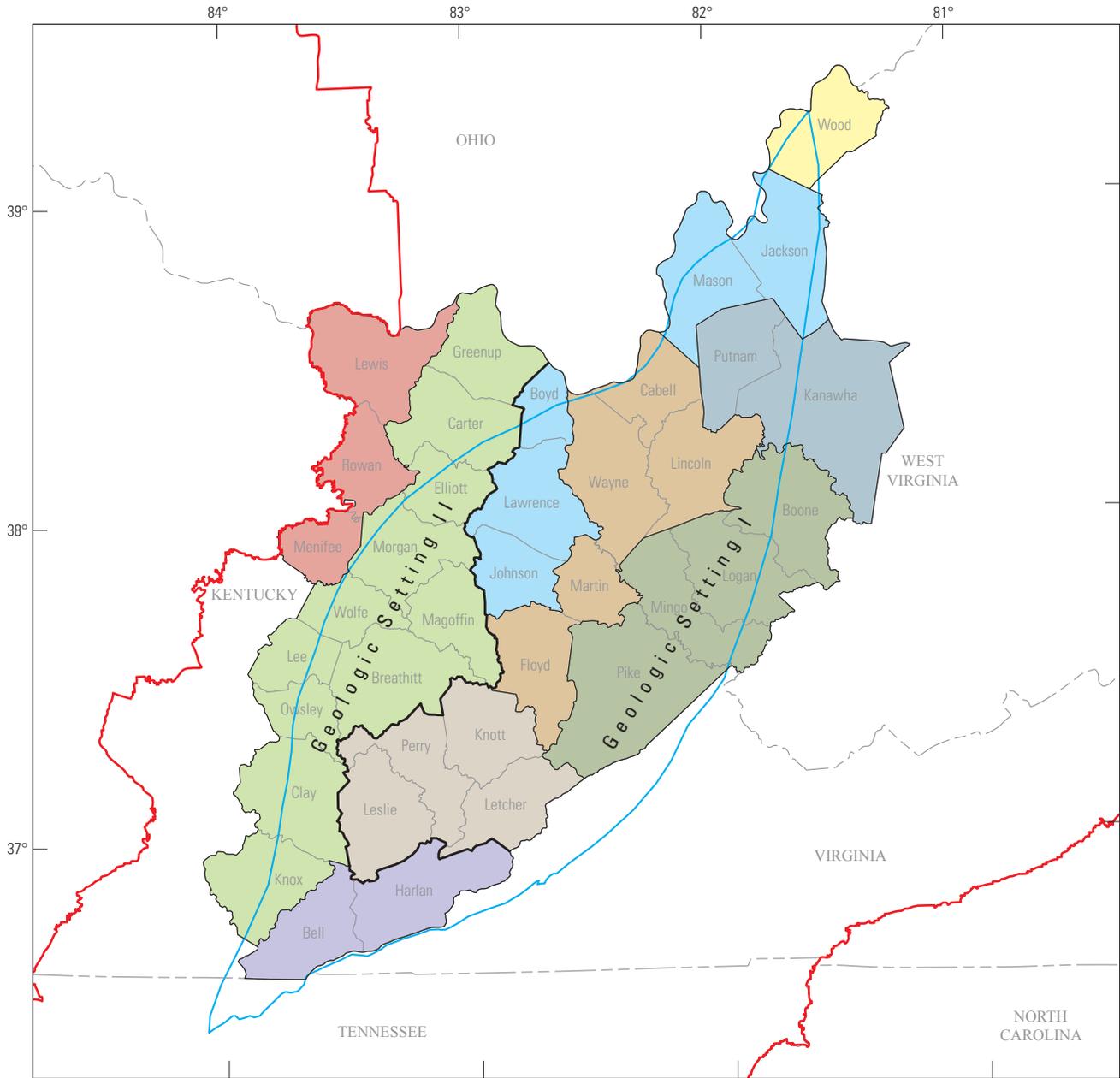


Figure 21. Map showing the locations of gas wells and named gas fields producing from Devonian shale in the Greater Big Sandy Assessment Unit (data from Roen and Walker, 1996). The gas field locations are approximate field centers.

Figure 20 (facing page). Map showing the relation of the Greater Big Sandy Assessment Unit to regional geologic structure. Structural geology is adapted from Ryder and others (2008).



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

0 10 20 MILES
 0 10 20 KILOMETERS

EXPLANATION

Geological Setting I (areas of known production) in Kentucky and West Virginia (from Kuuskraa and others, 1985)

Geological Setting II (areas of limited production) in Kentucky (from Kuuskraa and others, 1985)

- Area I
- Area II
- Area III
- Area IV
- Area V
- Area VI

- Shallow target
- Medium target
- Deep target

- Boundary of Appalachian Basin Petroleum Province
- Boundary of Greater Big Sandy Assessment Unit

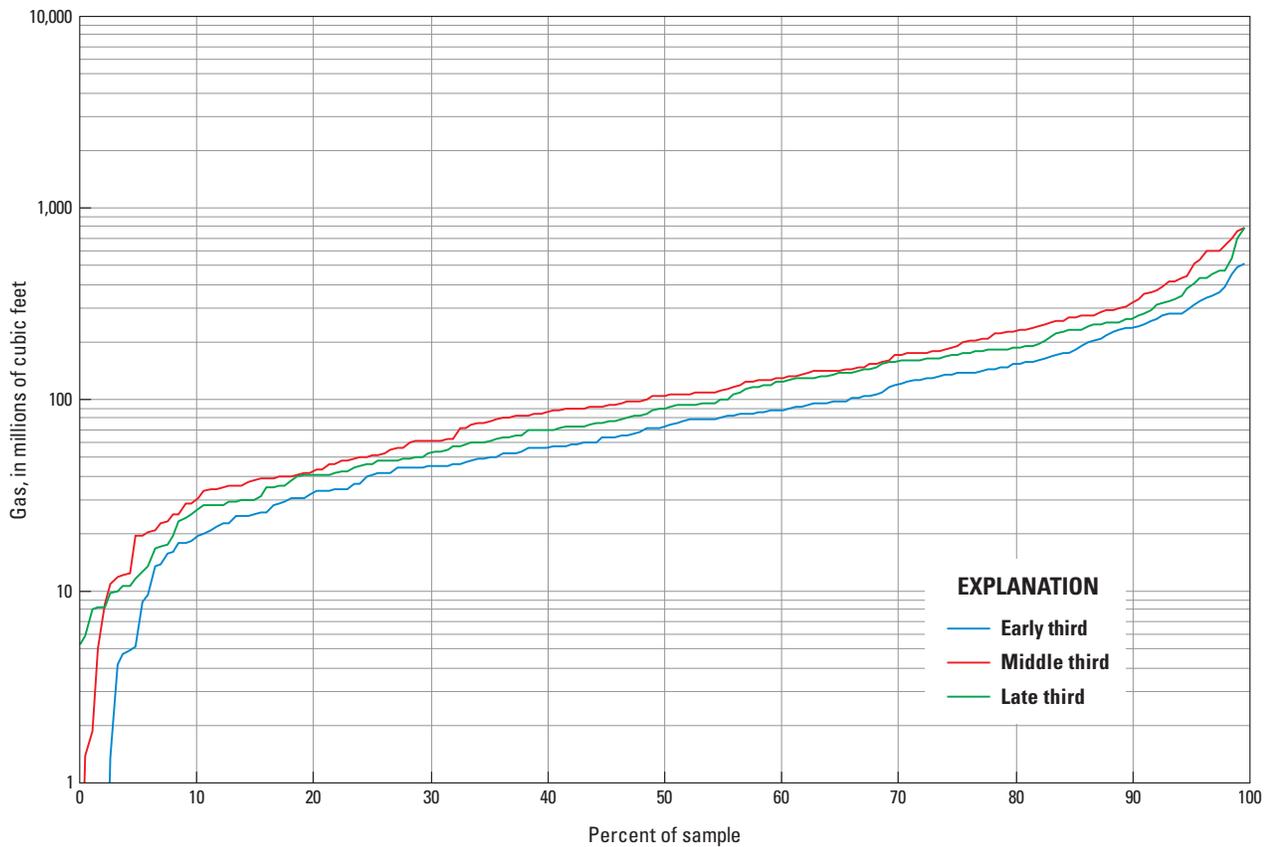


Figure 23. Graph showing the distribution of estimated ultimate recovery (EUR) values per well for wells in Devonian shale of eastern Kentucky (Troy Cook, U.S. Geological Survey, unpub. data, 2002; using data from Roen and Walker, 1996). The EUR data were sorted according to date and then partitioned chronologically into three groups, each of which had the same number of data. Separate graphs are shown for the early third, middle third, and late third of EUR values.

Figure 22 (facing page). Map showing the geological settings and partitioned areas of Kuuskraa and others (1985) in the Greater Big Sandy Assessment Unit. Geologic setting III (areas of speculative production) is not shown. See table 2 for estimates of gas-in-place (GIP) resources in plays described by Charpentier and others (1993), and see table 3 for gas geochemistry data from Streib (1981).



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Extent of Northwest Ohio Shale Assessment Unit**
- Boundary of Appalachian Basin Petroleum Province**
- Line of section, showing wells—See figures 25 and 26**
- Well (not located along line of section)**

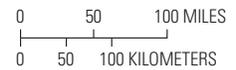


Figure 24 (facing page). Map showing the outline of the Northwestern Ohio Shale Assessment Unit, the location of the Amerada No.1 Ullman well, and the locations of cross sections *E-E'* (fig. 25) and *F-F'* (fig. 26). Well locations are from de Witt and others (1993) and Ryder and others (1998).

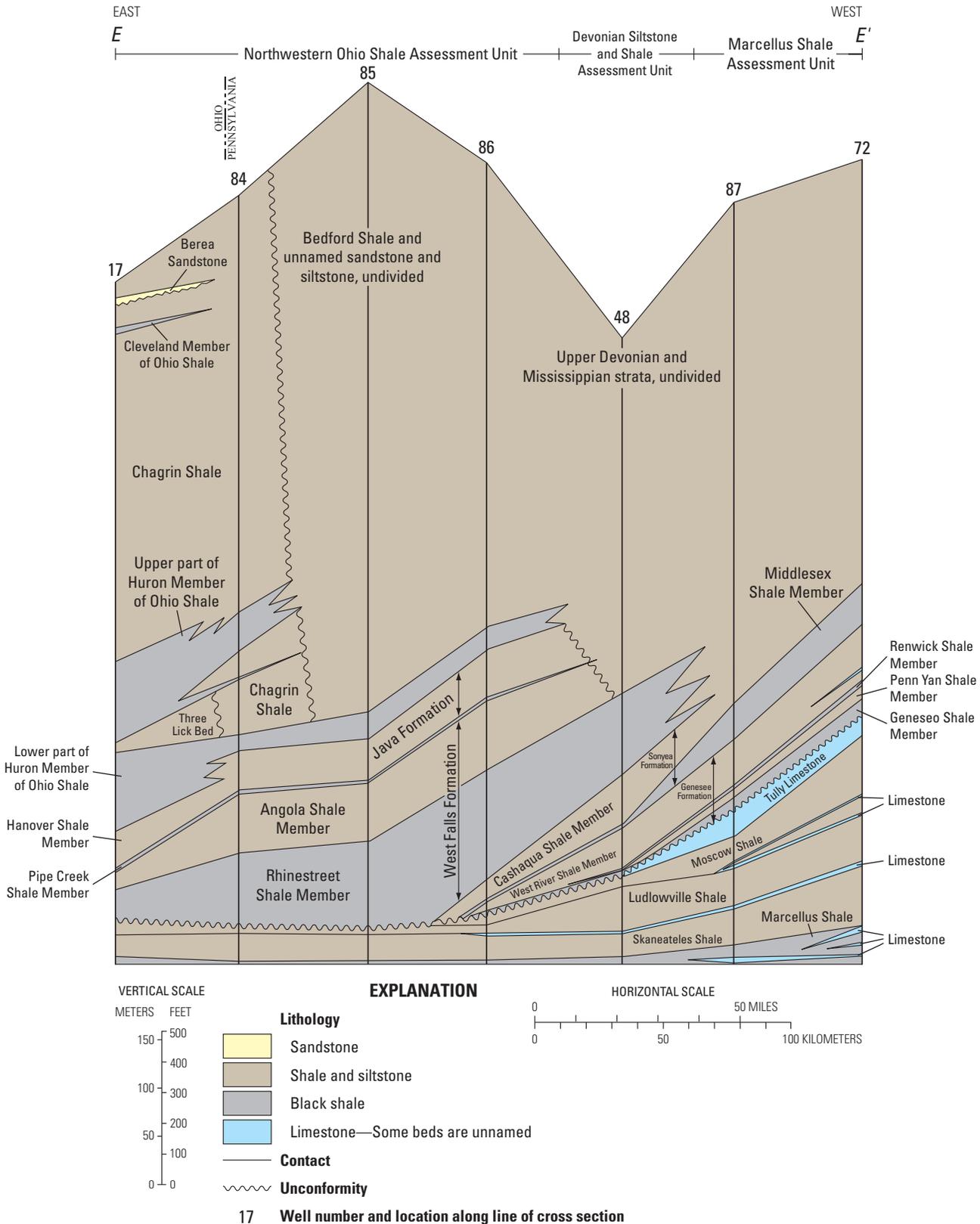


Figure 25. Cross section E-E', showing the Devonian and Lower Mississippian strata across western Pennsylvania and northeastern Ohio (after de Witt and others, 1993, pl. 6, section E-E'). Numbers along top of section refer to the well numbers of de Witt and others (1993). Cross section location is shown in figure 24.

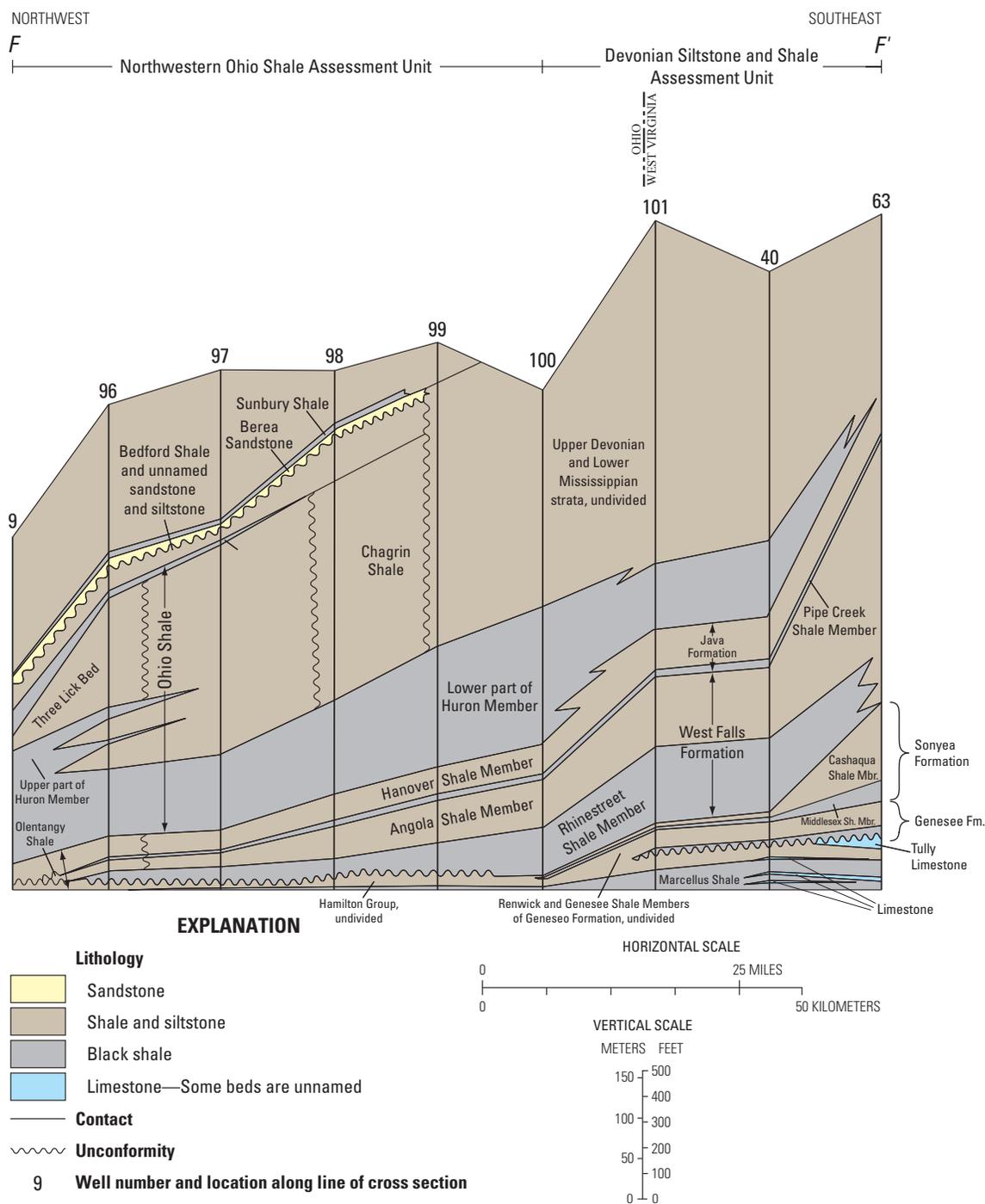
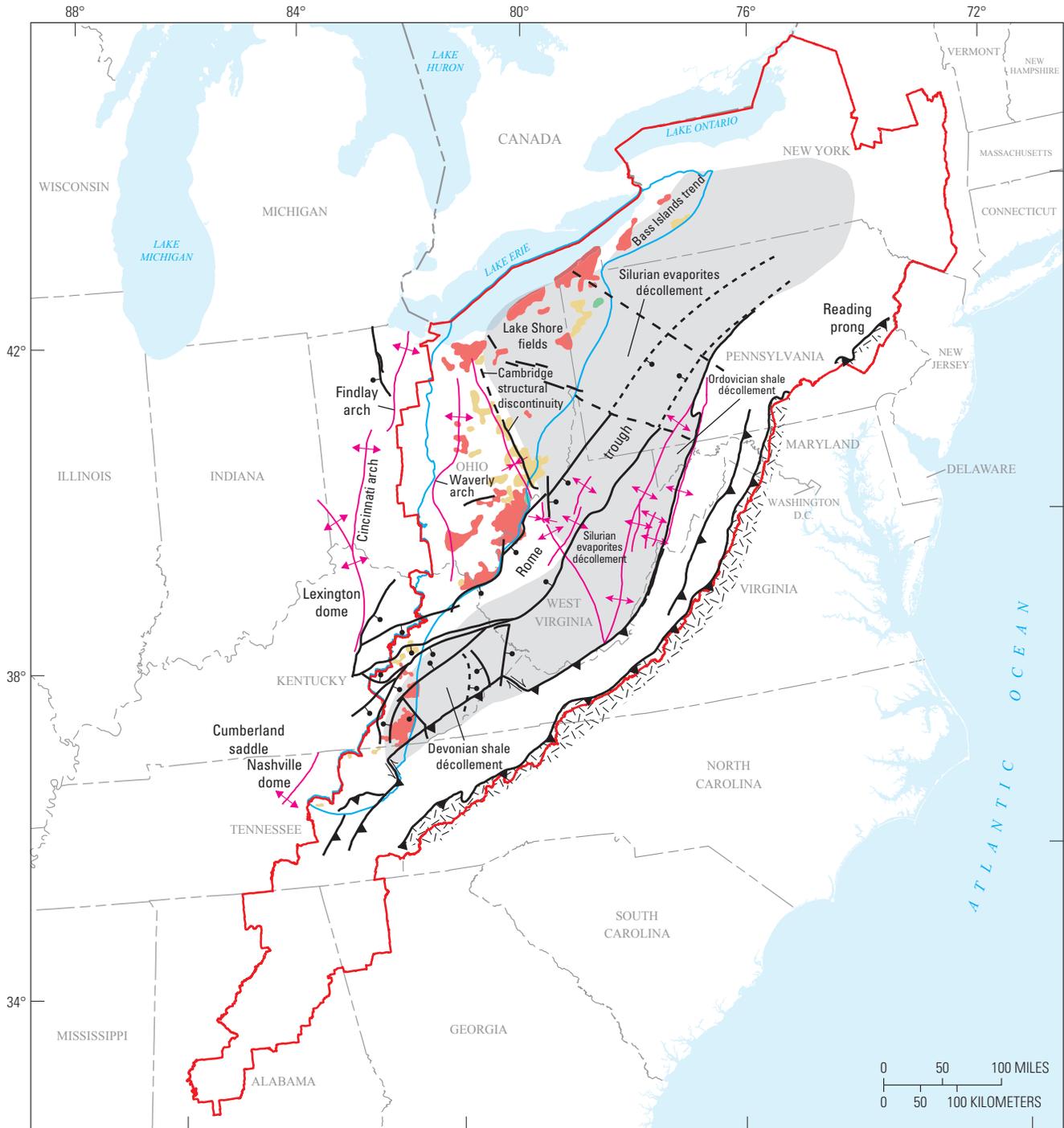


Figure 26. Cross section *F-F'*, showing the Devonian and Lower Mississippian strata across western West Virginia and east-central Ohio (after de Witt and others, 1993, pl. 8, section *G-G'*). Numbers along top of section refer to the well numbers of de Witt and others (1993). Cross section location is shown in figure 24.

58 Coal and Petroleum Resources in the Appalachian Basin



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

- Cluster of gas wells
- Cluster of oil wells and gas wells
- Cluster of oil wells
- Area of limited décollement
- Crystalline rocks
- Boundary of Appalachian Basin Petroleum Province
- Boundary of Northwestern Ohio Shale Assessment Unit

EXPLANATION

- Faults**
- Normal fault—Bar and ball on downthrown block
- Strike-slip fault—Arrows show sense of relative movement
- Thrust fault—Teeth on upper plate
- Transverse fault—Dashed where uncertain
- Folds**
- Anticline
- Syncline
- Axis of arch

Figure 27 (facing page). Map showing the relation of the Northwestern Ohio Shale Assessment Unit to geologic structure. Structural geology is adapted from Ryder and others (2008). Décollement data are from Colton (1970), Frey (1973), Patenaude and others (1986), and Sanford (1993).

60 Coal and Petroleum Resources in the Appalachian Basin



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Cluster of gas wells
- Cluster of oil wells and gas wells
- Cluster of oil wells
- Boundary of Appalachian Basin Petroleum Province
- Boundary of Northwestern Ohio Shale Assessment Unit
- Named gas field



Figure 28. Map showing named fields in the Northwestern Ohio Shale Assessment Unit (data from Roen and Walker, 1996).

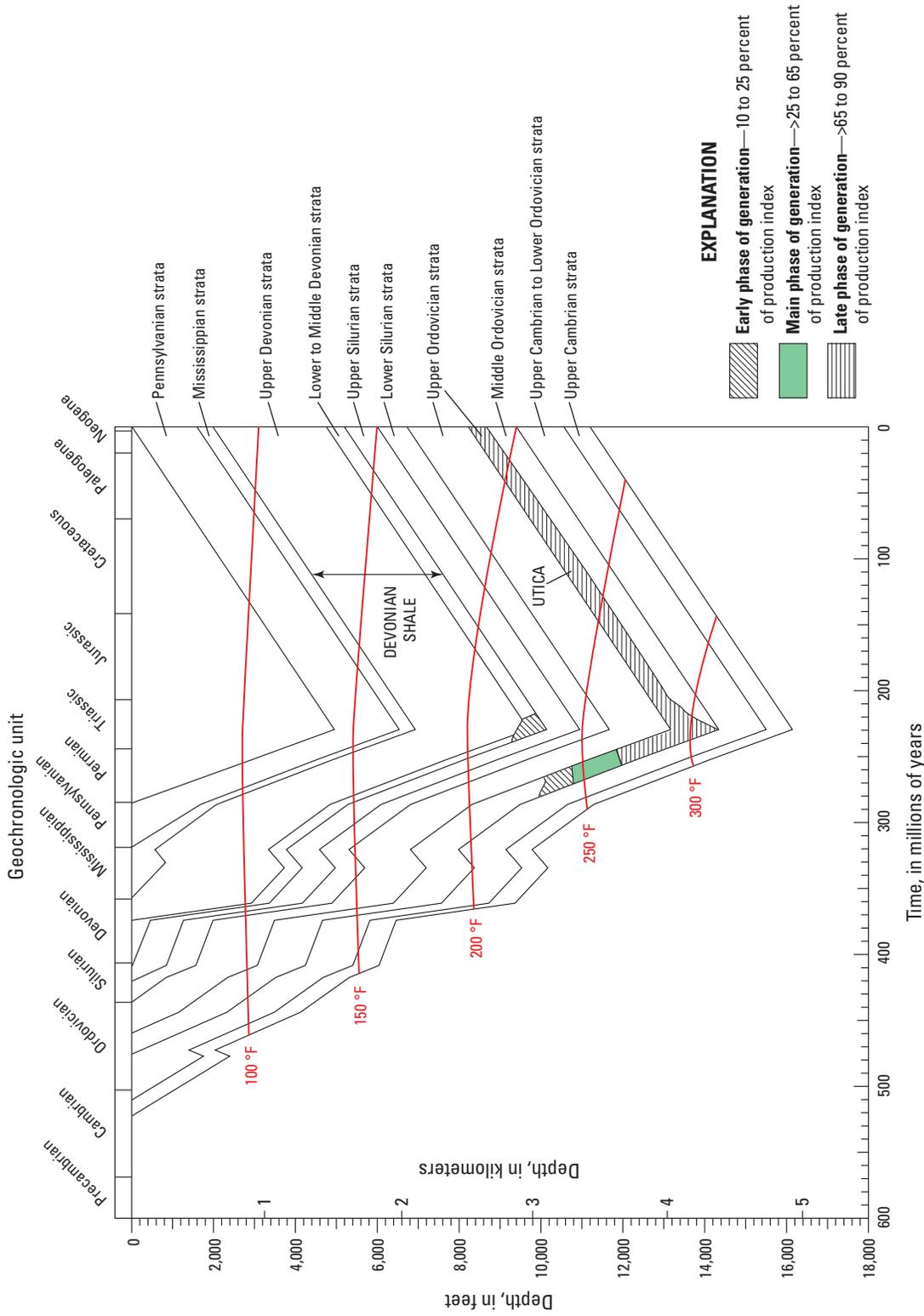
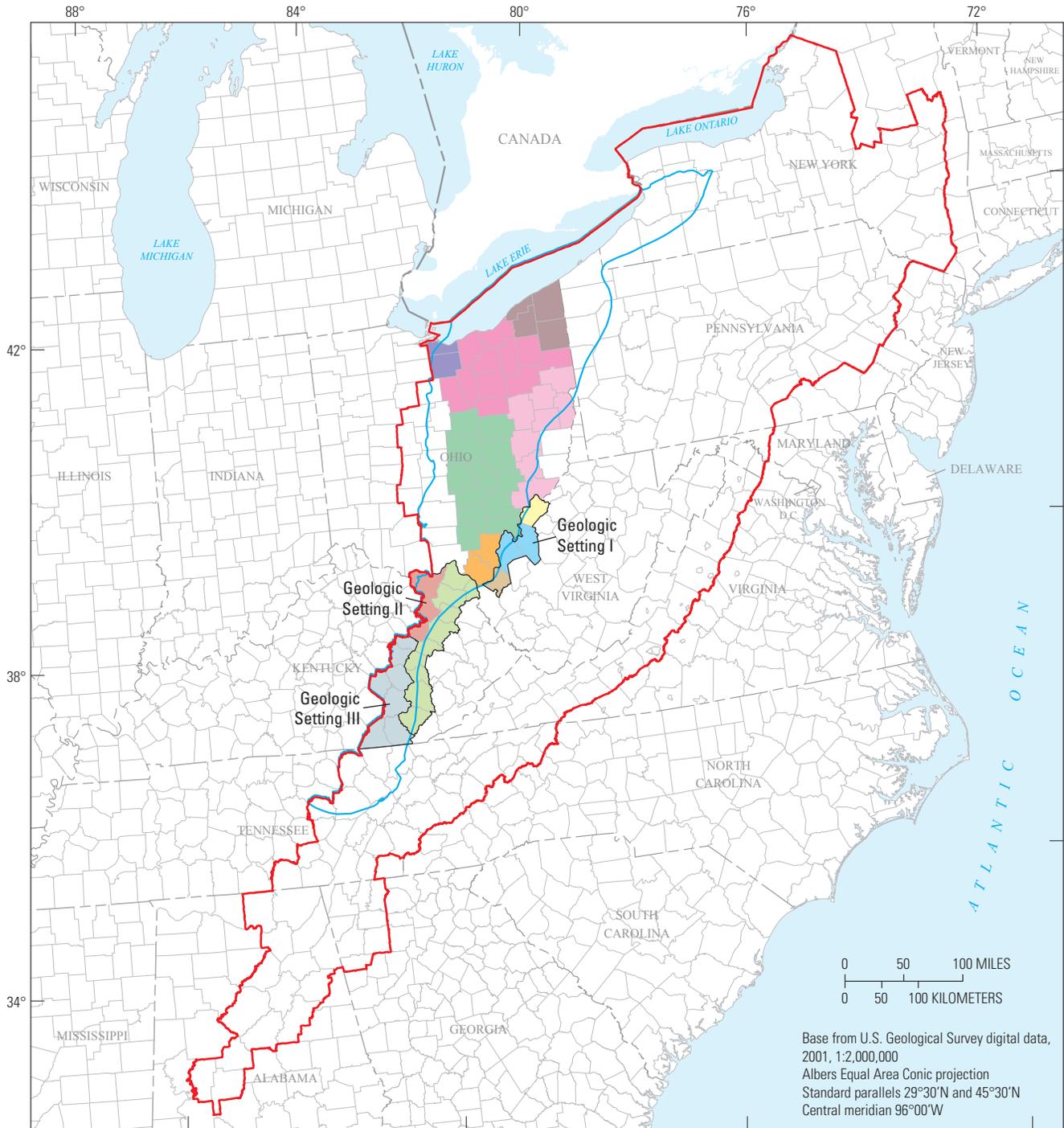


Figure 29. Graph showing a burial and hydrocarbon generation plot for the Amerada No. 1 Ullman well in Noble County, Ohio (modified from Ryder and others, 1998). The location of the well is shown in figure 24.



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- | | | |
|--|---|--|
| <p>Geological Setting I (areas of known production) in West Virginia according to Kuuskraa and others (1985)</p> <ul style="list-style-type: none"> Area I Area IV Area VI <p>Geological Setting II (areas of limited production) in Kentucky according to Kuuskraa and others (1985)</p> <ul style="list-style-type: none"> Shallow target Medium target Geological Setting III (areas of speculative production) in Kentucky according to Kuuskraa and others (1985) | <p>Partitioned areas in Ohio according to Kuuskraa and others (1985)</p> <ul style="list-style-type: none"> Area I Area II Area III Area IV Area V Area VI | <ul style="list-style-type: none"> Boundary of Appalachian Basin Petroleum Province Boundary of Northwestern Ohio Shale Assessment Unit |
|--|---|--|

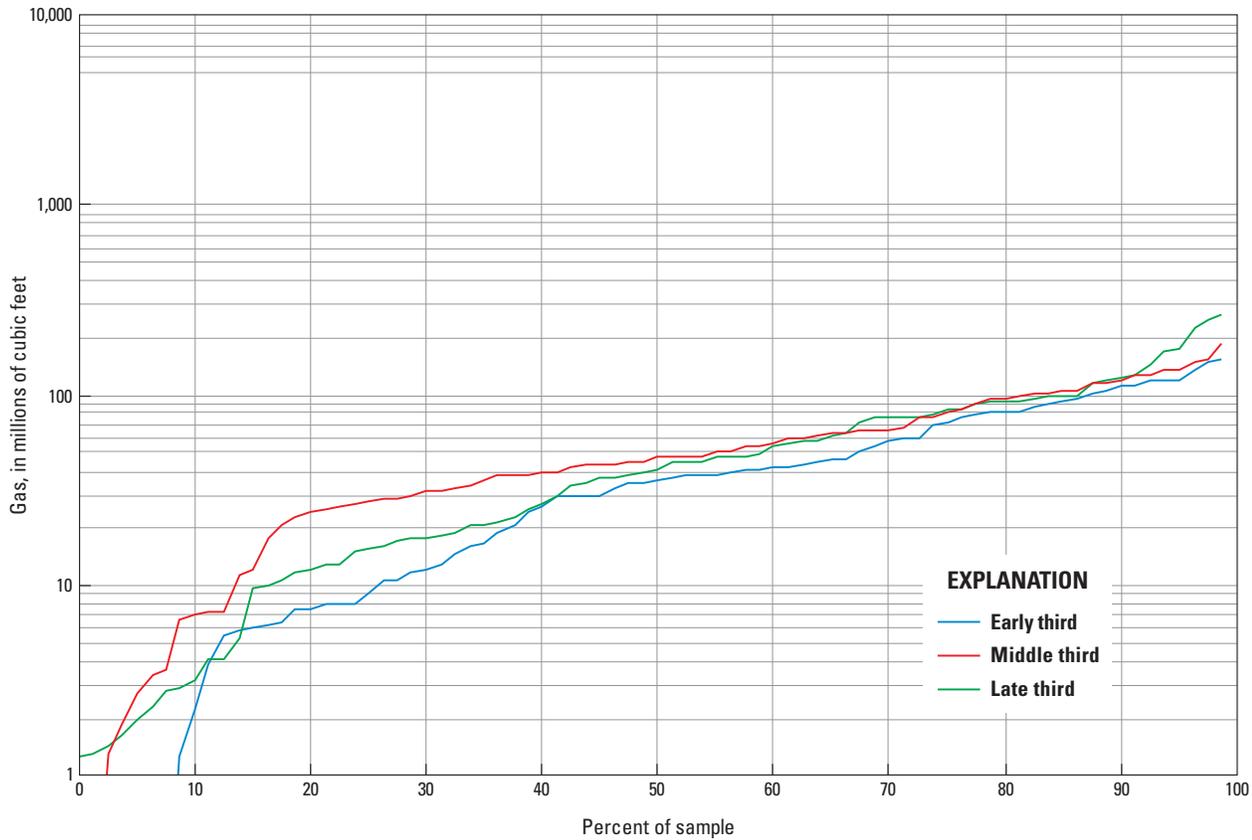
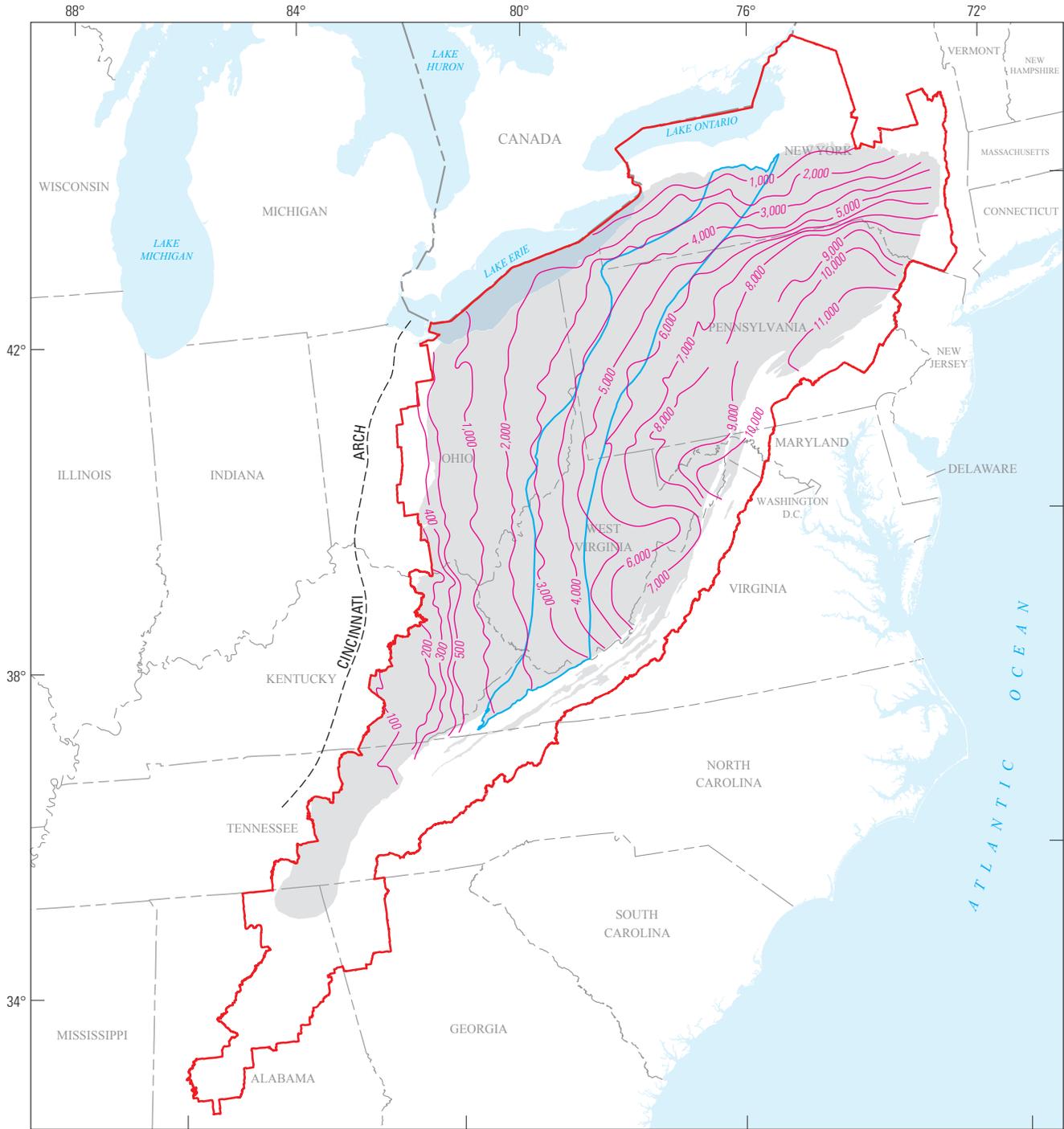


Figure 31. Graph showing the distribution of estimated ultimate recovery (EUR) values per well for wells in the Northwestern Ohio Shale Assessment Unit (Troy Cook, U.S. Geological Survey, unpub. data, 2002; using data from Roen and Walker, 1996). The EUR data were sorted according to date and then partitioned chronologically into three groups, each of which had the same number of data. Separate graphs are shown for the early third, middle third, and late third of EUR values.

Figure 30 (facing page). Map showing the geological settings and partitioned areas of Kuuskraa and others (1985) in the Northwestern Ohio Shale Assessment Unit.



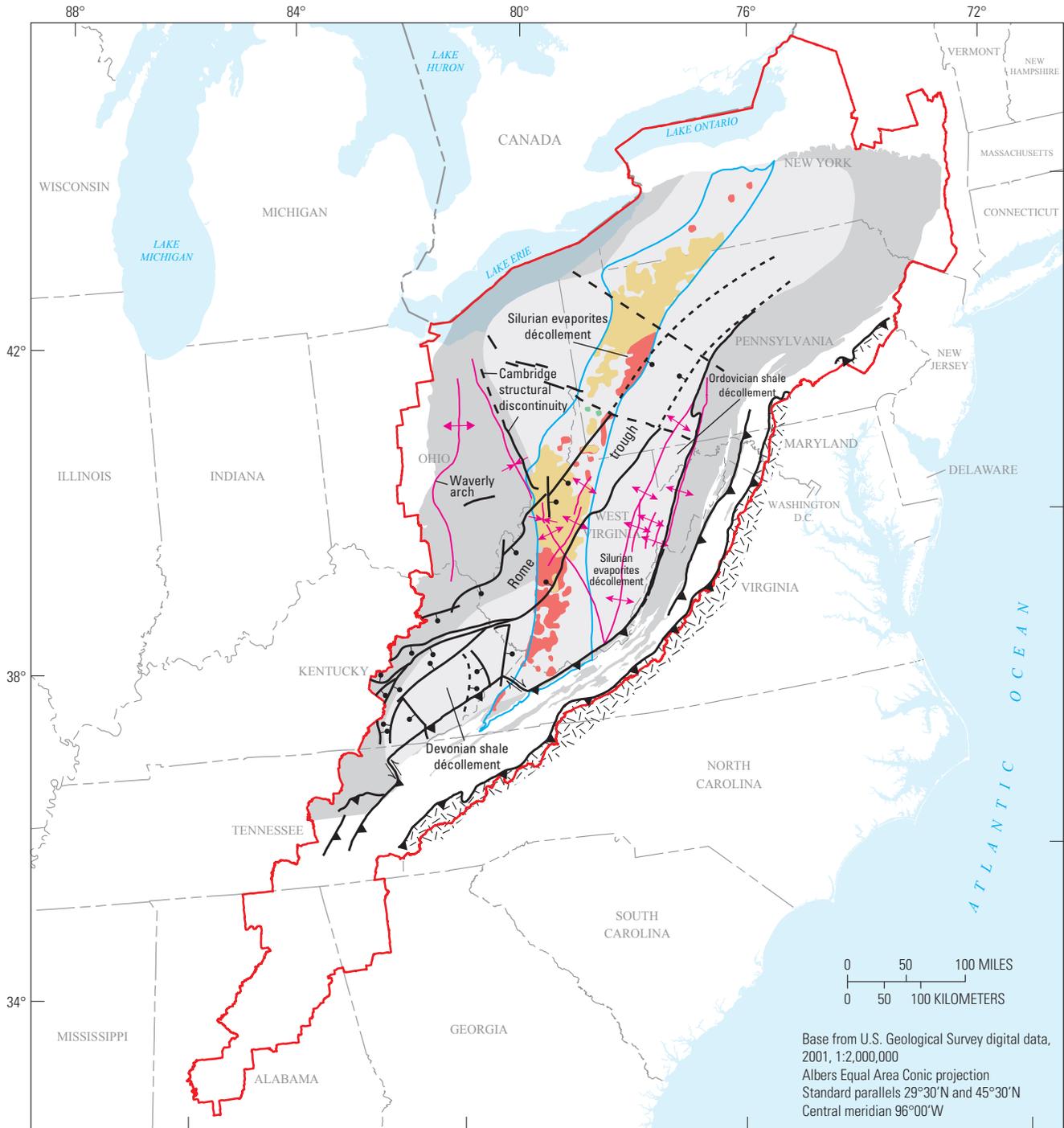
Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Extent of Devonian strata, including area beyond Devonian Siltstone and Shale Assessment Unit**
- Isopach showing thickness of Devonian strata—Contour interval 1,000 feet (ft). West of 1,000-ft isopach line, contour interval is 100 ft.**
- Boundary of Devonian Siltstone and Shale Assessment Unit**
- Approximate trace of Cincinnati arch**
- Boundary of Appalachian Basin Petroleum Province**



Figure 32 (facing page). Map showing the extent and thickness of Devonian strata in the Appalachian Basin Petroleum Province and the Devonian Siltstone and Shale Assessment Unit (adapted from de Witt and others, 1975).



EXPLANATION

- Cluster of gas wells
- Cluster of oil wells and gas wells
- Cluster of oil wells
- Area of limited décollement
- Extent of Devonian shale beyond area of limited décollement
- Crystalline rocks
- Boundary of Appalachian Basin Petroleum Province
- Boundary of Devonian Siltstone and Shale Assessment Unit

- Faults**
- Normal fault—Bar and ball on downthrown block
 - Strike-slip fault—Arrows show sense of relative movement
 - Thrust fault—Teeth on upper plate
 - Transverse fault—Dashed where uncertain
- Folds**
- Anticline
 - Syncline
 - Axis of arch

Figure 33 (facing page). Map showing relation of the Devonian Siltstone and Shale Assessment Unit to geologic structure. Structural geology is adapted from Ryder and others (2008). Décollement data are from Colton (1970), Frey (1973), Patenaude and others (1986), and Sanford (1993).

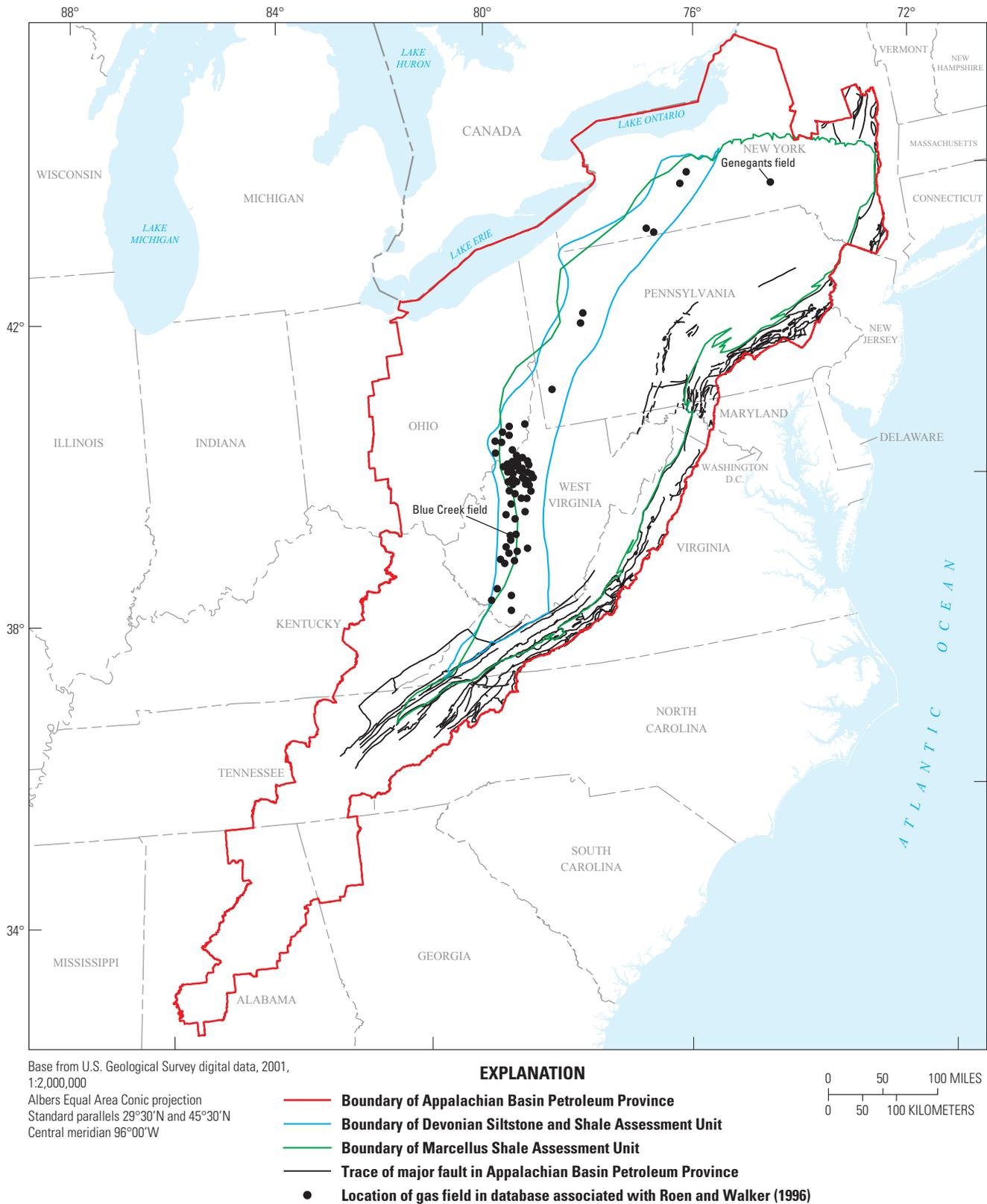
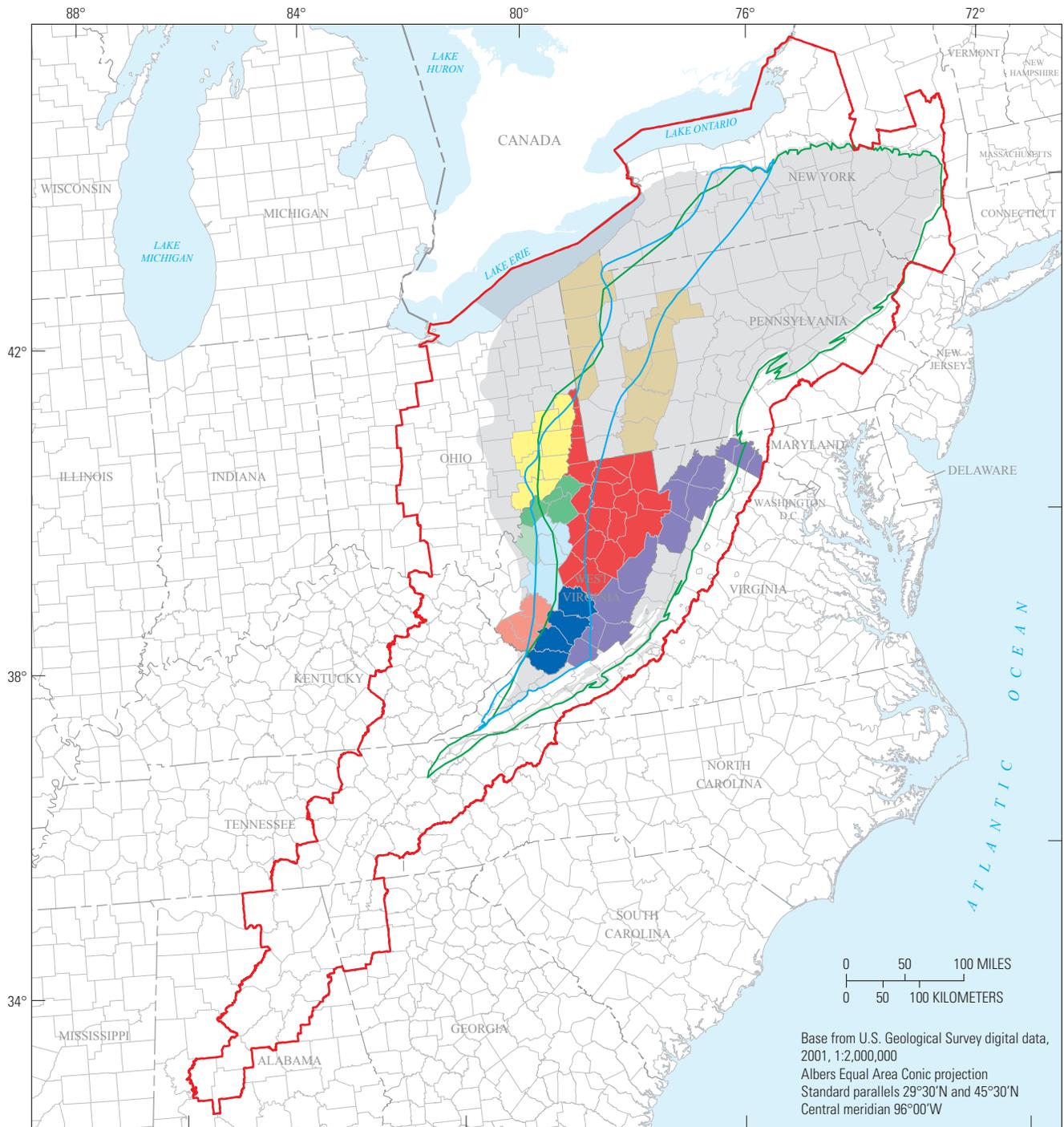


Figure 34. Map showing locations of named fields in the Devonian Siltstone and Shale Assessment Unit and the Marcellus Shale Assessment Unit (data from Roen and Walker, 1996).



EXPLANATION

- Extent of Devonian Shale**—Includes areas beyond boundary of Devonian Siltstone and Shale Assessment Unit and Marcellus Shale Assessment Unit
- Area in Pennsylvania with estimated favorable gas-in-place (GIP) resource potential between 482 and 790 trillion cubic feet**
- Boundary of Appalachian Basin Petroleum Province**
- Boundary of Devonian Siltstone and Shale Assessment Unit**
- Boundary of Marcellus Shale Assessment Unit**

Non-USGS estimates of gas-in-place (GIP) resources for the Huron Member of the Ohio Shale, Rhinestreet Shale Member of the West Falls Formation, and Marcellus Shale—In billions of cubic feet. Compiled from Tetra Tech (1981), Lewin and Associates (1983), Kuuskraa and Wicks (1984), and Kuuskraa and others (1985).

1.53	3.96	5.22	7.41
3.53	4.66	6.39	9.87

Figure 35. Map showing estimated gas-in-place (GIP) resources for the Huron Member of the Ohio Shale, the Rhinestreet Shale Member of the West Falls Formation, and the Marcellus Shale (data from Tetra Tech, 1981; Lewin and Associates, 1983; Kuuskraa and Wicks, 1984; Kuuskraa and others, 1985).

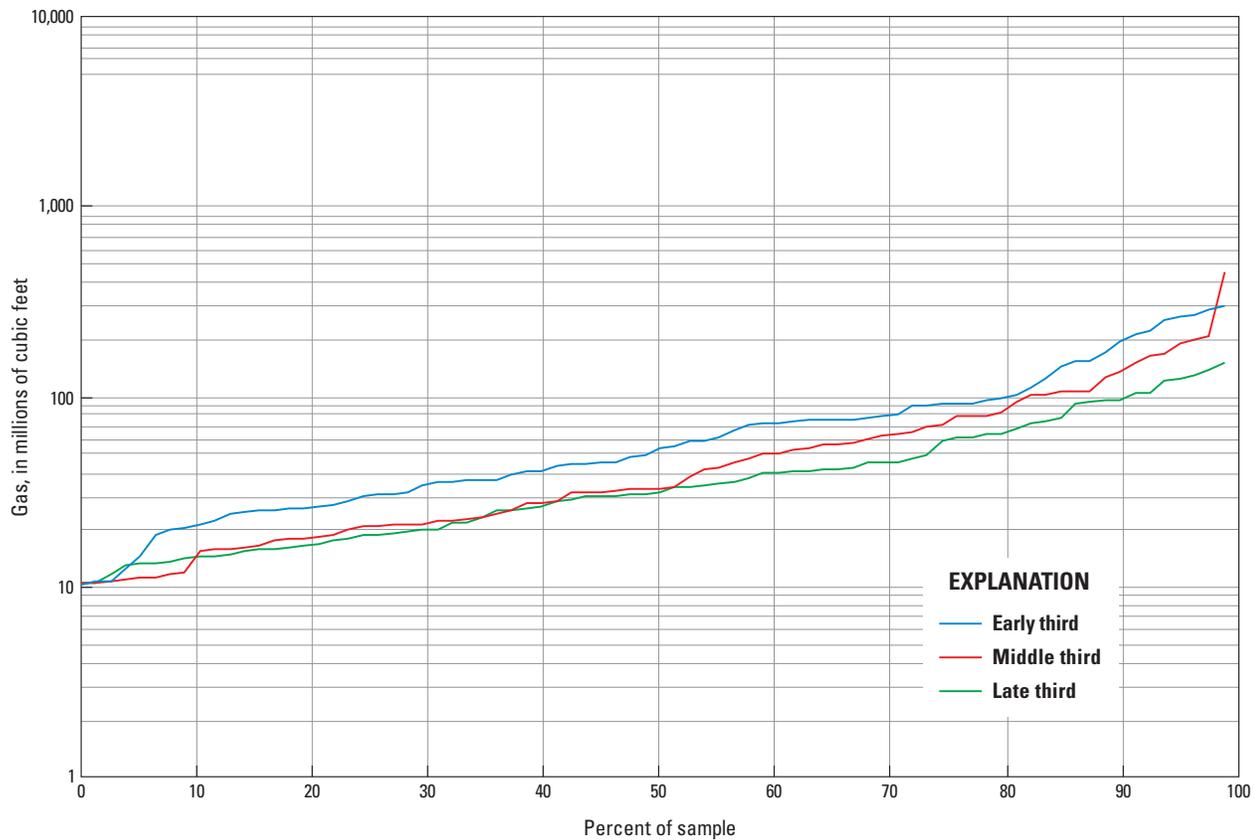
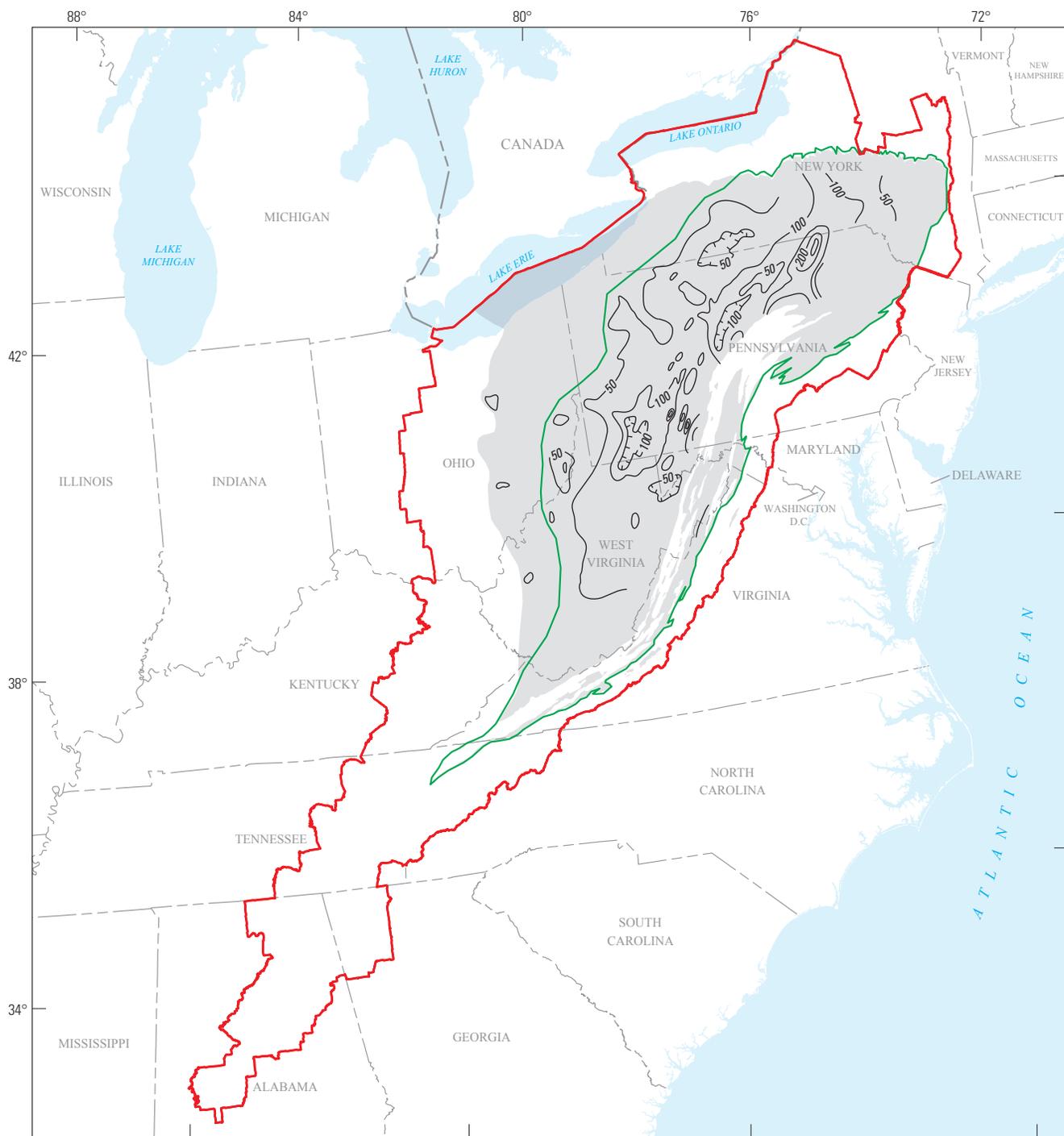


Figure 36. Graph showing the distribution of estimated ultimate recovery (EUR) values per well for wells for the Devonian Siltstone and Shale Assessment Unit (Troy Cook, U.S. Geological Survey, unpub. data, 2002; using data from Roen and Walker, 1996). The EUR data were sorted according to date and then partitioned chronologically into three groups, each of which had the same number of data. Separate graphs are shown for the early third, middle third, and late third of EUR values.



Base from U.S. Geological Survey digital data, 2001,
 1:2,000,000
 Albers Equal Area Conic projection
 Standard parallels 29°30'N and 45°30'N
 Central meridian 96°00'W

EXPLANATION

- Extent of Marcellus and Millboro Shales**
- Boundary of Appalachian Basin Petroleum Province**
- Boundary of Marcellus Shale Assessment Unit**
- Isopach**—Showing thickness of Marcellus Shale, in feet. Hachures indicate direction of thinning



Figure 37. Isopach map of the Marcellus Shale (modified from de Witt and others, 1993). Note that the extent of the Marcellus Shale Assessment Unit, as used by the 2002 USGS assessment, is less than the total extent of the Marcellus Shale stratigraphic unit. The Marcellus Shale Assessment Unit includes the Millboro Shale in Virginia (see Milici and Swezey, 2006).

Table 1. Characterization of assessment units for the U.S. Geological Survey 2002 assessment of undiscovered oil and gas resources in the Appalachian Basin Petroleum Province (summarized by Milici and others, 2003).

Assessment unit (AU)	Source rock	Maturation	Migration	Reservoir rock	Traps	Seal
Conventional						
Oriskany Sandstone Structural AU	Needmore and Marcellus Shales	Carboniferous to Permian	Lateral updip; downward	Fine- to coarse-grained sandstone	Structural	Marcellus Shale
Oriskany Sandstone Stratigraphic AU	Needmore and Marcellus Shales	Carboniferous to Permian	Lateral updip; downward	Fine- to coarse-grained sandstone	Stratigraphic	Marcellus Shale
Greenbrier Limestone AU	Devonian shale	Carboniferous to Permian	Lateral updip; upward	Fractured oolitic limestone, dolomite, and sandstone	Stratigraphic	Carboniferous shale
Mississippian Sandstone AU	Devonian shale	Carboniferous to Permian	Lateral updip; upward	Fine- to coarse-grained sandstone	Stratigraphic	Carboniferous shale
Continuous						
Greater Big Sandy AU	Devonian shale	Carboniferous to Permian	Autogenic (self-sourced)	Fractured shale	Continuous	Devonian shale
Northwestern Ohio Shale AU	Devonian shale	Immature with respect to oil generation(?)	Autogenic (self-sourced)	Fractured shale	Continuous	Devonian shale
Devonian Siltstone and Shale AU	Devonian shale	Carboniferous to Permian	Autogenic (self-sourced)	Fractured shale and siltstone	Continuous	Devonian shale
Marcellus Shale AU	Marcellus Shale	Late Devonian(?) to Permian	Autogenic (self-sourced)	Fractured shale	Continuous	Devonian shale
Catskill Sandstones and Siltstones AU	Devonian shale	Late Devonian(?) to Permian	Lateral updip; upward	Fine- to coarse-grained sandstone	Continuous	Devonian shale and siltstones
Berea Sandstone AU	Devonian shale	Carboniferous to Permian	Lateral updip; upward	Fine- to coarse-grained sandstone	Continuous	Sunbury Shale

Table 2. Estimates of gas-in-place (GIP) resources in plays identified in figure 19 from Charpentier and others (1993), as allocated to the Devonian shale assessment units in the Appalachian Basin Petroleum Province.

[F95 denotes the 95th fractile; the probability of more than the amount F95 is 95 percent. F5 is defined similarly. Because of the dependency between plays, these fractiles (unlike those in many other studies) are additive. Dashes, —, denote areas where the plays as identified by Charpentier and others (1993) are not present in the assessment units as identified by Milici and others (2003). AU, Assessment Unit; TCF, trillion cubic feet]

Play number and name	Natural gas resources (TCF)			Allocation of natural gas-in-place resources, by assessment unit (in percent of mean and by amount)									
	Low (F95)	High (F5)	Mean	Greater Big Sandy AU		Northwestern Ohio Shale AU		Devonian Siltstone and Shale AU		Marcellus Shale AU			
				Percent of mean in play	Gas-in-place (TCF)	Percent of mean in play	Gas-in-place (TCF)	Percent of mean in play	Gas-in-place (TCF)	Percent of mean in play	Gas-in-place (TCF)		
1—North-Central Ohio	17.9	34.2	25.9	—	—	100	25.90	—	—	—	—		
2—Western Lake Erie	21.7	31.3	26.5	—	—	100	26.50	—	—	—	—		
3—Eastern Lake Erie	2.1	3.3	2.7	—	—	100	2.70	—	—	—	—		
4—Plateau Ohio	44.4	76.2	59.9	—	—	100	59.90	—	—	—	—		
5—Eastern Ohio	35.2	55.1	44.7	—	—	100	44.70	—	—	—	—		
6—Western Penn-York	20.4	28.2	24.3	—	—	50	12.15	50	12.15	—	—		
7—Southern Ohio Valley	19.7	36.2	27.7	10	2.77	90	24.93	—	—	—	—		
8—Western Rome trough	38.0	74.0	56.0	80	44.80	20	11.20	—	—	—	—		
9—Tug Fork	13.7	25.9	19.7	65	12.81	—	—	35	6.90	—	—		
10—Pine Mountain	10.7	18.7	14.6	100	14.60	—	—	—	—	—	—		
11—Plateau Virginia	3.9	10.2	7.1	20	1.42	—	—	80	5.68	—	—		
12—Pittsburgh Basin	76.8	129.9	102.1	—	—	30	30.63	55	56.16	15	15.32		
13—Eastern Rome Trough	70.7	132.5	100.3	—	—	—	0.00	40	40.12	60	60.18		
14—New River	38.5	91.7	63.1	—	—	—	0.00	40	25.24	60	37.86		
15—Portage Escarpment	8.5	21.3	14.6	—	—	20	2.92	70	10.22	10	1.46		
16—Cattaraugus Valley	10.4	23.2	16.6	—	—	20	3.32	80	13.28	—	0.00		
17—Penn-York Plateau	98.1	195.2	146.0	—	—	—	—	40	58.40	60	87.60		
18—Western Susquehanna	24.1	67.7	44.9	—	—	—	—	—	—	100	44.90		
19—Catskill	22.1	75.8	47.6	—	—	—	—	—	—	100	47.60		
Total	577.1	1,130.8	844.3				76.40		244.85		228.14		294.92

Table 3. Devonian shale geochemistry data from the Appalachian Basin Petroleum Province (compiled from Streib, 1981).

[EGSP, Eastern Gas Shales Project of the U.S. Department of Energy (2007); n.d., no data]

State	County	EGSP well number	Stratigraphic unit	Depth (feet)	Thickness (feet)	Gas volume (cubic feet)	Total carbon (percent)	Total organic carbon (percent)	Mean vitrinite reflectance (percent)
Greater Big Sandy Assessment Unit									
Kentucky	Johnson	KY#4	Cleveland Member of Ohio Shale	1,002	93	0.69	3.61	3.83	0.52
Kentucky	Johnson	KY#4	Lower part of Huron Member of Ohio Shale	1,304	119	0.60	6.03	4.84	0.58
Kentucky	Johnson	KY#4	Middle part of Huron Member of Ohio Shale	1,188	116	0.69	4.42	2.52	0.55
Kentucky	Johnson	KY#4	Upper part of Huron Member of Ohio Shale	1,121	67	0.64	2.49	2.47	0.55
Kentucky	Martin	KY#3	Cleveland Member of Ohio Shale	2,432	80	0.56	5.66	3.58	0.53
Kentucky	Martin	KY#3	Lower part of Huron Member of Ohio Shale	2,910	218	0.55	3.90	2.88	0.46
Kentucky	Martin	KY#3	Rhinestreet Shale Member of West Falls Formation	3,360	60	0.43	3.79	1.64	0.49
Kentucky	Martin	KY#3	Upper part of Huron Member of Ohio Shale	2,654	141	0.09	3.16	3.08	0.48
Kentucky	Perry	KY#1	Cleveland Member of Ohio Shale	2,369	61	n.d.	5.80	5.63	n.d.
Kentucky	Perry	KY#1	Huron Member (undivided) of Ohio Shale	2,455	213	n.d.	3.77	3.53	n.d.
Kentucky	Perry	KY#1	Rhinestreet Shale Member of West Falls Formation	2,686	22	n.d.	2.17	1.34	n.d.
Virginia	Wise	VA#1	Cleveland Member of Ohio Shale	4,870	68	1.41	4.55	4.35	0.97
Virginia	Wise	VA#1	Lower part of Huron Member of Ohio Shale*	5,330	50	1.20	3.24	3.40	1.01
Virginia	Wise	VA#1	Rhinestreet Shale Member of West Falls Formation	6,530	48	n.d.	n.d.	n.d.	n.d.

Table 3. Devonian shale geochemistry data from the Appalachian Basin Petroleum Province (compiled from Streib, 1981).—Continued

[EGSP, Eastern Gas Shales Project of the U.S. Department of Energy (2007); n.d., no data]

State	County	EGSP well number	Stratigraphic unit	Depth (feet)	Thickness (feet)	Gas volume (cubic feet)	Total carbon (percent)	Total organic carbon (percent)	Mean vitrinite reflectance (percent)
Greater Big Sandy Assessment Unit—Continued									
Virginia	Wise	VA#1	Upper part of Huron Member of Ohio Shale	5,036	50	n.d.	n.d.	n.d.	n.d.
West Virginia	Jackson	#12041	Lower part of Huron Member of Ohio Shale	3,220	430	n.d.	1.84	1.56	n.d.
West Virginia	Lincoln	#20403	Cleveland Member of Ohio Shale	2,945	63	0.09	2.06	2.08	n.d.
West Virginia	Lincoln	#20403	Lower part of Huron Member of Ohio Shale	3,404	258	0.36	3.85	3.52	n.d.
West Virginia	Lincoln	#20403	Marcellus Shale	4,022	29	1.13	5.80	n.d.	n.d.
West Virginia	Lincoln	#20403	Rhinestreet Shale Member of West Falls Formation	3,942	70	0.87	3.79	4.66	n.d.
West Virginia	Lincoln	#20403	Upper part of Huron Member of Ohio Shale	3,074	122	0.16	1.03	0.68	n.d.
West Virginia	Mason	WV#5	Lower part of Huron Member of Ohio Shale	2,714	318	0.20	3.08	2.74	0.58
West Virginia	Mason	WV#5	Rhinestreet Shale Member of West Falls Formation	3,300	65	0.44	n.d.	n.d.	0.66
Northwestern Ohio Shale Assessment Unit									
Ohio	Ashtabula	OH#4	Dunkirk Shale Member of Perrysburg Formation	838	24	0.69	n.d.	4.69	0.40
Ohio	Ashtabula	OH#4	Marcellus Shale	1,330	30	0.90	n.d.	4.22	0.48
Ohio	Ashtabula	OH#4	Rhinestreet Shale Member of West Falls Formation	1,060	142	0.62	n.d.	4.86	0.44
Ohio	Gallia	OH#6-1	Cleveland Member of Ohio Shale	1,770	44	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-2	Cleveland Member of Ohio Shale	1,728	36	n.d.	n.d.	n.d.	n.d.

Table 3. Devonian shale geochemistry data from the Appalachian Basin Petroleum Province (compiled from Streib, 1981).—Continued

[EGSP, Eastern Gas Shales Project of the U.S. Department of Energy (2007); n.d., no data]

State	County	EGSP well number	Stratigraphic unit	Depth (feet)	Thickness (feet)	Gas volume (cubic feet)	Total carbon (percent)	Total organic carbon (percent)	Mean vitrinite reflectance (percent)
Northwestern Ohio Shale Assessment Unit—Continued									
Ohio	Gallia	OH#6-3	Cleveland Member of Ohio Shale	2,000	40	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-4	Cleveland Member of Ohio Shale	1,980	38	0.75	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-5	Cleveland Member of Ohio Shale	1,678	36	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	Average	Cleveland Member of Ohio Shale	n.d.	n.d.	n.d.	n.d.	7.46	n.d.
Ohio	Gallia	OH#6-1	Lower part of Huron Member of Ohio Shale	2,318	245	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-2	Lower part of Huron Member of Ohio Shale	2,260	238	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-3	Lower part of Huron Member of Ohio Shale	2,546	245	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-4	Lower part of Huron Member of Ohio Shale	2,543	247	0.36	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-5	Lower part of Huron Member of Ohio Shale	2,206	240	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	Average	Lower part of Huron Member of Ohio Shale	n.d.	n.d.	n.d.	n.d.	3.27	n.d.
Ohio	Gallia	OH#6-1	Middle part of Huron Member of Ohio Shale	2,134	184	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-2	Middle part of Huron Member of Ohio Shale	2,087	173	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-3	Middle part of Huron Member of Ohio Shale	2,367	179	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-4	Middle part of Huron Member of Ohio Shale	2,350	193	0.27	n.d.	n.d.	n.d.

Table 3. Devonian shale geochemistry data from the Appalachian Basin Petroleum Province (compiled from Streib, 1981).—Continued

[EGSP, Eastern Gas Shales Project of the U.S. Department of Energy (2007); n.d., no data]

State	County	EGSP well number	Stratigraphic unit	Depth (feet)	Thickness (feet)	Gas volume (cubic feet)	Total carbon (percent)	Total organic carbon (percent)	Mean vitrinite reflectance (percent)
Northwestern Ohio Shale Assessment Unit—Continued									
Ohio	Gallia	OH#6-5	Middle part of Huron Member of Ohio Shale	2,034	172	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	Average	Middle part of Huron Member of Ohio Shale	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-1	Upper part of Huron Member of Ohio Shale	2,007	127	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-2	Upper part of Huron Member of Ohio Shale	1,968	119	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-3	Upper part of Huron Member of Ohio Shale	2,224	143	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-4	Upper part of Huron Member of Ohio Shale	2,200	150	0.56	n.d.	n.d.	n.d.
Ohio	Gallia	OH#6-5	Upper part of Huron Member of Ohio Shale	1,900	134	n.d.	n.d.	n.d.	n.d.
Ohio	Gallia	Average	Upper part of Huron Member of Ohio Shale	n.d.	n.d.	n.d.	n.d.	1.94	n.d.
Ohio	Knox	OH#3	Cleveland Member of Ohio Shale	579	33	0.77	11.30	5.43	0.51
Ohio	Knox	OH#3	Huron Member (undivided) of Ohio Shale	712	442	0.45	4.24	2.84	0.56
Ohio	Lorain	OH#5	Cleveland Member of Ohio Shale	299	129	0.30	n.d.	3.14	n.d.
Ohio	Lorain	OH#5	Lower part of Huron Member of Ohio Shale	901	187	0.95	n.d.	7.79	n.d.
Ohio	Lorain	OH#5	Middle part of Huron Member of Ohio Shale	814	87	0.99	n.d.	5.59	n.d.

Table 3. Devonian shale geochemistry data from the Appalachian Basin Petroleum Province (compiled from Streib, 1981).—Continued

[EGSP, Eastern Gas Shales Project of the U.S. Department of Energy (2007); n.d., no data]

State	County	EGSP well number	Stratigraphic unit	Depth (feet)	Thickness (feet)	Gas volume (cubic feet)	Total carbon (percent)	Total organic carbon (percent)	Mean vitrinite reflectance (percent)
Northwestern Ohio Shale Assessment Unit—Continued									
Ohio	Lorain	OH#5	Upper part of Huron Member of Ohio Shale	735	79	0.99	n.d.	4.38	n.d.
Ohio	Trumbull	OH#7	Huron Member (undivided) of Ohio Shale	1,729	423	0.45	n.d.	n.d.	n.d.
Ohio	Trumbull	OH#7	Marcellus Shale	2,672	36	n.d.	n.d.	n.d.	n.d.
Ohio	Trumbull	OH#7	Rhinestreet Shale Member of West Falls Formation	2,490	94	n.d.	n.d.	n.d.	n.d.
Pennsylvania	Erie	PA#3	Dunkirk Shale Member of Perrysburg Formation	375	262	0.10	n.d.	2.64	0.43
Pennsylvania	Erie	PA#3	Marcellus Shale	1,218	30	0.25	n.d.	3.99	0.55
Pennsylvania	Erie	PA#3	Rhinestreet Shale Member of West Falls Formation	948	92	0.42	n.d.	4.97	0.49
Devonian Siltstone and Shale Assessment Unit									
New York	Allegany	NY#1	Dunkirk Shale Member of Perrysburg Formation	370	144	0.03	0.40	0.12	0.67
New York	Allegany	NY#1	Rhinestreet Shale Member of West Falls Formation	1,335	1011	0.24	0.61	0.34	1.32
Ohio	Washington	OH#2	Lower part of Huron Member of Ohio Shale*	3,160	570	0.50	2.35	1.92	0.58
Pennsylvania	Allegheny	PA#2	Marcellus Shale	7,332	164	0.33	6.86	3.34	2.47
Pennsylvania	McKean	PA#1	Marcellus Shale	5,088	81	0.39	5.78	2.46	1.26
West Virginia	Wetzel	WV#7	Marcellus Shale	6,570	55	0.28	10.25	6.19	1.71
West Virginia	Wetzel	WV#7	Rhinestreet Shale Member of West Falls Formation	6,102	77	0.29	1.85	0.49	1.58

Table 3. Devonian shale geochemistry data from the Appalachian Basin Petroleum Province (compiled from Streib, 1981).—Continued

[EGSP, Eastern Gas Shales Project of the U.S. Department of Energy (2007); n.d., no data]

State	County	EGSP well number	Stratigraphic unit	Depth (feet)	Thickness (feet)	Gas volume (cubic feet)	Total carbon (percent)	Total organic carbon (percent)	Mean vitrinite reflectance (percent)
Marcellus Shale Assessment Unit									
West Virginia	Monongalia	WV#6	Marcellus Shale	7,396	104	0.38	6.79	n.d.	2.30
Not assessed									
Tennessee	Grainger	TN#9	Cleveland Member of Ohio Shale	1,134	102	<0.01	n.d.	2.84	n.d.
Tennessee	Grainger	TN#9	Lower part of Huron Member of Ohio Shale	1,632	102	0.12	n.d.	3.73	n.d.
Tennessee	Grainger	TN#9	Middle part of Huron Member of Ohio Shale	1,502	130	<0.01	n.d.	2.06	n.d.
Tennessee	Grainger	TN#9	Rhinestreet Shale Member of West Falls Formation	1,834	22	0.33	n.d.	2.58	n.d.
Tennessee	Grainger	TN#9	Upper part of Huron Member of Ohio Shale	1,418	84	n.d.	n.d.	n.d.	n.d.

*Different samples were analyzed for total organic carbon.

**Cored interval is in the lower part of the Huron Member of the Ohio Shale from 3,491 to 3,711 feet.

Table 4. Summary of total organic carbon (TOC) content of samples from the Devonian Marcellus Shale and the Rhinestreet Shale Member of the West Falls Formation (compiled from Weary and others, 2000; Repetski and others, 2002, 2005).

[DSS, Devonian Siltstone and Shale; GBS, Greater Big Sandy; MS, Marcellus Shale; NWOS, Northwestern Ohio Shale; —, no data]

New York Marcellus Formation (Weary and others, 2000)			West Virginia Marcellus Formation (Repetski and others, 2005)			Pennsylvania Marcellus Formation (Repetski and others, 2002)			West Virginia Rhinestreet Shale Member of West Falls Formation (Repetski and others, 2005)		
Assessment Unit	County	Total organic carbon (percent)	Assessment Unit	County	Total organic carbon (percent)	Assessment Unit	County	Total organic carbon (percent)	Assessment Unit	County	Total organic carbon (percent)
DSS	Ontario	1.77	DSS	Marshall	1.98	DSS	Forest	6.1	DSS	Raleigh	1.94
DSS/MS	Yates	6.22	DSS	Wyoming	1.8	DSS	Greene	5.92	DSS	Roane	1.22
DSS/MS	Seneca	1.72	DSS	Fayette	1.68	DSS	Allegheny	5.38	DSS	Wirt	1.09
DSS/MS	Steuben	1.57	DSS	Fayette	1.61	DSS	Armstrong	5.26	DSS	Ritchie	0.87
DSS/ NWOS	Livingston	11.05	DSS	Clay	1.43	DSS	Mercer	5.01	DSS	Roane	0.27
DSS/ NWOS	Livingston	6.6	DSS	McDowell	0.99	DSS	Warren	3.99	DSS/GBS	Kanawha	1.89
DSS/ NWOS	Livingston	6.24	DSS	Raleigh	0.72	DSS	Clarion	3.98	DSS/GBS	Wood	1.85
DSS/ NWOS	Cattaraugus	5.77	DSS	Doddridge	0.56	DSS	Warren	1.92	DSS/GBS	Wood	0.61
MS	Chemung	6.98	DSS/GBS	Boone	1.75	DSS	Butler	0.79	DSS/GBS	Kanawha	0.47
MS	Schuyler	5.77	MS	Greenbrier	1.95	DSS/MS	Washington	3.35	GBS	Cabell	2.30
MS	Cayuga	3.54	MS	Tucker	1.85	DSS/MS	McKean	2.86	GBS	Jackson	2.12
MS	Chenango	2.19	MS	Greenbrier	1.74	DSS/ NWOS	Venango	4.6	GBS	Wayne	1.51
MS	Cortland	2.11	MS	Greenbrier	1.48	MS	Northumberland	6.2	GBS/DSS	Logan	1.60
MS	Madison	1.71	MS	Preston	1.43	MS	Elk	5.13	—	—	—
MS	Tompkins	0.58	MS	Marion	1.38	MS	Somerset	5.07	—	—	—
MS	Broome	0.26	MS	Tucker	1.28	MS	Snyder	4.76	—	—	—
NWOS	Wyoming	7.07	MS	Monongalia	1.09	MS	Fayette	4.74	—	—	—
NWOS	Genesee	5.7	MS	Harrison	0.47	MS	Tioga	4.68	—	—	—
NWOS	Erie	4.86	MS/DSS	Nicholas	2.61	MS	Clinton	3.56	—	—	—
—	—	—	MS/DSS	Braxton	1.69	MS	Sullivan	3.41	—	—	—
—	—	—	MS/DSS	Nicholas	0.98	MS	Bradford	3.23	—	—	—
—	—	—	MS/DSS	Summers	0.34	MS	Clinton	3.1	—	—	—
—	—	—	—	—	—	MS	Lycoming	3.07	—	—	—
—	—	—	—	—	—	MS	Cambria	3.03	—	—	—

Table 4. Summary of total organic carbon (TOC) content of samples from the Devonian Marcellus Shale and the Rhinestreet Shale Member of the West Falls Formation (compiled from Weary and others, 2000; Repetski and others, 2002, 2005).—Continued

[DSS, Devonian Siltstone and Shale; GBS, Greater Big Sandy; MS, Marcellus Shale; NWOS, Northwestern Ohio Shale; —, no data]

New York Marcellus Formation (Weary and others, 2000)			West Virginia Marcellus Formation (Repetski and others, 2005)			Pennsylvania Marcellus Formation (Repetski and others, 2002)			West Virginia Rhinestreet Shale Member of West Falls Formation (Repetski and others, 2005)		
Assessment Unit	County	Total organic carbon (percent)	Assessment Unit	County	Total organic carbon (percent)	Assessment Unit	County	Total organic carbon (percent)	Assessment Unit	County	Total organic carbon (percent)
—	—	—	—	—	—	MS	Wayne	1.86	—	—	—
—	—	—	—	—	—	MS	Susquehanna	1.76	—	—	—
—	—	—	—	—	—	MS	Carbon	1.46	—	—	—
—	—	—	—	—	—	MS	Pike	1.16	—	—	—
—	—	—	—	—	—	MS	Wyoming	0.42	—	—	—
—	—	—	—	—	—	MS	Blair	0.26	—	—	—
—	—	—	—	—	—	MS	Indiana	0.23	—	—	—
—	—	—	—	—	—	MS/DSS	Jefferson	3.71	—	—	—
—	—	—	—	—	—	MS/DSS	Potter	3.43	—	—	—
—	—	—	—	—	—	NWOS	Erie	8.55	—	—	—
—	—	—	—	—	—	NWOS	Mercer	3.36	—	—	—
—	—	—	—	—	—	NWOS/DSS	Lawrence	4.54	—	—	—
Average		4.30	Average		1.40	Average		3.61	Average		1.36
Number of samples		19	Number of samples		22	Number of samples		37	Number of samples		13