Overview of the Potential and Identified Petroleum Source Rocks of the Appalachian Basin, Eastern United States

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Chapter G.13 of

Coal and Petroleum Resources in the Appalachian Basin: Distribution, Geologic Framework, and Geochemical Character

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Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 1983).

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By James L. Coleman, Jr.,[1] Robert T. Ryder,[1] Robert C. Milici,[1] and Stephen Brown[2]

Abstract

The Appalachian basin is the oldest and longest producing commercially viable petroleum-producing basin in the United States. Source rocks for reservoirs within the basin are located throughout the entire stratigraphic succession and extend geographically over much of the foreland basin and fold-and-thrust belt that make up the Appalachian basin. Major source rock intervals occur in Ordovician, Devonian, and Pennsylvanian strata with minor source rock intervals present in Cambrian, Silurian, and Mississippian strata.

Introduction

The first instance of commercial production of petroleum in the United States was in the Appalachian basin (de Witt and Milici, 1989; de Witt, 1993). The vast majority of the produced oil and natural gas (in all its forms and viscosities) is generated from petroleum source rocks interspersed within Paleozoic strata that contain both siliciclastic and carbonate reservoir rocks. The main source rock intervals, which have been geochemically typed to produced petroleum, are the Ordovician Utica Shale and the Upper and Middle Devonian and Lower Mississippian shale formations (including the Devonian Ohio Shale and the Mississippian Sunbury Shale). The source of coalbed methane is primarily the Pennsylvanian coals. Local accumulations of petroleum have been generated from other less prolific source rocks. Throughout the Appalachian basin, the generated petroleum ranges from crude oil to natural gas. Most of the analyzed petroleum fluids were thermogenically derived during the evolution of the Appalachian foreland basin and fold-and-thrust belt. The evolutionary sequence involving the biogenic formation of methane within the Appalachian basin is not completely understood and thus is not included in this review.

This report examines the currently identified and potentially recognized petroleum source rocks of the Appalachian basin within and adjacent to the Appalachian Basin Province (Province 67 of Dolton and others, 1995), for which Milici and others (2003) summarized the 2002 assessment of undiscovered oil and gas resources by the U.S. Geological Survey (USGS). For this report, the structural Appalachian basin includes strata of the Black Warrior basin because some petroleum resources extend across basin boundaries. The boundary of the Appalachian Basin Province is shown in figure 1.

Effective petroleum source rocks are typically considered to be stratigraphic intervals having an original total organic carbon (TOC) content that is greater than 1.0 weight percent (Dow, 1977, 1978; Tissot and Welte, 1984; Peters and Moldowan, 1993; Law, 1999; Peters and others, 2005). Although some studies (which were mainly conducted early in the analysis of a basin's petroleum systems) suggest that thick intervals having an average TOC lower than 1 percent may be as effective in generating large amounts of petroleum as much thinner intervals that are substantially richer in organic matter (for example, Nwachukwu and Chukwura, 1985; Doust and Omatsola, 1989; Goddard and others, 2008), there is little evidence to indicate that thick, but lean, stratigraphic intervals are major source rocks that dominate the petroleum systems of a basin. In the Appalachian basin, the major source rocks identified to date are predominantly lithic shales rather than carbonaceous lime mudstones, although less extensive source rocks may be carbonaceous lime mudstones. Petroleum source rocks have been identified or hypothesized in each of the Paleozoic stratigraphic systems of the Appalachian basin.

The mere presence of a sedimentary unit that has a TOC content greater than 1.0 percent does not guarantee that it will be an effective source rock. Sufficient convertibility (S_2, the second petroleum peak generated by pyrolysis) and thermal maturation (expressed as the percent vitrinite reflectance (%R_o) or indicated by conodont color alteration indices (CAI)) are also required. Generally, levels of S_2 equivalent to or greater than 5 milligrams of hydrocarbon per gram of dry rock (mgHC/g rock) and a thermal maturation equivalent to or greater than 0.65 %R_o are required for the efficient generation of liquid petroleum (oil) (Waples, 1980; Tissot and Welte, 1984; Peters, 1986). When and where these levels of S_2 and vitrinite reflectance have not been reached, only the formation of biogenic methane is a reasonable possibility (Rice, 1993). Source rocks in which the kerogen is predominantly algal in

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nature (Type I or II kerogen) tend to produce oil and some natural gas (Peters and others, 2005). However, source rocks that contain mainly woody (Type III) kerogen tend to produce natural gas, with some possible liquid component, if the kerogen content and temperature gradient over geologic time permit (Peters and others, 2005). High levels of thermal alteration (equivalent to or greater than 1.2 %R_o) will normally "crack" (breaking up complex, heavier, higher carbon number organic molecules into simpler, lighter, lower carbon number organic molecules) any remaining oil to gas (after it has converted the algal kerogen to oil and residual bitumen during the increase in pressure and temperature to 1.2 %R_o). Cracking eventually transforms the remainder of the convertible kerogen to gas, producing a high gas content petroleum charge (that is, more gas than oil) (Peters and others, 2005). Thermal alteration greater than 0.5 %R_o and less than 1.2 %R_o will commonly convert Type III kerogen to natural gas and possibly some associated natural gas liquids (Peters and others, 2005). All of the stratigraphic intervals discussed in this chapter have gone into thermal regimes high enough to generate oil at some point in space and time in the evolution of the Appalachian basin.

In the Appalachian basin, the source rocks deposited from the Precambrian to the Silurian are expected to contain lacustrine Type I or marine Type II kerogen, both of which are prone to initially generate oil. In part (or perhaps all) of the Appalachian basin, Devonian and younger source rocks commonly contain terrigenous Type III kerogen in addition to or instead of marine Type II kerogen (Peters and others, 2005).

In this study, recent USGS work by Milici (2005), Ryder and others (2005, 2007), and Milici and Swezey (2006) has been compiled with older work to develop a synthesis of the petroleum source rock potential for the Appalachian basin. Previously unpublished work by Repetski and others (2008; also see chapter F.1 of this volume) formed the basis for the interpretation of the source rock potential of the Ordovician and Devonian strata (fig. 1; also, see Repetski and others, 2008, and this volume, chap. F.1, for locations of Devonian samples used herein).

These data and reports were supplemented with data acquired through the purchase of a proprietary[3] study by Exlog/Brown and Ruth Laboratories, Inc. (undated; hereinafter referred to as "the Brown and Ruth study"). The Brown and Ruth study contained sample descriptions, TOC data, and pyrolysis data from 58 stratigraphically and regionally significant wells in the Appalachian basin as of 1984 (table 1). Not all wells contained samples from the entire Cambrian to Pennsylvanian stratigraphic interval, and not all wells with samples from a complete stratigraphic unit contained the main source rock. The Brown and Ruth study also included charts that depicted the lithostratigraphy and associated TOC and were examined for indications that intervals of source-rock quality might be present in the Paleozoic basin fill. If rocks in a selected interval had a TOC value of greater than 1.0 percent, then the entire interval was examined and a single TOC value that represented the interval was estimated. In order to accurately reflect the organic content of the Pennsylvanian and Mississippian carbonaceous shales, the high TOC values that were obviously associated with interspersed coal beds were excluded. In all of the maps presented in this study, the TOC values incorporated from the Brown and Ruth study are neither the maximum values recorded nor the arithmetic averages, so that neither the very few high values nor the very numerous low values overweigh the aggregate. The values from the Brown and Ruth study were incorporated along with additional data from outcrops, wells, and maps from Schmoker (1980); Snowdon (1984); Cole and others (1987); Wallace and Roen (1989); Carroll and others (1995); Ryder and others (1998, 2005, 2007); Milici and Swezey (2006); Patchen and others (2006); Robert C. Milici (USGS), Frank T. Dulong (USGS), Catherine B. Enomoto (USGS, formerly with Virginia Department of Mines, Minerals and Energy), James Leone (New York Geological Survey), John Harper (Pennsylvania Bureau of Topographic and Geologic Survey), Jaime Kostelnik (Pennsylvania Bureau of Topographic and Geologic Survey), Ronald Riley (Ohio Division of Geological Survey), Katharine Lee Avary (West Virginia Geological and Economic Survey), Brian Grothaus (West Virginia Geological and Economic Survey), David C. Harris (Kentucky Geological Survey), and William L. Lassetter (Virginia Department of Mines, Minerals and Energy), unpub. data, 2007; Repetski and others (2008; see also chapter F.1 of this volume); Ryder (2008); and Vermont Agency of Natural Resources (2009).

[3]The specific data from this proprietary study are not provided in this report. The percent total organic carbon from the samples in the report are included within the ranges of percent total organic carbon shown in figures 3 through 8.

Potential Precambrian Source Rocks

Precambrian units are present in and near the Appalachian basin (fig. 2), but, to date, no confirmed Precambrian petroleum source rocks have been identified from the Appalachian basin. Elsewhere in the United States, Precambrian source rocks have been identified in the Midcontinent Rift (Hatch and Morey, 1985; Yarus and others, 1987; Imbus and others, 1990; Palacas, 1997; Burruss and Palacas, 1999; Peters and others, 2005), in the Chuar Group of the Grand Canyon area of Arizona and Utah (Uphoff, 1997; Peters and others, 2005), and in the Belt Supergroup of Idaho and Montana (Palacas, 1997). Seismic-reflection data and wildcat gas shows suggest the possibility of Precambrian source rocks in the Rough Creek graben of western Kentucky (Drahovzal, 1998; Shirley, 2002).

In the Appalachian basin, the Anakeesta Formation and generally equivalent strata of the Great Smoky Group are structurally in the most favorable position to be potential Precambrian source rocks (Aleinikoff and others, 2006). These strata, which crop out within the Great Smoky Mountains National Park of North Carolina and Tennessee, are metamorphosed, carbonaceous, black shales. The Anakeesta Formation in the central Great Smoky Mountains is almost 1,220 meters (m) thick (King, 1964). The TOC values of the Anakeesta Formation range from 0.03 to 1.6 percent (Nora Foley, USGS, written commun., 2007). The TOC values of similar but unidentified Precambrian black shales in the Great Smoky Mountains National Park range from 0.34 to 2.79 percent (Nora Foley, USGS, written commun., 2007). The metamorphic grade of the Anakeesta Formation ranges from slate to schist (King, 1964), which indicates that it is too thermally mature to be currently considered an effective, potential petroleum source rock. To date, no petroleum has been geochemically tied to the Anakeesta Formation or any of the other black shales in the Great Smoky Group.

A depleted metal content suggests that the Anakeesta may have contributed to the Mississippi Valley-type ore bodies of the Ordovician strata in eastern Tennessee, which locally have oil fluid inclusions and petroleum residue (Roedder, 1971; Haynes and Kesler, 1989; Furman, 1992; Foley and others, 2001). Oils produced in eastern Tennessee and southwestern Virginia that might be logically and spatially associated with a hypothetical Precambrian source rock, such as the Anakeesta Formation of the Great Smoky Mountains area, have been geochemically associated with an as-yet unidentified Paleozoic (possibly Ordovician) source (Dennen and others, this volume, chap. G.12).

Identified and Potential Cambrian Source Rocks

Cambrian petroleum source rocks in the Eastern United States have been identified in intracratonic areas and along the cratonic Precambrian to Cambrian rift margin. The intracratonic rifts are latest(?) Precambrian to Cambrian in age and extend from Pennsylvania to eastern Kentucky as the Rome trough (fig. 3) and to western Kentucky as the Rough Creek graben. Additional extensions of these main rift zones have been identified or suggested (Potter and Drahovzal, 1994; Stark, 1997; Sutton, 1981). Ryder and others (2005) documented shale that was rich in organic matter from the Cambrian Conasauga Group in the Rome trough of West Virginia and Kentucky that had TOC values ranging from 0.09 to 3.26 percent and S_2 values ranging from 0.01 to 13.61 mgHC/g of organic carbon (orgC). Elsewhere in the main part of the Appalachian basin, only one well (Orange County, New York) had TOC values greater than 1.0 percent (Exlog/Brown and Ruth Laboratories, Inc., undated). Silberman (1972) reported a Cambrian shale in Elliott County, Kentucky, that probably has high organic-matter content. This shale, which is located in the Rome trough about 20 mi west of the organic-matter-rich shale reported by Ryder and others (2005), has been identified as the source rock for the Homer field in Elliott County, Kentucky (Harris and others, 2004).

Unpublished work by J.L. Coleman, Jr., during the 1980s suggested that the Conasauga Formation in the southern Appalachian basin was a potential petroleum source rock. The Conasauga is located in the footwall of the Great Smoky thrust fault in outcrops in the Carters Dam area, Murray County, Georgia; the outcrop samples from the Carters Dam area had TOC values ranging from 1.1 to 1.4 percent. Other samples from outcrops and shallow cores in the Conasauga Formation of Alabama had substantially lower TOC values, suggesting that the potential for the Conasauga as a source rock might be extremely limited spatially.

In light of these earlier findings, a new gas play (the Conasauga shale gas play) was developed within the Conasauga Formation in the southern Appalachian fold-and-thrust belt of Alabama, where the Conasauga is highly fractured and faulted (Pashin and others, 2012); this play, however, is no longer active. Reservoir intervals within this new play are presumed to be self-sourced based on their structural position within a complex duplex zone (Thomas, 2001). No strata of source-rock quality were reported by Osborne and others (2000) in their examination of the stratigraphic framework and sedimentology of the Conasauga Formation and equivalent units in the Appalachian fold-and-thrust belt of Alabama. Limited TOC data from wells within the play trend range from 0.2 to 1.8 percent, with only one value greater than 1.0 percent (Pashin and others, 2012).

The thicknesses of potential Cambrian source rocks in the Appalachian basin are not well known. In selected wells in the Rome trough, intervals with a documented potential source-rock quality are about 38 m thick (Ryder and others, 2005); however, the Cambrian source rock at the Carters Dam outcrop is only a few meters thick. Within the Conasauga shale gas play in northeastern Alabama, the structurally thickened Conasauga is at least 2,835 m thick based on seismic and well-control data (Thomas, 2001). Across the Appalachian basin, the thermal maturity of Cambrian strata ranges from late oil to early gas generation in wells in the Rome trough to past peak gas to metamorphic grade in the footwall outcrops of the Great Smoky thrust fault in Georgia. The thermal maturity of the Conasauga in the Alabama Conasauga shale gas play ranges from 1.1 to 1.95 %R_o (Pashin and others, 2012).

Identified and Potential Ordovician Source Rocks

In the Appalachian basin, source rocks within the Ordovician strata are richer and more widespread (fig. 4) than those in the underlying Cambrian strata (fig. 3). Wallace and Roen (1989), Ryder and others (1998), and Patchen and others (2006) illustrated the distribution of Ordovician source rocks in the northern part of the Appalachian basin. The source rocks are concentrated in the Utica Shale (or Formation) and equivalent Antes Shale (or Formation), which extend across the basin from northern West Virginia through eastern Ohio, most of Pennsylvania, and into southern and eastern New York. Their stratigraphic equivalents are the highly petroliferous Collingwood Member of the Lindsay Formation in Ontario,

Table 1. List of wells from Exlog/Brown and Ruth Laboratories, Inc. (undated).

[See figure 1 for a map of approximate sample locations (except for those in Vermont). List order is generally from north to south. The Exlog/Brown and Ruth Laboratories, Inc. (undated) report contains proprietary geochemical data that are included in the ranges of total organic carbon shown in figures 3 through 8. Operator and lease names are exactly as shown on source records and may not contain conventional spelling or punctuation]

Operator name	Well number	Lease name	County	State	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of latitude and longitude
American Petrofina and Falcon Seaboard Drilling Co.	1	Alburg	Grand Isle	Vermont	44.9186	73.28	Vermont Agency of Natural Resources (2009).
Vermont Natural Gas and Mineral Corp.	1	Gregoire	Chittenden	Vermont	44.5417	73.228	Vermont Agency of Natural Resources (2009).
Duschscherer, William J.	1	Searles Clayton	Orleans	New York	43.306780	78.452600	New York State Department of Environmental Conservation (2013).
Hoover Moble C.	1	Frankish George C 1	Ontario	New York	42.812680	77.202550	New York State Department of Environmental Conservation (2013).
New York Natural Gas Co.	1	Danisevich J	Madison	New York	42.796370	75.404260	New York State Department of Environmental Conservation (2013).
Joyne Western Corp. (originally Fenix & Scisson)	1	Richards	Broome	New York	42.323530	75.947510	New York State Department of Environmental Conservation (2013).
Pennzoil Products Co. (originally Wolfs Head)	1	Harrington	Chautauqua	New York	42.183640	79.337540	New York State Department of Environmental Conservation (2013).
Amoco Prod. Co.	1	Harry P Dewey	Tioga	Pennsylvania	41.689397	77.546975	Pennsylvania Bureau of Topographic and Geologic Survey (2013).
Arco Metals Co. (originally Arco Oil & Gas Corp.)	1	Aroc 1 Susi 1 (originally Susi Rudolph)	Ulster	New York	41.662510	74.126660	New York State Department of Environmental Conservation (2013).
Gulf Oil Corp.	1	Whole Earth	Orange	New York	41.425220	74.565300	New York State Department of Environmental Conservation (2013).
Texaco Incorporated	C–1	St Forest Lands	Pike	Pennsylvania	41.416528	75.141588	Pennsylvania Bureau of Topographic and Geologic Survey (2013).
Texaco Incorporated	1	Penn Forest Tr 285	Clinton	Pennsylvania	41.371292	77.566622	Pennsylvania Bureau of Topographic and Geologic Survey (2013).
Peoples Natural Gas	1	Temple Robert W	Mercer	Pennsylvania	41.351260	80.176427	Pennsylvania Bureau of Topographic and Geologic Survey (2013).
Anschutz Corp.	1-A	Kramer	Wood	Ohio	41.342532	83.681783	Ohio Division of Oil and Gas Resources (2013).
Peoples Natural Gas	1 /4634/	Nellie C Martin	Armstrong	Pennsylvania	40.884825	79.346824	Pennsylvania Bureau of Topographic and Geologic Survey (2013).
Dominion East Ohio (originally East Ohio Gas Co.)	1–2468	Denny Elden E	Columbiana	Ohio	40.875231	80.988417	Ohio Division of Oil and Gas Resources (2013).

Table 1. List of wells from Exlog/Brown and Ruth Laboratories, Inc. (undated).—Continued

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Operator name	Well number	Lease name	County	State	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of latitude and longitude
Amoco Prod. Co.	1	Wilhour Gas Unit	Northumberland	Pennsylvania	40.857434	76.674258	Pennsylvania Bureau of Topographic and Geologic Survey (2008).
Anschutz Corp.	1	Gracely Farms	Marion	Ohio	40.586316	83.254278	Ohio Division of Oil and Gas Resources (2013).
Kerr-McGee Corp.	1	Schellsburg	Bedford	Pennsylvania	40.103171	78.617918	Pennsylvania Bureau of Topographic and Geologic Survey (2008).
Historic owner (originally Lakeshore Pipeline)	1	W Marshall Comm	Guernsey	Ohio	40.036768	81.720457	Ohio Division of Oil and Gas Resources (2013).
Amoco Prod. Co.	1	Leonard Svetz	Somerset	Pennsylvania	39.977764	79.333869	Pennsylvania Bureau of Topographic and Geologic Survey (2008).
Occidental	1	Burley	Marshall	West Virginia	39.761768	80.530082	West Virginia Geological and Economic Survey (2008).
Anschutz Corp.	1	Diffendahl	Pickaway	Ohio	39.615651	83.100425	Ohio Division of Oil and Gas Resources (2013).
Shell Oil Co.	1	O B & R Duckworth	Hampshire	West Virginia	39.49773	78.63372	West Virginia Geological and Economic Survey (2013).
Historic owner (originally Huggins Merle T)	1	M & H Hockman	Hocking	Ohio	39.398533	82.389389	Ohio Division of Oil and Gas Resources (2008).
Occidental	1	Sandhill	Wood	West Virginia	39.200000	81.700000	Exlog/Brown and Ruth Laboratories, Inc. (undated).
Pennzoil Co.	1	Maxwell	Doddridge	West Virginia	39.195900	80.774710	Exlog/Brown and Ruth Laboratories, Inc. (undated).
Exxon Company, USA	1	Charles H Bean	Hardy	West Virginia	39.137772	78.990108	West Virginia Geological and Economic Survey (2013).
Shell Oil Co.	1	R J Whetzel	Rockingham	Virginia	38.763806	78.956117	Virginia Division of Gas and Oil (2008).
United Fuel Gas Co.	1	Ray Sponaugle	Pendleton	West Virginia	38.547775	79.512327	West Virginia Geological and Economic Survey (2013).
Inland Gas	1	Fannin	Boyd	Kentucky	38.375000	82.666670	Kentucky Geological Survey (2008).
Columbia Gas Transmission Corp.	20659–T	Sally D Todd	Kanawha	West Virginia	38.370715	81.370715	West Virginia Geological and Economic Survey (2013).
Exxon Company, USA	1	Jay P Smith	Wayne	West Virginia	38.221803	82.534439	West Virginia Geological and Economic Survey (2013).

Table 1. List of wells from Exlog/Brown and Ruth Laboratories, Inc. (undated).—Continued

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Operator name	Well number	Lease name	County	State	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of latitude and longitude
U S Signal	1972	Elkhorn Coal Company	Johnson	Kentucky	37.799560	82.729873	Kentucky Geological Survey (2008).
Texaco Incorporated	1	B E Perkins	Madison	Kentucky	37.783745	84.432122	Kentucky Geological Survey (2008).
Columbia Gas Transmission	20750–T	Tredegar Co	Botetourt	Virginia	37.693168	79.779674	Virginia Division of Gas and Oil (2008).
Signal O&G Co Incorp.	1	Henry Stratton	Pike	Kentucky	37.482015	82.463083	Kentucky Geological Survey (2008).
California Co.	1	Kipps Anthracite	Montgomery	Virginia	37.186814	80.460526	Virginia Division of Gas and Oil (2008).
Amerada Hess Corp	1	Ray Edwards Et Al	Pulaski	Kentucky	37.087315	84.560290	Kentucky Geological Survey (2008).
Gulf Oil Corp.	1	Russell Price	Russell	Virginia	36.872481	82.237308	Virginia Division of Gas and Oil (2008).
Arco Oil & Gas Corp.	1	Campbell W (Slemp)	Lee	Virginia	36.791556	82.848817	Virginia Division of Gas and Oil (2008).
Associated-Pennzoil	1	F-A Sells	Pickett	Tennessee	36.571056	85.041833	Tennessee Department of Environment and Conservation database (2008).
Atha Howard D	1	Kitchen Coal	Scott	Tennessee	36.566361	84.374250	Tennessee Department of Environment and Conservation database (2008).
Amoco Prod. Co.	1	Reed Paul H	Hancock	Tennessee	36.469556	83.336389	Tennessee Department of Environment and Conservation database (2008).
Arco Oil & Gas Corp.	1	Sanford Heirs et al	Anderson	Tennessee	36.167861	84.167250	Tennessee Department of Environment and Conservation database (2008).
Amoco Prod. Co.	1	K S Driver	DeKalb	Tennessee	36.003694	85.903361	Tennessee Department of Environment and Conservation database (2008).
Ladd Petroleum Corp.	1	Kemmer T J et al	Cumberland	Tennessee	35.940667	84.819944	Tennessee Department of Environment and Conservation database (2008).
Musser S T	1	Pearl Yarberry	Sevier	Tennessee	35.877833	83.691417	Tennessee Department of Environment and Conservation database (2008).
Weaver O&G Corp.	1	Lewis (Pope)	Sequatchie	Tennessee	35.435694	85.338861	Tennessee Department of Environment and Conservation database (2008).
Amoco Prod. Co.	1	Brothers Jack J	Coffee	Tennessee	35.394778	85.923083	Tennessee Department of Environment and Conservation database (2008).
California Co.	1	E W Beeler	Giles	Tennessee	35.331056	87.136028	Tennessee Department of Environment and Conservation database (2008).

Table 1. List of wells from Exlog/Brown and Ruth Laboratories, Inc. (undated).—Continued

[See figure 1 for a map of approximate sample locations (except for those in Vermont). List order is generally from north to south. The Exlog/Brown and Ruth Laboratories, Inc. (undated) report contains proprietary geochemical data that are included in the ranges of total organic carbon shown in figures 3 through 8. Operator and lease names are exactly as shown on source records and may not contain conventional spelling or punctuation]

Operator name	Well number	Lease name	County	State	Latitude (decimal degrees)	Longitude (decimal degrees)	Source of latitude and longitude
Sonat Expl. Inc.	1	Brown	Dade	Georgia	34.921470	85.470610	Visually estimated from Coleman (1988).
Sonat	1	Cureton	Dade	Georgia	34.676944	85.523333	Swanson and Gernazian (1979)
Atlanta Gas Light Co.	3ST	Fee	Floyd	Georgia	34.260440	85.260060	Estimated from land district and land lot location information in well log header.
Saga-Petro US Incorp.	1	Hudson 16-7	Blount	Alabama	34.166310	86.434360	State Oil and Gas Board of Alabama (2012)
US Steel	1	Disposal	Jefferson	Alabama	33.533000	86.867000	Estimated from township-range-section location information in well log header.
Arco Oil & Gas Corp.	1	Arco-Anschutz 15-11	Shelby	Alabama	33.289670	86.528850	State Oil and Gas Board of Alabama (2008)
Shell Oil Co.	1	L H Sterling 17-14	Greene	Alabama	32.969050	88.017530	State Oil and Gas Board of Alabama (2008)

the Point Pleasant Formation in northwestern Ohio, the Gulf Stream Formation in New York (Lehmann and others, 1995), and the Iberville Formation in Vermont. The TOC values from the Utica, Antes, and equivalent shale units range from 0.28 to 4.46 percent, with a median of 1.81 percent (Ryder and others, 1998). Martin and others (2005) discussed Utica samples from eastern New York, Ontario, and Quebec for which TOC values ranged from 2 to 15 percent. The TOC data from the Brown and Ruth study range from a low of 0.10 percent to a high of 3.00 percent, with a mean of 0.79 percent.

Ordovician shales with TOC values greater than 1.0 percent have also been found farther south in the southwestern Virginia thrust belt (Schultz, 1988). Similar values have been found in isolated, weathered outcrops and quarries in the Sevier and Athens Formations in Alabama, Georgia, and eastern Tennessee (Benson and Stock, 1986; Saunders and Savrda, 1993; and Robert C. Milici (USGS), Frank T. Dulong (USGS), Catherine B. Enomoto (USGS, formerly with Virginia Department of Mines, Minerals and Energy), James Leone (New York Geological Survey), John Harper (Pennsylvania Bureau of Topographic and Geologic Survey), Jaime Kostelnik (Pennsylvania Bureau of Topographic and Geologic Survey), Ronald Riley (Ohio Division of Geological Survey), Katharine Lee Avary (West Virginia Geological and Economic Survey), Brian Grothaus (West Virginia Geological and Economic Survey), David C. Harris (Kentucky Geological Survey), and William L. Lassetter (Virginia Department of Mines, Minerals and Energy), unpub. data, 2007.

The Ordovician shales are the source rocks for oil and natural gas in Middle Ordovician to Silurian reservoirs throughout Ohio and Indiana as well as Ontario, Canada. Where structurally favorable, they also have been the source rocks for stratigraphically lower reservoirs, such as those formed at the Knox unconformity (Cole and others, 1987; Ryder and others, 1998; Coleman and others, 2006). On the basis of gas chromatograph signatures, oil from isolated fields in the southern Appalachian basin of southwestern Virginia and eastern Tennessee has also been geochemically tied to Ordovician source rocks (Dennen and others, this volume, chap. G.12). The spatial coincidence of Ordovician oil and Mississippi Valley-type lead-zinc deposits suggests that Ordovician strata were the primary sources of both the petroleum and the sulfide minerals in the southern Appalachian basin (Saunders and Savrda, 1993).

The thickness of Ordovician source-rock strata ranges from 60 m in western Ohio to between 90 and 120 m in the main generative basin area of Pennsylvania and eastern Ohio. The source-rock strata reach a maximum thickness of 180 to more than 200 m in the eastern reaches of the Appalachian thrust belt in eastern New York, southern Pennsylvania, northern West Virginia, and western Maryland (Wallace and Roen, 1989; Martin and others, 2005). In thrust-belt outcrops in Tennessee, Georgia, and Alabama, the thicknesses of the potential source-rock strata (Athens, Blockhouse, and Sevier Shales and generally equivalent strata) range from over 80 m in Alabama to as much as 300 m in Tennessee (Neuman, 1955; Benson and Stock, 1986). The thermal maturity of the Ordovician source rocks ranges from immature to past the peak of gas generation (Epstein and others, 1977; Harris and others, 1978; Patchen and others, 2006; Repetski and others, 2008, and this volume, chap. F.1)

Potential Silurian Source Rocks

Until recently, source rocks of Silurian age have not been well documented in the Appalachian basin. However, Ryder and others (2007) indicated the presence of Silurian source rocks on the basis of new TOC and pyrolysis data from samples from the interval spanning the Salina Formation (or Group), Wills Creek Formation (or Shale), and Tonoloway Formation (or Limestone). They reported five samples with TOC values greater than 1.00 percent from four wells in West Virginia and Pennsylvania. These samples consisted of dark-gray to black shale with locally interbedded brown, dark-gray, and (or) black limestone and dolomite; the potential thicknesses of the source-rock strata were estimated to range from 15 to 50 m. Figure 5 shows areas of potential Silurian source rocks.

Data from the Brown and Ruth study indicate that only one well in Ohio had Silurian strata containing TOC values greater than 1.0 percent. Cole and others (1987) investigated organic geochemistry and oil-source rock correlations in the Paleozoic strata of Ohio and reported that only 3 of 436 samples had TOC values greater than 1.0 percent and that the highest value was 1.31 percent in their interval containing Silurian and Lower Devonian strata. However, effective Silurian source rocks have been identified in the Michigan basin of Michigan and Ontario (Gill, 1979; Gardner and Bray, 1984; Powell and others, 1984; Obermajer and others, 1998; Hatch and others, 2004). On the basis of Devonian thermal maturity maps, the thermal maturity of the underlying Silurian strata ranges from peak oil generation in Ohio to past the peak of gas generation in Pennsylvania (Epstein and others, 1977; Harris and others, 1978; Repetski and others, 2008, and this volume, chap. F.1).

Identified and Potential Devonian Source Rocks

Devonian shale-rich source rocks that have yielded high-quality oil and gas are present throughout the Appalachian basin (fig. 6). The majority of the petroleum found to date and estimated as undiscovered in the Appalachian basin originated from these shale-rich rocks (de Witt and Milici, 1989; Klemme and Ulmishek, 1991; de Witt, 1993; Roen and Walker, 1996; Milici and Swezey, 2006). The TOC values from these source rocks range from <1.0 to 27 percent, whereas visual and log-based approximations range from 2 to 22 percent, with most values ranging from 2 to 4 percent (Conant and Swanson, 1961; Schmoker, 1980; Charpentier and Schmoker, 1982; Cole and others, 1987; Hill and others, 2004; Milici and Swezey, 2006). Shale samples from wells in the Brown and Ruth study had TOC values that ranged from 0.25 to 5.0 percent, with an average of 2.25 percent.

Devonian source rocks are present throughout the stratigraphic section in the basin, but they are most concentrated in the border region in Ohio, Kentucky, West Virginia, and Pennsylvania and represent the distal ends of the Catskill delta (Gray and others, 1982; Roen and Kepferle, 1993; Woodrow and Sevon, 1995; Milici and Swezey, 2006). This depositional setting introduced more gas-prone, terrigenous kerogen into an otherwise marine algae-rich environment. Consequently, most of the Devonian source rocks produce gas, even at thermal maturity levels equivalent to peak oil generation (Milici and Swezey, 2006). Whereas some of this gas is thermogenic, some of it is biogenic, and there appears to be a mixing zone where both thermogenic and biogenic gas coexist (Milici and Swezey, 2006; McIntosh and Martini, 2008).

The progressively westward deposition of the Catskill delta from the eroding highlands east of present-day Pennsylvania, Maryland, and New Jersey displaced the locus of deposition of the oil-prone source-rock facies from east to west and from older strata to younger strata. Consequently, the Middle Devonian source-rock facies are thickest to the east of the Upper Devonian source-rock facies (Gray and others, 1982; Milici and Swezey, 2006). The depositional pattern placed effective Devonian source rocks throughout the entire Appalachian basin from New York to Mississippi. When these source rocks reached their peak generating potential during the Carboniferous to Permian, oil and natural gas were generated over the entire Appalachian basin and accumulated in a variety of reservoir rocks (Milici and Swezey, 2006).

The Devonian source-rock strata range in thickness from near zero at the margins of the basin (Conant and Swanson, 1961; de Witt and others, 1993) to over 300 m along the Kentucky-West Virginia border (Schmoker, 1980). The thermal maturity values for the Devonian source rocks range from immature to past the peak for gas generation (Milici and Swezey, 2006; Repetski and others, 2008, this volume, chap. F.1).

Identified and Potential Mississippian Source Rocks

Mississippian source rocks are located in the Floyd Shale (and equivalent units) of the southern Appalachians and in the Sunbury Shale (and equivalent units) of the central Appalachians of Kentucky, Ohio, and West Virginia. In this report, the Sunbury is considered to be the Lower Mississippian genetic extension of the underlying Upper Devonian Chattanooga Shale, New Albany Shale, and Ohio Shale (all black shales) and is included with the Devonian strata in figure 6, whereas the Floyd Shale and Maccrady Formation represent synorogenic, Upper Mississippian outer-shelf, slope, and basinal shales and are included with the Mississippian strata in figure 7. The Floyd Shale is geographically restricted to the Appalachian basin of Alabama and Georgia and the Black Warrior basin of Mississippi and Alabama. The TOC values range from 0.5 to 10.0 percent with a mean of 1.8 percent from 19 samples in the Black Warrior basin (Carroll and others, 1995; Pawlewicz and Hatch, 2007). In eastern Ohio and western West Virginia, TOC values equal to or greater than 1.0 percent were recorded from two wells in strata above the Sunbury and its overlying sandstone units (Exlog/Brown and Ruth Laboratories, Inc., undated); the values indicated that the strata were relatively organically lean, but of source-rock quality. This interval is probably within the Maccrady Formation (or its stratigraphic equivalents) as inferred by a study of the Mississippian Cuyahoga Formation and its stratigraphic equivalents by Matchen (2004), who indicated that the Maccrady Formation is the only formation in this stratigraphic position that contains thin, discontinuous coal beds and associated organic-matter-rich shale.

The Floyd Shale ranges in thickness from near zero to over 60 m in the southern Appalachian and Black Warrior basins, where it ranges in thermal maturity from 0.9 to 1.6 $\%R_o$ (Carroll and others, 1995; Pawlewicz and Hatch, 2007). The Maccrady Formation ranges in thickness from 0 to 15 m in West Virginia, where it is commonly cut out by the overlying Pennsylvanian to Mississippian unconformity (Matchen, 2004). In eastern Ohio and western West Virginia, the thermal maturity of the Maccrady ranges from 0.5 to 0.7 $\%R_o$ (Exlog/Brown and Ruth Laboratories, Inc., undated).

In the central Appalachians of Virginia, coal beds in the Price Formation have the potential for generating methane that may be trapped in adjacent reservoirs (Milici, 2004). Coal beds in the Price range from about 0.7 to 7 m or more in thickness (Stanley and Schultz, 1983). Vitrinite-reflectance values range from 1.2 to 2.7 $\%R_o$, indicating that these coals are all at peak gas to past peak gas levels of thermal maturity (Lewis and Hower, 1990; Milici, 2004).

Identified and Potential Pennsylvanian Source Rocks

Organic-matter-rich strata in the Pennsylvanian of the Appalachian basin are associated with Pennsylvanian coal (fig. 8) and adjacent organic-matter-rich shale. These lithologies extend throughout the Appalachian basin and are known to be significant source rocks for natural gas in both shallow sandstone and coalbed-methane reservoirs. Locally, Pennsylvanian strata are the source rocks for the isolated shallow oil reservoirs in Pennsylvania and Ohio (Fettke, 1923; Martino, 2005). Milici (2004) analyzed the coalbed-methane potential for the Appalachian and Black Warrior basins. Presumably, where there are high gas generative coal beds and associated shales, there is high potential for gas-producing coals and shales.

The thermal maturity of the Pennsylvanian coals ranges from early (≤0.7 $\%R_o$) to the peak level of gas generation (1.4 $\%R_o$) in the Black Warrior basin (Hatch and Pawlewicz, 2007). In the Appalachian basin, the thermal maturity of the Pennsylvanian coals ranges from immature (or pre-generation; 0.4 $\%R_o$) along the western limb of the Appalachian basin to ultimately greater than past peak gas generation (>5.0 $\%R_o$) in the anthracite region of eastern Pennsylvania (Levine, 1992; Ruppert, cited in Milici, 2004).

Potential Permian Source Rocks for Biogenic Methane

Coal beds within the uppermost Pennsylvanian to Lower Permian Dunkard Group lie within the phreatic groundwater zone in southwestern Pennsylvania and currently are not likely candidates for thermogenic petroleum source rocks because their thermal maturity is too low (Pennsylvania Department of Environmental Protection, Bureau of Mining Programs, 1999). The possibility does exist, however, for the development and accumulation of biogenic methane associated with these coal zones (Pittsburgh Geological Society, undated).

Summary

Petroleum source rocks (both proven and potential) are present throughout the late Precambrian and Paleozoic strata in the Appalachian basin. Localized occurrences of Precambrian and Cambrian organic-matter-rich shale indicate that the oldest potential source rocks may be very restricted geographically and may not have contributed substantially to the overall volume of generated and expelled Appalachian basin petroleum. Ordovician source rocks are present in the northern Appalachian basin of the United States and southern Canada and in the fold-and-thrust belt of the southern Appalachians. These Ordovician source rocks have been geochemically associated with much of the oil present within the lower Paleozoic reservoir rocks in the Appalachian basin trend. Silurian source rocks are relatively insignificant within the Appalachian basin, even though they are significant locally in the Michigan basin. The most important source rocks for Appalachian basin petroleum are the shales of Middle and Late Devonian and earliest Mississippian age. These shales range in thickness from just a few meters to several thousand meters and extend throughout the Appalachian basin from Alabama to New York. Whereas coal-bearing strata in the Mississippian rocks have some petroleum-generating capability in Virginia, West Virginia, and possibly Pennsylvania, the main source rocks for the Mississippian are the Upper Mississippian strata that are present only in the southernmost Appalachian basin and adjacent Black Warrior basin of Alabama and Mississippi. Coal beds within the Pennsylvanian are a source of significant volumes of natural gas throughout the Appalachian basin. Some Pennsylvanian shale beds appear to be capable of generating oil, but they appear to be geographically restricted to the shallow, and therefore thermodynamically cooler, portions of the basin in Ohio and Pennsylvania. Coal beds in the uppermost Pennsylvanian to Lower Permian Dunkard Group are within the phreatic groundwater zone and were probably never buried deeply enough to have generated thermogenic natural gas. Generation and migration of biogenic methane, however, might be possible from these Permian coals.

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Figures 1–8

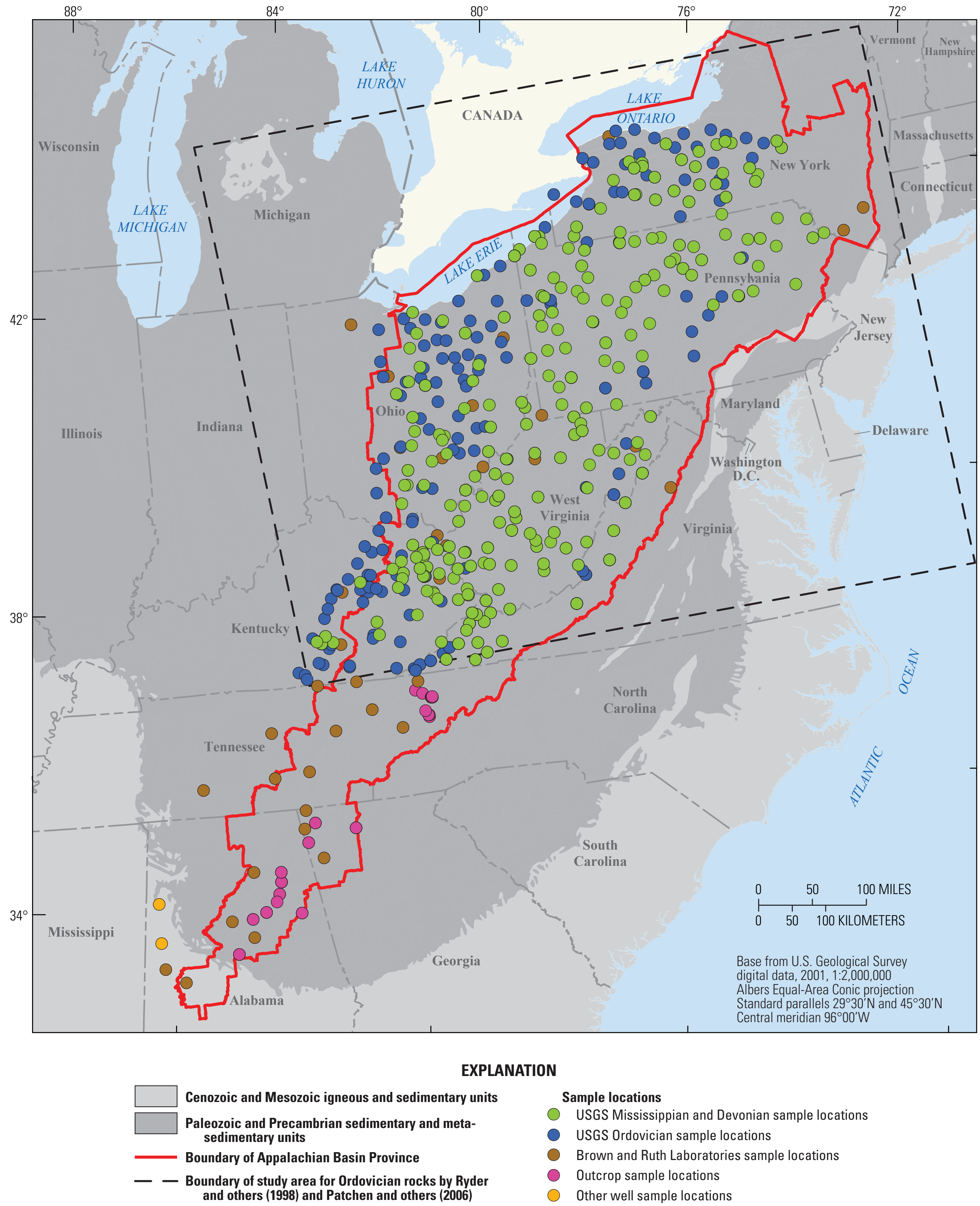
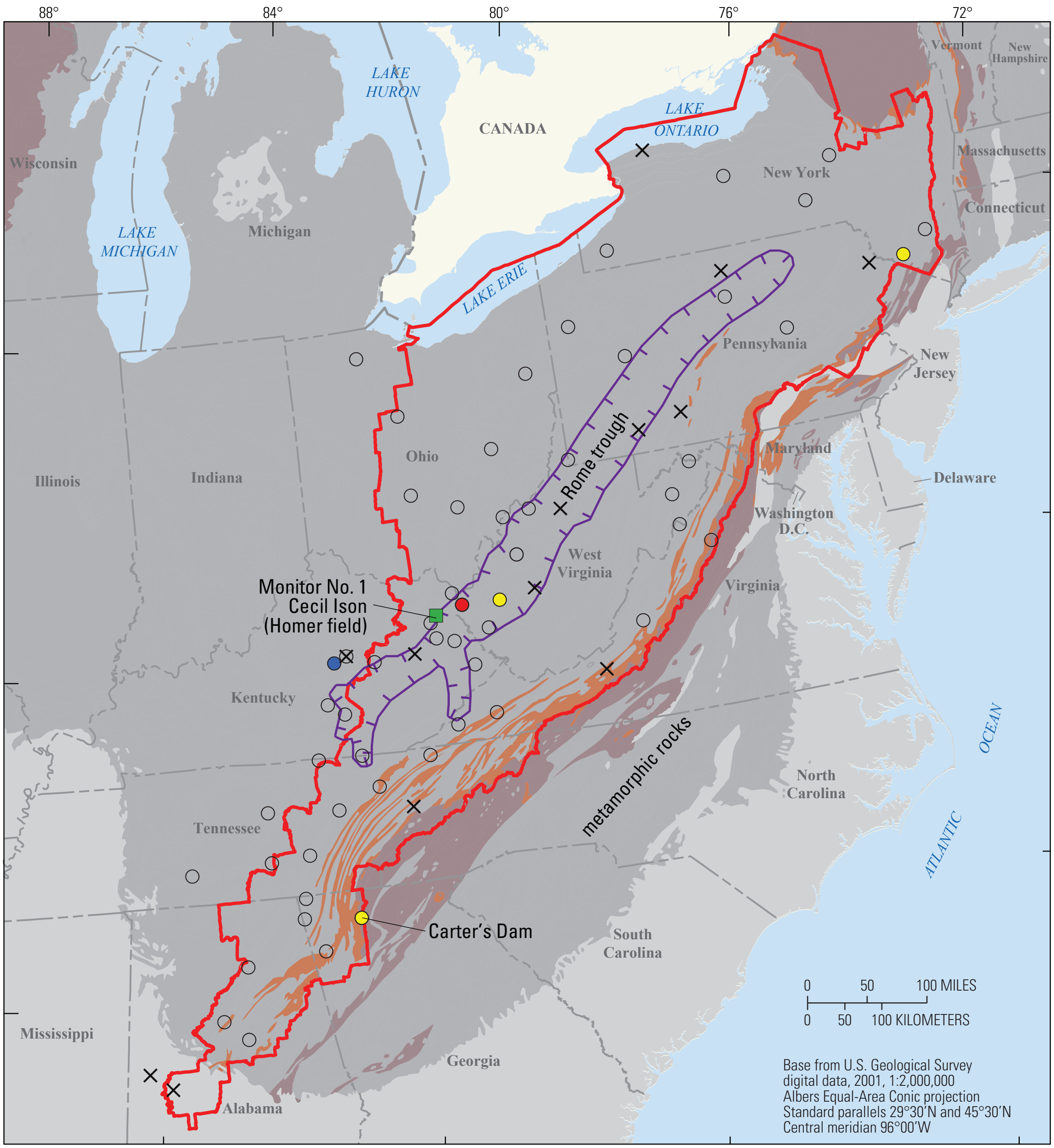

88°
84°
80°
76°
72°
42°
38°
34°
LAKE HURON
LAKE MICHIGAN
LAKE ONTARIO
LAKE ERIE
CANADA
Wisconsin
Michigan
Illinois
Indiana
Ohio
Kentucky
Tennessee
Mississippi
Alabama
Georgia
South Carolina
North Carolina
Virginia
West Virginia
Maryland
Washington D.C.
Delaware
New Jersey
Pennsylvania
New York
Vermont
New Hampshire
Massachusetts
Connecticut
ATLANTIC OCEAN
0 50 100 MILES
0 50 100 KILOMETERS
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
Cenozoic and Mesozoic igneous and sedimentary units
Paleozoic and Precambrian sedimentary and meta-sedimentary units
Boundary of Appalachian Basin Province
Boundary of study area for Ordovician rocks by Ryder and others (1998) and Patchen and others (2006)
Sample locations
USGS Mississippian and Devonian sample locations
USGS Ordovician sample locations
Brown and Ruth Laboratories sample locations
Outcrop sample locations
Other well sample locations

Figure 1 (facing page). Map of the Eastern United States showing locations of wells and outcrops from which samples were obtained. Well and outcrop data are from Bentley and others (1966); Silberman (1972); J.L. Coleman, Jr., (USGS, unpub. data, 1980–1989); Benson and Stock (1986); Wallace and Roen (1989); Saunders and Savrda (1993); Carroll and others (1995); Ryder and others (1998, 2005, 2007); Harris and others (2004); Patchen and others (2006); Robert C. Milici (USGS), Frank T. Dulong (USGS), Catherine B. Enomoto (USGS, formerly with Virginia Department of Mines, Minerals and Energy), James Leone (New York Geological Survey), John Harper (Pennsylvania Bureau of Topographic and Geologic Survey), Jaime Kostelnik (Pennsylvania Bureau of Topographic and Geologic Survey), Ronald Riley (Ohio Division of Geological Survey), Katharine Lee Avery (West Virginia Geological and Economic Survey), Brian Grothaus (West Virginia Geological and Economic Survey), David C. Harris (Kentucky Geological Survey), and William L. Lassetter (Virginia Department of Mines, Minerals and Energy), unpub. data, 2007; Repetski and others (2008); and Exlog/Brown and Ruth Laboratories, Inc. (undated). The boundary of the Appalachian Basin Province, which was defined for the 1995 National Oil and Gas Assessment (and differs from the structural Appalachian basin), is from Dolton and others (1995).


88°
84°
80°
76°
72°
42°
38°
34°
LAKE HURON
CANADA
LAKE ONTARIO
Vermont
New Hampshire
Massachusetts
Connecticut
New York
Wisconsin
LAKE MICHIGAN
Michigan
LAKE ERIE
Pennsylvania
New Jersey
Ohio
Indiana
Illinois
Maryland
Delaware
Washington D.C.
West Virginia
Virginia
Kentucky
North Carolina
General area of Anakeesta Formation
Tennessee
ATLANTIC OCEAN
South Carolina
Mississippi
Alabama
Georgia
0 50 100 MILES
0 50 100 KILOMETERS
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
Cenozoic and Mesozoic igneous and sedimentary units
Paleozoic sedimentary and metasedimentary units
Upper Precambrian sedimentary and metasedimentary units
Precambrian igneous and metamorphic units
Boundary of Appalachian Basin Province

Figure 2 (facing page). Map of the Eastern United States showing the extent of potential Precambrian petroleum source rocks in the Appalachian basin. Geology is simplified from Schruben and others (1998).



EXPLANATION
[TOC, total organic carbon]

Cenozoic and Mesozoic igneous and sedimentary units

Permian through Ordovician sedimentary and meta-sedimentary units

Cambrian units

Precambrian units

Boundary of Rome trough—Includes only mature source rocks. Hachures point into the trough

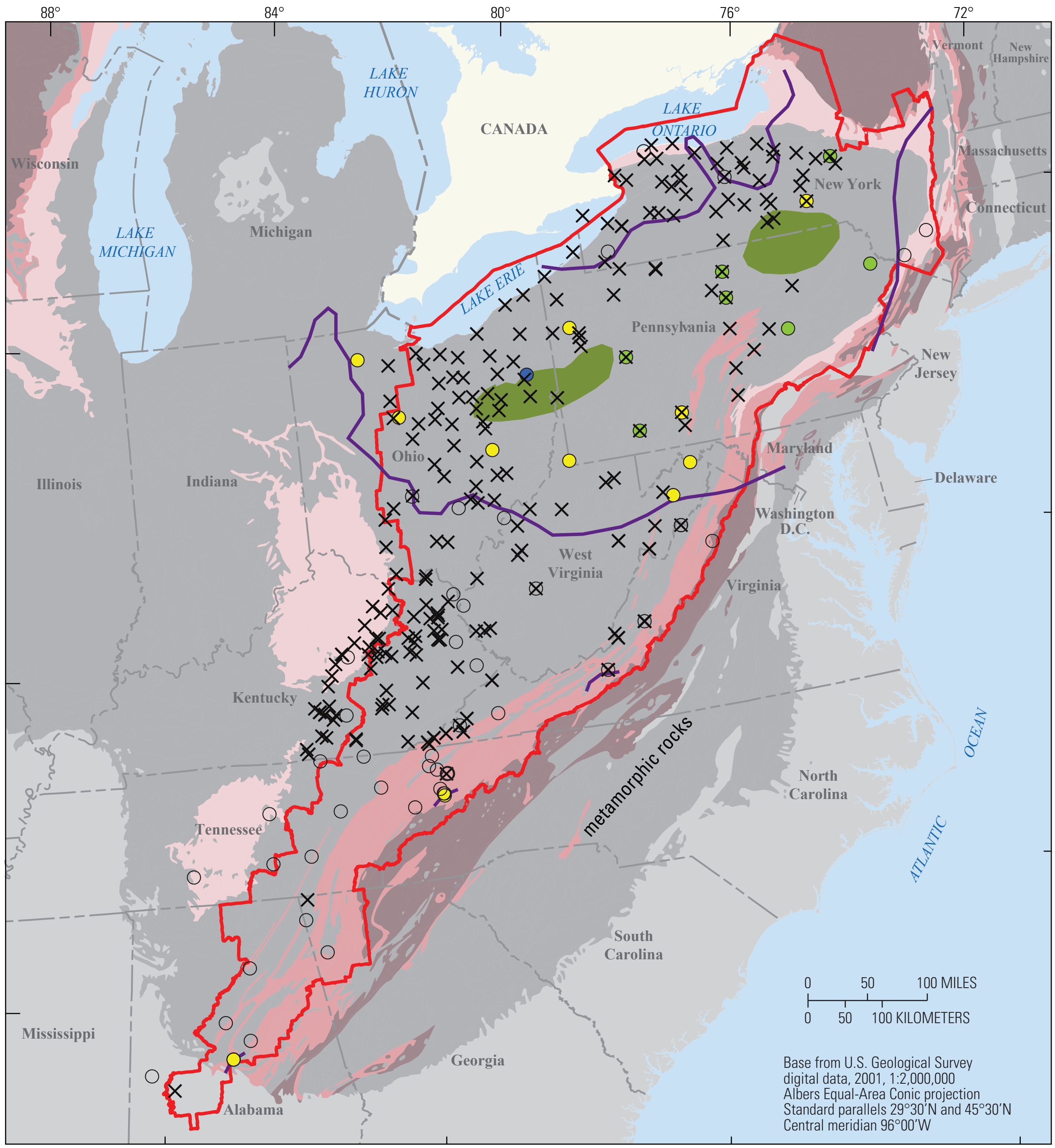
Boundary of Appalachian Basin Province

Location of Monitor No. 1 Cecil Ison (Homer field)

Sample locations—TOC value falls into one of 11 ranges; not all ranges are represented; some samples yielded no value

- > 10.0
- 8.0 to 10.00
- 7.0 to 7.99
- 6.0 to 6.99
- 5.0 to 5.99
- 4.0 to 4.99
- 3.0 to 3.99
- 2.0 to 2.99
- 1.0 to 1.99
- 0.1 to 0.99
- No value

Figure 3 (facing page). Map of the Eastern United States showing the extent of identified and potential Cambrian petroleum source rocks in the Appalachian basin. Well data are from Bentley and others (1966), J.L. Coleman, Jr. (USGS, unpub. data 1980–1989), Harris and others (2004), Ryder and others (2005), and Exlog/Brown and Ruth Laboratories, Inc. (undated). Locations of Rome trough and Monitor No. 1 Cecil Ison are from Ryder and others (2005). Location of Carter's Dam is from Bentley and others (1966). Geology is simplified from Schruben and others (1998).



EXPLANATION

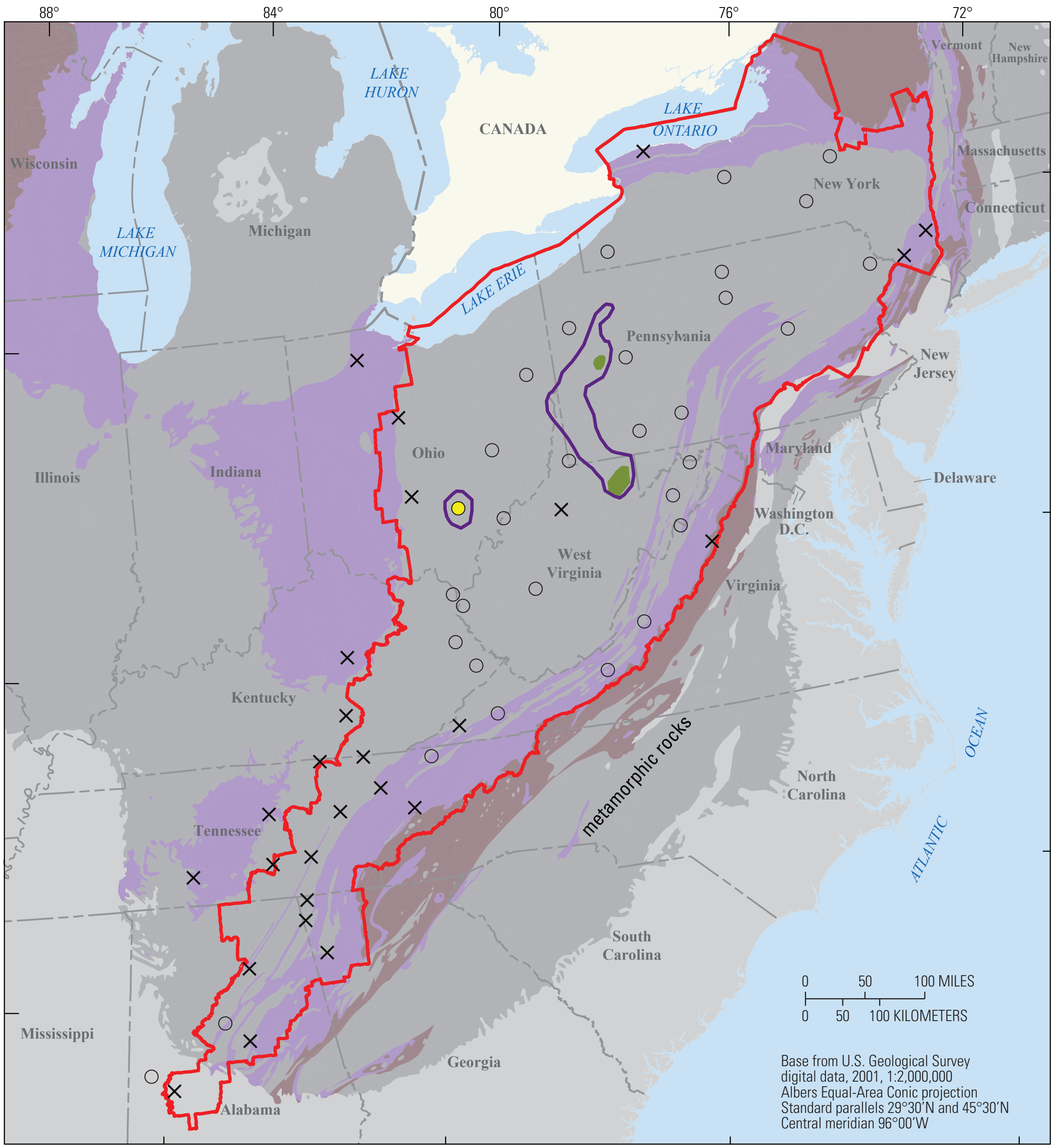
[TOC, total organic carbon]

- **Cenozoic and Mesozoic igneous and sedimentary units**
- **Permian through Ordovician sedimentary and meta-sedimentary units**
- **Upper and Middle Ordovician units**
- **Lower Ordovician, Ordovician (undivided), and Cambrian units**
- **Precambrian units**
- **Area in which TOC values from Ordovician samples are ≥3 percent**
- **Boundary of area within which TOC values from Ordovician samples are ≥1 percent**
- **Boundary of Appalachian Basin Province**

Sample locations—TOC value falls into one of 11 ranges; not all ranges are represented; some samples yielded no value

- > 10.0
- 8.0 to 10.00
- 7.0 to 7.99
- 6.0 to 6.99
- 5.0 to 5.99
- 4.0 to 4.99
- 3.0 to 3.99
- 2.0 to 2.99
- 1.0 to 1.99
- 0.1 to 0.99
- No value

Figure 4 (facing page). Map of the Eastern United States showing the extent of identified and potential Ordovician petroleum source rocks in the Appalachian basin. The areas of Ordovician strata that have total organic carbon (TOC) values ≥1 percent (delineated by the purple line) and ≥3 percent (shown as dark-green units) were developed by assimilating data and maps from Exlog/Brown and Ruth Laboratories, Inc. (undated), Ryder and others (1998), Patchen and others (2006), and Wallace and Roen (1989). The data sources are from Wallace and Roen (1989), Ryder and others (1998), Patchen and others (2006) and Exlog/Brown and Ruth (undated). A close examination of these data shows that, in some cases, different analyses from the same wells (or at least from wells in close proximity to each other) yielded different TOC values. Consequently, the delineated areas of ≥1 percent and ≥3 percent may not strictly reflect all of the data displayed in this figure or in Wallace and Roen (1989), Ryder and others (1998), and Patchen and others (2006); rather, they summarize the results of these four studies. Geology is simplified from Schruben and others (1998).



EXPLANATION

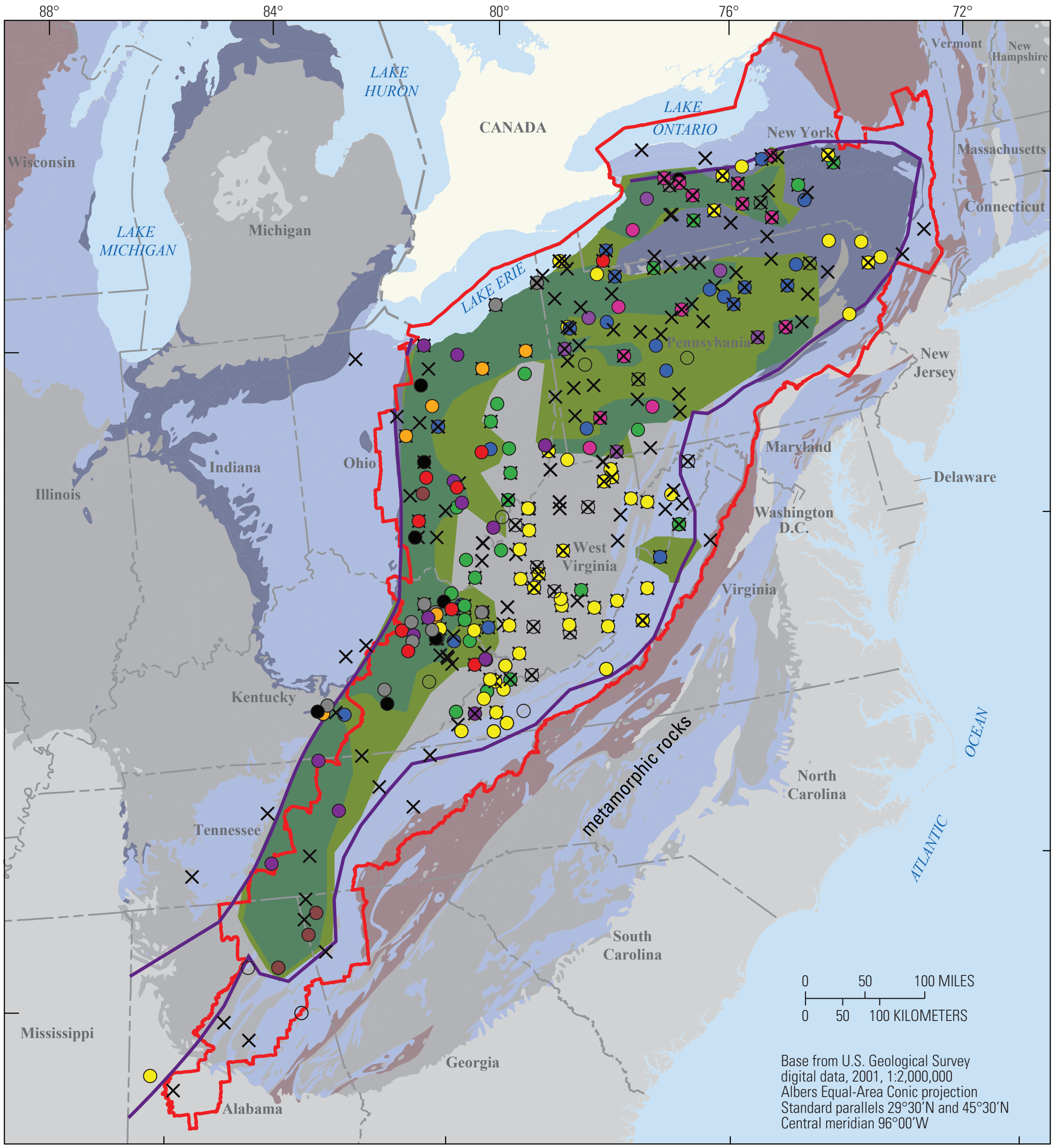
[TOC, total organic carbon]

- **Cenozoic and Mesozoic igneous and sedimentary units**
- **Permian through Ordovician sedimentary and meta-sedimentary units**
- **Silurian through Cambrian units**
- **Precambrian units**
- **Area in which TOC values from Ordovician samples are ≥3 percent**
- **Boundary of area within which TOC values from Ordovician samples are ≥1 percent**
- **Boundary of Appalachian Basin Province**

Sample locations—TOC value falls into one of 11 ranges; not all ranges are represented; some samples yielded no value

- > 10.0
- 8.0 to 10.00
- 7.0 to 7.99
- 6.0 to 6.99
- 5.0 to 5.99
- 4.0 to 4.99
- 3.0 to 3.99
- 2.0 to 2.99
- 1.0 to 1.99
- 0.1 to 0.99
- No value

Figure 5 (facing page). Map of the Eastern United States showing the extent of potential Silurian petroleum source rocks in the Appalachian basin. Well data are from Ryder and others (2007) and Exlog/Brown and Ruth Laboratories (undated). The Silurian source rocks shown in southwestern Pennsylvania and northern West Virginia are from Ryder and others (2007). Geology is simplified from Schruben and others (1998).



EXPLANATION

[TOC, total organic carbon]

- **Cenozoic and Mesozoic igneous and sedimentary units**
- **Permian through Mississippian sedimentary and meta-sedimentary units**
- **Upper and Middle Devonian units**
- **Devonian through Cambrian units**
- **Precambrian units**
- **Area in which TOC values from Devonian samples are ≥5 percent**
- **Area in which TOC values from Devonian samples are ≥3 percent**
- **Boundary of area within which TOC values from Devonian samples are ≥1 percent**
- **Boundary of Appalachian Basin Province**

Sample locations—TOC value falls into one of 11 ranges; not all ranges are represented; some samples yielded no value

- > 10.0
- 8.0 to 10.00
- 7.0 to 7.99
- 6.0 to 6.99
- 5.0 to 5.99
- 4.0 to 4.99
- 3.0 to 3.99
- 2.0 to 2.99
- 1.0 to 1.99
- 0.1 to 0.99
- No value

Figure 6 (facing page). Map of the Eastern United States showing the extent of identified and potential Devonian petroleum source rocks in the Appalachian basin. Data are from Carroll and others (1995), Repetski and others (2008; also see chapter F.1 of this volume), and Exlog/Brown and Ruth Laboratories, Inc. (undated). Geology is simplified from Schruben and others (1998).

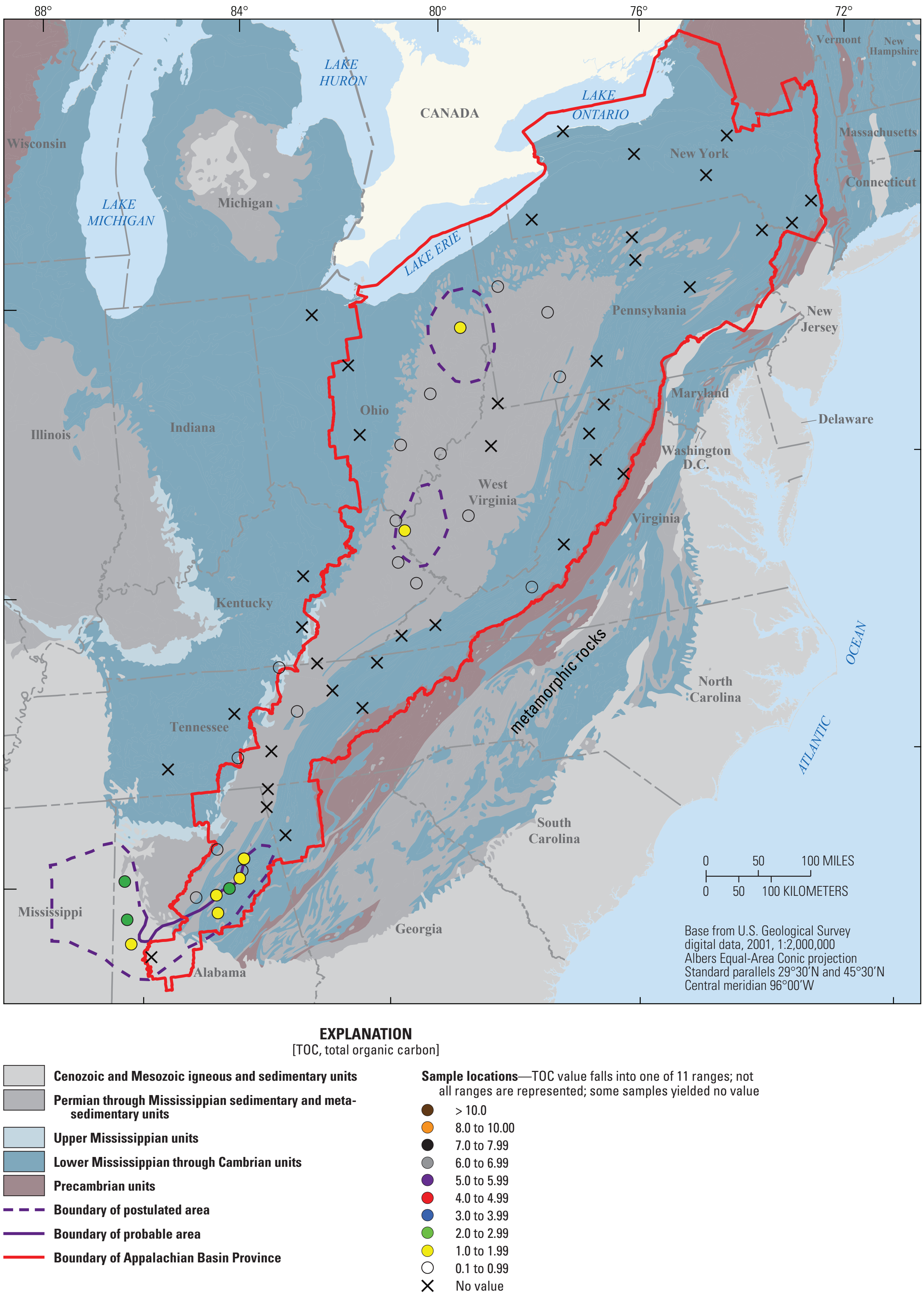
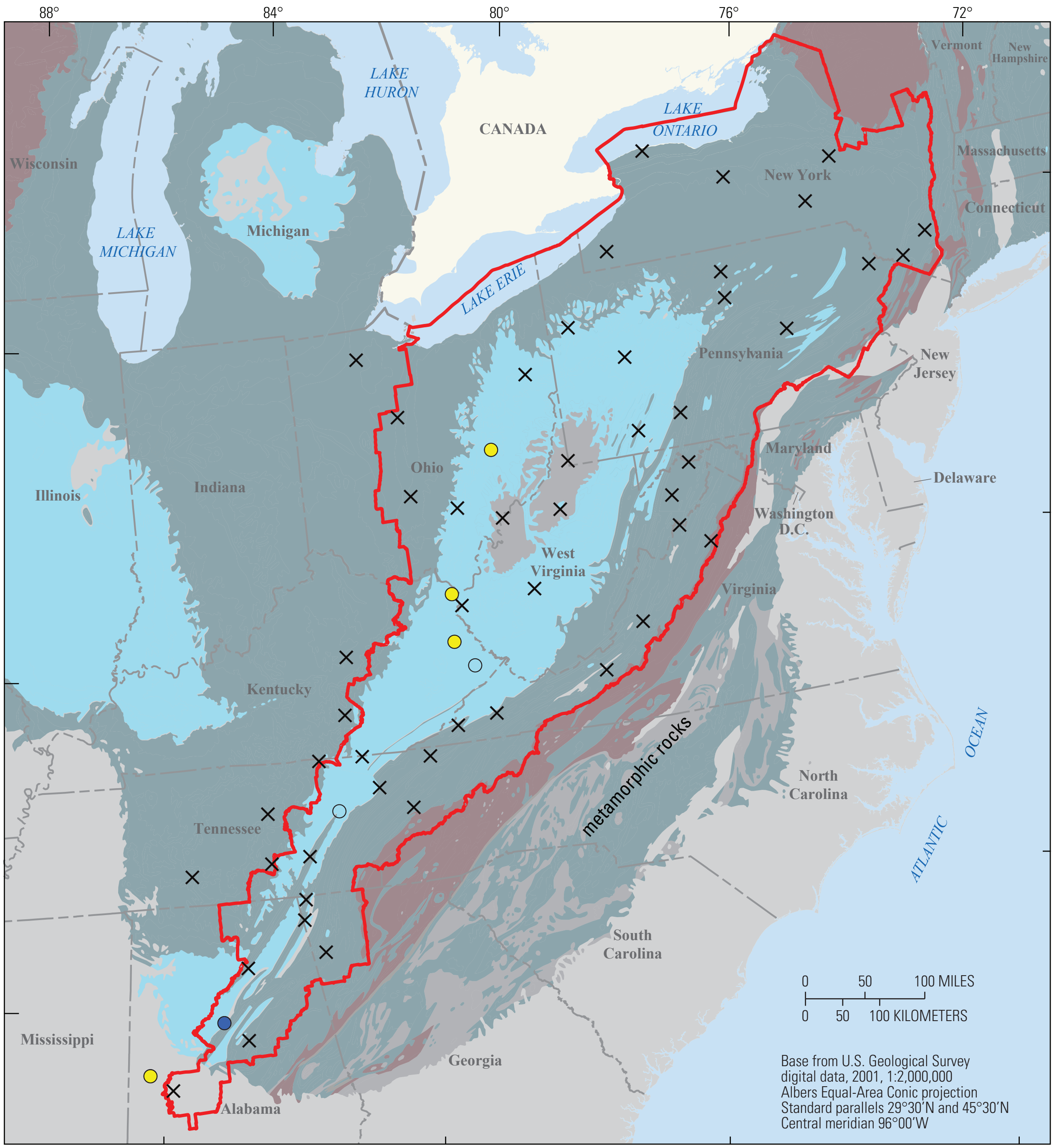

88°
84°
80°
76°
72°
42°
38°
34°
LAKE HURON
CANADA
LAKE ONTARIO
LAKE MICHIGAN
LAKE ERIE
Vermont
New Hampshire
Massachusetts
Connecticut
Wisconsin
Michigan
New York
Pennsylvania
New Jersey
Ohio
Indiana
Illinois
Maryland
Delaware
Washington D.C.
West Virginia
Virginia
Kentucky
Tennessee
North Carolina
South Carolina
Georgia
Alabama
Mississippi
metamorphic rocks
ATLANTIC OCEAN
0 50 100 MILES
0 50 100 KILOMETERS
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
[TOC, total organic carbon]
Cenozoic and Mesozoic igneous and sedimentary units
Permian through Mississippian sedimentary and meta-sedimentary units
Upper Mississippian units
Lower Mississippian through Cambrian units
Precambrian units
Boundary of postulated area
Boundary of probable area
Boundary of Appalachian Basin Province
Sample locations—TOC value falls into one of 11 ranges; not all ranges are represented; some samples yielded no value
> 10.0
8.0 to 10.00
7.0 to 7.99
6.0 to 6.99
5.0 to 5.99
4.0 to 4.99
3.0 to 3.99
2.0 to 2.99
1.0 to 1.99
0.1 to 0.99
No value

Figure 7 (facing page). Map of the Eastern United States showing the extent of identified and potential Mississippian petroleum source rocks in the Appalachian basin. Geology is simplified from Schruben and others (1998). Data points are from Carroll and others (1995) and Exlog/Brown and Ruth (undated). A postulated area is one in which the area around a single point suggests that a source rock with a TOC content of 1.0 percent or greater is likely present. A probable area is one in which the area around several points indicates more confidently that a source rock with a TOC content of 1.0 percent or greater is probably present.



EXPLANATION
[TOC, total organic carbon]

- **Cenozoic and Mesozoic igneous and sedimentary units**
- **Permian sedimentary and metasedimentary units**
- **Pennsylvanian units**
- **Mississippian through Cambrian sedimentary and metasedimentary units**
- **Precambrian units**
- **Boundary of Appalachian Basin Petroleum Province**

Sample locations—TOC value falls into one of 11 ranges; not all ranges are represented; some samples yielded no value

- > 10.0
- 8.0 to 10.00
- 7.0 to 7.99
- 6.0 to 6.99
- 5.0 to 5.99
- 4.0 to 4.99
- 3.0 to 3.99
- 2.0 to 2.99
- 1.0 to 1.99
- 0.1 to 0.99
- No value

Figure 8 (facing page). Map of the Eastern United States showing the extent of identified and potential Pennsylvanian petroleum source rocks in the Appalachian basin. Well data are from Exlog/Brown and Ruth Laboratories (undated). Geology is simplified from Schruben and others (1998).