In Search of a Silurian Total Petroleum System in the Appalachian Basin of New York, Ohio, Pennsylvania, and West Virginia

By Robert T. Ryder, Christopher S. Swezey, Michael H. Trippi, Erika E. Lentz, K. Lee Avary, John A. Harper, William M. Kappel, and Ronald G. Rea

Chapter G.11 of

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

Edited by Leslie F. Ruppert and Robert T. Ryder

Supersedes USGS Open-File Report 2007–1003

Professional Paper 1708

U.S. Department of the Interior
U.S. Geological Survey

Suggested citation:
Ryder, R.T., Swezey, C.S., Trippi, M.H., Lentz, E.E., Avary, K.L., Harper, J.A., Kappel, W.M., and Rea, R.G., 2014, In search of a Silurian total petroleum system in the Appalachian basin of New York, Ohio, Pennsylvania, and West Virginia, chap. G.11 *of* Ruppert, L.F., and Ryder, R.T., eds., Coal and petroleum resources in the Appalachian basin; Distribution, geologic framework, and geochemical character: U.S. Geological Survey Professional Paper 1708, 8 p., http://dx.doi.org/10.3133/pp1708G.11. (Supersedes USGS Open File Report 2007–1003.)

Contents

Figures

[Figures 1–8 as separate files; click link to access]

Tables

[Tables 1–2 as separate files; click link to access]

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Mass	
milligram (mg)	0.00003527	ounce avoirdupois
gram (g)	0.03527	ounce avoirdupois

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$°F = (1.8 \times °C) + 32$

In Search of a Silurian Total Petroleum System in the Appalachian Basin of New York, Ohio, Pennsylvania, and West Virginia

By Robert T. Ryder,[1] Christopher S. Swezey,[1] Michael H. Trippi,[1] Erika E. Lentz,[1] K. Lee Avary,[2] John A. Harper,[3] William M. Kappel,[4] and Ronald G. Rea[5]

Abstract

Oil and gas fields in Silurian carbonate and sandstone reservoirs in the Appalachian basin probably originated from one or more of the following source rocks: (1) Upper Ordovician Utica Shale, (2) Middle to Upper Devonian black shale, and (3) Lower to Upper Silurian shale and carbonate units. In this reconnaissance study, selected Silurian shale and carbonate rocks in the subsurface of New York, Ohio, Pennsylvania, and West Virginia were analyzed for total organic carbon (TOC) content and Rock-Eval parameters to evaluate whether or not a Silurian total petroleum system exists in the Appalachian basin. A total of 308 samples were collected and analyzed for this investigation. Dark-gray to black shale and argillaceous carbonate intervals in the Salina Group (and equivalent units), Cabot Head Shale, Rochester Shale, Rose Hill Formation, Lockport Dolomite (or Group), and McKenzie Limestone (or Member) were prioritized for sampling and analysis.

Twenty nine of the 308 samples analyzed had TOC values of 0.50 or greater that qualify them as a petroleum source rock. Also, 24 of the 29 samples (with TOC values of 0.50 or greater) had TOC values between 0.50 and less than 1.00 weight percent. Only 5 samples in the dataset are classified as good to very good source rocks (TOC values of 1.00 to 3.35 weight percent). The majority (n=18) of the 29 samples of potential source rocks with a TOC value of 0.5 or greater are located in the Upper Silurian Salina Group and equivalent Wills Creek Formation. Moreover, all of the good to very good source rocks are located in the Salina Group and Wills Creek Formation in southwestern Pennsylvania and northern West Virginia. The remainder (n=11) of the 29 potential source rocks (TOC values of 0.50 to less than 1.00 weight percent) are located in the Lower Silurian Cabot Head Shale (n=2), Rochester Shale (n=6), Rose Hill Formation (n=1), and Lower to Upper Silurian Lockport Dolomite (n=2). These source rocks of secondary importance are widely distributed across eastern Ohio, western Pennsylvania, and West Virginia.

Although the TOC analyses in this study indicate that good to very good source rocks are present in the Salina Group and Wills Creek Formation of southwestern Pennsylvania and northern West Virginia, data are insufficient to propose a new Silurian total petroleum system in the Appalachian basin. However, the analytical results of this investigation are encouraging enough to undertake more systematic studies of the source rock potential of the Salina Group, Wills Creek Formation, and perhaps the Tonoloway Formation (Limestone) and McKenzie Limestone (or Member).

Introduction

Oil and gas reservoirs are present throughout much of the Paleozoic strata of the Appalachian basin, but not all of the petroleum source rocks have been identified and characterized. In an overview of oil and gas plays in the basin, de Witt (1993) indicated that the two primary petroleum source rocks are an older sequence of Middle to Late Ordovician shales and a younger sequence of Devonian to Early Mississippian shales. More recently, Swezey (2002) used data compiled from "The Atlas of Major Appalachian Gas Plays" (Roen and Walker, 1996) to propose four discrete groups of source rocks, each clustered around one of the four major packages of siliciclastic strata in the basin (Lower Cambrian, Upper Ordovician to Lower Silurian, Middle Devonian to Lower Mississippian, and Upper Mississippian to Pennsylvanian). Subsequently, in the 2002 assessment of undiscovered oil and gas resources in the Appalachian basin, the U.S. Geological Survey (USGS) identified the following six total petroleum systems (TPS), which are named according their respective source rocks and

[1]U.S. Geological Survey, Reston, Va.
[2]West Virginia Geological Survey, Morgantown, W. Va.
[3]Pennsylvania Geological Survey, Pittsburgh, Pa.
[4]U.S. Geological Survey, Ithaca, N.Y.
[5]Ohio Geological Survey, Columbus, Ohio.

associated reservoir intervals (Milici and others, 2003): (1) the Conasauga-Rome/Conasauga TPS; (2) the Sevier-Knox/Trenton TPS; (3) the Utica-Lower Paleozoic TPS; (4) the Devonian Shale-Middle and Upper Paleozoic TPS; (5) the Carboniferous Coal-bed Gas TPS; and (6) the Pottsville Coal-bed Gas TPS.

In the 2002 USGS oil and gas assessment of the Appalachian basin, most of the oil and gas in Silurian sandstone and carbonate reservoirs (fig. 1) were assigned to the Utica-Lower Paleozoic TPS (Milici and others, 2003). However, most of the oil and gas in Silurian reservoirs have yet to be correlated conclusively with specific source rocks.

At least three different potential source rocks have been proposed for oil and gas in the Silurian reservoirs. The Upper Ordovician Utica Shale (fig. 2) is the most commonly proposed source rock for oil and gas fields in Silurian reservoirs. Most oil and gas fields in Silurian reservoirs in eastern Ohio, western Pennsylvania, western New York, and West Virginia are underlain by the Utica Shale, which is mature with respect to oil and gas generation. Moreover, the Utica Shale consistently has total organic carbon (TOC) values of approximately 1.5 to 4.0 weight percent (Jenden and others, 1993; Drozd and Cole, 1994; Patchen, 1996; Ryder and others, 1998). A second group of potential source rocks is the Middle and Upper Devonian black shale units (fig. 2), which overlie many of the Silurian reservoirs (Cole and others, 1987; Ryder, 1995; Patchen, 1996). In eastern Kentucky, for example, Upper Devonian shales rest unconformably on many of the Silurian reservoirs (Ray, 1971), and TOC values for the Upper Devonian Ohio Shale in eastern Kentucky range from approximately 3.0 to 6.2 weight percent (Curtis and Faure, 1997). Finally, Silurian shale and carbonate units constitute a third group of potential source rocks for the Silurian reservoirs (Knight, 1969; de Witt, 1993; Jenden and others, 1993; Van Tyne, 1996). Unfortunately, very few of these Silurian shale and carbonate units have been analyzed by organic geochemical techniques to determine if they have the appropriate characteristics of petroleum source rocks. An organic geochemistry dataset that was published by Cole and others (1987) reported TOC analyses of 436 Silurian to Middle Devonian rock samples in Ohio. However, only 32 of the samples had sufficient organic matter (TOC greater than or equal to 0.5 weight percent) to qualify as source rocks, and only 4 of these 32 samples had TOC values greater than 1.0 weight percent.

Despite the paucity of data from the U.S. portion of the Appalachian basin, viable Silurian source rocks have been identified in the Canadian portion of the Appalachian basin and in both the Canadian and U.S. portions of the adjacent Michigan basin. For example, Powell and others (1984) identified the Upper Silurian Eramosa Formation of the Lockport Group as a source rock for oil in the overlying Upper Silurian Guelph Formation in Ontario (which is in both the Appalachian and Michigan basins). The Eramosa Dolomite extends about 25 miles (mi) into western New York, where it contains bitumen and emits a petroliferous odor (Zenger, 1965; Yager, 2000). In the Michigan basin (both the U.S. and Canadian portions), various studies have identified the Upper Silurian Niagara Group (including the Guelph Formation of the Niagara Group) and the Upper Silurian Salina Group as source rocks for oil and gas in the Niagara Group and Salina Group (Rullkötter and others, 1986; Obermajer and others, 2000; Hatch and others, 2004).

This report provides an evaluation of the source-rock potential of Silurian strata in the U.S. portion of the Appalachian basin, using new TOC and Rock-Eval data. The study area consists of all or parts of Kentucky, New York, Ohio, Pennsylvania, and West Virginia (fig. 1). The stratigraphic intervals that were sampled for this study are as follows: (1) the Lower Silurian Cabot Head Shale, Castanea Member of the Tuscarora Formation, carbonates and shales (undivided), Rochester Shale, and Rose Hill Formation; (2) the Lower and Upper Silurian McKenzie Limestone (or Member), Lockport Dolomite, and Upper Silurian Eramosa Dolomite of the Lockport Group; and (3) the Upper Silurian Wills Creek Formation, Tonoloway Limestone (or Formation), Salina Group, Keyser Formation (or Limestone), and Bass Islands Dolomite (fig. 2). These Silurian stratigraphic intervals were chosen because they are cited in previous publications as potential source rocks, they are easily identified and relatively continuous across the basin, and they contain beds of dark-gray to black shale and (or) black argillaceous limestone and dolomite.

Methods

Specifically for this study, 308 samples were collected and analyzed. Of the 308 samples, 302 were collected from drill-hole cuttings and 6 were collected from cores. As shown in figure 3, these 308 samples are distributed across western New York (n=4), central and eastern Ohio (n=107), central and western Pennsylvania (n=102), and West Virginia (n=95). Commonly, more than one sample was collected per well, so that the 308 samples are distributed among 128 wells (fig. 3).

Most samples for this study were collected from drill cuttings and cores in the repository holdings of the State geological surveys of Ohio, Pennsylvania, and West Virginia. In addition, several core samples from western New York were collected from a USGS storage facility in Ithaca, N.Y.

Dark-gray to black shale and argillaceous carbonate intervals were given the highest priority for sampling. Where possible, specific stratigraphic units (for example, the Cabot Head Shale) were sampled over intervals that ranged from about 30 to 50 feet (ft). About 58 of the samples (mostly from West Virginia) were composites of several units representing from about 100 ft to several hundred feet of stratigraphic section (for example, the Wills Creek Formation and Tonoloway Limestone). For these composite samples, we judged which stratigraphic unit was best represented by a given analysis (see Notes column on table 1). Most samples averaged about 50 grams (g) in weight.

All samples were shipped to the USGS in Reston, Va., where they were organized, visually inspected, and culled. As part of the inspection process, the samples were compared with lithologic logs constructed by the Geological Sample Log Company (Mount Lebanon, Pa.). Humble Geochemical Services (Humble, Tex.) processed and analyzed the samples for TOC (using LECO instrumentation) and Rock-Eval data (tables 1, 2).

Distribution of Oil and Gas Fields in Silurian Reservoirs and Their Possible Source Rocks

Lower Silurian Regional Oil and Gas Accumulation

The dominant oil and gas fields present in Silurian reservoirs are located in the Lower Silurian regional oil and gas accumulation that extends across eastern Ohio, northwestern Pennsylvania, and western New York (McCormac and others, 1996; Ryder and Zagorski, 2003). The major reservoirs consist of the "Clinton"[6] and Medina sandstones in Ohio and the Medina Group sandstones in Pennsylvania and New York (figs. 1, 2). Ryder and Zagorski (2003) estimated that approximately 8.7 trillion cubic feet (ft^3) of natural gas and 400 million barrels of oil have been produced from the "Clinton" sandstone, Medina sandstone, and Medina Group reservoirs. Furthermore, Milici and others (2003) considered the "Clinton" sandstone, Medina sandstone, and Medina Group petroleum resource to be a continuous-type accumulation that contains a mean of 24 trillion ft^3 of recoverable undiscovered natural gas.

The Lower Silurian Tuscarora Sandstone, an eastern equivalent of the "Clinton" and Medina sandstones of Ohio and the Medina Group of Pennsylvania and New York, is the reservoir for several gas fields in Pennsylvania and West Virginia (figs. 1, 2). Examples of such gas fields include the Devils Elbow field in central Pennsylvania and the Leadmine and Indian Creek fields in West Virginia (fig. 1), both of which are characterized by gas that has a low calorific value (British thermal units, Btu) and a large percentage of nitrogen or carbon dioxide (Avary, 1996).

The most probable source rock for the oil and gas in the Lower Silurian regional accumulation and the Tuscarora Sandstone is the Utica Shale (Drozd and Cole, 1994; Ryder and others, 1998). Devonian black shale source rocks may have contributed some oil and gas to the "Clinton" and Medina sandstone reservoirs (Cole and others, 1987), but widespread evaporite units in the Salina Group probably minimized large-scale mixing of petroleum derived from Ordovician and Devonian rocks (Drozd and Cole, 1994). Lower Silurian shales (Cabot Head Shale and Rochester Shale) were suggested by Knight (1969) and de Witt (1993) as possible source rocks for the oil and gas in "Clinton" and Medina sandstones reservoirs.

"Newburg Zone" and Newburg Sandstone

Small gas fields in the Lower and Upper Silurian Lockport Dolomite (or Group) are distributed across east-central Ohio, northwestern Pennsylvania, and western New York (figs. 1, 2). In Ohio, the reservoir interval is called the "Newburg zone" where bioherms with thin zones of vuggy dolomite are present (Santini and Coogan, 1983; Noger and others, 1996). In west-central West Virginia, several medium-sized gas fields occur in the informally named Upper Silurian Newburg sandstone, a thin sandstone unit located between the Wills Creek Formation and the McKenzie Limestone (Patchen, 1996) (figs. 1, 2).

The oil and gas in the Lockport Dolomite (or Group) of Ohio, Pennsylvania, and New York were derived either from the Utica Shale or from presently unrecognized Silurian source rocks associated with the biohermal buildups. Patchen (1996) suggested that the most likely source of the natural gas in the Newburg sandstone is Ordovician or Devonian black shale.

Bass Islands Trend Fields

In westernmost New York and adjoining northwestern Pennsylvania, oil and gas is produced from small fields in the Upper Silurian Akron Dolomite (equivalent to the Bass Islands Dolomite), Salina Group, and several overlying Lower and Middle Devonian reservoirs (figs. 1, 2). This narrow, northeast-trending zone of thrust-fault-controlled oil and gas fields is known commonly as the Bass Islands trend (Van Tyne, 1996). Devonian black shale (probably the Middle Devonian Marcellus Shale) is the most likely source rock for the oil and gas in the Bass Islands trend (Jenden and others, 1993) because this black shale is located within several hundred feet above the reservoir units and, in some places, is juxtaposed against several of the reservoirs by thrust faults. However, Van Tyne (1996) favored a Silurian source rock (Akron Dolomite or Salina Group) based on unpublished data provided by R.W. Beardsley (Columbia Gas, oral commun., 1984). Jenden and others (1993) also mentioned the possibility of a Salina Group source rock.

[6] The "Clinton" sandstone in Ohio was miscorrelated by early drillers with strata in the type Clinton Group of New York, when in fact it is equivalent to the underlying Medina Group of New York. Although this miscorrelation has caused confusion in nomenclature, the term continues to be widely used in the literature and by the oil and gas industry. Early drillers correctly identified the informal Medina sandstone in Ohio as a partial equivalent of the type Medina Group of New York.

"Corniferous" Carbonate Formations and Keefer Sandstone (Big Six Sandstone)

Numerous small to medium oil and gas fields occur in Silurian reservoirs in eastern Kentucky (fig. 1), where the reservoirs consist primarily of the Lower Silurian Keefer Sandstone (also known as the informal Big Six sandstone) and the Silurian to Middle Devonian "Corniferous" carbonate formations interval (Lockport Dolomite, Salina Group, Helderberg Limestone, Oriskany Sandstone, and Onondaga Limestone) (Meglen and Noger, 1996; Noger and others, 1996) (fig. 2). As stated in the introduction, oil and gas in Silurian sandstone and carbonate reservoirs in eastern Kentucky very likely were derived from the Upper Devonian Ohio Shale (Ray, 1971).

Results of Analyses

Total Organic Carbon (TOC) Analysis

Using criteria established by Peters and Cassa (1994), the majority of the 308 samples (n=279) had TOC values of approximately 0.20 to less than 0.50 weight percent that were too low to qualify them as source rocks (figs. 4, 5). About 9 percent of the samples (n=29) had TOC values of 0.50 weight percent or greater that were large enough to qualify them as source rocks, and of these 29 samples, 24 had TOC values less than the 1 weight percent lower limit generally required for an effective petroleum source rock (Tissot and Welte, 1984; Peters and Moldowan, 1993) (figs. 4, 5). Only 5 samples in the dataset are classified as good to very good source rocks (TOC is 1.00 to 3.35 weight percent) (figs. 4, 5).

None of the 116 samples collected and analyzed from the Cabot Head Shale (n=57), Rochester Shale (n=48), Rose Hill Formation (n=9), undivided Lower Silurian carbonates and shales (n=1), and Castanea Member of the Tuscarora Formation (n=1) had TOC values of 1.00 weight percent or greater (figs. 5, 6). Of the 9 samples that are characterized as source rocks, all are classified as fair source rocks with TOC values ranging from 0.50 to 0.68 weight percent. Two samples of the fair source rocks were from the Cabot Head Shale (Harrison and Noble Counties, Ohio), 6 samples were from the Rochester Shale (Tuscarawas County, Ohio; Beaver, Clarion, Mercer, and Warren Counties, Pa.), and 1 sample was from the Rose Hill Formation (Wayne County, W. Va.) (figs. 4, 6; tables 1, 2).

Of the 29 samples collected and analyzed from the McKenzie Limestone (or Member) (n=17), Lockport Dolomite (n=8), and Eramosa Dolomite of the Lockport Group (n=4), 2 had TOC values greater than 0.5 weight percent (figs. 5, 7). Both of these samples are from the Lockport Dolomite (Mercer and Venango Counties, Pa.) and both are catagorized as fair source rocks (TOC is 0.62 weight percent) (figs. 4, 7; tables 1, 2). Somewhat surprising were the low TOC values (0.22 to 0.34 weight percent) for the Eramosa Dolomite in Niagara County, N.Y.

The highest TOC values in the study were measured in the 163 samples collected from the Salina Group (n=119) and the correlative Wills Creek Formation (n=26) and Tonoloway Limestone (or Formation) (n=12). Other samples in this group were taken from the Upper Silurian to Lower Devonian Keyser Limestone (or Formation) and Upper Silurian Bass Islands Dolomite (n=6). In about 25 percent of the wells, the samples from the Salina-Wills Creek-Tonoloway interval are composite samples that overlap one another or overlap units such as the McKenzie Limestone (or Member), Bass Islands Dolomite, and Keyser Limestone (or Formation). Of the 18 samples that are characterized as source rocks, 13 are in the fair source-rocks category with TOC values ranging from 0.50 to 0.98 weight percent. Five samples in the fair source-rocks category were from Pennsylvania (Clarion, Elk, Forest, and Somerset Counties), whereas 8 samples in the fair source-rocks category were from West Virginia (Clay, Hancock, Kanawha, Mercer, Monongalia, Pocahontas, and Preston Counties) (figs. 4, 8; tables 1, 2).

Five of the 18 samples in the Salina-Wills Creek-Tonoloway interval are characterized as good (TOC is 1.00 to 1.99 weight percent) to very good (TOC is 2.00 to 3.99 weight percent) source rocks. The good source rocks are located in the No. A–1 May well in Monongalia County, W. Va. (TOC is 1.04 weight percent) and the No 1. Minesinger well in Hancock County, W. Va. (TOC is 1.19 weight percent), whereas the very good source rocks are located in the No. 1 J.S. Walker well in Butler County, Pa. (TOC is 2.78 weight percent) and in the No. 1–A Walls well in Preston County, W. Va. (TOC is 3.0 and 3.35 weight percent) (figs. 4, 8; tables 1, 2).

The good source rock in the No. A–1 May well (TOC is 1.04 weight percent) is present in a 500-ft-thick interval that consists of the lower part of the Wills Creek Formation (300 ft), the Newburg sandstone (50 ft), and the upper part of the McKenzie Limestone (150 ft). Based on a lithologic log described by the Geological Sample Log Company (Mount Lebanon, Pa.) from the No. 1 A–1 May well that was sampled in this study, the lower part of the Wills Creek Formation consists of interbedded medium-dark-gray dolomite (some slightly anhydritic), greenish-gray shale, dark-gray to black shale, and brown to black limestone. Approximately 65 net ft of black shale are present in the Wills Creek part of the sample. According to the lithologic log described by the Geological Sample Log Company from the No. A–1 May well, the McKenzie Limestone contains dark-gray to black shale (about 50 net ft) interbedded with brown to black limestone. The unsampled lower 100 ft of the McKenzie Limestone contains an additional 50 net ft of black shale. As noted in table 1, the Wills Creek Formation probably yielded the measured TOC value.

The good source rock identified in the No. 1 Minesinger well (TOC is 1.19 weight percent) is located in a 130-ft-thick interval in the upper part of the Salina Group. Based on a lithologic log by the Geological Sample Log Company, this source rock consists of interbedded anhydritic dolomite, anhydrite, and dark-gray to black shale. This lithologic assemblage extends downhole for at least another 165 ft in the Salina Group, over which interval a TOC value of 0.93 weight percent was recorded. Approximately 60 net ft of black shale is present in the sampled 295-ft-thick interval. Because the upper part of the Salina Group in the No. 1 Minesinger well is located almost 600 ft below the Middle Devonian Marcellus Shale, the analyzed sample was unlikely to be contaminated by black shale from the Marcellus that caved downhole.

In the No. 1 J.S. Walker well, the very good source rock (TOC is 2.78 weight percent) is located in a 150-ft-thick interval in the upper part of the Salina Group (Camillus Shale) that consists of interbedded medium- to dark-brown dolomite, dark-grayish-brown limestone, anhydritic dolomite, and dark-brownish-gray shale, according to a lithologic log described by the Geological Sample Log Company. The shale in this interval consists of thin, discontinuous laminations in the dolomite and limestone, and thus is difficult to characterize in net feet. Because the upper part of the Salina Group in the No. 1 J.S. Walker well is located about 450 ft below the Middle Devonian Marcellus Shale, the analyzed sample was unlikely to be contaminated by black shale from the Marcellus that caved downhole.

Two sampled intervals in the No. 1–A Walls well are identified as having very good source rocks. The 520-ft-thick lower interval (TOC is 3.0 weight percent) consists largely of the Wills Creek Formation (400 ft) with interbedded medium- to dark-gray dolomite, anhydritic dolomite, local anhydrite, medium- to dark-gray limestone, and gray to black shale (Geological Sample Log Company, Mount Lebanon, Pa.). Approximately 60 net ft of gray to black shale is present in the Wills Creek Formation part of the 520-ft-thick interval. The lower 120 ft of the 520-ft-thick interval consists of the Newburg sandstone (30 ft) and the uppermost 90 ft of the McKenzie Limestone. In this interval, the McKenzie Limestone consists of interbedded light-gray to brownish-gray, fossiliferous limestone and gray to black shale. The McKenzie Limestone contains approximately 15 net ft of gray to black shale. The upper source rock interval (TOC is 3.35 weight percent) in the No. 1–A Walls is 200 ft thick, rests directly on the lower unit, and consists of the uppermost part of the Wills Creek Formation (40 ft) and lowermost part of the Salina Group (160 ft). Both units have a lithology that is characterized by interbedded medium- to dark-gray dolomite, anhydrite, and black shale. This 200-ft-thick interval contains about 20 net ft of black shale. As noted in table 1, the Wills Creek Formation probably yielded the measured TOC values of 3.0 and 3.35 weight percent.

Another sampled interval in the lower part of the Salina Group in the No. 1–A Walls well had a TOC value (0.98 weight percent) that qualifies the sample as a source rock. This sample interval is 190 ft thick and is located 50 ft above the previously described upper-source-rock interval. The lithology of the 190-ft-thick Salina Group interval consists of interbedded medium- to dark-gray dolomite, anhydrite, and black shale. The black shale constitutes about 25 net ft of the interval. The TOC value (0.98 weight percent) of this interval and the TOC values of 3.0 and 3.35 weight percent from the underlying intervals demonstrate the overall source-rock potential of the lower part of the Salina Group and the underlying Wills Creek Formation in the No. 1–A Walls well. Because the interval that includes the lower Salina Group and Wills Creek Formation in the No. 1–A Walls well is located about 1,200 ft below the Middle Devonian Marcellus Shale (TOC is 1.43 weight percent; Repetski and others, 2008), the analyzed samples were unlikely to have been contaminated by black shale from the Marcellus that caved downhole.

Rock-Eval Analysis

Rock-Eval analyses of the 308 samples provided additional data that may be useful for characterizing Silurian source rocks. The first and second hydrocarbon peaks (S_1 and S_2, respectively) generated by Rock-Eval analysis (values are in milligrams of hydrocarbon per gram of sample, or mg HC/g sample) suggest that several samples in the dataset either have generated petroleum or have the potential to generate petroleum. Overall, the S_1 values (0.66–2.32 mg HC/g sample, with an average of 1.41) and S_2 values (0.86–10.08 mg HC/g sample, with an average of 4.88) are highest for the 5 samples identified as good to very good source rocks (based on TOC values) in the Salina-Wills Creek interval (tables 1, 2). The S_1 and S_2 values for the 13 samples identified as fair source rocks (based on TOC values) in the Salina-Wills Creek interval range from 0.11 to 1.81 (with an average of 0.52) to 0.23 to 2.28 (with an average of 0.83), respectively (tables 1, 2). Relatively high S_1 and S_2 values were measured in a single sample of the Rochester Shale (TOC is 0.59 weight percent, S_1 is 3.96 mg HC/g sample, S_2 is 1.17 mg HC/g sample) and 2 samples of the Lockport Dolomite (TOC is 0.62 weight percent, S_1 is 1.11 to 3.72 mg HC/g sample, S_2 is 0.80 to 1.00 mg HC/g sample) (tables 1, 2), but these values may be influenced by petroleum contamination from the “Clinton” sandstone and Medina Group sandstones that underlie the samples by about 100 to 200 ft. Relatively high S_1 and S_2 values in 1 sample of the Keyser Formation (TOC is 0.20 weight percent, S_1 is 4.34 mg HC/g sample, S_2 is 1.30 mg HC/g sample) (tables 1, 2) and in 2 samples of the McKenzie Limestone (or Member) (TOC is 0.28 to 0.36 weight percent, S_1 is 0.63 to 0.99 mg HC/g sample, S_2 is 0.56 to 1.81 mg HC/g sample) (tables 1, 2) cannot be readily explained.

Hydrogen indexes (HI) (expressed as milligrams of hydrocarbon per gram of organic carbon, or mgHC/g org C) for the 308 samples are relatively low. Of the 308 samples, 274 (about 90 percent) have HIs of 199 mg HC/g org C or less and another 27 samples have HIs of 200 to 299 mg HC/g org C (tables 1, 2). Seven samples have HIs of 300 or greater, but less than or equal to 635, and only 2 of these samples are identified as good to very good source rocks. Also, only 8 HI values in the dataset are associated with TOC values ranging from 0.9 to 1.0 weight percent, maximum temperatures (T_{max}) ranging from 400°C to 450°C, and S_2 values ranging from 0.4 to 0.5 or greater (tables 1, 2), which are the generally accepted combination of parameters required for reliable HI values.

About 85 percent of the samples (n=263) have T_{max} values that are considered to be unreliable by the analyst, Humble Geochemical Services (tables 1, 2). In general, T_{max} values are considered unreliable when the S_2 values are less than about 0.4 to 0.5 mg HC/g sample and when a sharp, well-defined S_2 peak is absent. Of the 45 reliable samples, only about 7 samples have T_{max} values (T_{max} for oil window is approximately 435°C to 459°C; T_{max} for gas window is approximately 460°C or greater) that are consistent with the distribution of Silurian oil and gas fields shown on figure 1. Such a low reliability of the T_{max} values is another indication of the generally poor (lean) source-rock quality characterized by the dataset.

Conclusions and Further Studies

In this study, the only identified Silurian source rocks of possible importance for generating significant amounts of hydrocarbons are the Salina Group and the correlative Wills Creek Formation (and possibly the Tonoloway Limestone). Silurian source rocks of secondary importance are the Lockport Dolomite and the correlative McKenzie Limestone (or Member). Silurian strata with the best source-rock characteristics are concentrated in northern West Virginia and western Pennsylvania within or near the Salina-Tonoloway depocenter that Smosna and others (1977) identified (also see figure 8 for the distribution of Salina Group halite). Silurian reservoirs that may have been charged by Salina-Will Creek-Tonoloway source rocks are the Newburg sandstone, "Newburg zone" in the Lockport Dolomite, and Keefer Sandstone; however, areas where these reservoirs currently produce petroleum do not coincide with areas that seem to have the best Silurian source rocks (figs. 1, 8).

We cannot propose a Silurian total petroleum system based on the results of this study. Such a proposal would have to be supported by additional geologic, geochemical, and petroleum production studies. First, several bitumen extracts would have to be taken from the current dataset and analyzed by gas chromatography to establish the geochemical character of oil generated from the Salina Group and its equivalent units. Several samples in the Salina-Wills Creek-Tonoloway interval have S_1 values of greater than or equal to 1.0 and seem to have sufficient bitumen for extraction (tables 1, 2). Oil-source rock correlations could be made between these extracts and oils collected from Silurian reservoirs in nearby parts of the Appalachian basin. Also, natural gas would have to be collected and analyzed for selected isotope distributions, although a gas-source rock correlation is more difficult to establish. Secondly, additional regional stratigraphic studies would be needed to improve understanding of the distribution and thickness of black shale- and carbonate-bearing facies in the Salina Group and equivalent units. The study would have to concentrate on western and central New York, eastern Ohio, western and central Pennsylvania, and northern and central West Virginia. The Lockport Dolomite (or Group) and equivalent McKenzie Limestone (or Member) also could be included in these regional stratigraphic studies. In addition, a map of oil and gas fields (including shows) in Silurian reservoirs to accompany any resulting facies distribution maps would be useful. Once an updated stratigraphic framework has been established for the Salina Group and its equivalent strata, additional subsurface samples would be collected and analyzed for their TOC and Rock-Eval characteristics. Most of these new subsurface samples would be collected from wells in New York and from wells in Ohio, Pennsylvania, and West Virginia that were not included in this reconnaissance investigation; however, in wells where good to very good source rocks seem to be present, samples would be reanalyzed and (or) recollected and analyzed to establish reproducibility. All new samples would be collected from specific stratigraphic units, preferably at intervals of 30 to 50 ft or less.

References Cited

Avary, K.L., 1996, Play Sts; The Lower Silurian Tuscarora Sandstone fractured anticlinal play, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 151–155.

Berg, T.M., McInerney, M.K., Way, J.H., and MacLachlan, D.B., 1983, Stratigraphic correlation chart of Pennsylvania: Pennsylvania Topographic and Geologic Survey General Geology Report 75, 1 sheet.

Cole, G.A., Drozd, R.J., Sedivy, R.A., and Halpern, H.I., 1987, Organic geochemistry and oil-source correlations, Paleozoic of Ohio: American Association of Petroleum Geologists Bulletin, v. 71, no. 7, p. 788–809.

Colton, G.W., 1970, The Appalachian Basin–Its depositional sequences and their geologic relationships, *in* Fisher, G.W., Pettijohn, F.J., Reed, J.C., Jr., and Weaver, K.N., eds., Studies of Appalachian Geology: central and southern: New York, Wiley Interscience Publishers, p. 5–47.

Cotter, Edward, and Inners, J.D., 1986, Silurian stratigraphy and sedimentology in the Huntingdon County area, *in* Sevon, W.D., ed., Selected geology of Bedford and Huntingdon Counties, Guidebook, Fifty-first Annual Field Conference of Pennsylvania Geologists, Huntingdon, Pa., September 25–27, 1986: [Middletown, Pa.], The Field Conference of Pennsylvania Geologists, p. 27–39.

Curtis, J.B., and Faure, Gunter, 1997, Accumulation of organic matter in the Rome trough of the Appalachian basin and its subsequent thermal history: American Association of Petroleum Geologists Bulletin, v. 81, no. 3, p. 424–437.

de Witt, W., Jr., 1993, Principal oil and gas plays in the Appalachian basin (province 131): U.S. Geological Survey Bulletin 1839–I, 37 p.

Drozd, R.J. and Cole, G.A., 1994, Point Pleasant-Brassfield(!) petroleum system, Appalachian basin, U.S.A., *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system—From source to trap: American Association of Petroleum Geologists Memoir 60, p. 387–398.

Frey, M.G., 1973, Influence of Salina salt on structure in New York-Pennsylvania part of Appalachian Plateau: American Association of Petroleum Geologists Bulletin, v. 57, no. 6, p. 1027–1037.

Gradstein, F.M., Ogg, J.G., and Smith, A.G., eds., 2004, A geologic time scale 2004: Cambridge, U.K., Cambridge University Press, 610 p., 1 plate.

Hatch, J.R., Swezey, C.S., and Harrison, W.B., 2004, Use of natural gas compositions to identify Michigan Basin petroleum systems: American Association of Petroleum Geologists Annual Meeting Expanded Abstracts, v. 13, p. 60.

Jenden, P.D., Drazan, D.J., and Kaplan, I.R., 1993, Mixing of thermogenic natural gases in northern Appalachian basin: American Association of Petroleum Geologists Bulletin, v. 77, no. 6, p. 980–998.

Knight, W.V., 1969, Historical and economic geology of Lower Silurian Clinton sandstone of northeastern Ohio: American Association of Petroleum Geologists Bulletin, v. 53, no. 7, p. 1421–1452.

McCormac, M.P., Mychkovsky, G.O., Opritza, S.T., Riley, R.A., Wolfe, M.E., Larson, G.E., and Baranoski, M.T., 1996, Play Scm; Lower Silurian Cataract/Medina Group (“Clinton”) sandstone play, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 156–163.

Meglen, J.F., and Noger, M.C., 1996, Play DSu; Lower Devonian-Upper Silurian unconformity play, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 133–138.

Miles, P.M., 1972, Notes on “Corniferous” production in eastern Kentucky, *in* Hutcheson, D.W., ed., Proceedings of the Technical Sessions, Kentucky Oil and Gas Association 34th and 35th Annual Meetings, 1970 and 1971: Kentucky Geological Survey Special Publication 21, p. 46–49.

Milici, R.C., Ryder, R.T., Swezey, C.S., Charpentier, R.R., Cook, T.A., Crovelli, R.A., Klett, T.R., Pollastro, R.M., and Schenk, C.J., 2003, Assessment of undiscovered oil and gas resources of the Appalachian Basin Province, 2002: U.S. Geological Survey Fact Sheet 009–03, 2 p.

New York State Department of Environmental Conservation, 1986, New York State oil and gas fields: New York State Department of Environmental Conservation, Division of Mineral Resources, 1 sheet, scale 1:250,000.

Noger, M.C., Meglen, J.F., Humphries, Matthew, and Baranoski, M.T., 1996, Play Sld; Upper Silurian Lockport Dolomite-Keefer (Big Six) Sandstone, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 145–150.

Obermajer, Mark, Fowler, M.G., Snowdon, L.R., and MacQueen, R.W., 2000, Compositional variability of crude oils and source kerogen in the Silurian carbonate-evaporite sequences of the eastern Michigan Basin, Ontario, Canada: Bulletin of Canadian Petroleum Geology, v. 48, no. 4, p. 307–322.

Ohio Division of Geological Survey, 2004, Oil and gas field map of Ohio: Ohio Department of Natural Resources, Division of Geological Survey Map PG–1, generalized page-size version with text, 2 p., scale 1:2,000,000.

Patchen, D.G., 1996, Play Sns; Upper Silurian Newburg Sandstone play, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 139–144.

Pepper, J.F., 1947, Areal extent and thickness of the salt deposits of Ohio: The Ohio Journal of Science, v. 47, no. 6, p. 225–239.

Peters, K.E., and Cassa, M.R., 1994, Applied source rock geochemistry, *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system–From source to trap: American Association of Petroleum Geologists Memoir 60, p. 93–120.

Peters, K.E., and Moldowan, J.M., 1993, The biomarker guide; Interpreting molecular fossils in petroleum and ancient sediments: Englewood Cliffs, N.J., Prentice Hall, 363 p.

Powell, T.G., MacQueen, R.W., Barker, J.F., and Bree, D.G., 1984, Geochemical character and origin of Ontario oils: Bulletin of Canadian Petroleum Geology, v. 32, no. 3, p. 289–312.

Ray, E.O., 1971, Petroleum potential of eastern Kentucky, *in* Cram, I.H., ed., Future petroleum provinces of the United States—Their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 2, p. 1261–1268.

Repetski, J.E., Ryder, R.T., Weary, D.J., Harris, A.G., and Trippi, M.H., 2008, Thermal maturity patterns (CAI and %R_o) in Upper Ordovician and Devonian rocks of the Appalachian basin; A major revision of USGS Map I–917–E, using new subsurface collections: U.S. Geological Survey

Scientific Investigations Map 3006, 1 DVD. (Re-released as chapter F.1 of this volume. Also available at http://pubs.usgs.gov/sim/3006/.)

Rickard, L.V., 1969, Stratigraphy of the Upper Silurian Salina Group, New York, Pennsylvania, Ohio, Ontario: New York State Museum and Science Service Map and Chart Series 12, 57 p.

Roen, J.B., and Walker, B.J., eds., 1996, The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, 201 p.

Rullkötter, Juergen, Meyers, P.A., Schaefer, R.G., and Dunham, K.W., 1986, Oil generation in the Michigan Basin; A biological marker and carbon isotope approach: Organic Geochemistry, v. 10, no. 1–3, p. 359–375.

Ryder, R.T., 1995, Appalachian Basin Province (067), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 national assessment of United States oil and gas resources–Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, 1 CD–ROM.

Ryder, R.T., 2004, Stratigraphic framework and depositional sequences in the Lower Silurian regional oil and gas accumulation, Appalachian basin; From Ashland County, Ohio, through southwestern Pennsylvania, to Preston County, West Virginia: U.S. Geological Survey Geologic Investigations Series Map I–2810, 2 sheets, 11 p. (Re-released as chapter E.3.1 of this volume. Also available at http://pubs.usgs.gov/imap/i2810/.)

Ryder, R.T., Burruss, R.C., and Hatch, J.R., 1998, Black shale source rocks and oil generation in the Cambrian and Ordovician of the central Appalachian basin, USA: American Association of Petroleum Geologists Bulletin, v. 82, no. 3, p. 412–441.

Ryder, R.T., Crangle, R.D., Jr., Trippi, M.H., Swezey, C.S., Lentz, E.E., Rowan, E.L., and Hope, R.S., 2009, Geologic cross section *D–D′* through the Appalachian basin from the Findlay arch, Sandusky County, Ohio, to the Valley and Ridge province, Hardy County, West Virginia: U.S. Geological Survey Scientific Investigations Series Map SIM–3067, 2 sheets, 52 p. (Re-released as chapter E.4.1 of this volume. Also available at http://pubs.usgs.gov/sim/3067/.)

Ryder, R.T., Swezey, C.S., Crangle, R.D., Jr., and Trippi, M.H., 2008, Geologic cross section *E–E′* through the Appalachian basin from the Findlay arch, Wood County, Ohio, to the Valley and Ridge province, Pendleton County, West Virginia: U.S. Geological Survey Scientific Investigations Series Map SIM–2985, 2 sheets, 48 p. (Re-released as chapter E.4.2 of this volume. Also available at http://pubs.usgs.gov/sim/2985/.)

Ryder, R.T., Trippi, M.H., Swezey, C.S., Crangle, R.D., Jr., Hope, R.S., Rowan, E.L., and Lentz, E.E., 2012, Geologic cross section *C–C′* through the Appalachian basin from Erie County, north-central Ohio, to the Valley and Ridge province, Bedford County, south-central Pennsylvania: U.S. Geological Survey Scientific Investigations Map 3172, 2 sheets, 70 p. pamphlet. (Also available at http://pubs.usgs.gov/sim/3172/.)

Ryder, R.T., and Zagorski, W.A., 2003, Nature, origin, and production characteristics of the Lower Silurian regional oil and gas accumulation, central Appalachian basin, United States: American Association of Petroleum Geologists Bulletin, v. 87, no. 5, p. 847–872.

Santini, R.J., and Coogan, A.H., 1983, The Silurian Newburg (Lockport) gas pools in Summit County, Ohio; Complex structural-stratigraphic petroleum accumulations: Northeastern Geology, v. 5, no. 3–4, p. 181–191.

Smosna, R.A., Patchen, D.G., Warshauer, S.M., and Perry, W.J., Jr., 1977, Relationships between depositional environments, Tonoloway Limestone, and distribution of evaporates in the Salina Formation, West Virginia, *in* Fisher, J.H., ed., Reefs and evaporates—Concepts and depositional models: American Association of Petroleum Geologists Studies in Geology 5, p. 125–143.

Swezey, C.S., 2002, Regional stratigraphy and petroleum systems of the Appalachian basin, North America: U.S. Geological Survey Geologic Investigations Series Map I–2768, 1 sheet.

Tissot, B.P. and Welte, D.H., 1984, Petroleum formation and occurrence [2d ed.]: Berlin, Springer-Verlag, 699 p.

Van Tyne, A.M., 1996, Play Sbi; Upper Silurian Bass Islands Trend, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 130–132.

Wilson, E.N. and Sutton, D.G., 1976, Oil and gas map of Kentucky, sheet 4, eastern part: Kentucky Geological Survey, Series X, 1 sheet, scale 1:250,000.

Yager, R.M., 2000, Simulated transport and biodegradation of chlorinated ethenes in a fractured dolomite aquifer near Niagara Falls, New York: U.S. Geological Survey Water-Resources Investigations Report 00–4275, 55 p.

Zenger, D.H., 1965, Stratigraphy of the Lockport Formation (Middle Silurian) in New York State: New York State Museum and Science Service Bulletin 404, 210 p.