Evidence for Cambrian Petroleum Source Rocks in the Rome Trough of West Virginia and Kentucky, Appalachian Basin

By Robert T. Ryder, David C. Harris, Paul Gerome, Timothy J. Hainsworth, Robert C. Burruss, Paul G. Lillis, Daniel M. Jarvie, and Mark J. Pawlewicz

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
centimeter (cm)	0.3937	inch (in.)
	Volume	
barrel (bbl) (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic centimeter (cm^3)	0.06102	cubic inch ($in.^3$)
	Mass	
gram (g)	0.03527	ounce avoirdupois

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

°F=(1.8×°C)+32

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Evidence for Cambrian Petroleum Source Rocks in the Rome Trough of West Virginia and Kentucky, Appalachian Basin

By Robert T. Ryder,[1] David C. Harris,[2] Paul Gerome,[3] Timothy J. Hainsworth,[4] Robert C. Burruss,[1] Paul G. Lillis,[5] Daniel M. Jarvie,[6] and Mark J. Pawlewicz[5]

Abstract

A 130-foot-thick Cambrian black shale sampled from a core between 11,150 and 11,195 feet in the Exxon No. 1 Smith well in Wayne County, W. Va., has been identified as a good to very good source rock. The black shale is located in the Middle Cambrian Rogersville Shale of the Conasauga Group. Total organic carbon (TOC) values of four samples that range from 1.2 to 4.4 weight percent (average 2.6 weight percent) are the highest reported to date in the pre-Knox section of the Rome trough. Although the samples are probably in the zone of gas generation based on their low hydrogen index values (55 to 63) and temperature maximum of second hydrocarbon peak (S_2) values of about 465°C, first hydrocarbon peak (S_1) values of 0.81 to 2.71 indicate that they contain free extractable hydrocarbons. A bitumen sample extracted from the Rogersville Shale is characterized by (1) a broad spectrum of *n*-alkanes from *n*-C_{11} through *n*-C_{30}, (2) strong odd-carbon predominance in the *n*-C_{13} to *n*-C_{19} range, and (3) small but detectable amounts of isoprenoids pristane and phytane. The strong odd-carbon predominance of the *n*-C_{15} to *n*-C_{19} *n*-alkanes is commonly attributed to the Ordovician alga *Gloeocapsomorpha prisca*. This occurrence of *G. prisca* is among the first to be reported in Cambrian rocks. Thin black shale beds collected from the Lower to Middle Cambrian Rome Formation in the Texaco No. 1 Kirby well in Garrard County, Ky., have TOC values as high as 3.2 percent, hydrogen index values as high as 417, and bitumen extract characteristics similar to the Rogersville Shale.

The bitumen extract from the Rogersville Shale compares very closely with oils or condensates from Cambrian reservoirs in the Carson Associates No. 1 Kazee well, Homer gas field, Elliott County, Ky.; the Inland No. 529 White well, Boyd County, Ky.; and the Miller No. 1 well, Wolfe County, Ky. These favorable oil-source rock correlations suggest a new petroleum system in the Appalachian basin that is characterized by a Conasauga Group source rock and Rome Formation and Conasauga Group reservoirs. This petroleum system probably extends along the Rome trough from eastern Kentucky to at least central West Virginia.

Introduction

The Utica-Lower Paleozoic Total Petroleum System in the Appalachian basin as defined by Milici, Ryder, and Swezey (2003); and Milici, Ryder, Swezey, and others (2003) is moderately well documented by geochemical evidence (Drozd and Cole, 1994; Ryder and others, 1998). The Upper Ordovician Utica Shale is the source rock in the petroleum system and very likely accounts for oil and gas trapped in such reservoirs as the Upper Cambrian and Lower Ordovician Knox Dolomite, Upper Cambrian Rose Run Sandstone, Lower Ordovician Beekmantown Dolomite, and Upper Ordovician Black River and Trenton Limestones (fig. 1). Probable, but less certain, oil and gas accumulations associated with the Utica Shale source rock are those trapped in the Upper Ordovician Bald Eagle Sandstone (equivalent to the Oswego Sandstone), Upper Ordovician Queenston Shale, Lower Silurian sandstones (“Clinton” sandstone, Medina sandstone, Medina Group, and Tuscarora Sandstone), and Lower and Upper Silurian Lockport Dolomite (fig. 1).

Hypothetical migration pathways for Utica Shale-derived petroleum were suggested by Ryder and others (1998) along a regional geologic cross section through eastern Ohio and western West Virginia (fig. 2). In addition, the cross section of Ryder and others (1998) showed natural gas occurrences in Cambrian strata of the Rome trough of West Virginia (Exxon No. 1 McCoy and Exxon No. 1 Gainer-Lee wells) that cannot be explained by derivation from a Utica source rock (fig. 2).

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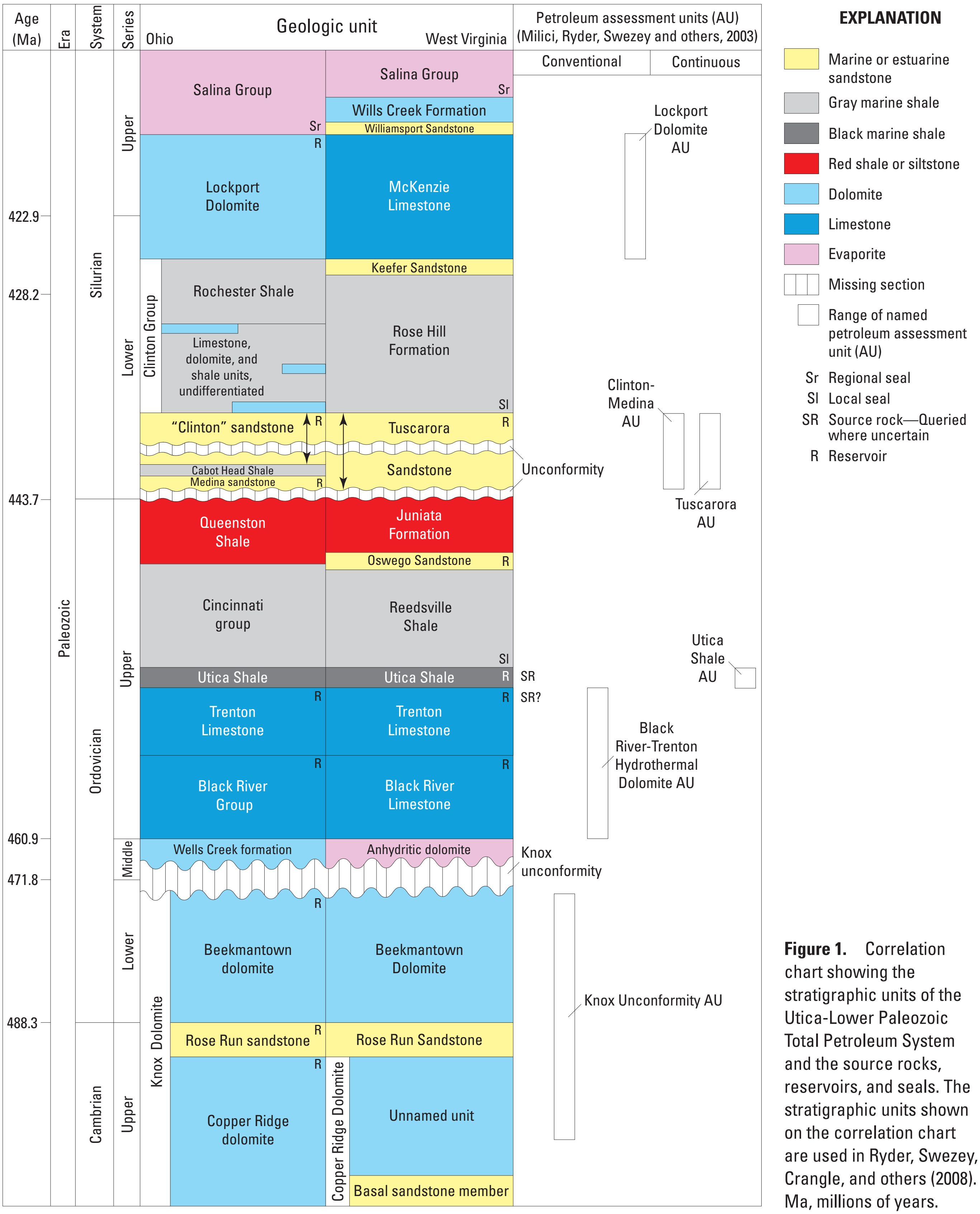


Figure 1. Correlation chart showing the stratigraphic units of the Utica-Lower Paleozoic Total Petroleum System and the source rocks, reservoirs, and seals. The stratigraphic units shown on the correlation chart are used in Ryder, Swezey, Crangle, and others (2008). Ma, millions of years.

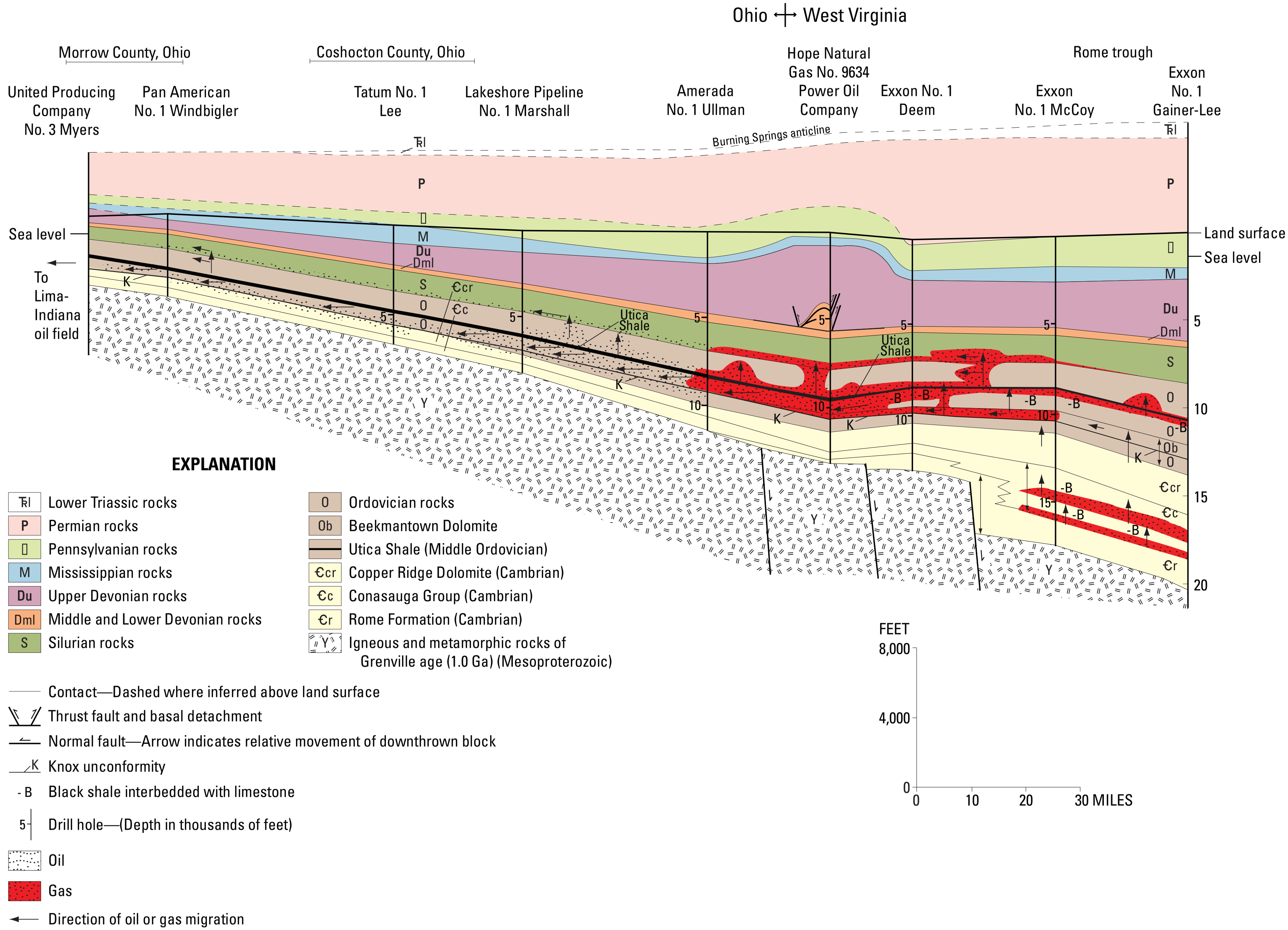


Figure 2. Generalized geologic cross section from central Ohio to central West Virginia showing proposed migration routes of oil and gas generated from the Ordovician Utica Shale and Cambrian Conasauga Group. The cross section is from Ryder and others (1998). See figure 4 for line of section.

Rome trough petroleum occurrences in wells (fig. 3) in West Virginia and Kentucky include (1) the Exxon No. 1 McCoy well, Jackson County, W. Va., where the Cambrian Maryville Limestone of the Conasauga Group initially produced natural gas at 6 to 9 million cubic feet per day (Harris and Drahovzal, 1996); (2) the Exxon No. 1 Gainer-Lee well, Calhoun County, W. Va., where 13.4 barrels of gas-cut mud were produced during a drill stem test from the Maryville Limestone; (3) the Inland No. 529 White well, Boyd County, Ky., where oil was initially produced at 32 barrels per day from the Cambrian Rome Formation (McGuire, 1968; Weaver and McGuire, 1977) or the Cambrian Maryville Limestone (this report); (4) the Carson Associates No. 1 Kazee well, Homer gas field, Elliott County, Ky., where gas, condensate, and oil is produced from the Cambrian Rome Formation and Conasauga Group (Lynch and others, 1999; Harris and others, 2004); and (5) the Miller No. 1 Bailey well, Wolfe County, Ky., where condensate and gas was tested in the Cambrian Rome Formation. Although Cambrian source rocks were suspected for these Rome trough gas and oil occurrences, most rock samples analyzed from the Cambrian to Lower Ordovician interval in the trough had a total organic carbon (TOC) content in weight percent that was too low for an effective source rock (Ryder and others, 1998).

New geochemical evidence presented by Ryder and others (2003) indicated that Cambrian source rocks are present in the Rome trough and they correlate favorably with oils in nearby Cambrian reservoirs. This evidence confirms a new petroleum system in the Rome trough of Kentucky and West Virginia that involves a source rock in the Cambrian Conasauga Group and reservoirs in the Cambrian Rome Formation and Conasauga Group (Milici, Ryder, and Swezey, 2003; Milici, Ryder, Swezey, and others, 2003). This report provides the supporting documentation for the Ryder and others (2003) presentation.

Conasauga-Rome/Conasauga Total Petroleum System

Source Rock Characteristics of Cambrian Rocks

Several deep wells (fig. 4) drilled into the Rome trough by Exxon Corporation in the 1970s were cored in the Cambrian Conasauga Group and Rome Formation. Of these cores, selected ones were sampled and analyzed, and TOC and Rock-Eval[7] analyses were reported by Ryder and others (1998). For example, Ryder and others (1998) reported that core samples collected from the Rome Formation and the Maryville Limestone of the Conasauga Group in the No. 1 McCoy well (figs. 4, 5; table 1) yielded TOC values ranging from 0.09 to 0.11 weight percent in the Rome Formation and from 0.19 to 0.59 weight percent in the Maryville Limestone (figs. 6, 7; table 1). A higher TOC value of 0.84 weight percent was reported from cuttings in the Rome Formation in the No. 1 McCoy well (fig. 6; table 1; Richard W. Beardsley, Triana Energy, written commun., March 1993). Additional samples were collected by Ryder and others (1998) from a core in the Columbia Gas Transmission No. 9674T Mineral Tract 10 well, Mingo County, W. Va. (figs. 4, 8, 9) where TOC contents in the Rome Formation ranged from 0.15 to 0.58 weight percent (fig. 9; table 1). Although these analyses (Ryder and others, 1998) indicated that organic carbon is present in the Cambrian section of the Rome trough, the TOC values are generally very low and are considered to be below the lower limit for an effective petroleum source rock (Peters and Moldowan, 1993; Peters and Cassa, 1994).

In early 2001, additional cores from the deep Exxon drill holes were shipped to Lexington, Ky., for sampling and analysis. Among these cores were four cored sections from the Exxon No. 1 Smith well, Wayne County, W. Va. (figs. 4, 8, 10): lower part of the Rome Formation (core 1), upper part of the Rome Formation (core 2), Rogersville Shale of the Conasauga Group (core 3), and Maryville Limestone of the Conasauga Group (core 4). New TOC analyses for the Rome Formation in the two deepest cores (1 and 2) yielded low values ranging from 0.13 to 0.22 weight percent (figs. 11, 12; table 1) that are consistent with analyses reported by Ryder and others (1998). Much higher TOC values, ranging from 1.20 to 4.40 weight percent, were obtained from four samples of the Rogersville Shale (figs. 13, 14; table 1). These high TOC values indicate a good to very good potential source rock that, based on the density log, may be about 123 feet (ft) thick (fig. 13). To test for contamination by migrated liquid petroleum, the shale sample with the highest TOC value (4.40 weight percent) was extracted and then reanalyzed. The resultant post-extraction TOC value of 3.16 weight percent compared with the original value of 4.40 weight percent suggests that the high TOC values are credible and that the majority of the extractable bitumen was probably locally derived from the shale (fig. 13; table 1). Photographs and descriptions of the core (figs. 14, 15) indicate that the Rogersville Shale at this locality is a slightly fossiliferous, dark-gray shale of marine origin, which commonly contains thin laminae and beds of siltstone and very fine grained sandstone and burrows filled with siltstone and (or) very fine grained sandstone.

First hydrocarbon peak (S_1) yields of 0.81 to 2.71 milligrams of hydrocarbon per gram of organic carbon (mgHC/g orgC), second hydrocarbon peak (S_2) yields of 0.75 to 2.58 mgHC/g orgC), maximum temperature (T_{max}) of the S_2 peak of 460°C to 469°C (414°C value is probably anomalous), and production index (PI) values 0.51 to 0.58 in the pre-extraction Rogersville Shale samples (table 1) suggest that these samples have reached the late stage of thermal maturity for oil and the early stage for gas (Peters and Moldowan, 1993).

[7]French Institute of Petroleum, Rusil-Malmaison, France.

Text continued on page 19.

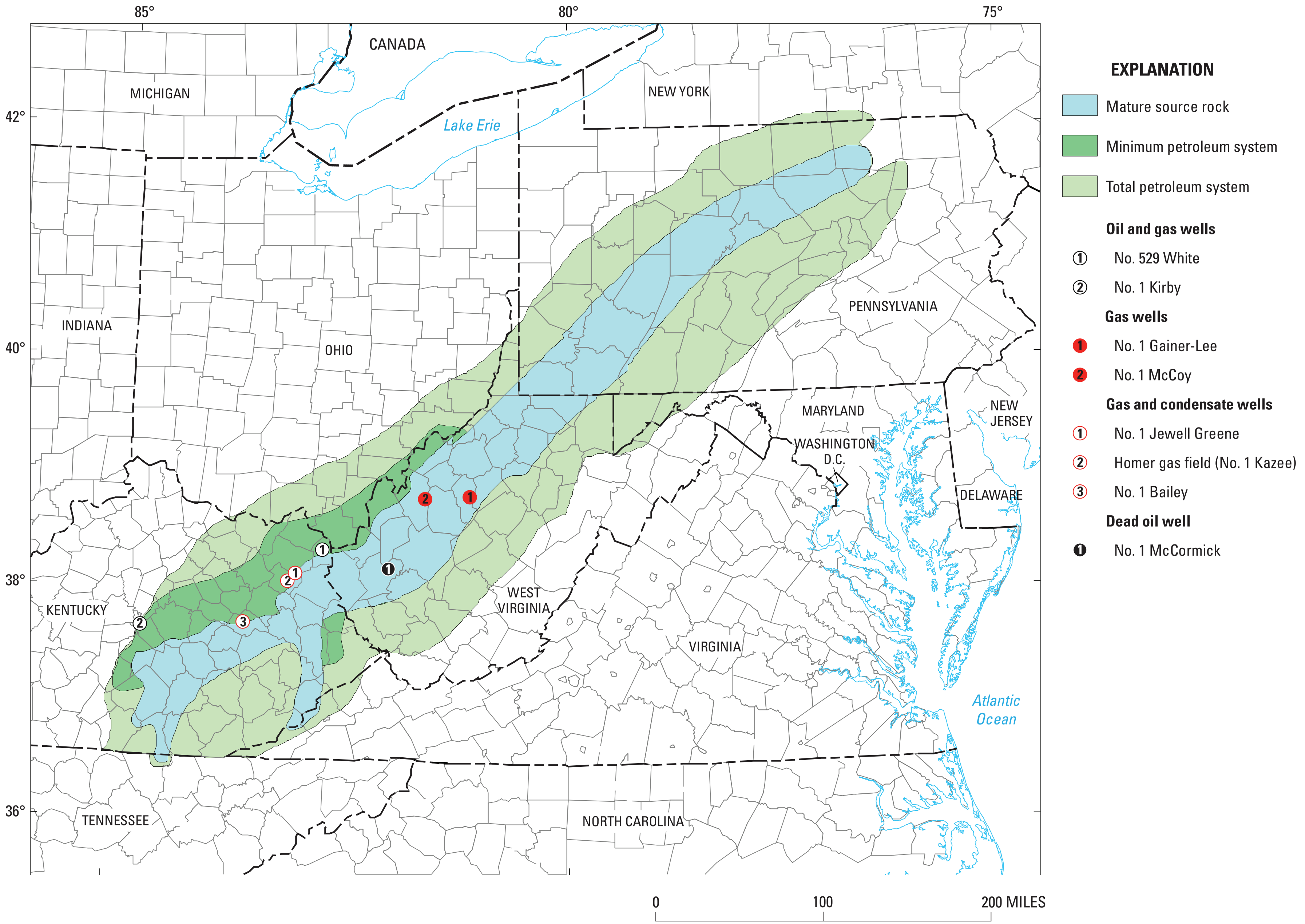


Figure 3. Map of the Conasauga-Rome/Conasauga Total Petroleum System showing the location of selected wells in the Rome trough with oil and gas production and shows.

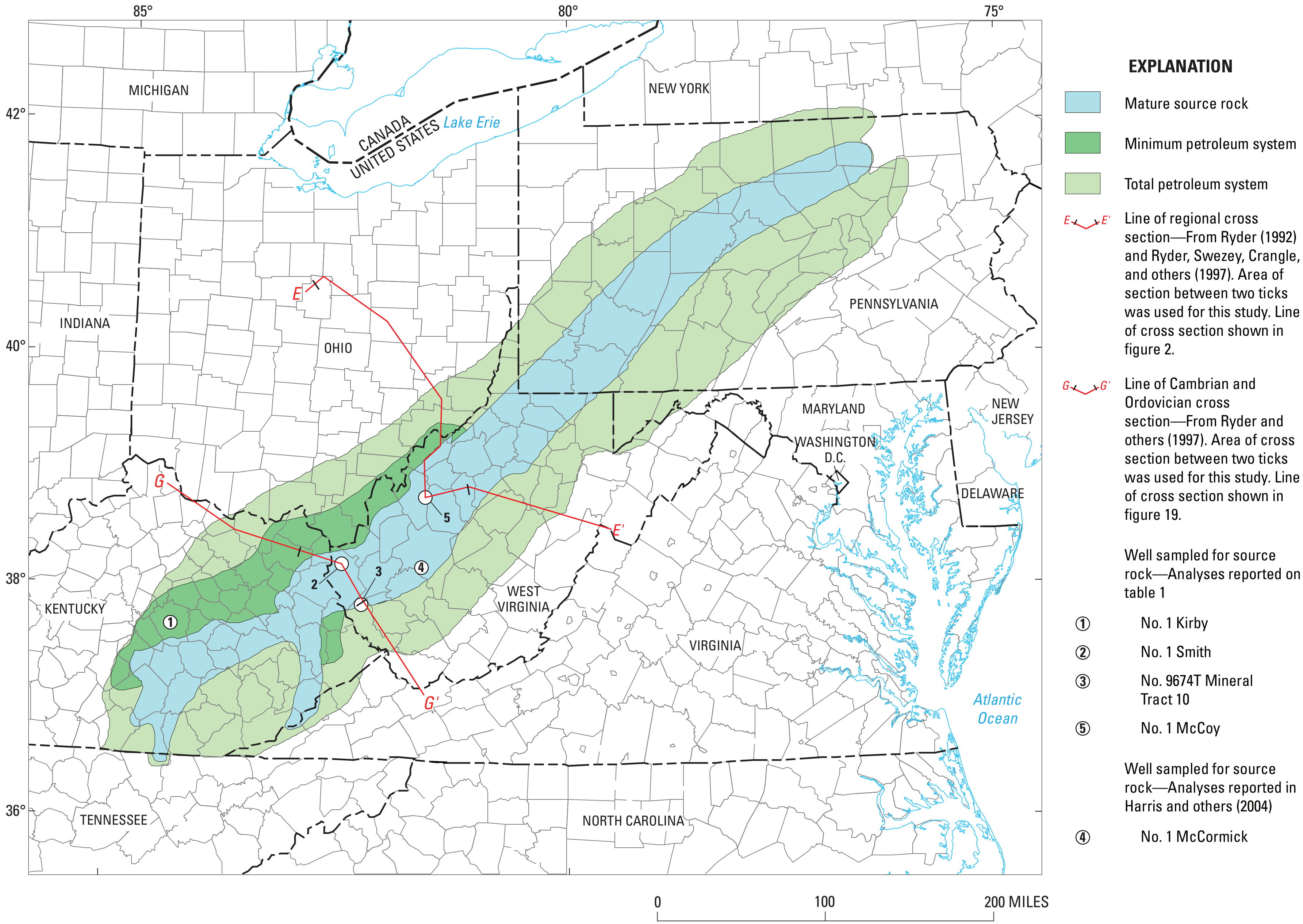


Figure 4. Map of Conasauga-Rome/Conasauga Total Petroleum System showing the location of Cambrian and Ordovician cross sections *E-E′* (fig. 5; partially shown as geologic cross section *E-E′* (Ryder and others, 1998) in figure 2) and *G-G′* (fig. 8; partially shown in figure 19) and wells in the Rome trough sampled for source rocks. This map also shows the location of the partial cross sections shown in figures 2 and 19. See Ryder and others (2008) for a regional cross section that trends along the same line of section shown here and continues to its west.

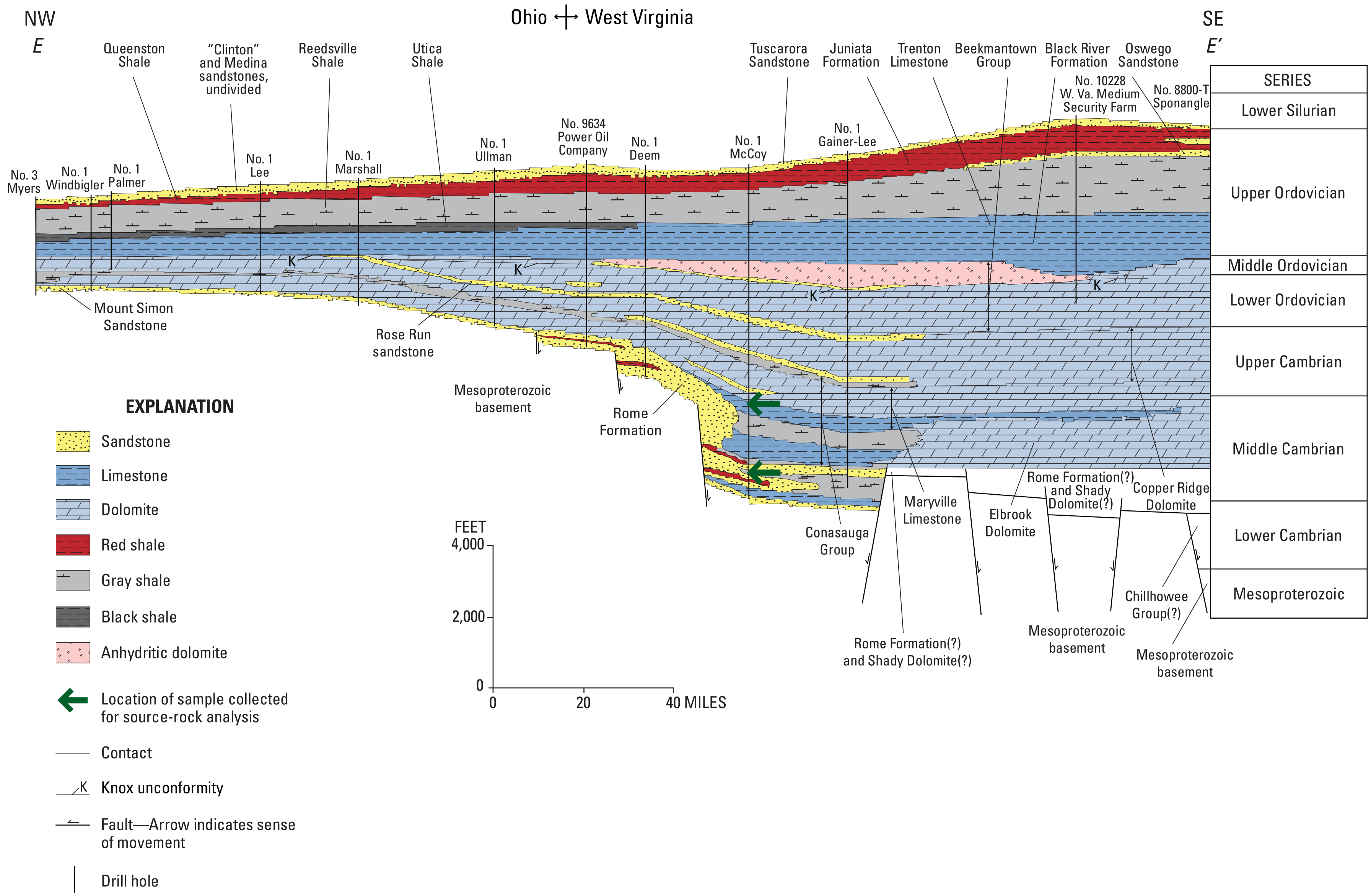


Figure 5. Cross section *E–E′* through Cambrian and Ordovician strata in the Appalachian basin of Ohio and West Virginia showing the Exxon No. 1 McCoy and No. 1 Gainer-Lee wells and source-rock sample locations. In Ohio, the Rose Run, Medina, and "Clinton" sandstones are used informally. Modified from Ryder (1992) and Ryder, Swezey, Crangle, and others (2008).

Table 1. Data for wells, including sample depths, total organic carbon content, and Rock-Eval analyses.

[Abbreviations and symbols are as follows: ft, feet; T_{max}, maximum temperature of S_2 peak, in degrees Celsius (°C); S_1, first hydrocarbon peak generated by Rock-Eval pyrolysis of sample (milligrams of hydrocarbon per gram of organic carbon (mgHC/g org C) of sample); S_2, second hydrocarbon peak generated by Rock-Eval pyrolysis of sample (mgHC/g orgC of sample); S_3, third peak generated by Rock-Eval pyrolysis of sample (milligrams of carbon dioxide per gram of organic carbon ($mgCO_2$/g orgC) of sample. Indexes are calculated as follows: Hydrogen index=$S_2\times100$/total organic carbon; oxygen index=$S_3\times100$/total organic carbon; production index=$S_1/(S_1+S_2)$]

Well name and location	Latitude and longitude	API number	Age and unit sampled	Sample depth (ft)	Total organic carbon (weight percent)	T_{max} (°C)	Hydrogen index (mgHC/g orgC)	Oxygen index ($mgCO_2$/g orgC)	S_1 (mgHC/g orgC)	S_2 (mgHC/g orgC)	S_3 ($mgCO_2$/g orgC)	Production index
Texaco No.1 Kirby, Garrard Co., Ky.	37°43′03″N., 84°37′56″W.	16–079–21048	Cambrian Rome Formation	4,628	3.26	444	417	11	0.55	13.61	0.35	0.04
				4,628.8	0.70	446	356	16	0.30	2.49	0.11	0.11
Columbia Gas Transmission No. 9674T Mineral Tract 10, Mingo Co., W. Va.	37°54′16″N., 82°10′10″W.	47–059–00805	Cambrian Rome Formation	16,233.5	0.15	–	33	180	0.04	0.05	0.27	0.50
				16,235.5	0.51	–	15	54	0.12	0.08	0.28	0.60
				16,239.5	0.58	–	15	46	0.15	0.09	0.27	0.62
Exxon No.1 McCoy, Jackson Co., W. Va.	38°43′50″N., 81°34′12″W.	47–035–01366	Cambrian Maryville Limestone of the Conasauga Group	14,364.5	0.19	–	26	200	0.02	0.05	0.38	0.33
				14,380.5	0.59	–	18	54	0.13	0.11	0.32	0.54
				14,386.5	0.25	–	40	112	0.09	0.10	0.28	0.50
				14,400.5	0.51	–	29	86	0.12	0.15	0.44	0.46
			Cambrian Rome Formation	16,310	0.84	428	49	–	0.23	0.41	–	0.36
				16,461	0.09	–	88	177	0.05	0.08	0.16	0.42
				16,493	0.11	–	63	190	0.05	0.07	0.21	0.42
Exxon No.1 Smith, Wayne Co., W. Va.	38°13′09″N., 82°32′05″W.	47–099–01572	Cambrian Rogersville Shale of the Conasauga Group	11,150.5	2.83	460	61	13	1.79	1.72	0.36	0.51
				11,161.5	4.40	469	59	6	2.71	2.58	0.27	0.51
				11,161.5 (extracted)	3.16	477	40	10	0.08	1.26	0.32	0.06
				11,180.5	1.20	414	63	23	0.81	0.75	0.27	0.52
				11,195.5	2.08	465	55	12	1.60	1.15	0.25	0.58
			Cambrian Rome Formation	12,440.3	0.15	475	13	100	0.03	0.02	0.15	0.60
				12,478.5	0.22	361	32	50	0.03	0.07	0.11	0.30
				12,497	0.14	299	7	50	0.03	0.01	0.07	0.75
				13,710.5	0.13	319	38	85	0.03	0.05	0.11	0.38
				13,734.5	0.21	299	43	48	0.04	0.09	0.10	0.31

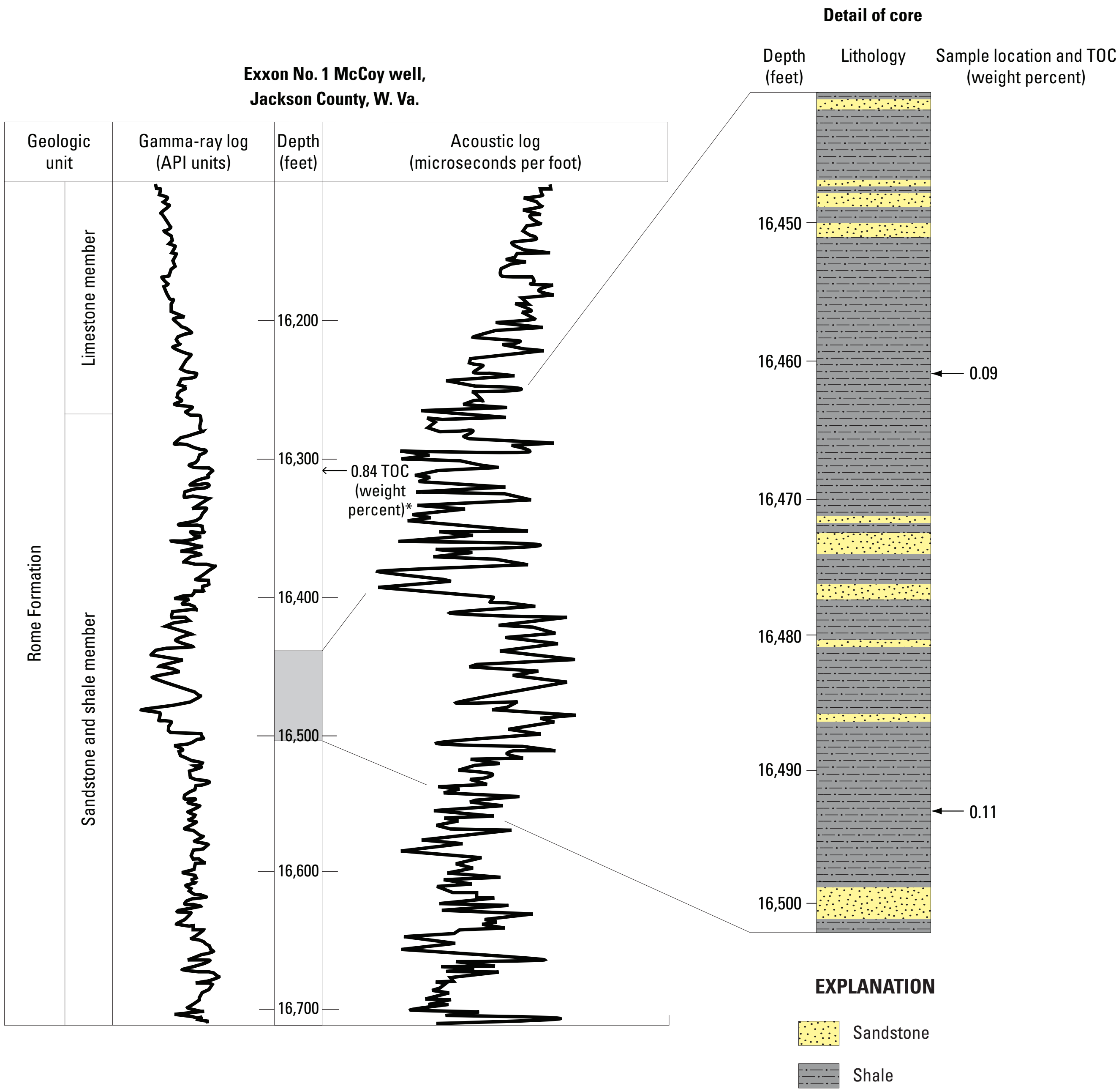


Figure 6. Diagram showing results of total organic carbon (TOC) analyses (in weight percent) for three samples from the Cambrian Rome Formation in the Exxon No. 1 McCoy well, Jackson County, W. Va. The core location is indicated by the shaded section of the depth column. See figures 3 and 4 for the location of the well. Asterisk indicates data from Richard W. Beardsley (written commun., Triana Energy, March 1993). See Ryder (1992) for a brief discussion of the sandstone and shale member and limestone member of the Rome Formation. API, American Petroleum Institute.

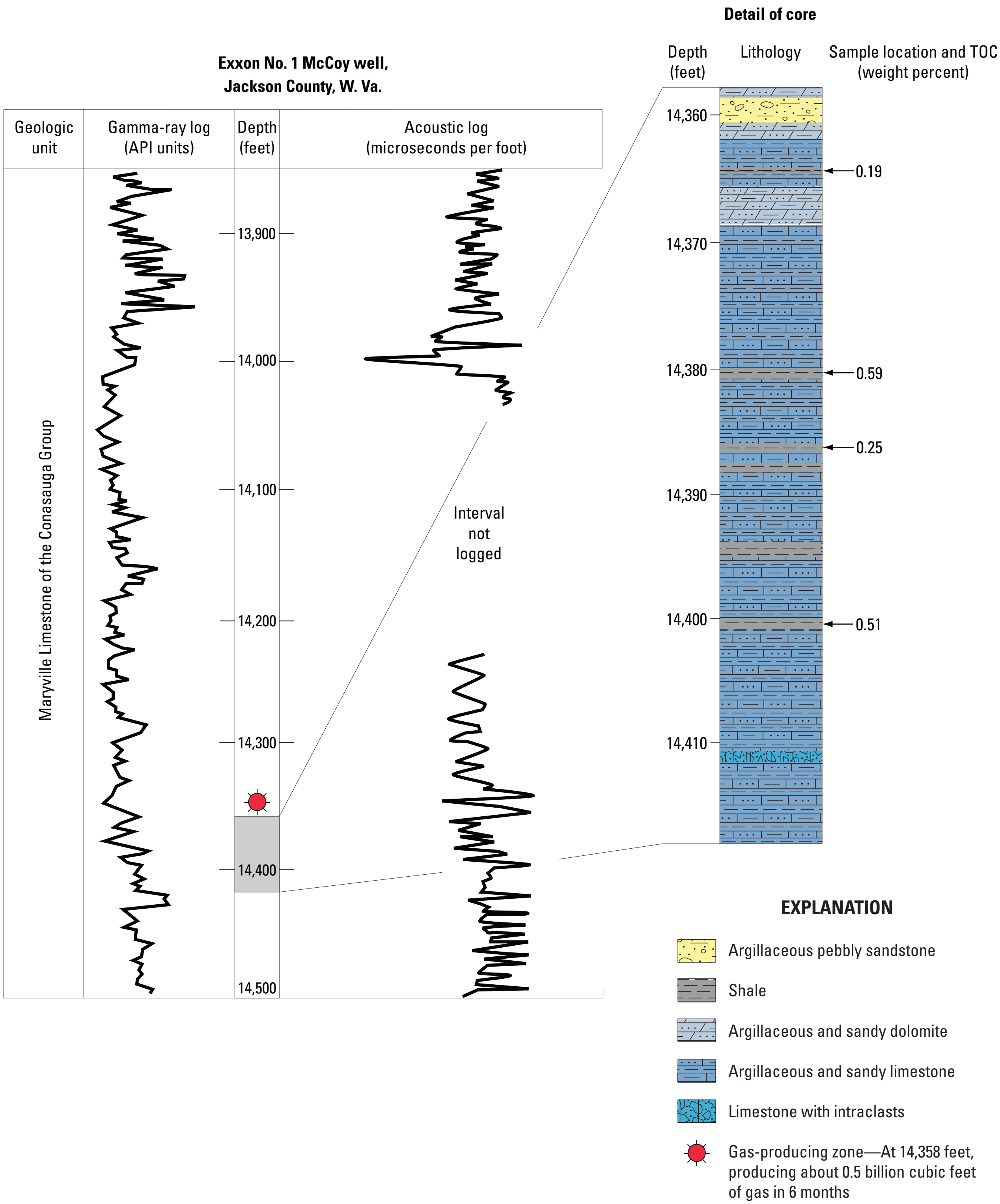


Figure 7. Diagram showing results of total organic carbon (TOC) analyses (in weight percent) for four samples from the Cambrian Maryville Limestone of the Conasauga Group in the Exxon No. 1 McCoy well, Jackson County, W. Va. The core location is indicated by the shaded section of the depth column. See figures 3 and 4 for the location of the well. See Ryder (1992) for a brief discussion of the Maryville Limestone of the Conasauga Group. API, American Petroleum Institute.

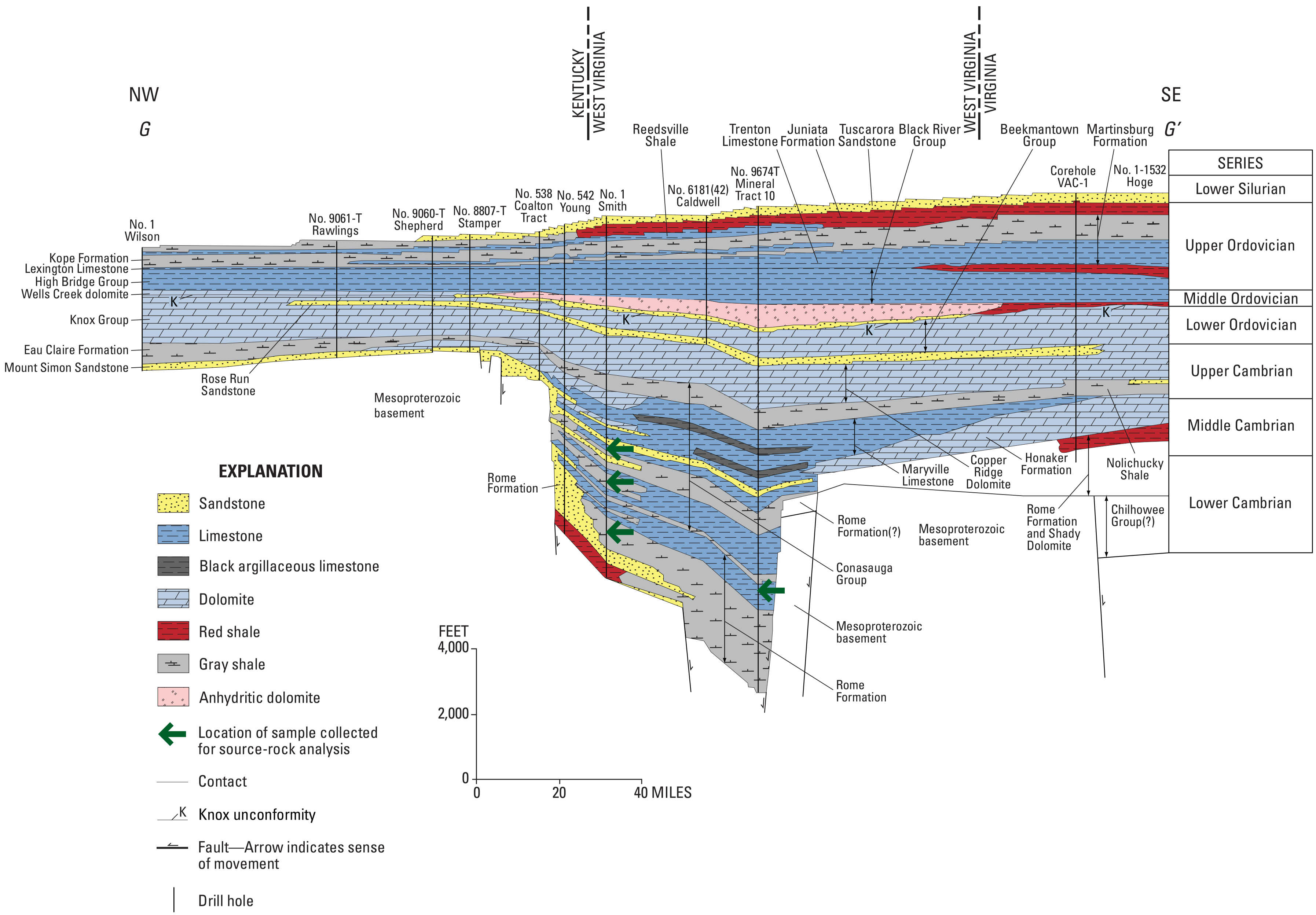


Figure 8. Cross section *G–G′* through Cambrian and Ordovician strata in the Appalachian basin of Kentucky, West Virginia, and Virginia, showing the Columbia Gas Transmission No. 9674T Mineral Tract 10 and the Exxon No. 1 Smith wells and source-rock sample locations. Modified from Ryder and others (1997).

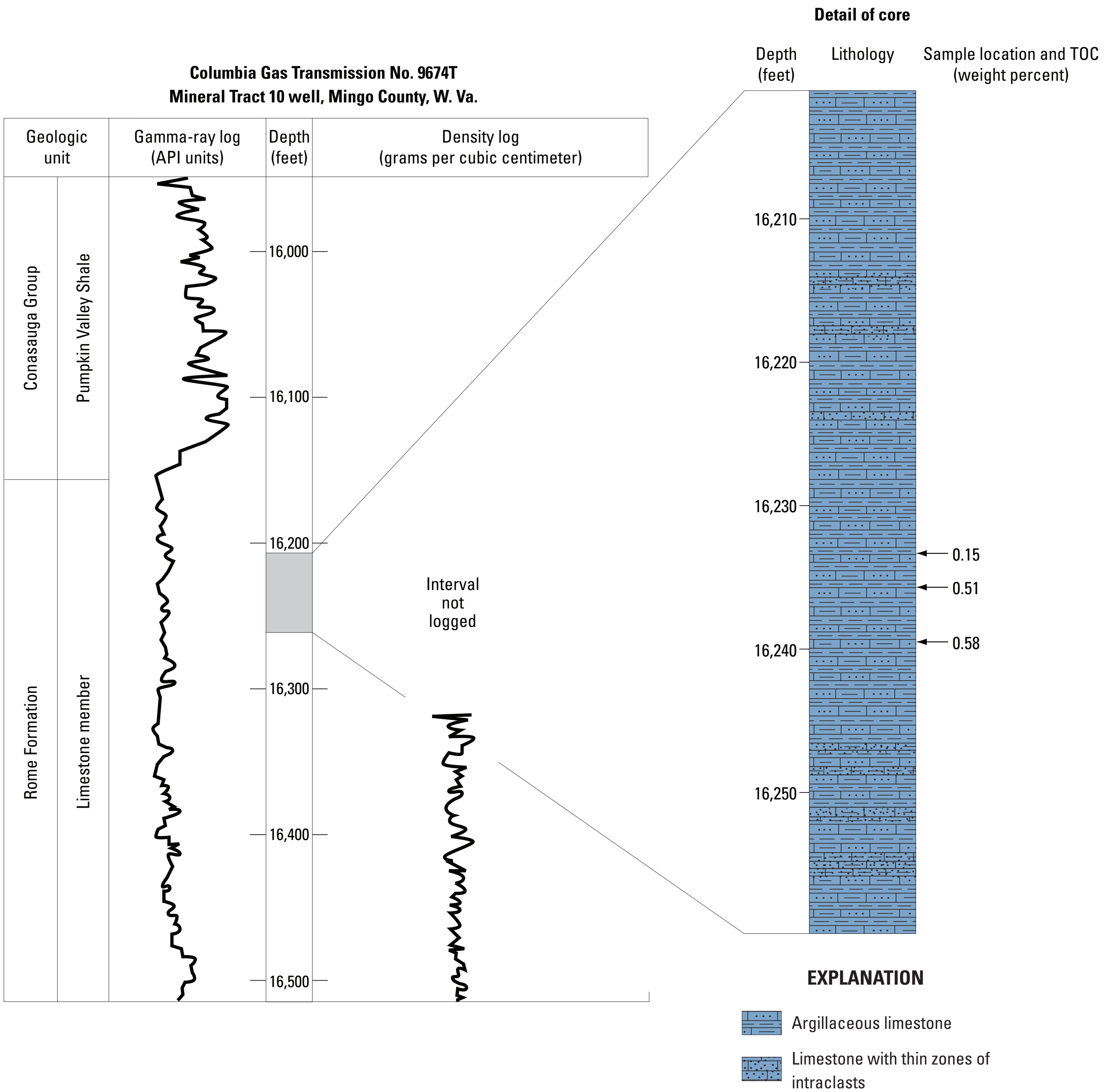


Figure 9. Diagram showing results of total organic carbon (TOC) analyses (in weight percent) for three samples from the Cambrian Rome Formation in the Columbia Gas Transmission No. 9674T Mineral Tract 10 well, Mingo County, W. Va. The core location is indicated by the shaded section of the depth column. See figure 4 for the location of the well. See Ryder (1992) for a brief discussion of the unnamed limestone member of the Rome Formation and the Pumpkin Valley Shale of the Conasauga Group. API, American Petroleum Institute.

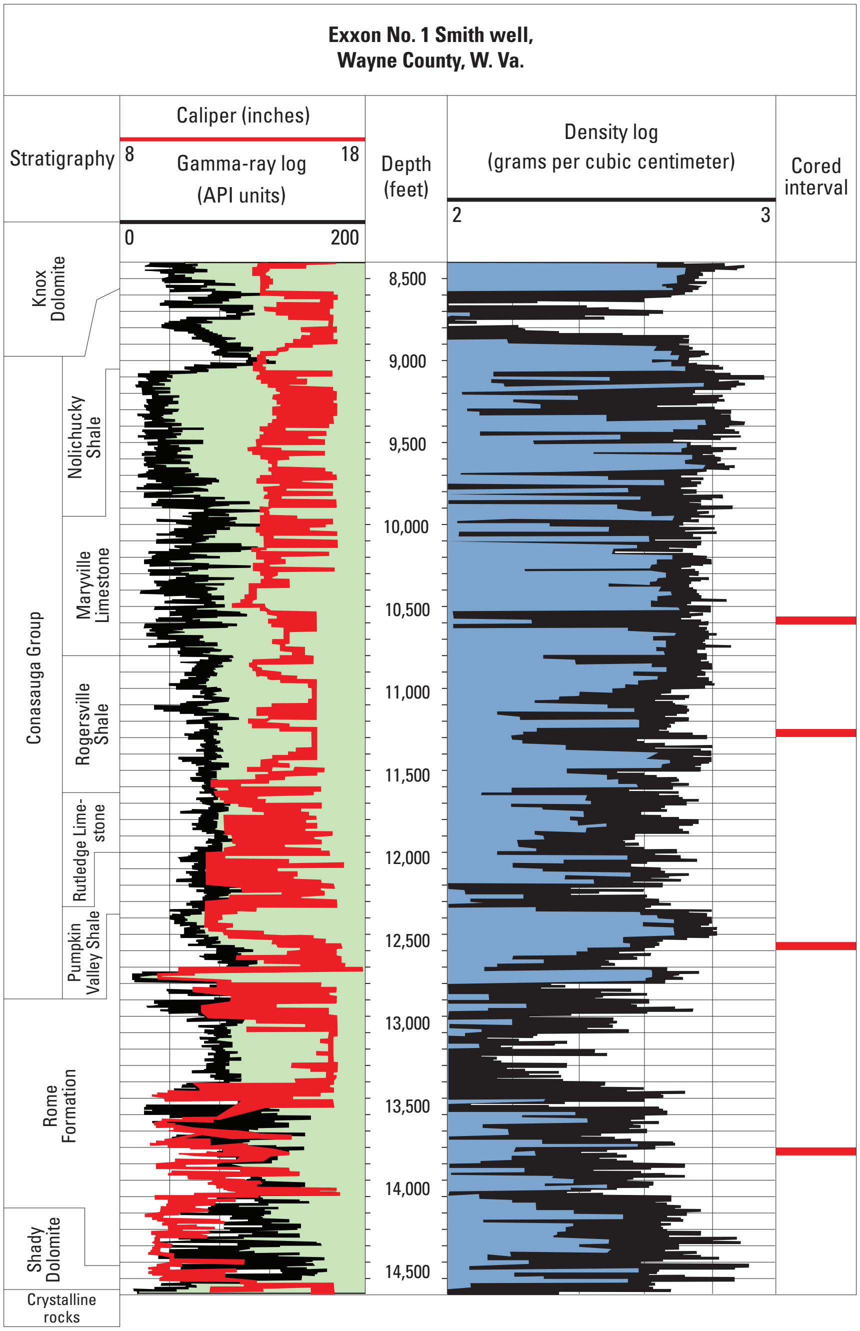


Figure 10. Diagram showing gamma-ray, caliper, and density logs from lower Paleozoic strata and the location of cored intervals in the Exxon No. 1 Smith well, Wayne County, W. Va. See figure 4 for the location of the well. API, American Petroleum Institute.

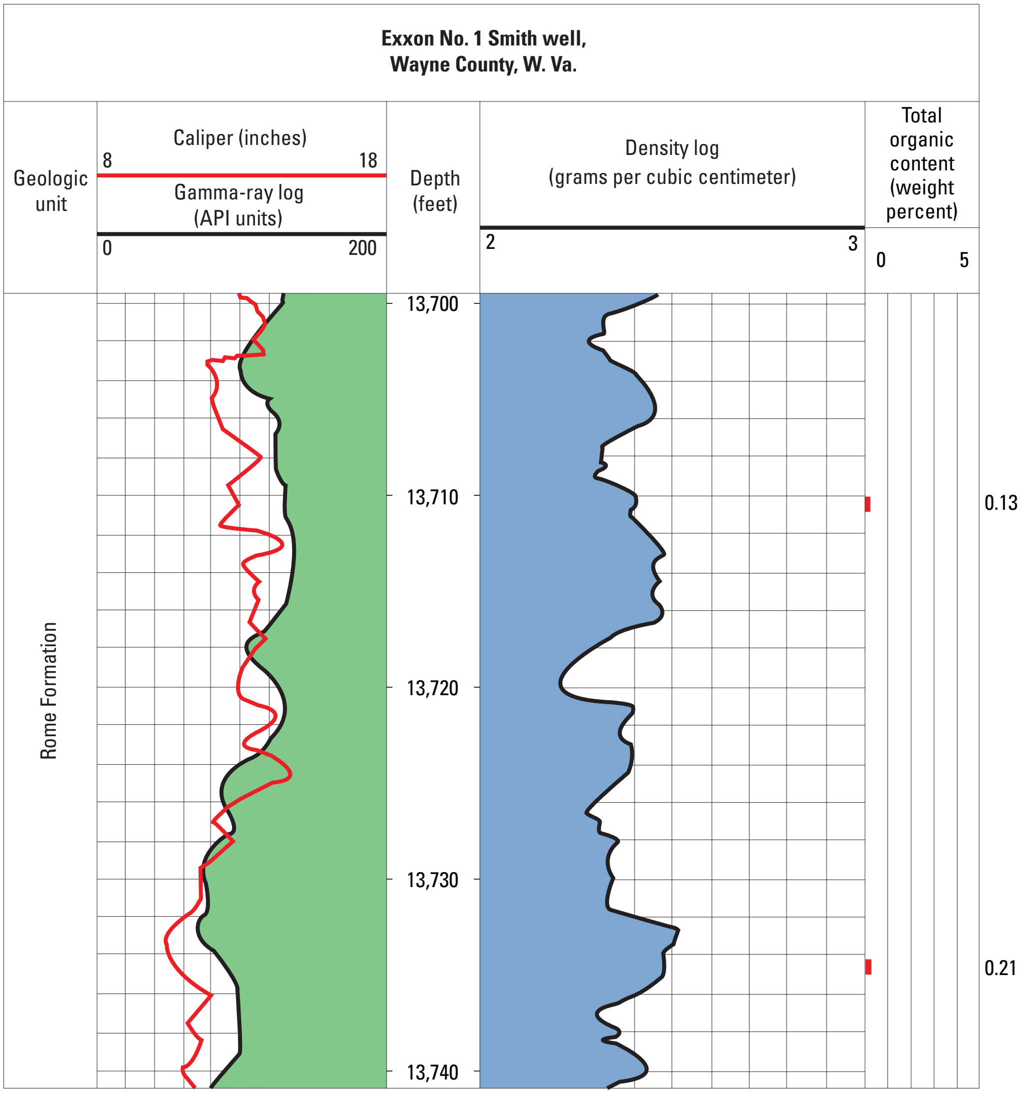


Figure 11. Diagram showing gamma-ray, caliper, and density logs and total organic carbon content (in weight percent) for two samples from the lower part of the Cambrian Rome Formation in the Exxon No. 1 Smith well, Wayne County, W. Va. See figure 4 for the location of the well.

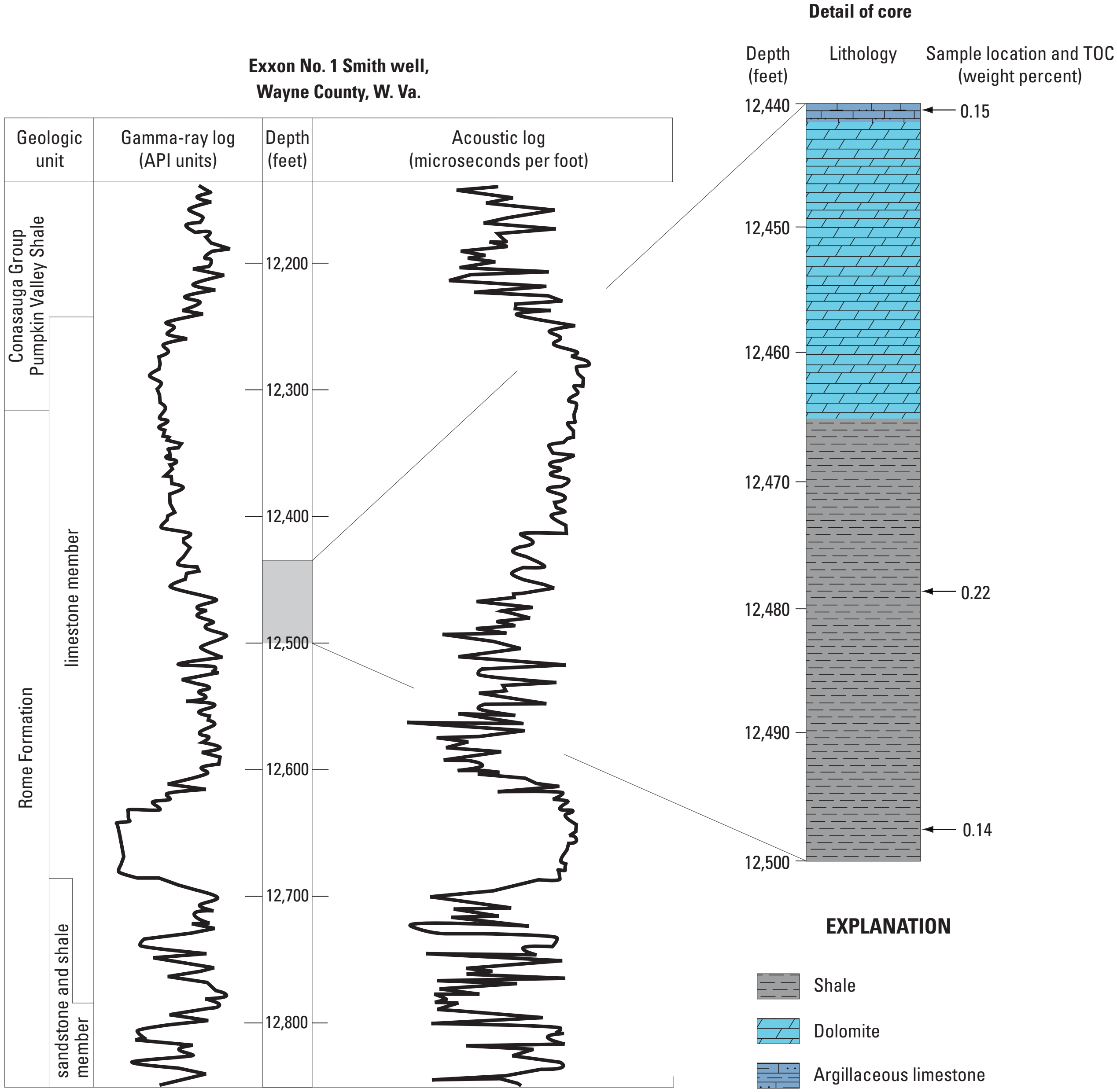


Figure 12. Diagram showing results of total organic carbon (TOC) analyses (in weight percent) for three samples from the upper part of the Cambrian Rome Formation in the Exxon No. 1 Smith well, Wayne County, W. Va. The core location is indicated by the shaded section of the depth column. See figure 4 for the location of the well. See Ryder (1992) and Ryder and others (1997) for a brief discussion of the unnamed limestone member of the Rome Formation and the Pumpkin Valley Shale of the Conasauga Group. API, American Petroleum Institute.

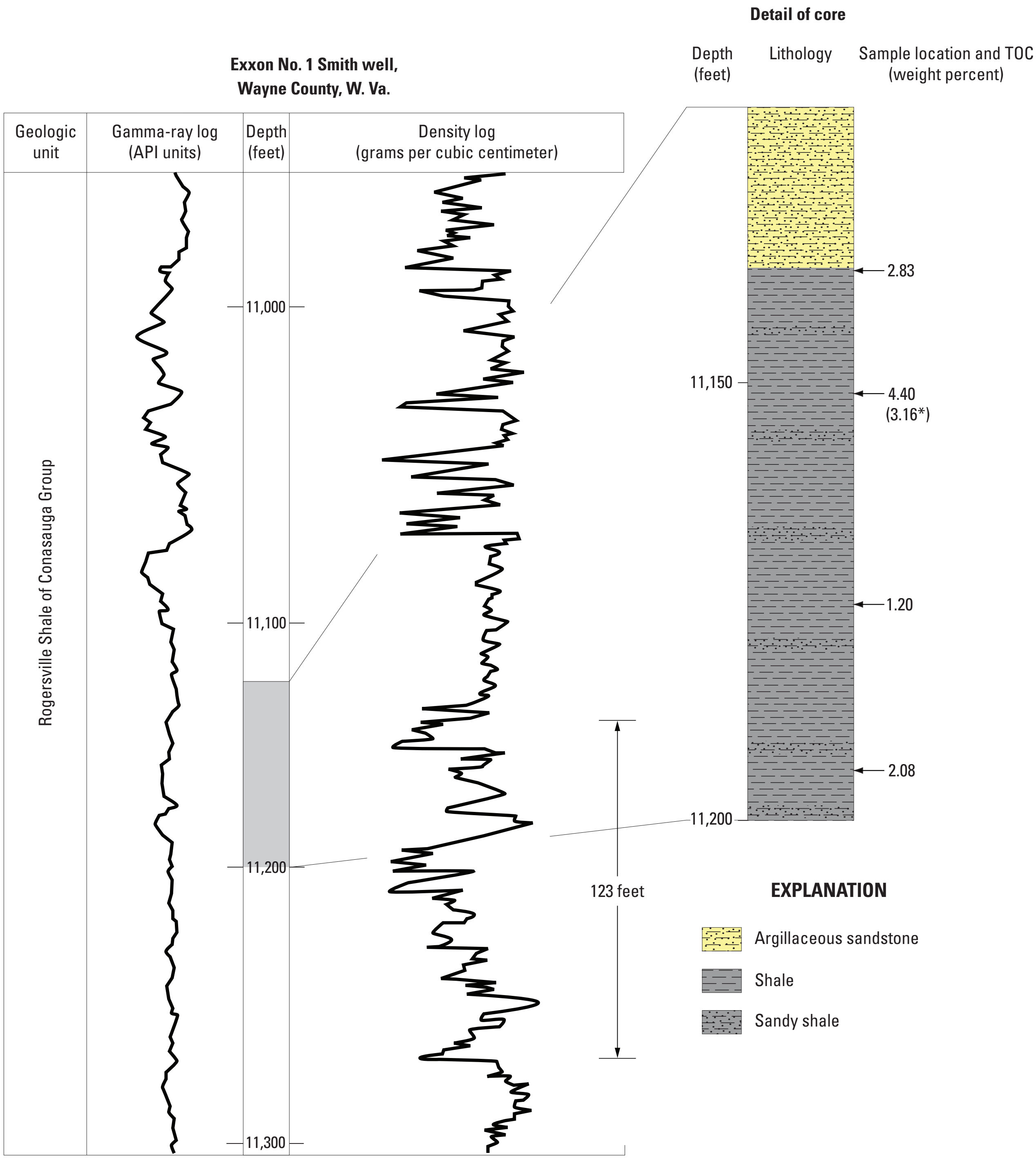


Figure 13. Diagram showing results of total organic carbon (TOC) analyses (in weight percent) for five samples from the Cambrian Rogersville Shale of the Conasauga Group in the Exxon No. 1 Smith well, Wayne County, W. Va. The core location is indicated by the shaded section of the depth column. See figure 4 for the location of the well. See Ryder (1992) and Ryder and others (1997) for a brief discussion of the Rogersville Shale of the Conasauga Group. Asterisk indicates the TOC value of the sample after bitumen extraction. API, American Petroleum Institute.

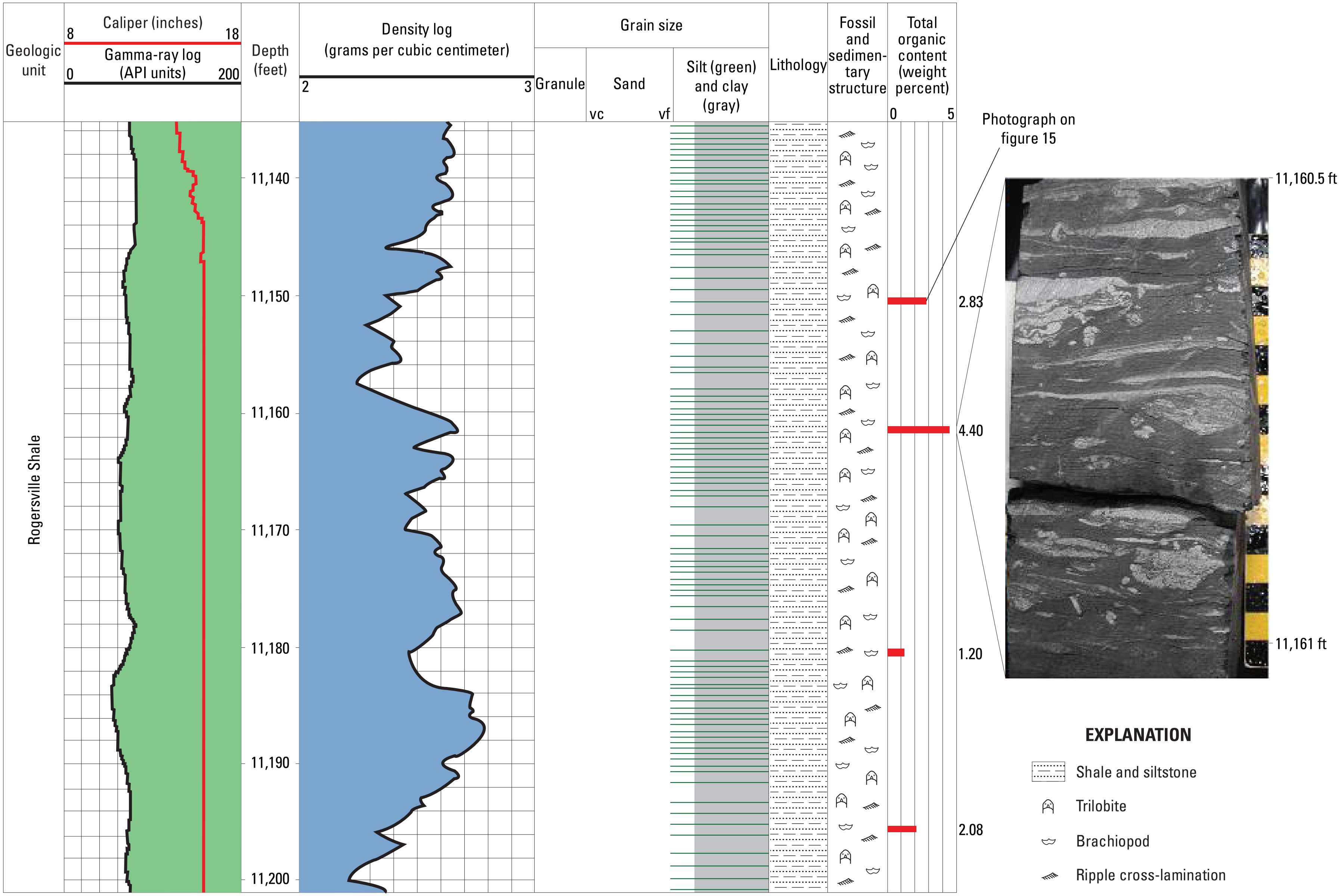


Figure 14. Diagram and photograph showing summary data for the cored interval of the Cambrian Rogersville Shale of the Conasauga Group in the Exxon No. 1 Smith well, Wayne County, W. Va. See figure 4 for the location of the well. The scale bar is in 1-centimeter (cm) increments. The cored section consists of dark-gray shale with thin (1 millimeter (mm) to 5 cm thick) siltstone and sandstone laminae and beds and calcite cement. Trilobite and lingulid brachiopods are common. The section is burrowed to bioturbated and displays flaser and ripple cross-lamination. Abbreviations are as follows: API, American Petroleum Institute; TOC, total organic carbon, in weight percent; vc, very coarse grained; vf, very fine grained.

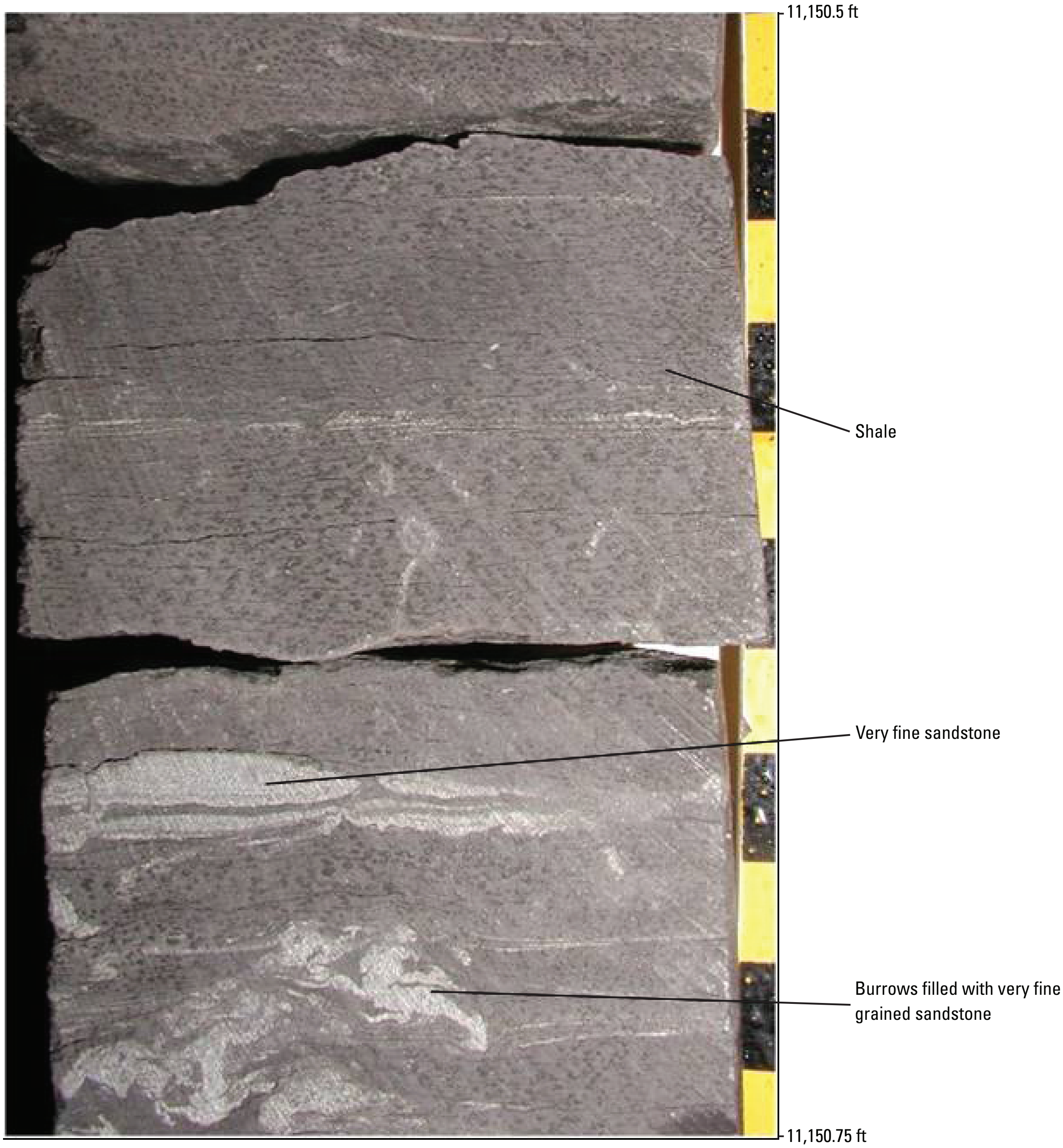


Figure 15. Photograph of a cored section of the Cambrian Rogersville Shale of the Conasauga Group at 11,150.5 ft in the Exxon No. 1 Smith well, Wayne County, W. Va. The scale bar is in 1-centimeter increments. See figure 4 for the location of the well. The cored interval shown in the photograph is located on figure 14.

The approximately 28 percent of extractable bitumen in the Rogersville Shale at 11,161.5 ft (based on the TOC decrease of 1.24 weight percent after extraction; table 1) could be the result of solid bitumen (with an extractable component) introduced into the siltstone and sandstone laminae and burrows from a different source rock. Moreover, the lithologic character of the Rogersville Shale in the core is inconsistent with known source rocks. Commonly, gray shale with siltstone and sandstone laminae and burrows have a TOC content of less than 0.5 weight percent. Despite these bothersome possibilities, we propose that the Rogersville Shale in the No. 1 Smith well is a credible source rock that was capable of generating petroleum in the Rome trough. The generation and introduction of solid bitumen from another source rock is discounted here because there is no visual evidence for it in the core, such as black, opaque coatings along laminae, pores, and burrows. We suggest that the high percentage of extractable bitumen in the Rogersville is a remnant of the original petroleum generated in place in the source rock. Although the lithologic character of the Rogersville is atypical for a petroleum source rock, it may represent a variety of poorly documented source rocks that are intermediate in organic richness.

Oil-Source Rock Correlations

A gas chromatogram of the bitumen extract (core depth=11,161.5 ft) is characterized by (1) a full spectrum of *n*-alkanes from *n*-C_{11} through *n*-C_{30} but with a reduced *n*-C_{20+} fraction, (2) a strong odd predominance of *n*-alkanes in the *n*-C_{13} through *n*-C_{19} range, and (3) very small amounts of pristane and phytane (fig. 16). These three characteristics are diagnostic of organic matter predominantly composed of the alga *Gloeocapsomorpha prisca*, whose age is commonly associated with Ordovician source rocks (Longman and Palmer, 1987; Jacobson and others, 1988). The character of this gas chromatogram presents compelling evidence that *G. prisca* or its precursor was living at least as early as Middle Cambrian time, approximately 50 million years before the appearance of the Ordovician organism. To our knowledge, the only other reported occurrence of *G. prisca* from Cambrian rocks is from a Middle Cambrian alginite in the Canadian Northwest Territories (Wielens and others, 1990).

We compared the geochemistry of the bitumen extract from the Rogersville Shale in the No. 1 Smith well, Wayne County, W. Va. (figs. 4, 8), with the geochemistry of oil produced from a Cambrian carbonate and sandstone reservoir in the No. 529 White well, Boyd County, Ky. (fig. 3). This well, which was drilled in the mid-1960s, yielded the first commercial oil production from Cambrian rocks in the Rome trough (McGuire, 1968; Weaver and McGuire, 1977). The No. 529 White well is located about 12 mi northwest and updip of the No. 1 Smith well (figs. 3, 4). Gas chromatograms for the bitumen extract from the Rogersville Shale in the No. 1 Smith well and for oil from the Cambrian reservoir in the No. 529 White well have a strong odd-carbon predominance in the *n*-C_{13} to *n*-C_{19} range and thus provide compelling evidence for a correlation between oil and source rock (fig. 17*A*, *B*). This evidence implies that the oil from the Cambrian reservoir in Boyd County, Ky., was derived from a source rock similar in composition to the Cambrian Rogersville Shale in Wayne County, W. Va. Additional compelling evidence for a link between Cambrian source rock and Cambrian oil is provided by the mud log for the No. 1 Smith well (fig. 18), which indicates excellent hydrocarbon shows above and below the Rogersville Shale cored section. On the basis of the mud log, we suggest that petroleum was generated from the Rogersville Shale source rock and migrated vertically into the 100-ft-thick overlying sandstone unit within the Rogersville. The cross section shown in figure 19 illustrates our interpretation that oil was generated in the Rogersville Shale in the vicinity of the No. 1 Smith well, migrated 15 to 20 miles (mi) updip along a sandstone carrier bed in the Rogersville, and was trapped in a structural feature that involved the Maryville Limestone near the No. 529 White well.

Geochemical characteristics representative of *G. prisca*-bearing oil were noted in other oils from the Cambrian Rome Formation in eastern Kentucky: (1) the Carson Associates No. 1 Kazee well in the Homer gas field, Elliott County, Ky. (fig. 3); (2) the Blue Ridge No. 1 Jewell Greene well, Elliott County, Ky. (Moldowan and Jacobson, 2000); and (3) the Miller No. 1 Bailey well, Wolfe County, Ky. Oil from the No. 1 Kazee well in the Homer gas field (fig. 20*C*) correlates most closely with the bitumen extract from the Rogersville Shale (Wayne County, W. Va.) (figs. 16, 17*A*) and oil from the Maryville Limestone (Boyd County, Ky.) (fig. 17*B*). Although condensate from the No. 1 Jewell Greene and No. 1 Bailey wells (fig. 20*A*, *B*) show a C_{20+} *n*-alkane distribution that is more attenuated than the oil from the No. 1 Kazee well in the Homer gas field (fig. 20*C*) the characteristic odd-predominance of *n*-alkanes in the *n*-C_{13} through *n*-C_{19} range is still present. All the oils or condensates shown in figure 20 very likely were generated from organic matter in the Rogersville Shale or from other compositionally similar shales in the Conasauga Group or Rome Formation. There is no evidence that Ordovician source rocks in eastern Kentucky and adjoining western West Virginia could have generated these oils.

At the western end of the Rome trough, a thin, dark-gray to black shale was sampled for this investigation from the Cambrian Rome Formation in the Texaco No. 1 Kirby well, Garrard County, Ky. (fig. 4). This well yielded shows of oil and low-heat-value gas (indicated by an average British thermal units (Btu) value of 227) from sandstone units in the Rome Formation (Harris and Baranoski, 1996). The TOC values of the shale ranged from 0.70 to 3.26 weight percent (fig. 21). A photograph of the core (fig. 22) shows that the shale is less than 1 inch thick and is associated with burrowed sandstone and conglomeratic sandstone. The moderate

Text continued on page 26.

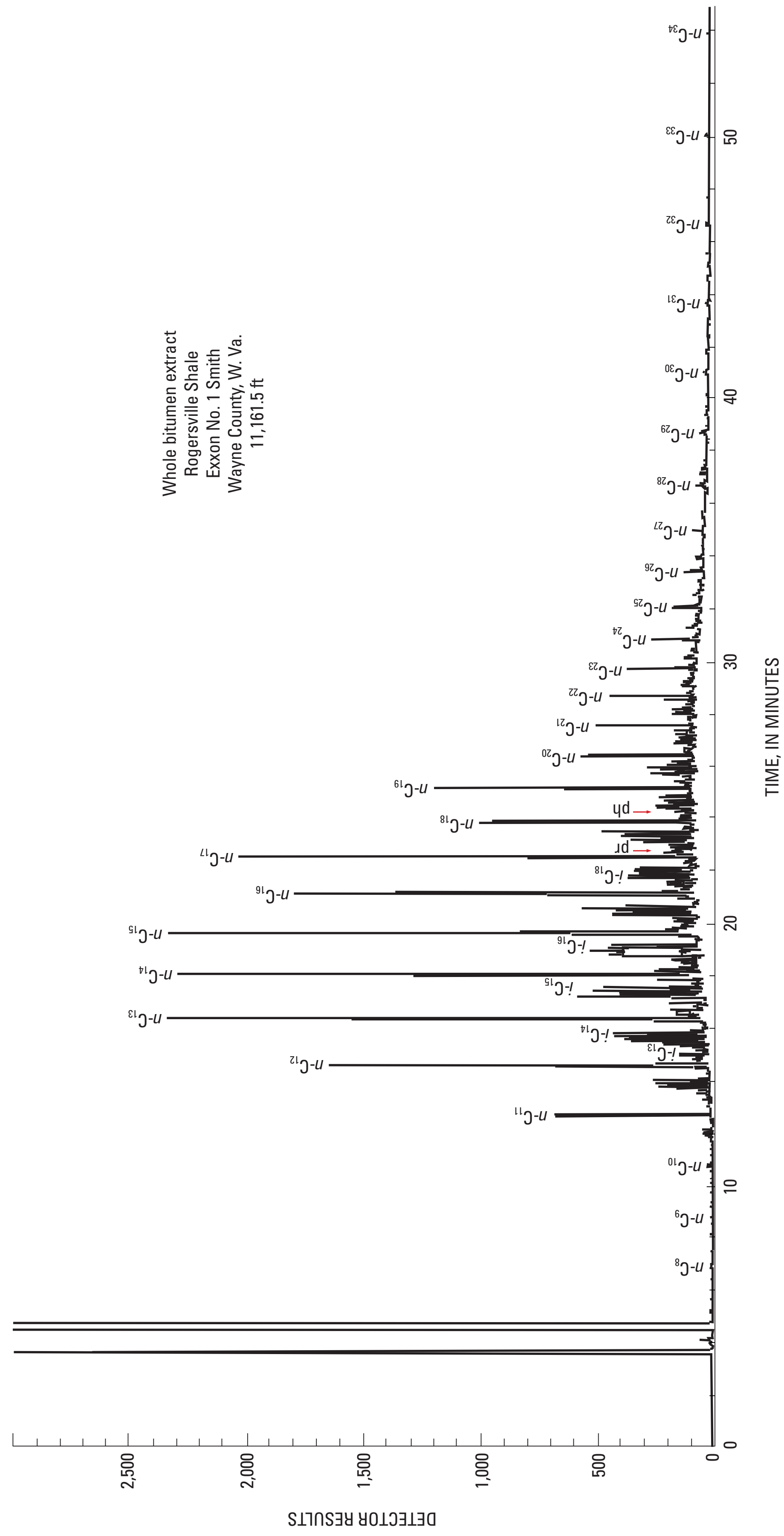


Figure 16. Gas chromatogram of a whole bitumen extract from the Cambrian Rogersville Shale of the Conasauga Group at 11,161.5 feet in the Exxon No. 1 Smith well, Wayne County, W. Va. The *n*-alkanes and the isoprenoids (for example, *i*-C_{18}), including pristane (pr) and phytane (ph), are identified. See figure 4 for the location of the well.

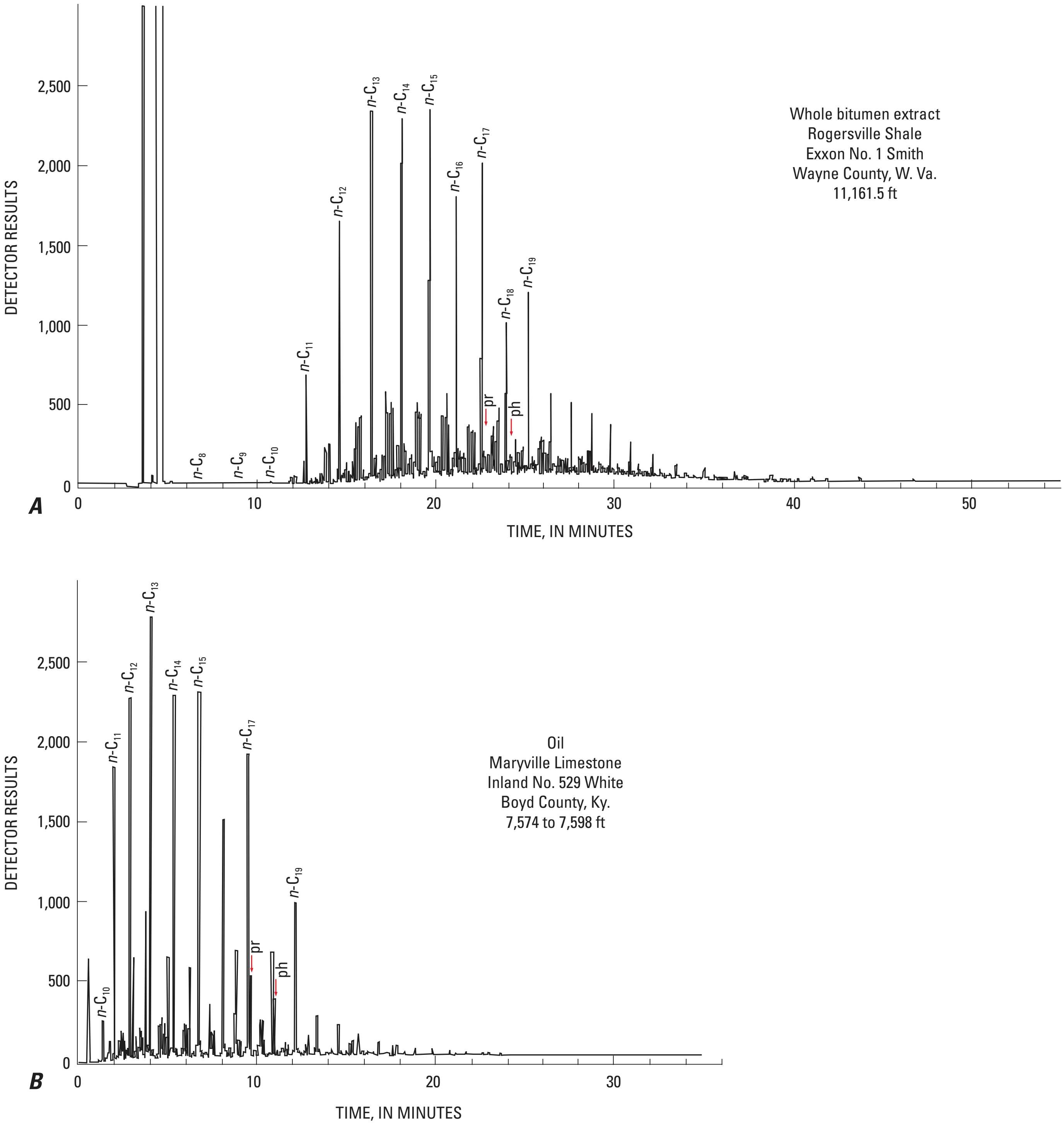


Figure 17. Gas chromatograms showing the oil-source rock correlation. *A*, Whole bitumen extract from the Rogersville Shale at 11,161.5 feet (ft) in the Exxon No. 1 Smith well, Wayne County, W. Va. *B*, Oil from the Maryville Limestone at 7,574 to 7,598 ft in the Inland No. 529 White well, Boyd County, Ky. The *n*-alkanes and the isoprenoids, including pristane (pr) and phytane (ph), are identified. Note the strong odd-carbon predominance in the n-C$_{13}$ to n-C$_{19}$ range in both gas chromatograms. See figure 4 for the location of the well. Oil data provided by Richard W. Beardsley (Triana Energy, written commun., December 1995).

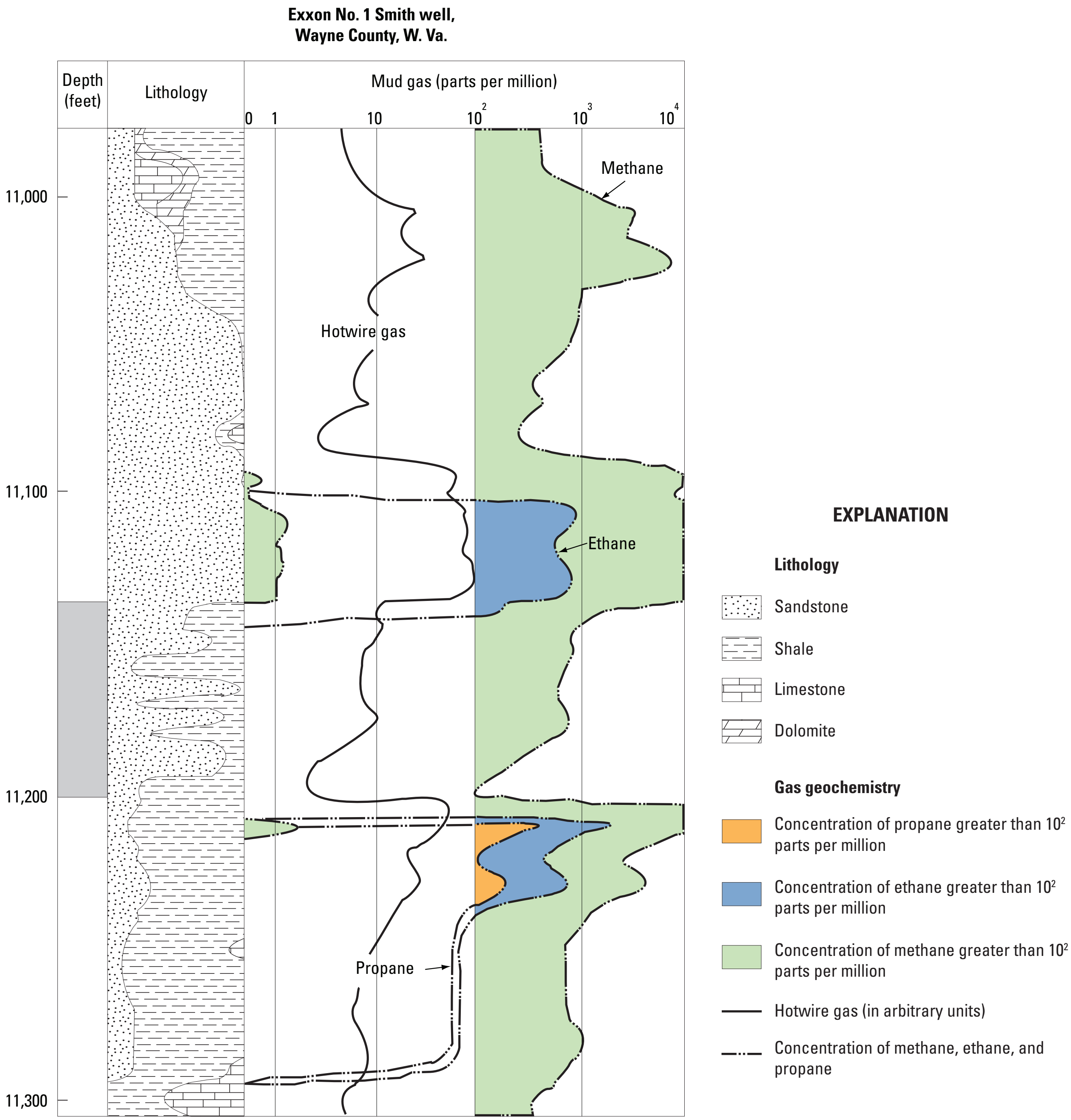


Figure 18. Mud log of part of the Conasauga Group interval showing a high gas concentration directly above and below the cored part of the Rogersville Shale in the Exxon No. 1 Smith well, Wayne County, W. Va. The core location is indicated by the shaded area in the depth column. See figure 4 for the location of the well. Hotwire gas is the initial concentration of gas detected in the drilling fluid (mud) by a heated platinum filament that forms one arm of a wheatstone bridge circuit. The drilling fluid (mud) is further analyzed by a gas chromatograph to determine the concentration of individual gases (methane, ethane, and propane) in parts per million. The high gas content in the mud log, above and below the cored section in the Rogersville Shale, suggests (1) that the gas was derived from the adjoining Rogersville Shale and (2) that the Rogersville Shale at this locality is a viable source rock for oil and gas.

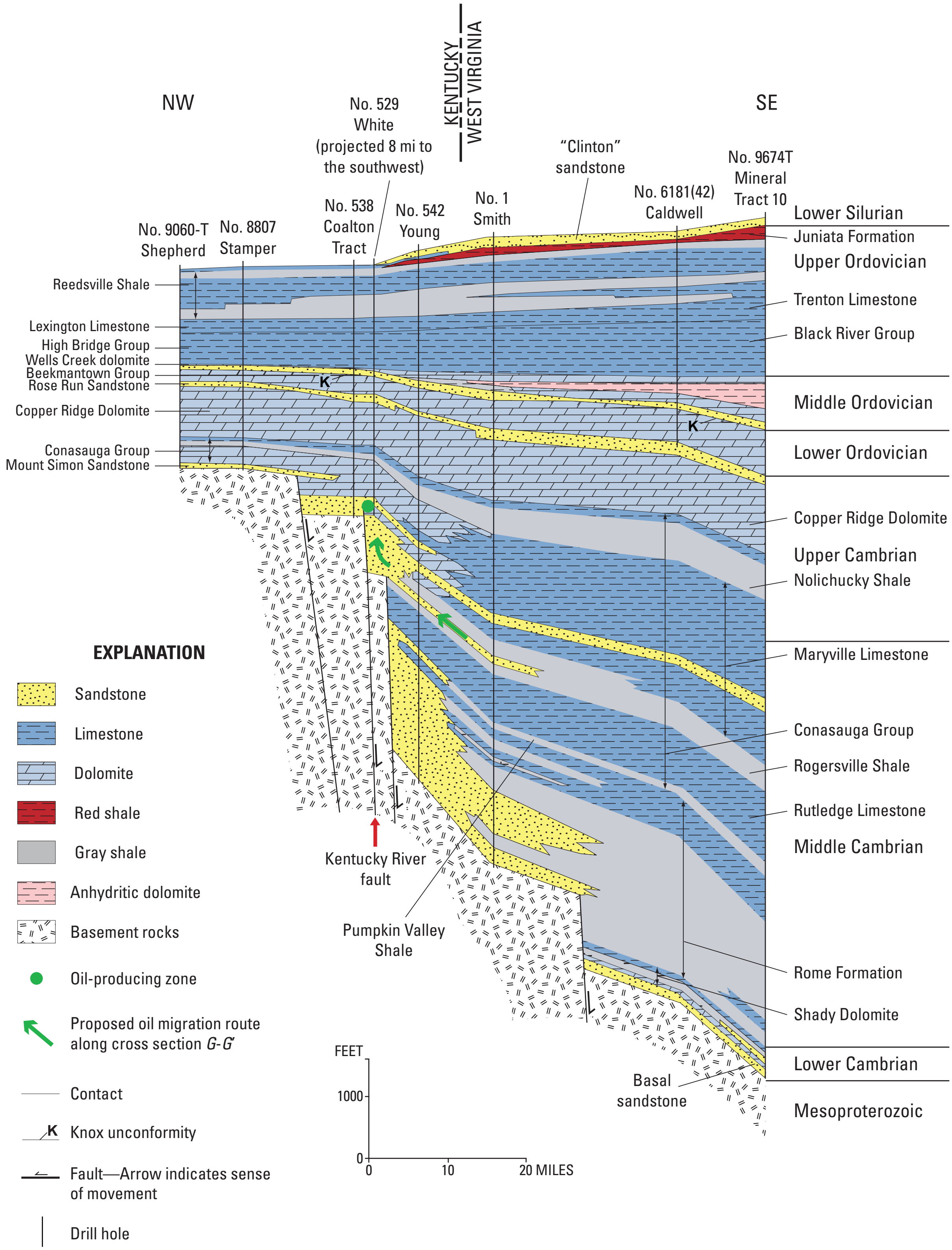


Figure 19. Part of cross section *G–G′* through the northern margin of the Rome trough. The cross section shows the proposed oil migration route from the Rogersville Shale source rock in the Exxon No.1 Smith well, Wayne County, W. Va., to the Maryville Limestone reservoir in the Inland No. 529 White well, Boyd County, Ky. This cross section is modified from Ryder and others (1997). See figures 3 and 4 for the location of the wells and the line of section and see figure 8 for a complete version of cross section *G–G′*. Lithologic data from Geologic Sample Log Company, Pittsburgh, Pa.

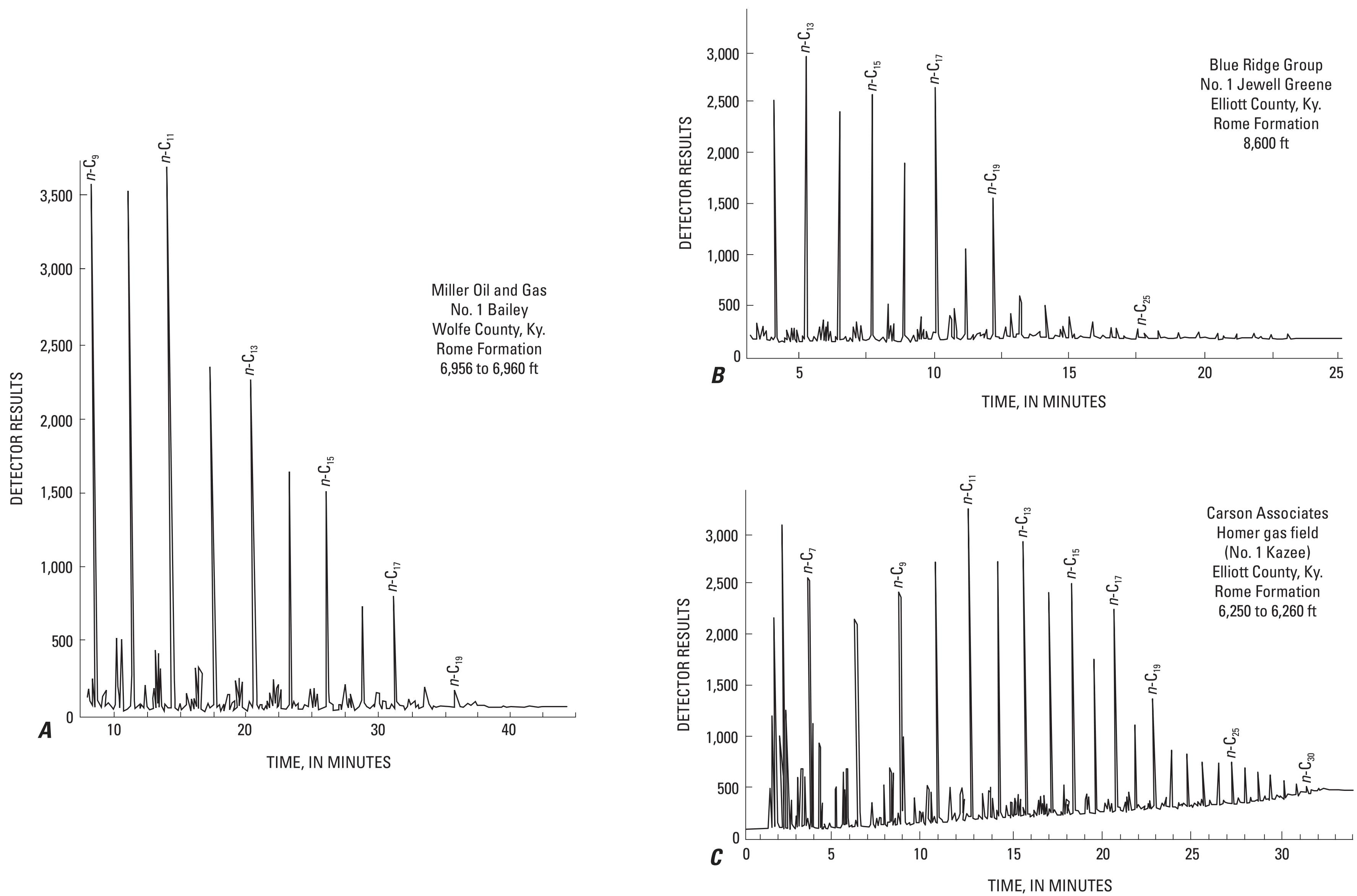


Figure 20. Gas chromatograms from selected oils or condensates in Cambrian reservoirs in eastern Kentucky wells. *A*, Miller Oil and Gas No. 1 Bailey well, Wolfe County, Ky., from 6,956 to 6,960 feet (ft). *B*, Blue Ridge Group No. 1 Jewell Greene well, Elliott County, Ky., at 8,600 ft (Moldowan and Jacobson, 2000). *C*, Homer gas field, Carson Associates No. 1 Kazee well, Elliott County, Ky., from 6,250 to 6,260 ft. The gas chromatograms for the No. 1 Bailey and No. 1 Kazee oils or condensates are whole-oil gas chromatograms. The type of gas chromatogram for the No. 1 Jewell Greene oil or condensate is unspecified. The *n*-alkanes are identified. See figure 3 for the location of the No. 1 Bailey well, the No. 1 Jewell Greene well, and the No. 1 Kazee well in the Homer gas field.

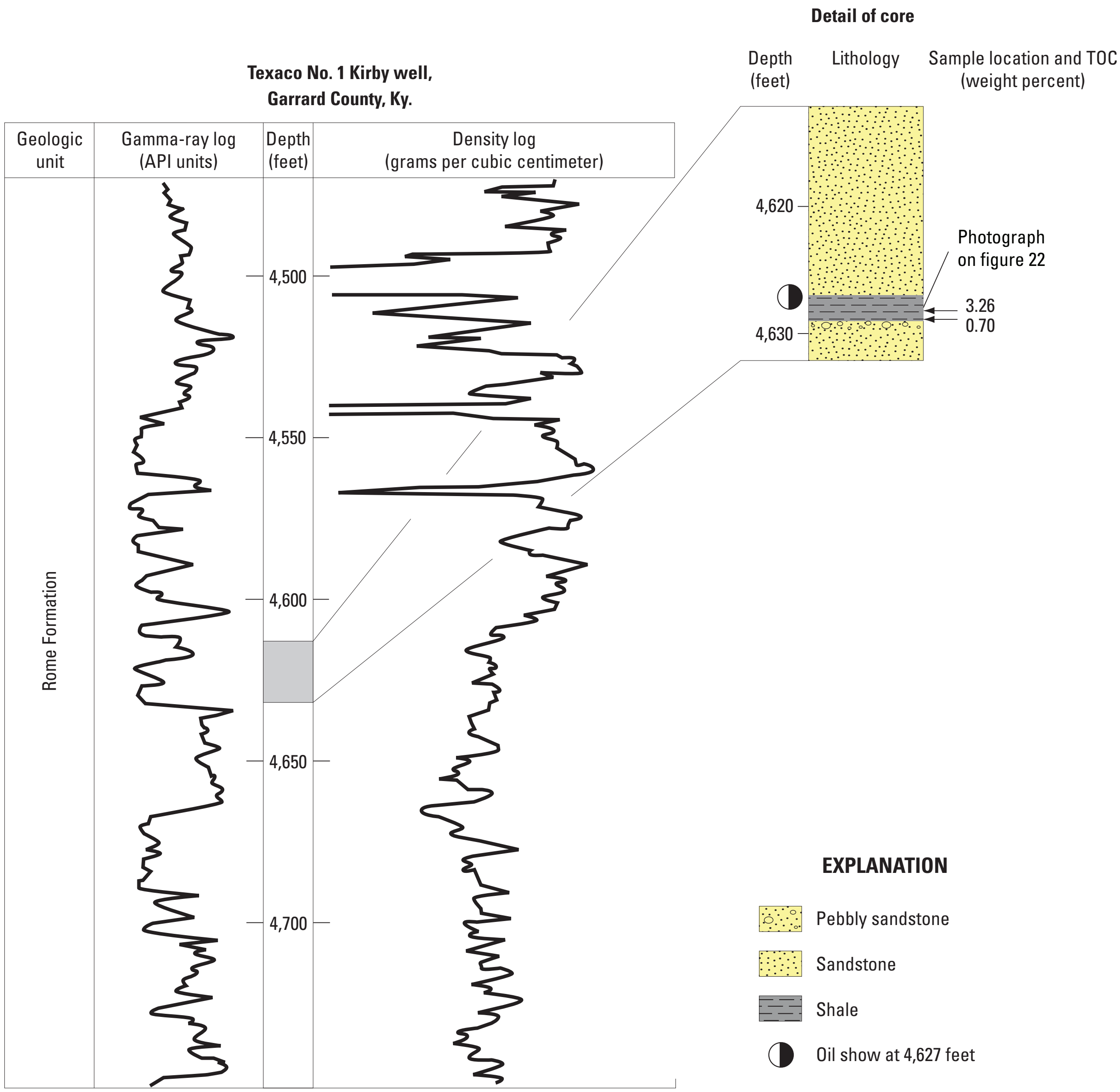


Figure 21. Diagram showing results of total organic carbon (TOC) analyses (in weight percent) for two samples from the Cambrian Rome Formation in the Texaco No. 1 Kirby well, Garrard County, Ky. The core location is indicated by the shaded section of the depth column. See figures 3 and 4 for the location of the wells. API, American Petroleum Institute.

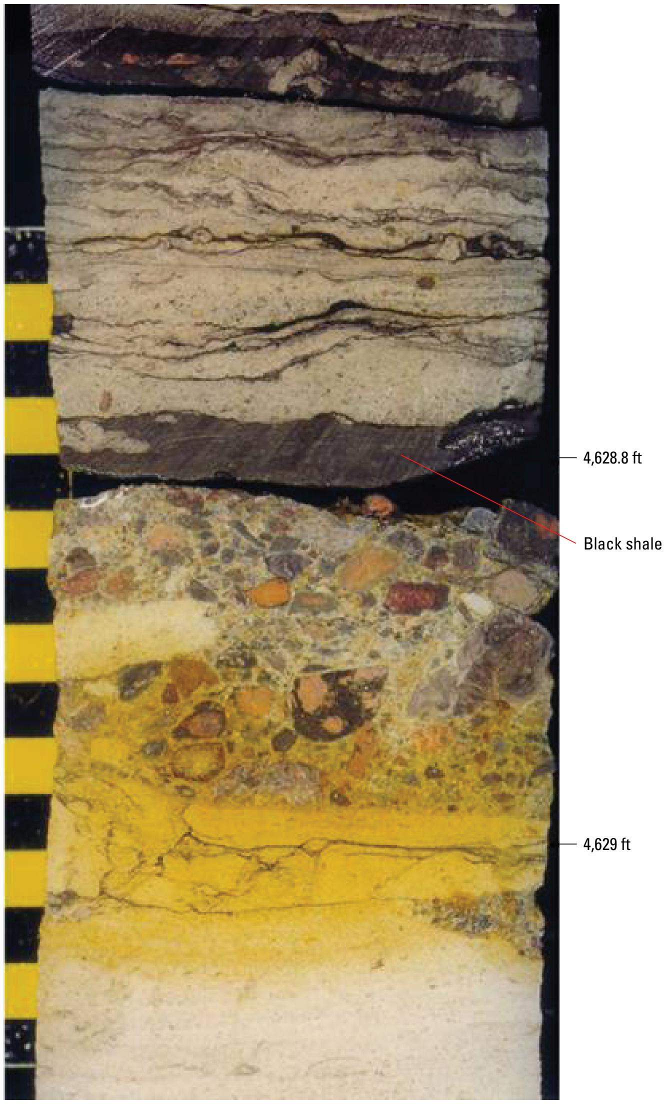


Figure 22. Photograph of a cored section of black shale in the Cambrian Rome Formation in the Texaco No. 1 Kirby well at 4,628.8 feet, Garrard County, Ky. The scale bar is in 1-centimeter increments. See figures 3 and 4 for the location of the well. The cored interval shown in the photograph is located on figure 21.

Rock-Eval S_1 yield for the Rome Formation shale samples, ranging from 0.30 to 0.55 mgHC/g org C (table 1), was sufficiently high for a bitumen extraction. The gas chromatography signature that characterizes this bitumen extract (fig. 23*B*, core depth=4,628.8 ft) is very similar (strong odd-carbon number dominance) to the one obtained from the Rogersville Shale (fig. 23*A*) and, thus, further corroborates the presence of the alga *G. prisca* or a predecessor in Cambrian rocks of the Rome trough. On the basis of sparse hydrogen index and oxygen index data from Rock-Eval analyses (fig. 24), the kerogen in the Rome shales probably can be characterized as type I (Tissot and Welte, 1984); because of its relatively high thermal maturity, however, kerogen in the Rogersville Shale plots near the origin of the plot showing oxygen index versus hydrogen index, which indicates that the original kerogen type is indeterminate (fig. 24). The marine origin implies that the original kerogen in the Rogersville Shale was most likely type II (Tissot and Welte, 1984). Although this thin shale in the No. 1 Kirby well has a moderately high total organic carbon content, it probably is only a local source rock. The presence of this thin shale, however, indicates that organic material accumulated in the Rome Formation and suggests the possibility that thicker accumulations of organic matter may exist in the Rome Formation elsewhere in the Rome trough.

Results and Discussion

On the basis of these new TOC and Rock-Eval analyses and initial oil-source rock correlations, we are able to identify a new petroleum system in the Appalachian basin. Shale units rich in organic matter in the Middle and Upper Cambrian Conasauga Group are the source rocks in the petroleum system and very likely account for known oil and gas accumulations trapped in sandstone reservoirs in the Cambrian Rome Formation and Conasauga Group (fig. 25). Source rocks in the Rome Formation are considered to be local. In eastern and central Kentucky and western West Virginia, oil and gas in the Cambrian Copper Ridge Dolomite and the Ordovician Beekmantown Dolomite, St. Peter Sandstone, High Bridge Group, and Lexington Limestone also may belong to this petroleum system because they migrated vertically along fractures from Conasauga Group source rocks (fig. 25). This petroleum system probably extends into West Virginia and perhaps into Pennsylvania where there are potential gas-bearing reservoirs in the Conasauga Group and equivalent units (fig. 25). Also in West Virginia and Pennsylvania, the possibility exists that some gas in deep Upper Cambrian, Ordovician, and Silurian reservoirs (assigned to the Utica-Lower Paleozoic Total Petroleum System) may be mixed with gas that has leaked upsection from the underlying Conasauga-Rome/Conasauga Total Petroleum System.

Preliminary burial and temperature history models for the No. 1 Smith (figs. 4, 8) and the No. 1 Gainer-Lee (fig. 5) wells suggest that oil generated from Middle Cambrian rocks in the central and southern West Virginia parts of the Rome trough was migrating actively no later than Late Silurian to Early Devonian time (figs. 26, 27). These models further suggest that gas generated from Middle Cambrian rocks in central West Virginia was migrating actively by the Early Carboniferous (fig. 27) and that gas generated from Middle Cambrian rocks in southern West Virginia was migrating actively in the early Mesozoic (fig. 26). The predicted Late Devonian timing of gas generation and Early Carboniferous active migration in central West Virginia resulted from the abrupt thickening of the Upper Devonian overburden that formed during Catskill delta sedimentation (fig. 27), whereas the predicted Late Permian timing of gas generation and early Mesozoic active migration in southern West Virginia resulted from an incremental burial history with fewer periods of abrupt overburden

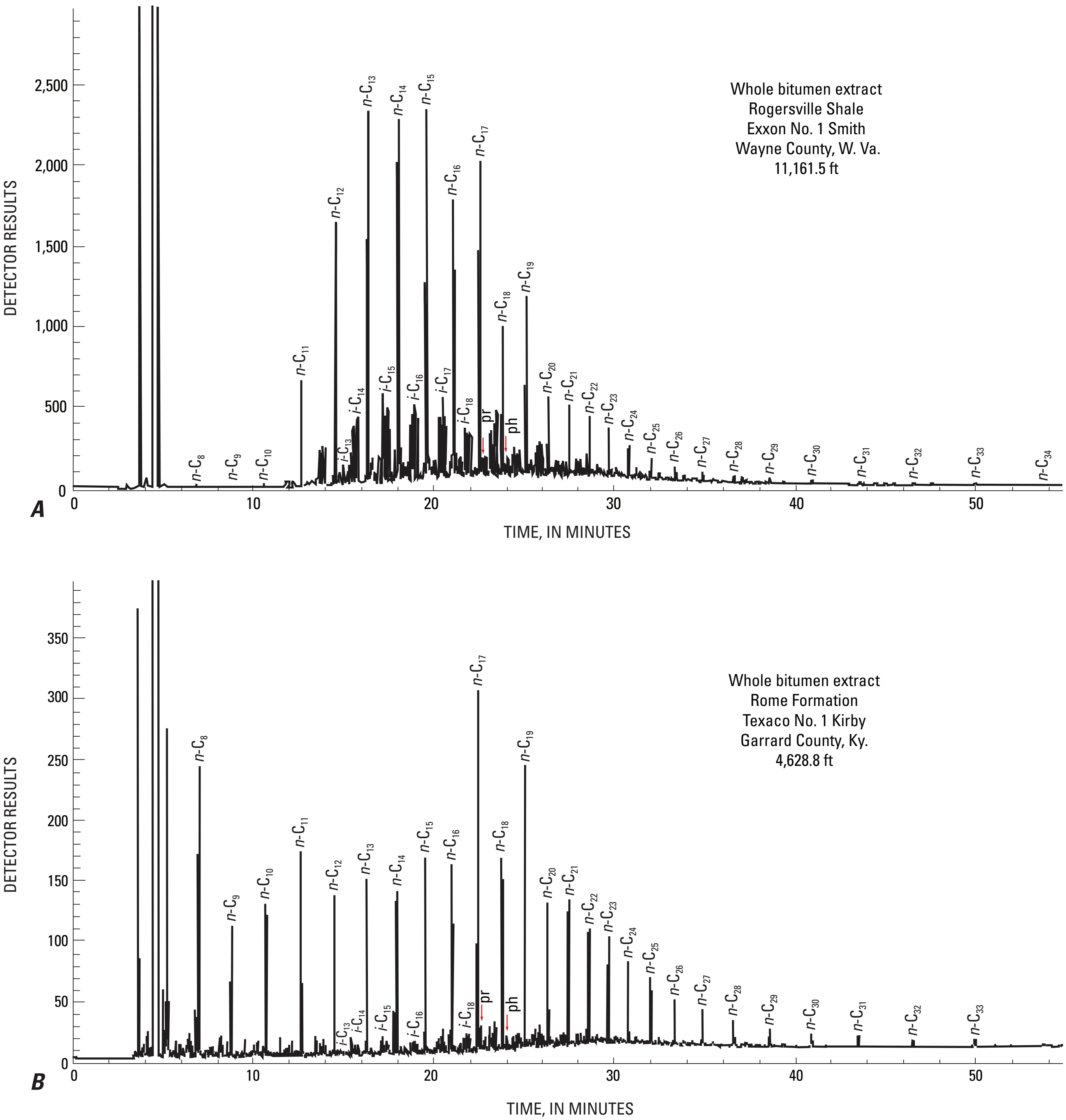


Figure 23. Gas chromatograms of whole bitumen extracts. *A*, From the Rogersville Shale in the Exxon No. 1 Smith well, Wayne County, W. Va. *B*, From the Rome Formation in the Texaco No. 1 Kirby well, Garrard County, Ky. The *n*-alkanes and the isoprenoids (for example, *i*-C_{18}), including pristane (pr) and phytane (ph), are identified. See figure 4 for the location of the wells.

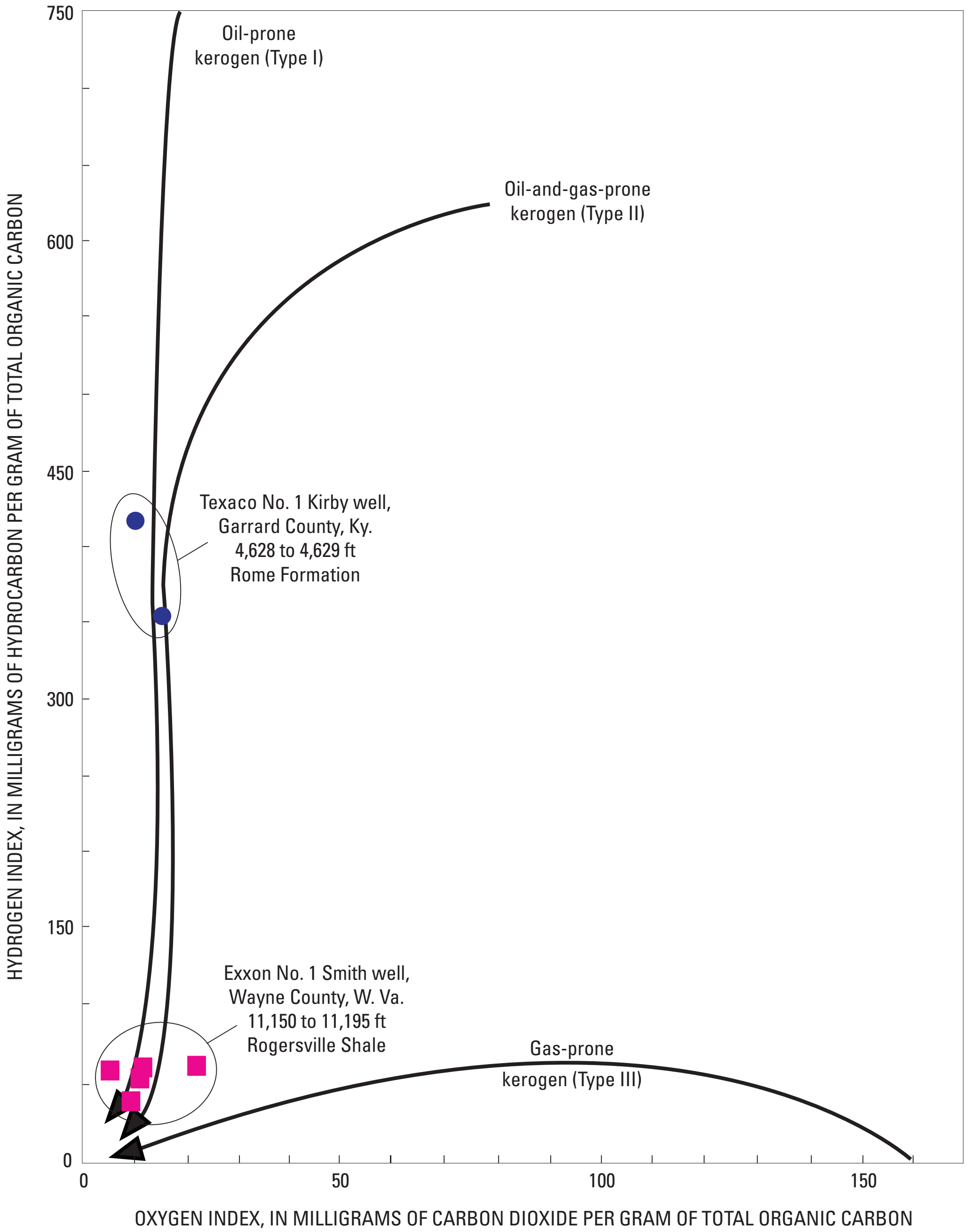


Figure 24. Modified Van Krevelen diagram showing oxygen index versus hydrogen index and thermal maturation pathways for kerogen types I, II, and III (Espitalié and others, 1977). Samples of Cambrian source rocks in the Rome trough are plotted. See figure 4 for the location of the wells. The kerogen in the Rome Formation with high hydrogen index values is probably type I, whereas the kerogen in the Rogersville Shale with very low hydrogen index values (because of their moderately high level of thermally maturity) cannot be characterized by kerogen type.

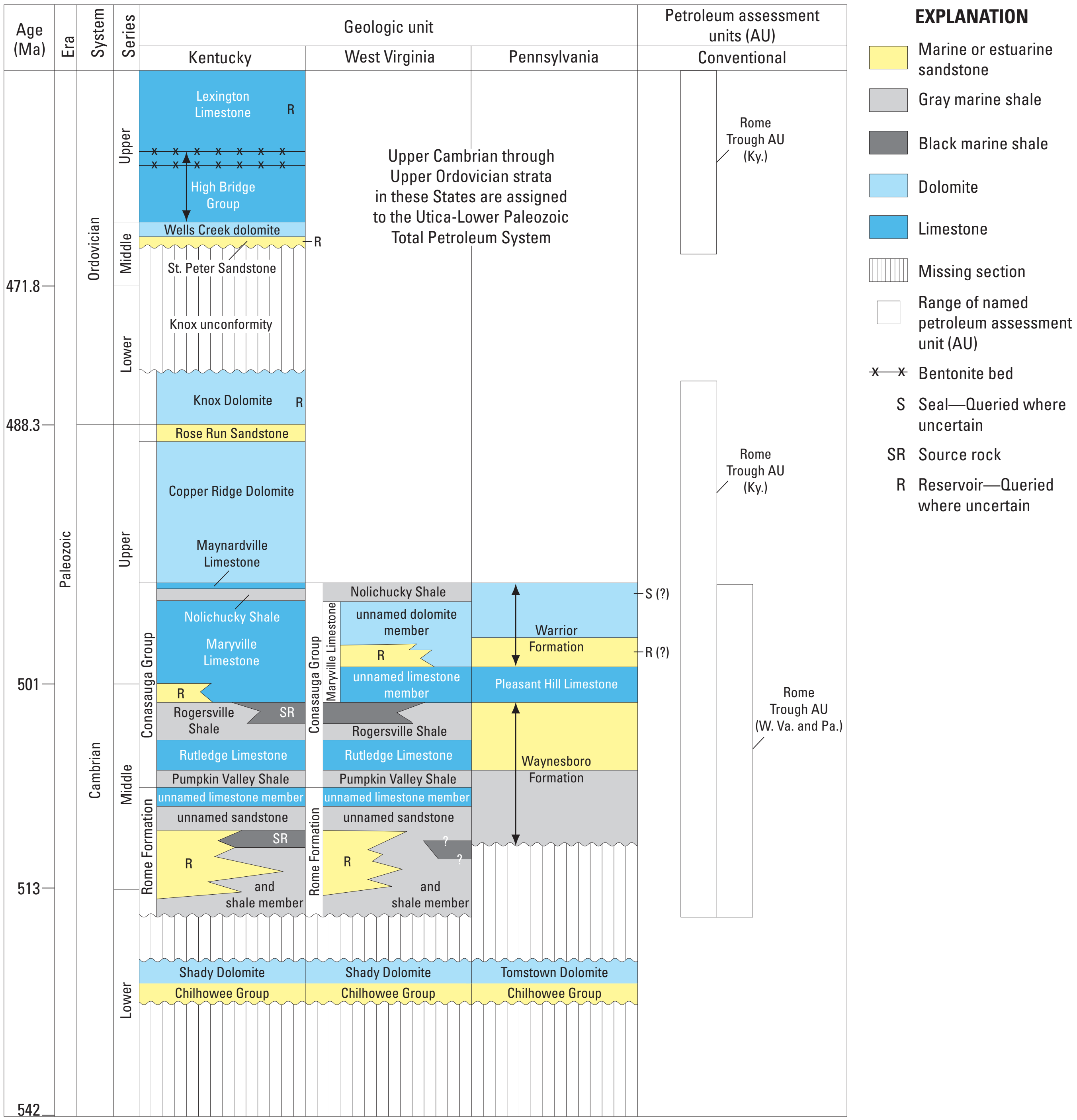


Figure 25. Correlation chart showing the stratigraphic units of the Conasauga-Rome/Conasauga Total Petroleum System and source rocks, reservoirs, and seal. The stratigraphic units shown on the correlation chart are used in Ryder and others (1997) and in Ryder, Swezey, Milici, and others (2008). Ma, millions of years.

thickening (fig. 26). The timing of oil and gas generation and migration in the Rome trough of Kentucky probably is very similar to the timing in southern West Virginia.

The events chart (fig. 28) shows the presence (or absence) of key elements in the petroleum system such as source rocks, reservoirs, seals, traps, and a favorable timing of petroleum generation and trap formation (Magoon and Dow, 1994). The events chart indicates that the Conasauga-Rome/Conasauga Total Petroleum System contains all the key elements of a viable petroleum system.

Although the Rome trough has known petroleum source rocks and known oil and gas accumulations, much uncertainty remains. Unanswered questions include the following:

1. What is the thickness and extent of the Cambrian source rocks? Are they widespread throughout the Rome trough or only locally distributed?

2. What is the nature of the available traps during optimum petroleum migration? Are structural traps most important or are stratigraphic traps also important?

3. What kinds of reservoirs exist in the deepest parts of the Rome trough? Are there sandstones with intergranular porosity? Are there carbonates with intercrystalline or vuggy porosity? Do open fractures exist in these potential reservoirs?

4. What is the extent and integrity of the seals? Are they leaky or tight? They had to have held petroleum for about 300 million years, possibly under fluid pressure that was greater than hydrostatic.

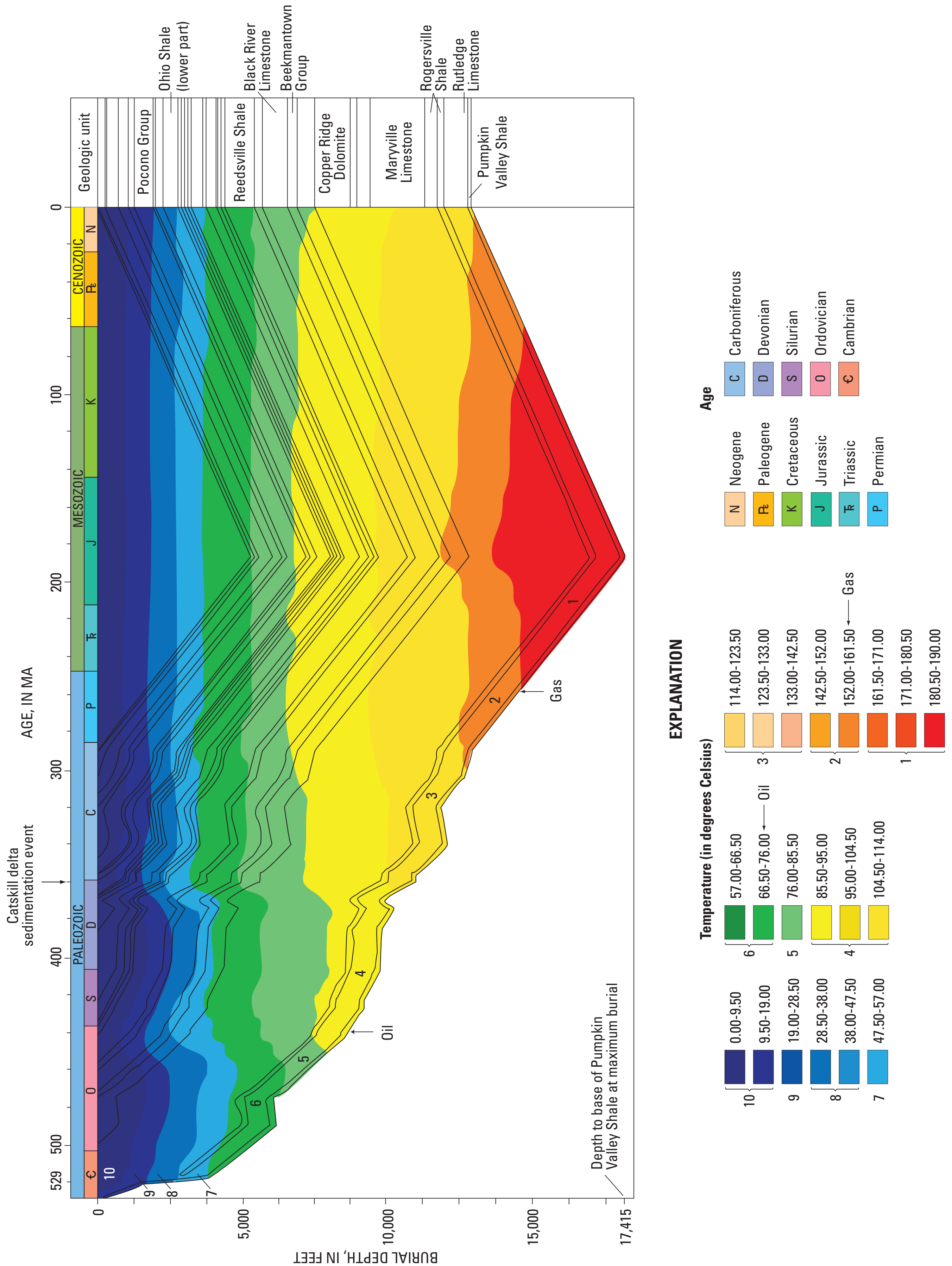
5. To what degree have gases generated from Cambrian source rocks in the Rome trough mixed with gases generated from the Ordovician Utica Shale? If a high degree of mixing is suspected, what geochemical characteristics might best diagnose such an occurrence?

6. What additional geochemical studies are needed to further understand the correlation between oils and source rocks reported here?

Conclusions

A 123-ft-thick section of Cambrian marine, dark-gray shale from a core between 11,150 and 11,195 ft in the No. 1 Smith well in Wayne County, W. Va., has good to very good source rock potential (as defined by Peters and Cassa, 1994) that, when combined with favorable oil-source rock correlations, demonstrates the presence of a new petroleum system in the Rome trough. This dark-gray shale occurs in the Middle Cambrian Rogersville Shale of the Conasauga Group. Total organic carbon (TOC) contents of four samples that range from 1.2 to 4.4 weight percent (average 2.6 weight percent), are the highest reported to date in the pre-Knox section of the Rome trough. The samples are in the thermal maturity zone of late oil to early gas generation based on T_{max} values of about 465°C. The S_1 values of 0.81 to 2.71 indicate that the four samples from the Rogersville contain free extractable hydrocarbons. The gas chromatogram of a whole bitumen extract is characterized by *n*-alkanes from *n*-C_{11} through *n*-C_{30}, strong odd-carbon predominance in the *n*-C_{13} to *n*-C_{19} range, and small amounts of pristane and phytane. The strong odd-carbon predominance is diagnostic of organic matter composed of the alga *G. prisca*, whose age is usually restricted to the Ordovician. These *G. prisca* characteristics have not been previously identified in Cambrian source rocks in the Appalachian basin. Thin, black shale in the Lower to Middle Cambrian Rome Formation in the No. 1 Kirby well in Garrard County, Ky. (which has a TOC content as high as 3.2 weight percent, a hydrogen index as high as 417, and gas chromatogram signatures for an extract that are similar to those of the Rogersville Shale), may be a secondary source rock interval in the petroleum system. The gas chromatogram signatures of the bitumen extract from the Rogersville Shale correlate closely with those for oils and condensates from Cambrian reservoirs in eastern Kentucky. These oils and condensates are from the No. 1 Kazee well in the Homer gas field in Elliott County, Ky., the No. 529 White well in Boyd County, Ky., and the No. 1 Bailey well in Wolfe County, Ky. The new petroleum system, named the Conasauga-Conasauga/Rome Total Petroleum System by Milici, Ryder, Swezey, and others (2003) probably extends along the Rome trough from eastern Kentucky to at least central West Virginia.

Figure 26 (facing page). Burial and temperature history model for the Exxon No. 1 Smith well, Wayne County, W. Va. See figure 4 for the location of the well. The timing of oil and gas generation at this locality is shown by vertical arrows. For example, oil generation occurred in the Late Ordovician to Early Silurian, whereas gas generation occurred in the Late Permian. Moreover, active oil and gas migration at this locality is interpreted to have occurred approximately 15 to 20 million years after generation. Using this criterion, oil was migrating actively in the Late Silurian, whereas gas was migrating actively in the early Mesozoic. Estimated temperatures of oil and gas generation at this locality are shown by horizontal arrows. For example, oil was generated between the temperatures of 95.00°C and 104.50°C, whereas gas was generated between the temperatures of 152.00°C and 161.50°C. The modeled temperatures (shown by 10 colors in the model) at this locality represent a range of temperatures (shown by 20 colors in the figure explanation). For example, the area of light yellowish green in the model in this figure actually represents the three ranges of temperatures shown by yellow and light green and grouped as category 4 in the figure explanation. The paleogeothermal gradient predicted by the model is approximately 30°C/kilometer (km). The geologic time scale used in the model differs slightly from the time scale used in figures 1 and 25. Abbreviations for age symbols are as follows: Ꞓ, Cambrian; O, Ordovician; S, Silurian; D, Devonian; C, Carboniferous; P, Permian; T̵R, Triassic; J, Jurassic; K, Cretaceous; P̵e, Paleogene; N, Neogene.


Catskill delta sedimentation event
AGE, IN MA
BURIAL DEPTH, IN FEET
Geologic unit
Pocono Group
Ohio Shale (lower part)
Reedsville Shale
Black River Limestone
Beekmantown Group
Copper Ridge Dolomite
Maryville Limestone
Rogersville Shale
Rutledge Limestone
Pumpkin Valley Shale
CENOZOIC
MESOZOIC
PALEOZOIC
Oil
Gas
Depth to base of Pumpkin Valley Shale at maximum burial
EXPLANATION
Temperature (in degrees Celsius)
0.00-9.50
9.50-19.00
19.00-28.50
28.50-38.00
38.00-47.50
47.50-57.00
57.00-66.50
66.50-76.00
76.00-85.50
85.50-95.00
95.00-104.50
104.50-114.00
114.00-123.50
123.50-133.00
133.00-142.50
142.50-152.00
152.00-161.50
161.50-171.00
171.00-180.50
180.50-190.00
Age
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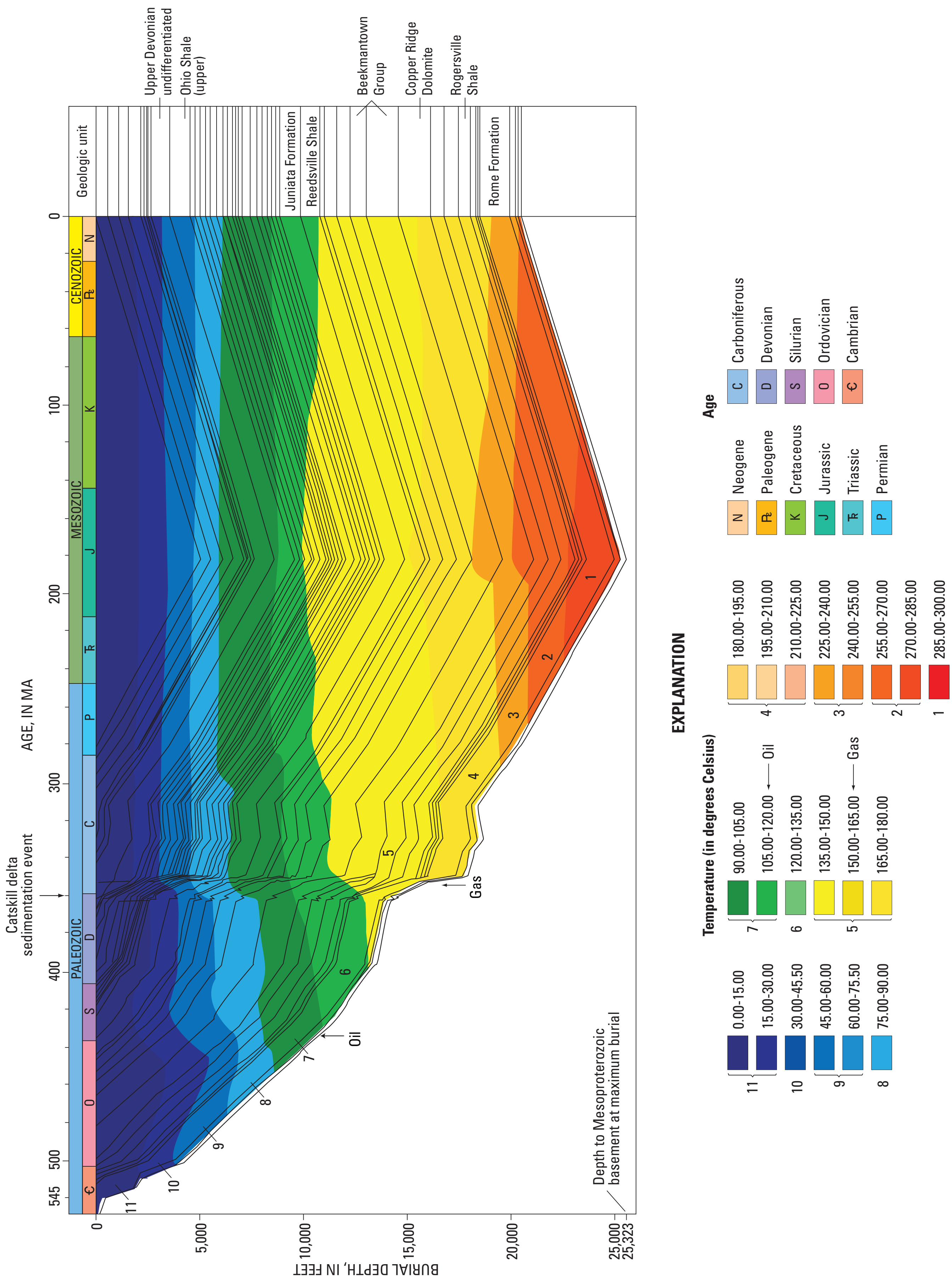
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian


Catskill delta
sedimentation event
AGE, IN MA
545
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PALEOZOIC
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BURIAL DEPTH, IN FEET
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10,000
15,000
20,000
25,000
25,323
Geologic unit
Upper Devonian
undifferentiated
Ohio Shale
(upper)
Juniata Formation
Reedsville Shale
Beekmantown
Group
Copper Ridge
Dolomite
Rogersville
Shale
Rome Formation
Oil
Gas
Depth to Mesoproterozoic
basement at maximum burial
1
2
3
4
5
6
7
8
9
10
11
EXPLANATION
Temperature (in degrees Celsius)
11 0.00-15.00
15.00-30.00
10 30.00-45.50
9 45.00-60.00
60.00-75.50
8 75.00-90.00
7 90.00-105.00
105.00-120.00 Oil
6 120.00-135.00
5 135.00-150.00
150.00-165.00 Gas
165.00-180.00
4 180.00-195.00
195.00-210.00
210.00-225.00
3 225.00-240.00
240.00-255.00
2 255.00-270.00
270.00-285.00
1 285.00-300.00
Age
N Neogene
Pɛ Paleogene
K Cretaceous
J Jurassic
Ŧ Triassic
P Permian
C Carboniferous
D Devonian
S Silurian
O Ordovician
Є Cambrian

Figure 27 (facing page). Burial and temperature history model for the Exxon No. 1 Gainer-Lee well, Calhoun County, W. Va. See figure 4 for the location of the well. The timing of oil and gas generation at this locality is shown by vertical arrows. For example, oil generation occurred in the Late Ordovician to Early Silurian, whereas gas generation occurred in the Late Devonian to Early Carboniferous. Moreover, active oil and gas migration at this locality is interpreted to have occurred approximately 15 to 20 million years after generation. Using this criterion, oil was migrating actively in the Late Silurian, whereas gas was migrating actively in the Early Carboniferous. Estimated temperatures of oil and gas generation at this locality are shown by horizontal arrows. For example, oil was generated between the temperatures of 105.00°C and 120.00°C, whereas gas was generated between the temperatures of 150.00°C and 165.00°C. The modeled temperatures (shown by 11 colors in the model) at this locality represent a range of temperatures (shown by 20 colors in the figure explanation). For example, the area of light yellowish green in the model in this figure actually represents the three ranges of temperatures shown by three shades of light yellow and light green and grouped as category 5 in the figure. The paleogeothermal gradient predicted by the model is approximately 35°C/kilometer (km). The geologic time scale used in the model differs slightly from the time scale used in figures 1 and 25. Abbreviations for age symbols are as follows: Є, Cambrian; O, Ordovician; S, Silurian; D, Devonian; C, Carboniferous; P, Permian; T̶R, Triassic; J, Jurassic; K, Cretaceous; P̶ɛ, Paleogene; N, Neogene.

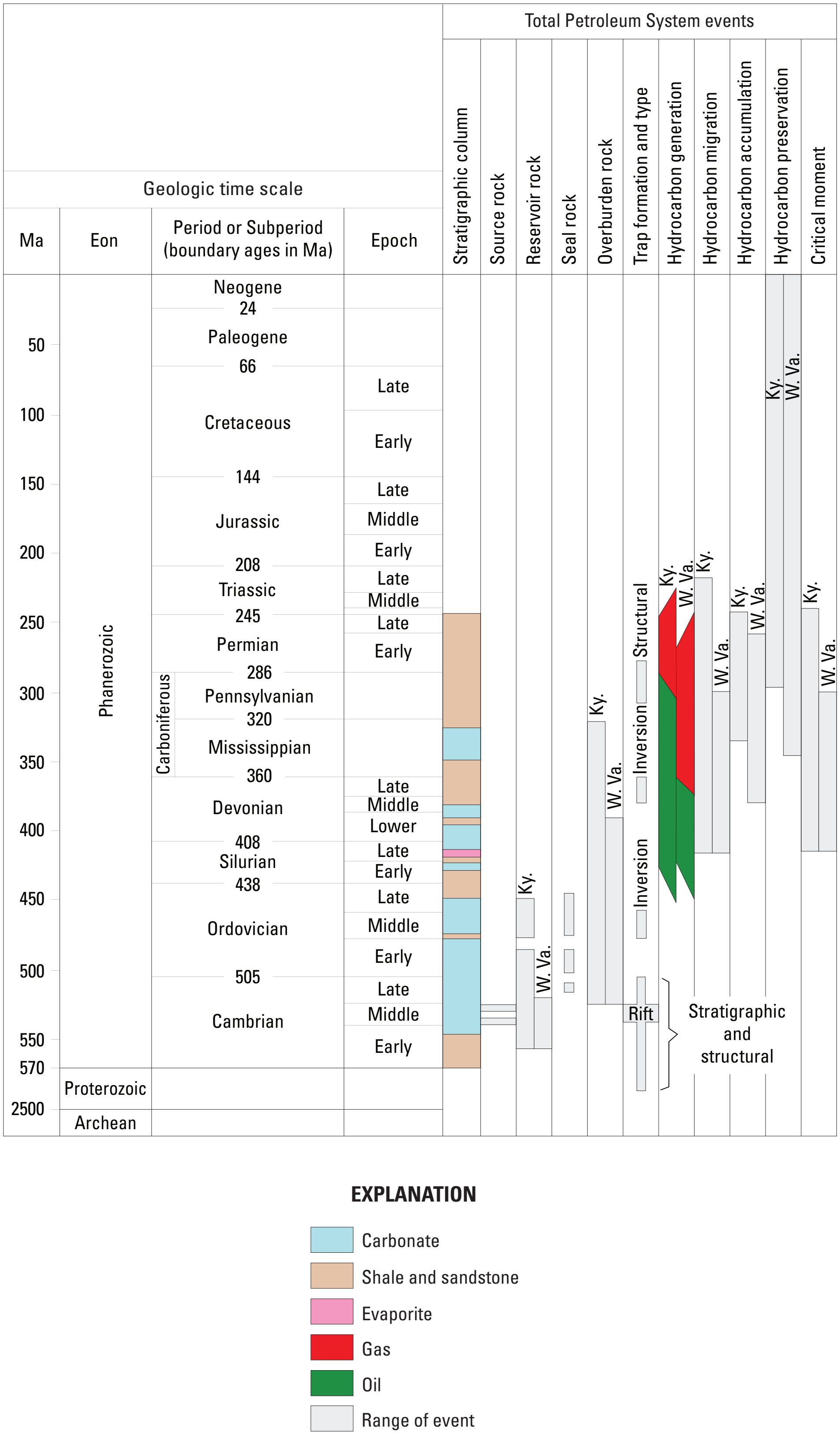

Figure 28. Events chart for the Conasauga-Rome/Conasauga Total Petroleum System. The geologic time scale used in the events chart differs slightly from the time scale used in figures 1 and 25.

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