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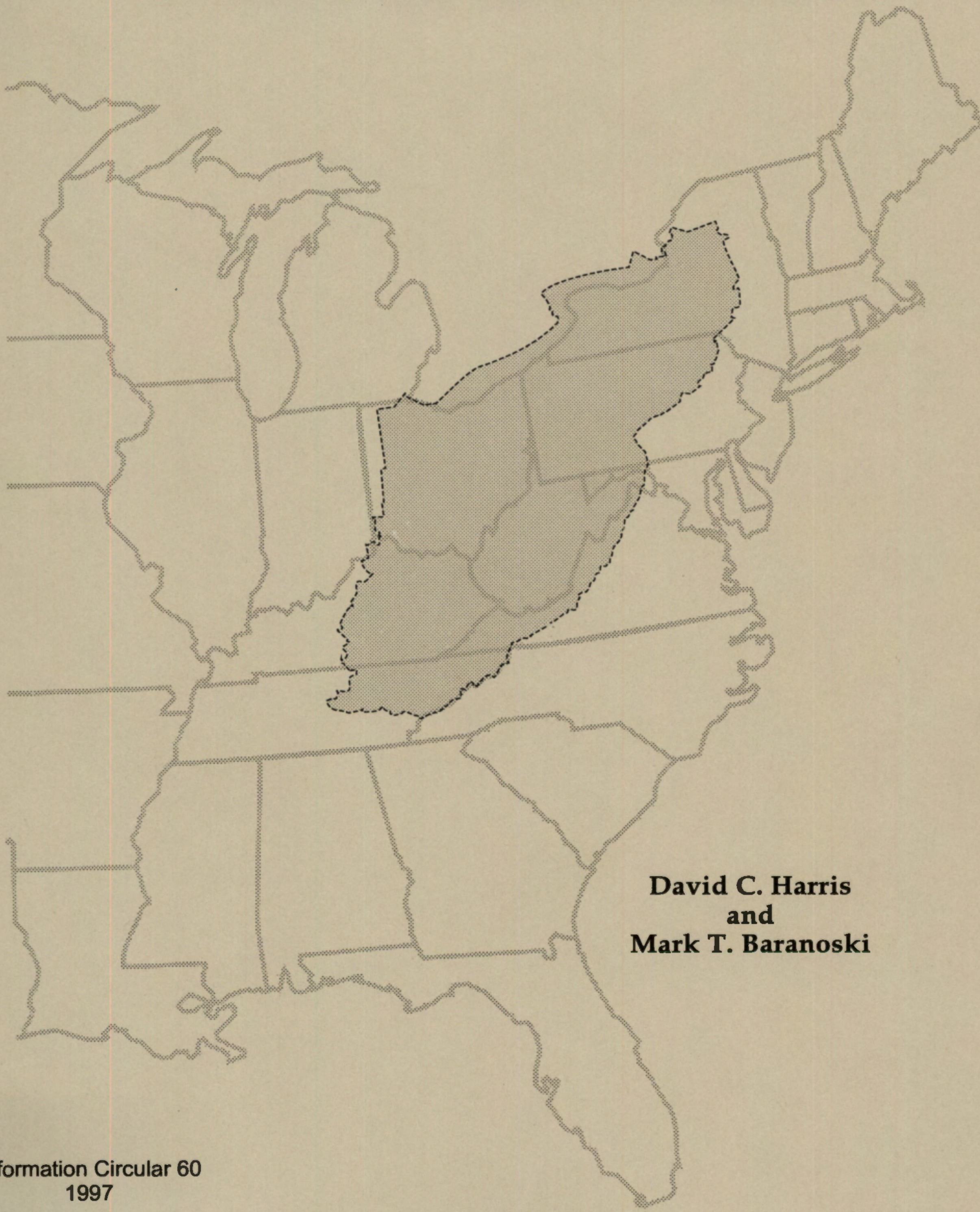
CAMBRIAN PRE-KNOX GROUP PLAY
IN THE APPALACHIAN BASIN



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CAMBRIAN PRE-KNOX GROUP PLAY IN THE APPALACHIAN BASIN

David C. Harris[1] and Mark T. Baranoski[2]

Abstract

Gas production from pre-Knox Group reservoirs in the Appalachian Basin has been reported from small fields in northeastern Ohio, northeastern Kentucky, northwestern West Virginia, and southwestern Ontario, Canada. Production from these reservoirs has been limited, and in many cases marginally economic, but the large number of gas shows reported from deep wells in the Appalachian Basin is indicative of significant future exploration potential. Cambrian clastic and carbonate units represent the deepest drilling targets in the basin, and much of the prospective interval remains untested.

The stratigraphic interval in this play includes all sedimentary units below the Cambrian–Ordovician Knox Group (and the equivalent Gatesburg Formation in Pennsylvania and New York). In Ohio this interval comprises, in ascending order, the Upper Cambrian Mt. Simon Sandstone, Rome Formation, Conasauga Formation (and the partially equivalent Eau Claire Formation), and the Kerbel Formation. This sequence extends into northern Kentucky, and abruptly thickens across several normal faults into the Rome Trough. This Cambrian basin extends from central Kentucky through northwestern West Virginia, into western Pennsylvania. The Rome Trough contains an older and dramatically thickened pre-Knox section, with as much as 12,000 ft of pre-Knox sediments in some areas. The basal Mt. Simon Sandstone of Ohio and northern Kentucky is not present in the Rome Trough, because of a facies relationship with Rome Formation siltstones and shales. Within the trough, an older sandstone, informally named the Basal sandstone, is present immediately above Precambrian crystalline basement rocks.

Definition

A play consists of geologically similar prospects that share the same source, reservoir, and trap controls, as well as common elements of risk. A play's name is based on its geologic age, formation name, reservoir facies, or trap type.

Location

Potential clastic and carbonate natural gas reservoirs of Cambrian age that are subjacent to the Knox Group or its equivalents occur throughout much of the Appalachian Basin. These potential reservoir rocks make up the Cambrian pre-Knox play, which extends from the western margin of the Appalachian Basin to the folded rocks just east of the Allegheny Front (Fig. 1). Commercial production from reservoirs in these rocks is currently confined to the western part of the play in Ontario, Canada, and to the central part of the play area in Kentucky and West Virginia.

Production History

Production from the pre-Knox play in the Appalachian Basin has been limited to fields at the western edge of the play in Ontario, and several single-well pools in Kentucky and West Virginia. The remaining activity in the play consists of approximately 57 other wells from which gas shows have been reported from the pre-Knox sequence.

The first recorded gas production from the pre-Knox interval occurred in 1948 in Wentworth County, Ontario, from the Rockton Pool (Fig. 2). This pool was noncommercial, but commercial production began in the 1960's with the discovery of four fields: Gobles, discovered in 1960; Innerkip, discovered in 1961; Willey, discovered in 1965; and Innerkip East, discovered in 1968. Other noncommercial gas pools in Ontario include the New Glasgow, Rockton, Electric, and St. Patricks (Fig. 2). Exploration for Cambrian reservoirs in Ontario over the last 135 years has been limited, despite drill-

[1] Kentucky Geological Survey, Lexington, Ky.

[2] Ohio Department of Natural Resources, Division of Geological Survey, Columbus, Ohio.

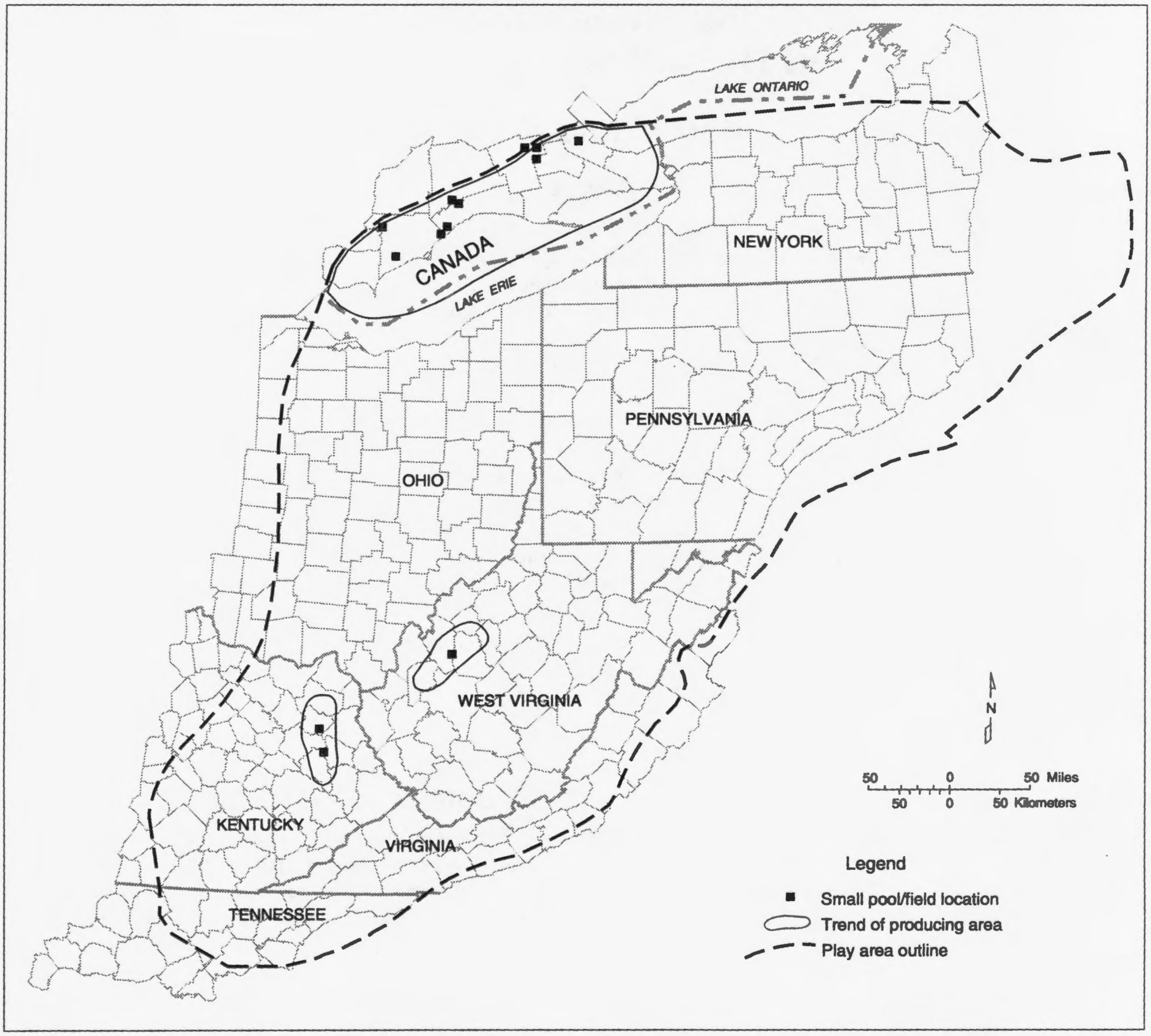

Figure 1. Area of pre-Knox Group play and locations of fields producing from Cambrian pre-Knox Group reservoirs.

ing depths of less than 3,500 ft. Only one significant gas field (Innerkip) and three oil fields have been discovered (Trevail, 1990). A new phase of development drilling at Innerkip in 1989 resulted in the discovery of additional reserves and a 148 percent increase in production in 1989, to 464 MMcf (Trevail, 1990).

Gas production from the pre-Knox interval in the rest of the basin is unrelated to activity in Ontario, and has been confined to the Rome Trough in Kentucky and West Virginia. The first commercial well in the Rome Trough was reported in 1975, with the completion of the Exxon No. 1 McCoy in Jackson County, W.Va. An initial open flow of 9.2 MMcf per day (MMcf/d) and sustained production of 5.6 MMcf/d was reported from a sandstone in the Conasauga Group from 14,350 to 14,360 ft. This well produced dry gas for about 6 months, and had a total cumulative production of 427 MMcf before increasing water production forced the well to be plugged (unpublished data from Exxon; Lytle and others, 1977; Petzet, 1991; DeWitt, 1993). The McCoy well holds the record for deepest production in the Appalachian Basin.

In 1986, a second commercial gas well was reported from the Rome Trough. The Ashland No. 1 Williams well, in Johnson County, Ky., was completed in the Conasauga Group (Rome Formation of Kentucky). Reported initial open flow

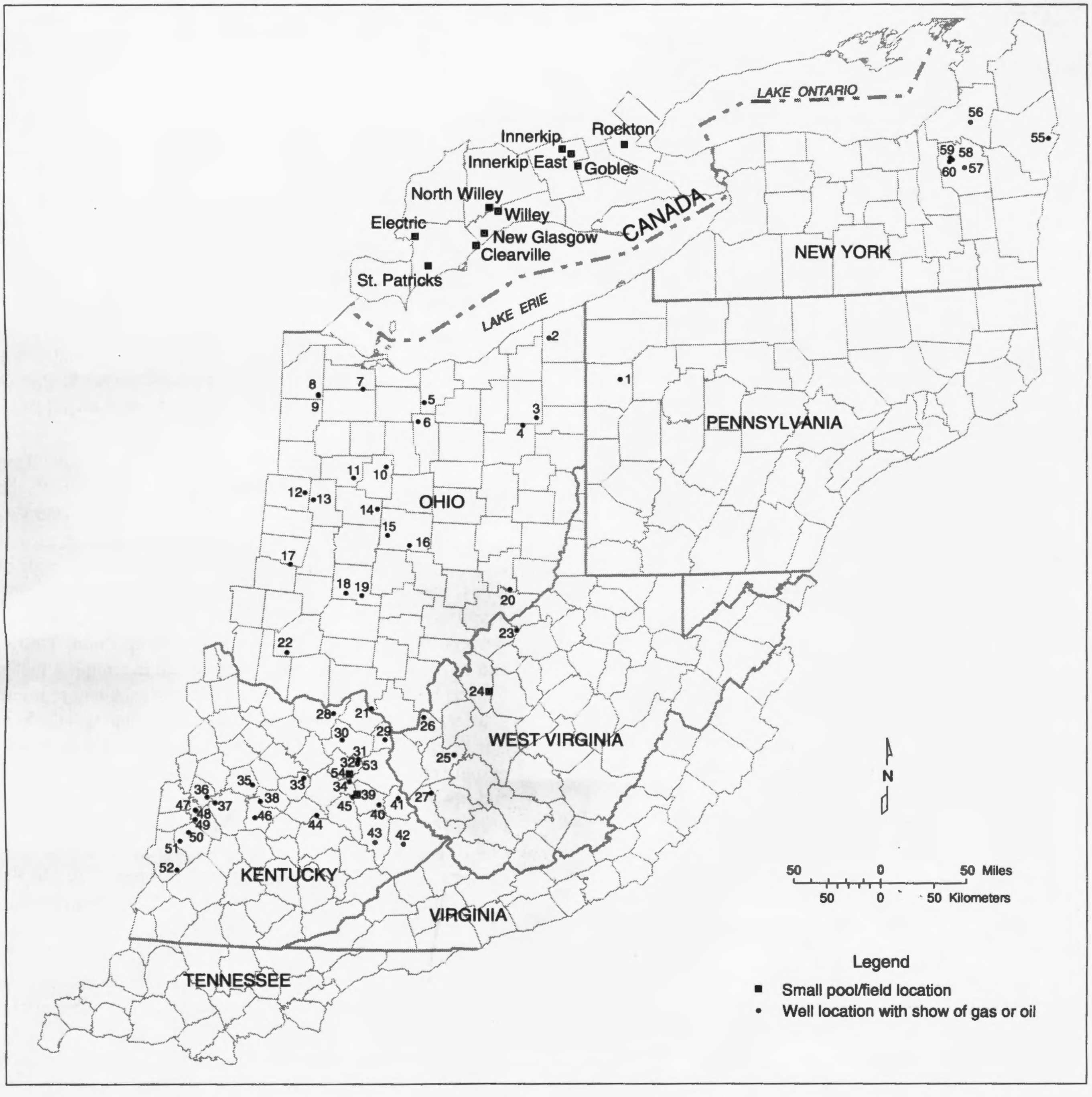

Figure 2. Distribution of commercial gas production and gas shows from pre-Knox units in the Appalachian Basin. Well numbers refer to data listed in Table 1.

was 1.055 MMcf/d from 6,250 to 6,350 ft in a fractured shale interval. A slight show of condensate was also mentioned on the completion report. This well was still producing in 1995, but production data are not available.

Most recently, in July 1994, the highest initial production to date was reported from a well in the Rome Trough in Elliott County, Ky. The Carson Associates No. 1 Kazee initially flowed 11 MMcf/d from a zone in the upper Conasauga Group/Rome Formation from 6,258 to 6,270 ft during an uncontrolled "blowout" during drilling. The producing zone is a fine- to medium-grained sandstone. Initial reservoir pressure was 2,708 psi. This well was producing approximately 500 thousand cubic feet of gas per day (Mcf/d) at a flowing pressure of 710 psi in mid-1995. The field has been named the Homer Pool by the operators, and several development wells were planned for 1995.

Cumulative pre-Knox gas production in Ontario from 1948 to the end of 1981 was 4.51 billion cubic feet (Bcf), 89 percent of which was produced from Innerkip, Willey, and Gobles Fields (Bailey Geological Services Ltd. and Cochrane, 1984). Innerkip Field alone had produced 3.9 Bcf by the end of 1989 (Trevail, 1990). By 1994, after additional development drilling, approximately 9.5 Bcf had been produced from Innerkip Field (P. Mitchell, Denbridge Gas Corp., oral communication, 1994). Innerkip East had only one producing well in 1981, which produced 18.41 MMcf in that year (Bailey Geological Services Ltd. and Cochrane, 1984). Cumulative production from Innerkip East through 1981 was 187.1 MMcf. Cumulative production data for the Rome Trough wells are only available for the Exxon No. 1 McCoy well discussed above. Estimated cumulative production from 1948 to 1995 for the pre-Knox interval in the whole basin is 12 Bcf.

At least 57 wells drilled in the Appalachian Basin have reported gas shows from the pre-Knox interval (Fig. 2, Table 1). In deeper parts of the basin, hydrocarbon shows date back to 1947, when gas and oil shows were reported from the Rome Formation in the South Central No. 1 Hall well in Powell County, Ky. (Table 1) (McGuire and Howell, 1963; Weaver and McGuire, 1977). A well in Boyd County, Ky., in the Rome Trough, the Inland No. 529 White, was completed as a Rome oil producer in 1967, but also produced about 90 Mcf/d from the same zone (unpublished data, Kentucky Geological Survey). In 1980 the Lancaster No. 1 Lee well in Garrard County, Ky., was reported to have flowed 750 Mcf/d from Rome Formation sandstones, but was never commercially produced.

No commercial gas production from pre-Knox rocks has occurred in Ohio, Pennsylvania, or New York, although several significant gas shows from the Rome, Potsdam, Warrior, and lower Theresa Formations have been reported (Fig. 2). At least eight wells in New York have recorded gas shows from the Potsdam Formation (Mt. Simon Sandstone equivalent) (Kreidler, 1959, 1963). Most of the New York wells were drilled in the 1890's, and available data are limited (see Table 1). Locations of 60 wells with gas shows or commercial production reported from pre-Knox units outside of Ontario are illustrated in Figure 2, and the corresponding well data are listed in Table 1.

Development of the pre-Knox play in the Rome Trough has been fairly steady since the late 1950's. Until the mid-1970's drilling prospects were found using limited well data, surface faulting, shallow structure, and gravity and magnetic data. No commercial gas discoveries resulted during this early period. The mid-1970's saw the introduction of regional seismic data acquisition, and a new phase of deep drilling began in Kentucky and West Virginia. Since then, seismic data have been the key exploration tool, and limited commercial success has been achieved. Reprocessing of older seismic data resulted in the most recent Elliott County, Ky., discovery. As reprocessing and new data acquisition continue, improved seismic interpretation will lead to further success.

STRATIGRAPHY

The stratigraphic interval of the play includes all sedimentary rocks below the Cambrian–Ordovician Knox Group. Because the Knox Group is not recognized throughout the Appalachian Basin, this play also includes units below the Gatesburg Formation in Pennsylvania, and the upper part of the Theresa Formation in New York. In Ontario, the Knox Group has been removed by erosion, and Cambrian units are unconformably overlain by the Middle Ordovician Shadow Lake Formation and Black River Group (Trevail, 1990). The play interval will be referred to as "pre-Knox" in this report, despite the absence of a formally recognized Knox Group in some areas.

The Cambrian units in the Appalachian Basin have been studied in outcrop for over 150 years, beginning with the first geological surveys of New York, Pennsylvania, and Virginia. Application of stratigraphic nomenclature from outcrop areas into subsurface areas, often covering hundreds of miles, has resulted in a wide variation in Cambrian stratigraphic names across the basin (Fig. 3). In addition, syndepositional faulting associated with the Rome Trough and other structural features has resulted in complex facies patterns and stratigraphic correlations. An excellent regional stratigraphic synthesis for the Cambrian in the Appalachian Basin has been published as a series of basinwide stratigraphic cross sections by Ryder (1991, 1992a–b) and Ryder and others (1992, in press a–b). Stratigraphic divisions and nomenclature in this discussion will follow Ryder's usage. Figure 4, modified from Ryder (1992a), illustrates the general stratigraphic configuration of Cambrian rocks in the basin. The age of the pre-Knox Paleozoic units in the Appalachian Basin ranges from Early to Late Cambrian.

Pre-Knox stratigraphy in the Appalachian Basin is presented here as three sequences, each of which corresponds to a different tectonic province: (1) a relatively stable craton in the northwest (northern Kentucky, Ohio, western Pennsylvania, western New York, and Ontario), (2) a Cambrian extensional graben, the Rome Trough, trending southwest–northeast from central Kentucky, through West Virginia and Pennsylvania, to southern New York, and (3) an eastern basin, lying between the Rome Trough and the Allegheny structural front (Figs. 4–5) (Ryder, 1992a). The cratonic area is the Stable Shelf of Harris (1975). The Rome Trough and eastern basin areas make up Harris's (1975) Unstable Shelf Province. Normal faults bounding these provinces were most active through the Middle Cambrian, and differential subsidence resulted in large variations in pre-Knox sequence thickness. The most dramatic stratigraphic thickening occurs in the Rome Formation and Conasauga Group intervals

Table 1. Wells in the Appalachian Basin (excluding Ontario, Canada) with hydrocarbon shows or production from Cambrian pre-Knox Group (or equivalent) formations. Producing wells shown in bold.

Map No.	*State*	*County*	*Permit*	*Operator*	*Lease*	*Total Depth (ft)*	*Formation and Depth (ft) of Show or Production*	*Gage*
1	Penn.	Mercer	20036	Peoples Nat. Gas	Temple	9,919	Upper Cambrian sandstone at 9,580; show gas	
2	Ohio	Ashtabula	191	Horizon	Rhoa	6,750	Rome at 6,421; show gas	
3	Ohio	Portage	2860	Viking	Viking	8,797	Mt. Simon at 8,506–8,712; show gas	
4	Ohio	Stark	4751	Kenoil	Bingham	7,725	Conasauga at 7,668–7,674; show oil and gas	50 Mcf/d
5	Ohio	Lorain	795	Ohio Fuel	Burge	4,513	Kerbel at 4,469–4,473; show gas	
6	Ohio	Ashland	3938	Bass Energy	Fingulin	5,140	Rome at 4,830; Mt. Simon at 4,930; show gas	
7	Ohio	Sandusky	248	Glory	Rohde	2,658	Kerbel at 2,632–2,658; show gas	
8	Ohio	Wood	364	Allerton	Dennis	2,290	Kerbel at 2,092; show oil	
9	Ohio	Wood	366	Allerton	Tienarend	2,200	Kerbel at 2,051; show gas	
10	Ohio	Morrow	4043	EEI	Hickok	4,707	Rome at 4,360–4,620; show oil and gas	
11	Ohio	Marion	149	X-Alpha	McNamera	3,076	Conasauga at 3,040; show oil	
12	Ohio	Logan	91	Allerton	Robson	3,010	Rome, Mt. Simon; show gas	
13	Ohio	Union	84	Majestic	Hutchins	2,765	Kerbel at 2,515–2,542; show gas	
14	Ohio	Delaware	354	Poling	Cockrell	4,860	Rome; show gas	
15	Ohio	Licking	5413	Clinton	Lynd	4,713	Kerbel at 4,430–4,495; show oil and gas	
16	Ohio	Licking	5446	Oxford	Church	5,273	Kerbel at 5,220; show gas	
17	Ohio	Clark	2	Friend	Mattison	4,648	Mt. Simon at 3,202; show gas	
18	Ohio	Pickaway	3	McM.-Bull.	Dunlap	3,525	Conasauga and Rome; show gas	
19	Ohio	Pickaway	6	Midwest	Miller	4,179	Rome at 3,949–3,958; show oil	
20	Ohio	Noble	1278	Amerada	Ullman	11,442	Conasauga at 10,611; gas cut water	

Table 1. Continued.

Map No.	*State*	*County*	*Permit*	*Operator*	*Lease*	*Total Depth (ft)*	*Formation and Depth (ft) of Show or Production*	*Gage*
21	Ohio	Scioto	N/A	Aristech	Aristech	5,650	Rome; show gas	
22	Ohio	Highland	16	Oxford	Heyob	3,296	Eau Claire at 2,806–2,844	100 Mcf/d
23	W.Va.	Wood	351	Hope Nat. Gas	Power Oil	13,391	Mt. Simon; show gas	
24	**W.Va.**	**Jackson**	**1366**	**Exxon**	**McCoy**	**17,675**	**Conasauga at 14,358; gas completion**	**9.1 MMcf/d**
25	W.Va.	Lincoln	1469	Exxon	McCormick	19,124	Conasauga at 11,608; show gas	
26	W.Va.	Cabell	537	Cyclops	Kingery	8,552	Pre-Knox; show gas	
27	W.Va.	Mingo	805	Columbia	Fee	19,537	Pre-Knox; show gas	
28	Ky.	Lewis	N/A	Thomas	Adams	4,190	Rome, Basal sandstone; show gas, oil	
29	Ky.	Boyd	18327	Inland Gas	White	7,676	Rome at 7,445; show gas; Rome at 7,516, 7,574; show oil and gas	15 bbl/d, 90 Mcf/d
30	Ky.	Carter	398E9	United Fuel Gas	Stamper	5,085	Basal sandstone; show gas	
31	Ky.	Carter	25730	Inland Gas	McDavid	9,980	Tomstown at 7,672; Basal sandstone at 8,898; show gas	
32	Ky.	Elliott	23542	Monitor Pet.	C. Ison	9,665	Rome; show gas; oil, condensate in three zones	
33	Ky.	Menifee	18101	United Fuel Gas	Brown	5,858	Rome; show gas in eight zones	
34	Ky.	Morgan	24194	Monitor Pet.	F. Ison	10,012	Rome; show gas	
35	Ky.	Clark	25602	Widener	Glover	4,690	Rome at 4,394; show gas	
36	Ky.	Jessamine	13950	Kin-Ark Oil	Hager	4,944	Conasauga at 3,277; Basal sandstone at 4,360; show gas	
37	Ky.	Madison	21905	Texaco	Perkins	6,415	Rome at 4,736; show gas	
38	Ky.	Powell	N/A	South Central	Hall	6,081	Rome at 5,500, 5,913; show oil and gas	15 bbl/d
39	**Ky.**	**Johnson**	**67549**	**Ashland Expl.**	**Williams**	**10,608**	**Rome at 6,250–6,350; gas/cond. completion; Tomstown(?) at 10,608; show gas**	**1,055 Mcf/d**
40	Ky.	Johnson	26311	U.S. Signal	Elkhorn	14,566	Rome; show gas	1,000 Mcf/d

Table 1. Continued.								
Map No.	*State*	*County*	*Permit*	*Operator*	*Lease*	*Total Depth (ft)*	*Formation and Depth (ft) of Show or Production*	*Gage*
41	Ky.	Martin	870E8	United Fuel Gas	Jasper	13,172	Conasauga-Rome, three zones; show gas	
42	Ky.	Pike	24577	Signal Oil	Stratton	12,450	Rome; show gas; Tomstown; show oil	
43	Ky.	Floyd	27524	Signal Oil	Hall	13,000	Rome at 7,839; show gas	
44	Ky.	Wolfe	30520	Exxon Corp.	Banks	12,288	Rome(?); show oil and gas	
45	Ky.	Johnson	60712	Ashland Expl.	McCarty	6,540	Rome at 6,420; show gas	411 Mcf/d
46	Ky.	Estill	21865	Texaco	Tipton	6,817	Pre-Knox(?); show gas(?)	
47	Ky.	Garrard	38876	Lancaster Expl.	Lee	4,596	Rome at 4,536; show gas	750 Mcf/d
48	Ky.	Garrard	21048	Texaco	Kirby	5,745	Rome at 4,550; show gas; Basal sandstone at 4,612; show oil	
49	Ky.	Garrard	25811	Widener	Burdette	4,465	Rome at 4,400; show oil and gas	
50	Ky.	Lincoln	22948	Rome Oil & Gas	Foster	5,781	Rome; show oil and gas	
51	Ky.	Lincoln	N/A	California Co.	Spears	6,117	Rome at 5,080; show oil; Basal sandstone at 5,703; show gas	
52	Ky.	Casey	34578	Cities Services	Garrett	8,251	Rome at 7,210, 7,285, 7,470; show gas	
53	Ky.	Elliott	67748	Ashland Expl.	Kazee	11,091	Rome at 7,186, 7,292, 8,883; show gas	
54	**Ky.**	**Elliott**	**85783**	**Carson Assoc.**	**Kazee**	**6,270**	**Rome at 6,258; gas completion**	**11,000 Mcf/d**
55	N.Y.	Oneida	N/A	unknown	Morgan	1,000+	Potsdam at 925–960; show gas	
56	N.Y.	Onondaga	N/A	Lupher & Kline	Yost-Yenny	5,000	Potsdam at 4,810; trace gas	
57	N.Y.	Onondaga	N/A	Empire Cement	Empire Cement	3,526+	Potsdam at 3,526; show gas	150 Mcf/d
58	N.Y.	Onondaga	N/A	Empire Cement	Sherwood	3,600	Potsdam at 3,526; show gas	100 Mcf/d
59	N.Y.	Onondaga	N/A	Empire Cement	Empire Cement	3,600	Potsdam at 3,526; show gas	
60	N.Y.	Oswego	N/A	Eastern Oil Co.	Carley	2,157	Potsdam; show gas	100 Mcf/d

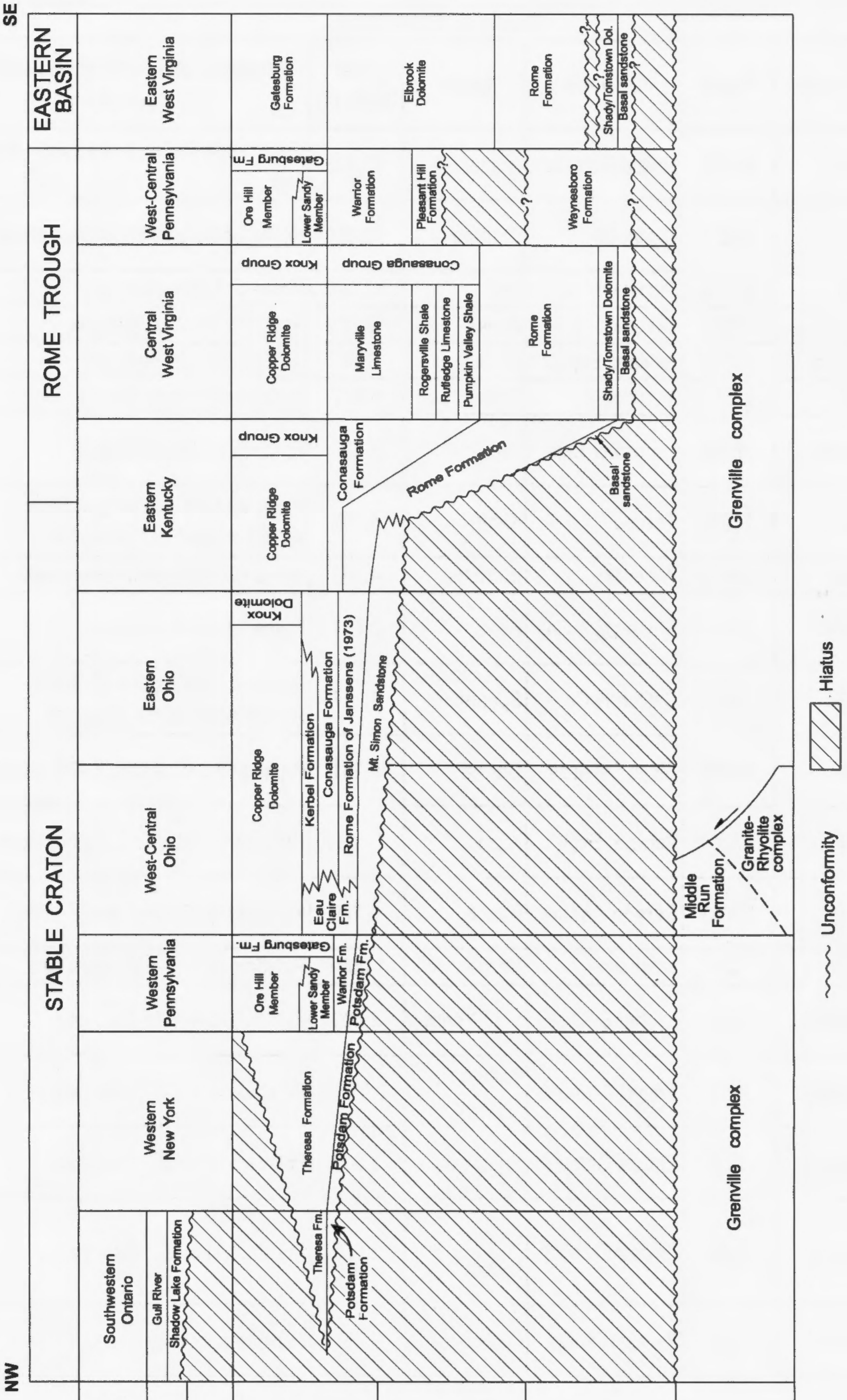

Figure 3. Stratigraphy for the Cambrian of the Appalachian Basin. Middle Ordovician rocks are also included for southwestern Ontario (compiled from Janssens, 1973; Bailey Geological Services Ltd. and Cochrane, 1984; Patchen and others, 1985; Milici and DeWitt, 1988; Ryder, 1992a; Ryder and others, 1992; and Riley and others, 1993).

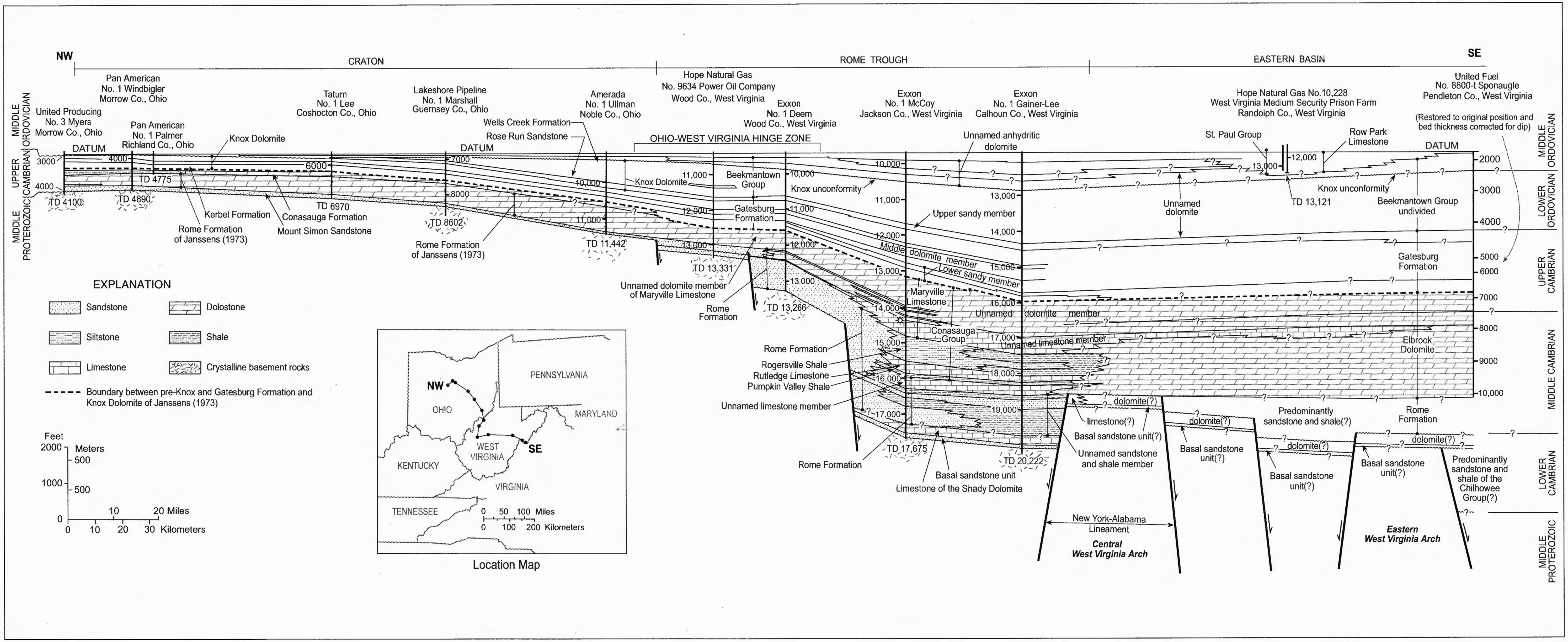

Figure 4. Sedimentary units and lithologies for the pre-Knox interval in the Ohio and West Virginia portions of the Appalachian Basin. Section is oriented northwest–southeast: from the craton, across the Rome Trough, into the eastern part of the basin. The dashed line separates pre-Knox units from Knox and equivalent strata. Lithologies are shown for pre-Knox units, where known (modified from Ryder, 1992a).

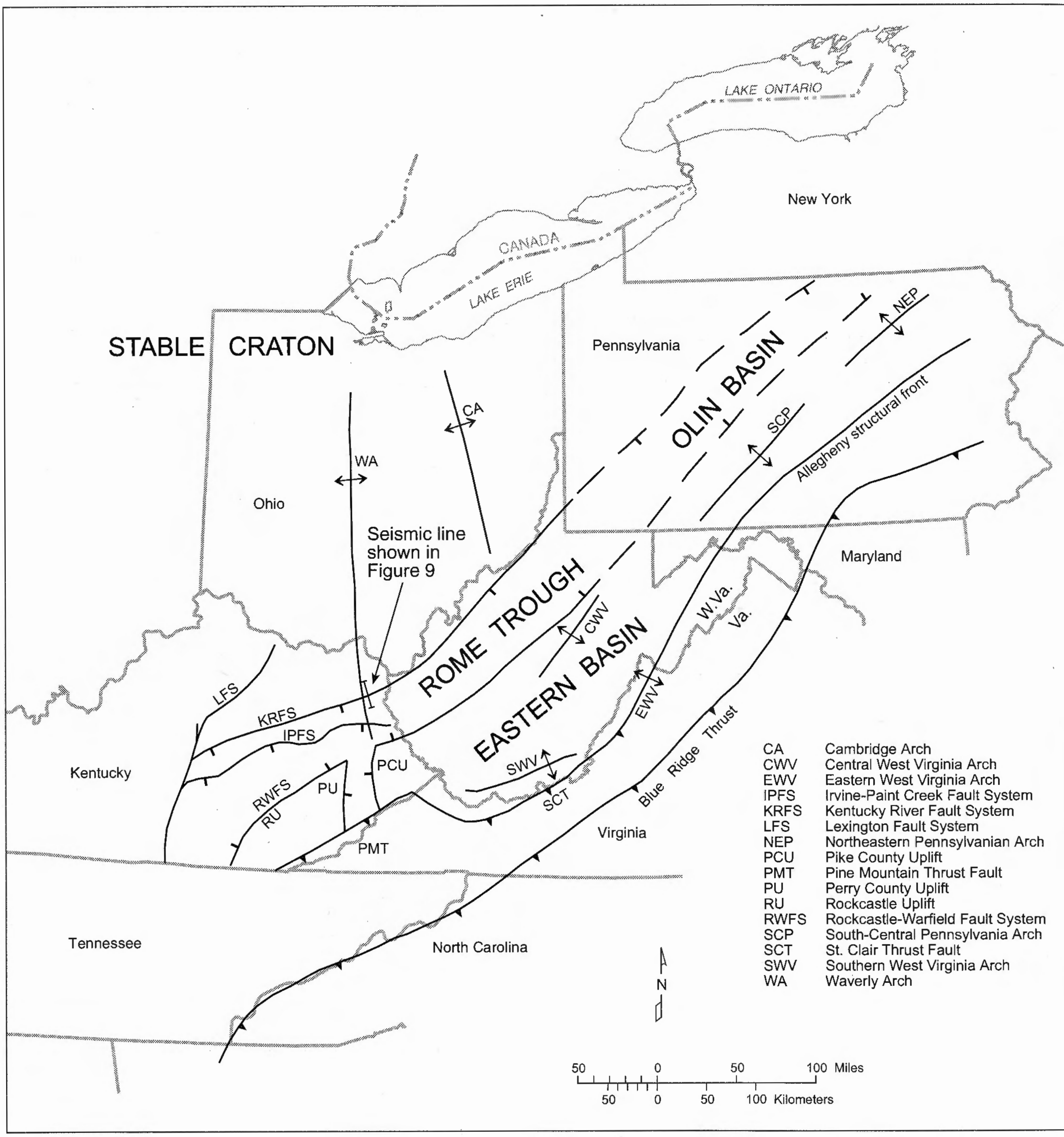

Figure 5. Major structural features and tectonic provinces for the Cambrian pre-Knox Group play. Location of seismic line (Fig. 9) shown.

in the Rome Trough. Continued reactivation of Cambrian basement faults affected stratigraphy in and around the trough throughout the Paleozoic. Cambrian units that have produced gas or are considered potentially productive below the Knox are, in descending stratigraphic order, the Kerbel Formation of Ohio; the Conasauga Group of Kentucky, Pennsylvania, West Virginia, and Virginia, and the Conasauga Formation of Ohio; the Rome Formation of Kentucky, Ohio, Pennsylvania, West Virginia, and Virginia; the Theresa/Eau Claire Formation of Ontario, the Mt. Simon Sandstone of Ohio and equivalent Potsdam Formation of Pennsylvania, New York, and Ontario; and the Shady or Tomstown Dolomite and basal sandstones within the Rome Trough of Kentucky, West Virginia, and Pennsylvania.

Cratonic Sequence

On the craton in Ohio and northern Kentucky, the pre-Knox interval comprises the Upper Cambrian Kerbel Formation (and the partially equivalent Eau Claire Formation), the Conasauga Formation, the Rome Formation, and the Mt. Simon Sandstone (Fig. 3) (McGuire and Howell, 1963; Janssens, 1973). In westernmost Pennsylvania this sequence is roughly equivalent to the Warrior and Potsdam Formations (Wagner, 1966a–b, 1976; Pees and Fox, 1990; Ryder, 1992a). A type log for the cratonic sequence in eastern Ohio is shown in Figure 6.

The Kerbel Formation was defined in Ohio by Janssens (1973) as a fine- to coarse-grained sandstone that overlies the Conasauga Formation and intertongues with the Eau Claire Formation. The unit is as much as 170 ft thick, generally coarsens upward, and may grade into dolomite or dolomitic sandstone near the top. Janssens (1973) interpreted Kerbel sandstones as deltaic fan deposits, and the interbedded carbonates, shales, and sandstones of Ohio's Conasauga Formation as prodelta marine deposits. The Conasauga sandstones merge with the lower sandy member of the Gatesburg Formation in the Rome Trough of West Virginia (Fig. 4). Figure 7 illustrates Janssens's (1973) interpretation of the relationships between the Kerbel, Conasauga, and Rome Formations of central Ohio.

The Conasauga Formation on the craton consists of red and green shales with interbedded glauconitic siltstones, limestones, and dolomite, and very fine-grained sandstones (Janssens, 1973). It ranges from 40 to about 450 ft thick in Ohio. The Conasauga Formation grades conformably into the overlying Kerbel Formation or Copper Ridge Dolomite (Knox Group) and into the underlying Rome Formation of Janssens (1973).

Janssens's (1973) Rome Formation consists largely of dolomite in eastern Ohio and contains a sandstone facies in central Ohio that appears to coincide with the trend of the ancestral Waverly Arch (Woodward, 1961). West of the sandstone facies Janssens's (1973) Rome Formation changes to glauconitic sandstone, siltstone, shale, and dolomite of the Eau Claire Formation (Janssens, 1973) (Fig. 8). The Rome Formation defined on the shelf in northeastern Kentucky by McGuire and Howell (1963) is similar to that described in Ohio by Janssens (1973).

The post-Knox unconformity truncates all the Cambrian units in southwestern Ontario above the Theresa Formation, which probably correlates to Janssens's Rome Formation in Ohio. Unconformably overlying the Theresa Formation in Ontario is the Middle Ordovician Shadow Lake Formation (Fig. 3). This unit is a bright-green shale, commonly con-

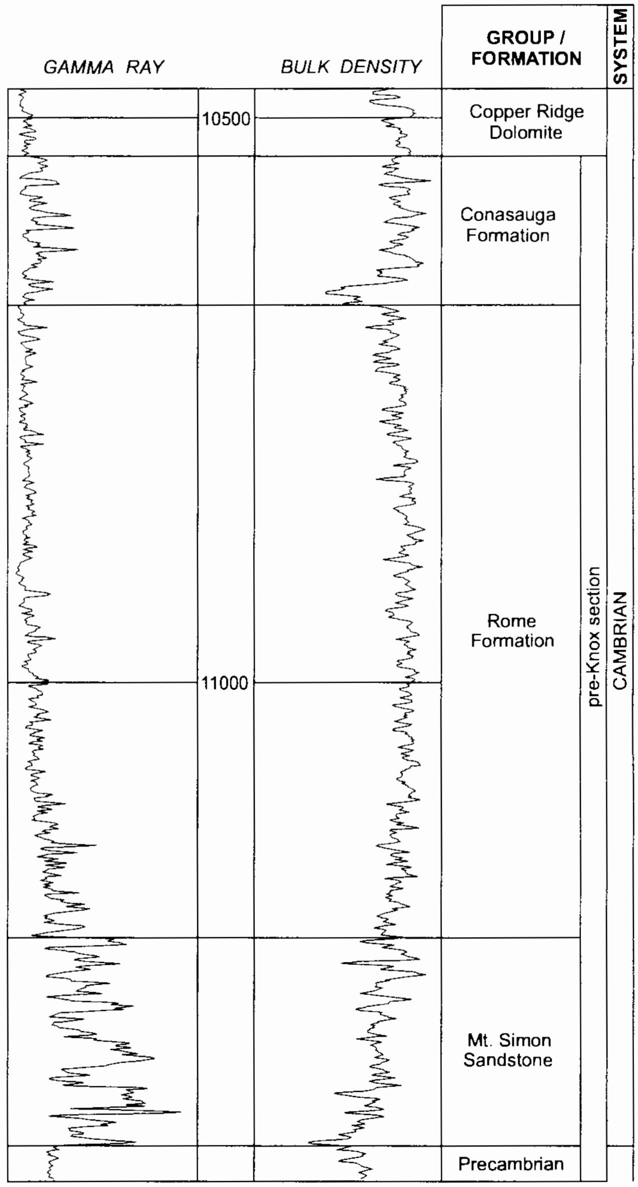

Figure 6. Type geophysical log for the pre-Knox sequence on the craton: gamma ray and bulk density logs for the Amerada No. 1 Ullman well, Noble County, Ohio. This well has a thinner pre-Knox sequence than wells in areas to the east and southeast.

taining floating quartz sand. It is interbedded in places with argillaceous green sandstones and red shales (Bailey Geological Services Ltd. and Cochrane, 1984). The Shadow Lake forms the top seal for most Cambrian reservoirs in Ontario.

The oldest Paleozoic sedimentary units on the craton are the Mt. Simon Sandstone and correlative Potsdam Sandstone of western Pennsylvania, New York, and Ontario (Ryder, 1992a–b; Ryder and others, 1992). These transgressive sandstones unconformably overlie middle Proterozoic metamorphic (Grenville Province) and sedimentary (Middle Run Formation) rocks in Ohio and north-central and northeast-

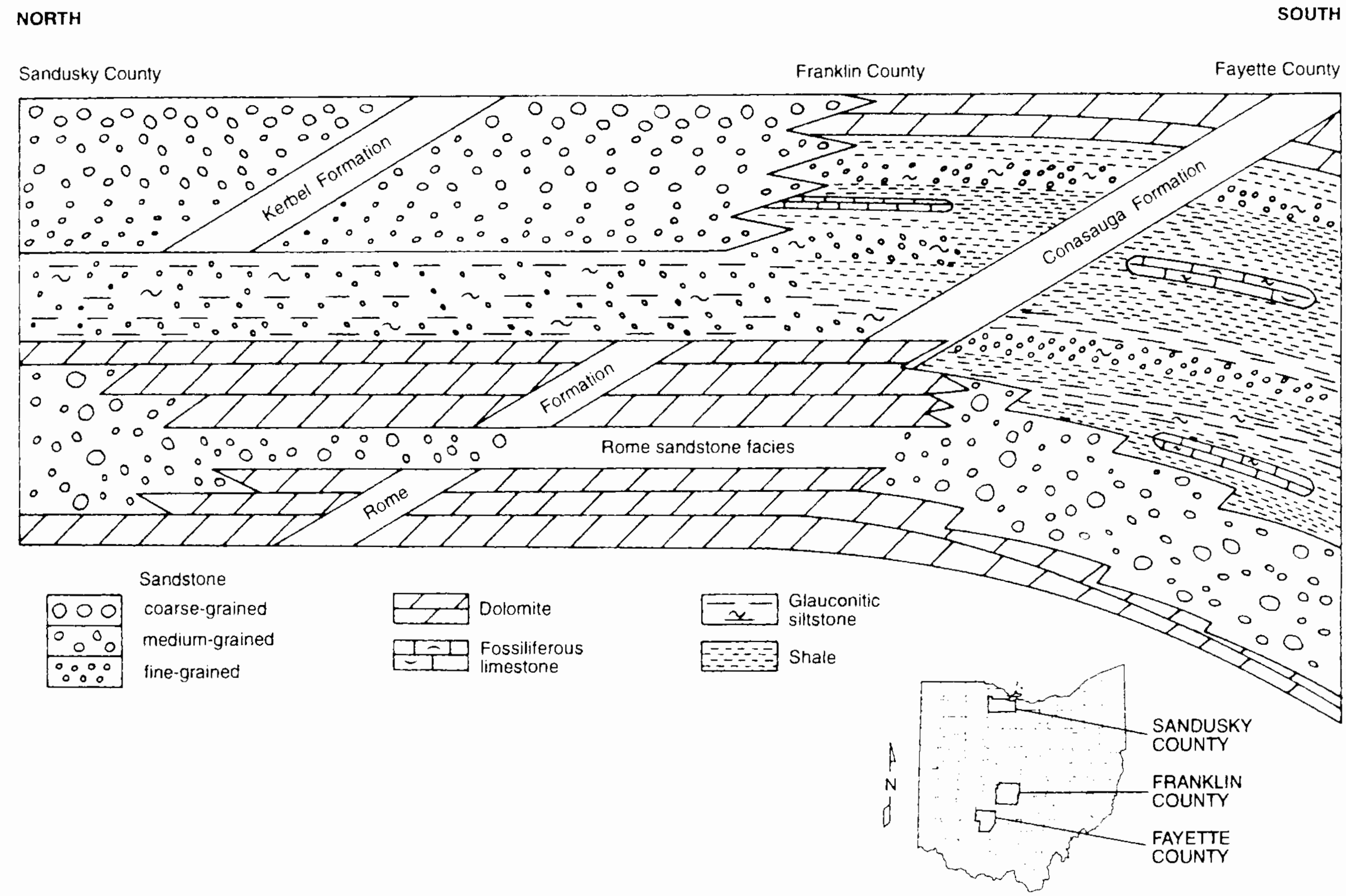

Figure 7. Schematic north–south cross section of the Kerbel and Conasauga Formations and the Rome Formation of Janssens (1973) across central Ohio (from Janssens, 1973).

ern Kentucky (McGuire and Howell, 1963; Janssens, 1973; Drahovzal and others, 1992). The Mt. Simon Sandstone ranges in age from latest Middle Cambrian in the southeast to early Late Cambrian in the northwest (Ryder and others, 1992). The sandstones are fine grained to conglomeratic, and vary from clean quartzarenites to arkosic and dolomitic sandstones (Janssens, 1973; Robinson, 1982). In New York the Potsdam Sandstone is gradational with sandstones and sandy dolomites of the Theresa Formation. Thicknesses range from zero at the post-Knox unconformity truncation along the southern shore of Lake Ontario to almost 1,500 ft at the New York-Pennsylvania border (Robinson, 1982). The Mt. Simon Sandstone is not recognized southeast of the northwestern boundary of the Rome Trough, which is the Ohio-West Virginia Hinge Zone of Ryder (1992a). The Mt. Simon correlates with the upper Rome Formation in the Rome Trough across this hinge zone (Fig. 4) (Webb, 1980; Ryder, 1992a).

Rome Trough Sequence

The cratonic units described above extend into northern Kentucky and northwestern West Virginia, but abruptly thicken across a series of extensional growth faults into a northeast–southwest-trending rift basin, the Rome Trough (Fig. 9) (Woodward, 1961; McGuire and Howell, 1963; Silberman, 1972, 1981; Cardwell, 1977; Harris, 1978; Webb, 1980; Sutton, 1981). This Cambrian rift basin extends from central Kentucky through West Virginia into western Pennsylvania, where it has also been referred to as the Olin Basin (Fig. 5) (Wagner, 1976; Harper, 1989). In the Rome Trough the pre-Knox section is older and dramatically thickened, with as much as 10,000 ft of pre-Knox sediments in some areas (Harris, 1978; Webb, 1980; Ryder and others, 1992). The Rome Trough may continue into southern New York, but data are sparse (Beardsley and Cable, 1983; Cable and Beardsley, 1984; Harper, 1989). Rocks as old as Early Cam-

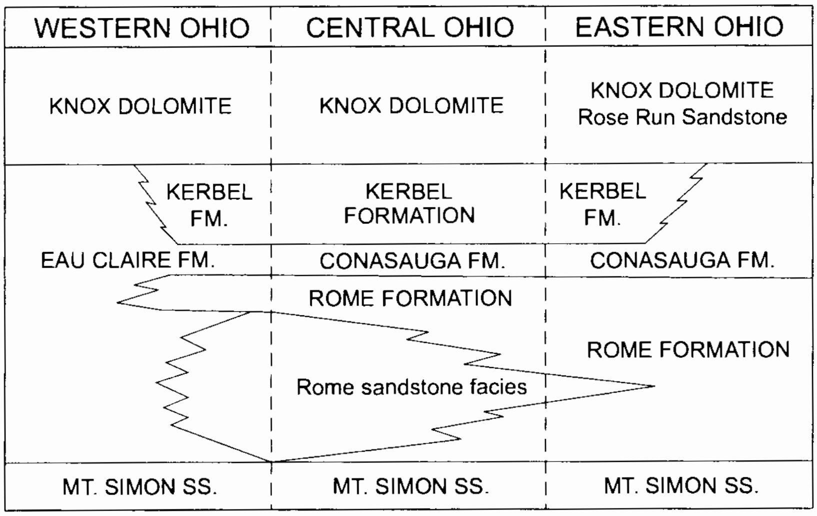

Figure 8. Schematic east–west cross section of the Eau Claire and equivalent Rome strata in Ohio (figure and nomenclature from Janssens, 1973).

brian are present within the trough, and have no equivalents to the northwest on the craton. The pre-Knox sequence within the Rome Trough of Kentucky and West Virginia consists of the Conasauga Group, Rome Formation, Shady/Tomstown Dolomite, and a basal sandstone zone. Equivalent units within the trough in Pennsylvania are largely unknown because of a lack of well data, but may consist of the Warrior Formation, Pleasant Hill Limestone, and Waynesboro Formation as correlated from outcrops by Ryder and others (1992) and Ryder (1992b). The expanded Cambrian section in the Rome Trough is largely conformable and predominantly marine in origin (Ryder, 1992a). A type log for the Rome Trough sequence is shown in Figure 10.

Stratigraphic correlations and nomenclature used within the Rome Trough vary significantly. The greatly expanded section makes correlation with outcrop or subsurface cratonic sequences difficult. The most significant discrepancies lie in the position of the Rome Formation-Conasauga Group contact, and the recognition of the Shady/Tomstown Dolomite (Thomas, 1960; McGuire and Howell, 1963; Webb, 1980; Sutton, 1981; Cable, 1984; Allen, 1988; Donaldson and others, 1988; Ryder, 1992a; Ryder and others, in press a). A discussion of these problems is beyond the scope of this paper; Ryder's (1992a) nomenclature and stratigraphic correlations within the trough, which are illustrated in Figure 4, will be utilized here. From this cross section (Fig. 4), the lithostratigraphic basis of Ryder's correlations within the Rome Trough are apparent.

The Conasauga Group consists of a 2,400- to 5,500-ft-thick sequence of shale, limestone, dolomite, and siltstone, which conformably overlies the Rome Formation in the Rome Trough (Ryder, 1992a; Ryder and others, in press b). Ryder (1992a) recognized four of the six formations in the subsurface of West Virginia that make up the Conasauga Group in outcrop in Tennessee. These four formations are, in descending order, the Maryville Limestone, composed of limestone, dolomite, and minor sandstone; the Rogersville Shale, consisting of shale, micritic limestone, and siltstone; the Rutledge Limestone, composed of micritic and sandy limestone and sandstone; and the Pumpkin Valley Shale, a gray shale and siltstone (Ryder, 1992a).

The Rome Formation is a 1,000- to 2,900-ft-thick sequence of sandstone, siltstone, shale, limestone, and dolomite that overlies the limestone of the Shady Dolomite (Ryder, 1992a; Ryder and others, in press b). Sandstone beds in the upper part of the Conasauga Group (in the middle part of the Maryville Limestone) correlate to the upper sandstone units of the Rome in the Ohio-West Virginia Hinge Zone and possibly to Janssens's (1973) Mt. Simon Sandstone west of the Ohio-West Virginia Hinge Zone (Ryder, 1992a) (Fig. 4). Depositional environments of the Conasauga Group and Rome Formation were interpreted for cores from two West Virginia wells by Donaldson and others (1975, 1988). They described carbonate and clastic facies deposited in tidal-flat, tidal-channel, and shallow subtidal marine environments.

Confined to the Rome Trough and the block-faulted terrane to the southeast is a carbonate unit, the Shady/Tomstown Dolomite, which underlies the Rome Formation and overlies a basal sandstone (McGuire and Howell, 1963; Ryder, 1992a). The Shady/Tomstown Dolomite interval consists of limestone in some areas, and is considered by Ryder (1992a) to be Early Cambrian in age.

The oldest sedimentary unit in the Rome Trough of Kentucky and West Virginia is a sandstone, informally named the Basal sandstone, which unconformably overlies middle Proterozoic crystalline basement rocks (McGuire and Howell, 1963; Webb, 1980; Sutton, 1981). This sandstone unit varies from 20 to 650 ft thick and is commonly arkosic. Previously this basal sandstone in the Rome Trough was correlated with the Mt. Simon Sandstone on the craton (McGuire and Howell, 1963). The Mt. Simon appears to be a much younger unit, and probably correlates with the uppermost part of the Rome Formation in the trough (Ryder, 1992a) (Fig. 4).

Eastern Basin Sequence

East and southeast of the Rome Trough, pre-Knox units become thinner across several basement fault blocks, but are much thicker than in areas on the craton, northwest of the trough (Beardsley and Cable, 1983; Ryder, 1991, 1992a–b; Thomas, 1991; Ryder and others, 1992). The area between the Rome Trough and the Allegheny structural front prob-

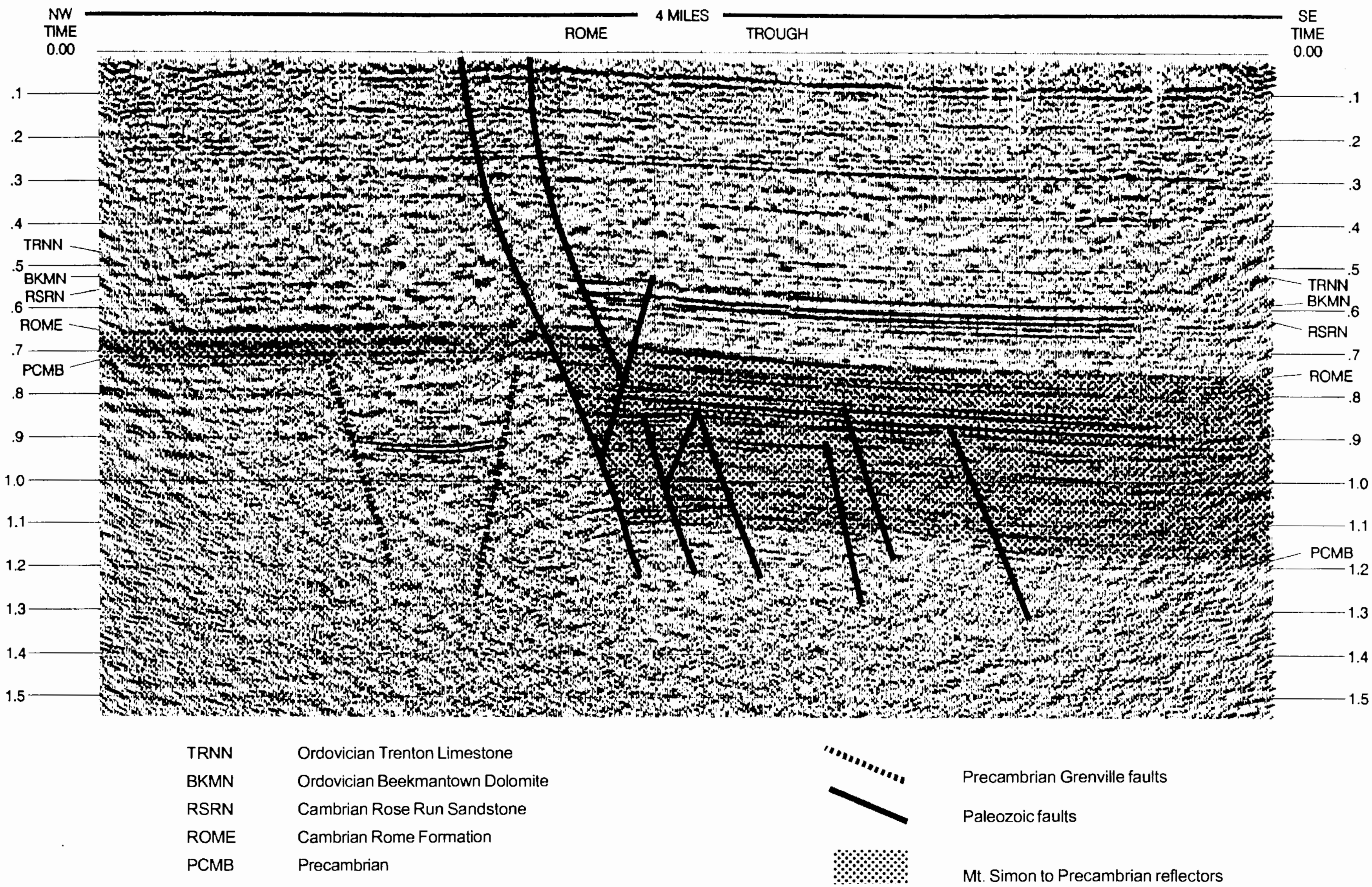

Figure 9. Seismic section across the northern boundary fault of the Rome Trough in Carter County, Ky. Data collected using a vibroseis source, 30-fold, migrated, with normal polarity. The Cambrian section increases in thickness south of the fault system, indicating growth faulting. Formation tops are also indicated. (Modified from Riley and others, 1993.)

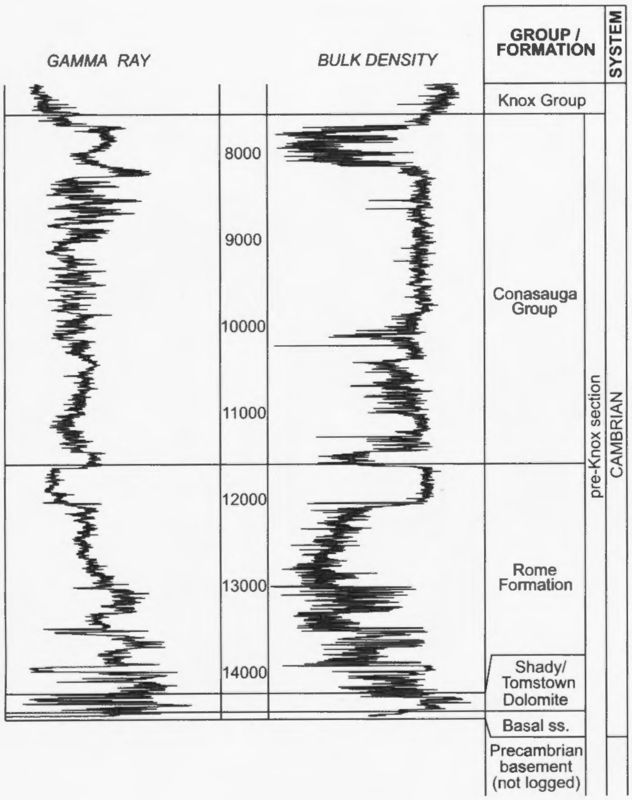

Figure 10. Type geophysical log for the pre-Knox section, Rome Trough: gamma ray and bulk density logs for the Signal No. 1 Elkhorn well, Johnson County, Ky., demonstrating an expanded pre-Knox section for this well. Stratigraphic correlations from Ryder and others (in press b).

ably is underlain by a series of horsts and grabens formed by faulting along inferred basement normal faults (Fig. 4). The pre-Knox stratigraphic section southeast of the Rome Trough becomes carbonate-dominated in West Virginia, as clastics of the Conasauga Group and Rome Formation thin and grade laterally into dolomites of the Elbrook Dolomite (Ryder, 1992a) (Fig. 4). The Shady Dolomite and Basal sandstone section is present throughout most of the eastern area. In northern West Virginia the section includes the Elbrook and Waynesboro Formations, Shady/Tomstown Dolomite, and Basal sandstone (Ryder, 1991). In east-central Pennsylvania the section consists of the Warrior Formation, Pleasant Hill Limestone, Waynesboro Formation, Shady/Tomstown Dolomite, and a basal sandstone (Ryder and others, 1992).

In summary, the pre-Knox interval in the Appalachian Basin represents an overall transgressive depositional sequence, in which progressively younger rocks were deposited in a northwesterly direction (Thomas, 1991). The sequence is almost entirely shallow marine in origin, and is composed of a complex package of sandstones, siltstones, carbonates, and shales. Much of the Rome Formation consists of thinly bedded, heterolithic intervals. Carbonates are better developed in the Conasauga Formation/Group, but also occur in the upper part of the Rome Formation. Deposition within the Rome Trough was influenced by faulting and more rapid subsidence than in surrounding areas, resulting in an expanded interval with the potential for fault-related and other types of hydrocarbon traps to occur.

Structure

Regional structure of the Cambrian pre-Knox play can also be defined in terms of the three areas discussed above: the western stable cratonic platform, the Rome Trough, and the eastern basin area (Fig. 5). Structure is an important component in much of the play area because of its direct influence on trapping, and because of possible syndepositional influence on reservoir character, particularly in the Rome Trough. Structure has an influence in the Canadian fields, but to a minor extent compared to its influence in the Rome Trough and other areas in the central part of the basin. Major structural elements in the play are shown in Figure 5.

Strata of the stable cratonic platform are characterized by regional east–southeast dip toward the central Appalachian Basin. This area, which includes Ontario, western New York, western Pennsylvania, Ohio, and northern Kentucky, has been affected by relatively small-scale basement faulting and associated gentle folds and faults in overlying strata. Faults and positive structures that may define structural closures in pre-Knox strata include the Waverly Arch (Woodward, 1961), the Cambridge Arch (Riley and others, 1993; Root, 1993), the Algonquin Arch in Ontario (Pounder, 1967; Bailey Geological Services Ltd. and Cochrane, 1984), and the Lexington Fault System in north-central Kentucky (Black and others, 1981) (Fig. 5). Reactivation of pre-existing Proterozoic faults associated with the Grenville Province (Black and others, 1981; Beardsley and Cable, 1983; Baranoski, 1993) cut overlying Cambrian sediments, forming the Lexington and Kentucky River Fault Systems in Kentucky. Structural traps, stratigraphic traps, and unusually thick reservoir units may be associated with these basement-controlled faults (see pinch out of Mt. Simon Sandstone in Figure 11). Subtle folds and small basement faults play a minor role in gas production from the Cambrian in Ontario.

The Rome Trough is the most significant structure affecting pre-Knox rocks in the Appalachian Basin. The trough, first recognized by Woodward (1961), is bounded in Kentucky by the Kentucky River and Irvine-Paint Creek Fault Systems on the north, and the Rockcastle/Warfield Fault System on the south (Figs. 5, 9) (McGuire and Howell, 1963; Ammerman and Keller, 1979; Webb, 1980; Silberman, 1981; Cable and Beardsley, 1984). The southern-bounding fault system is more discontinuous than the northern-bounding systems, and is defined by prominences, recesses, and subtle arches, as well as major fault segments. The Rome Trough

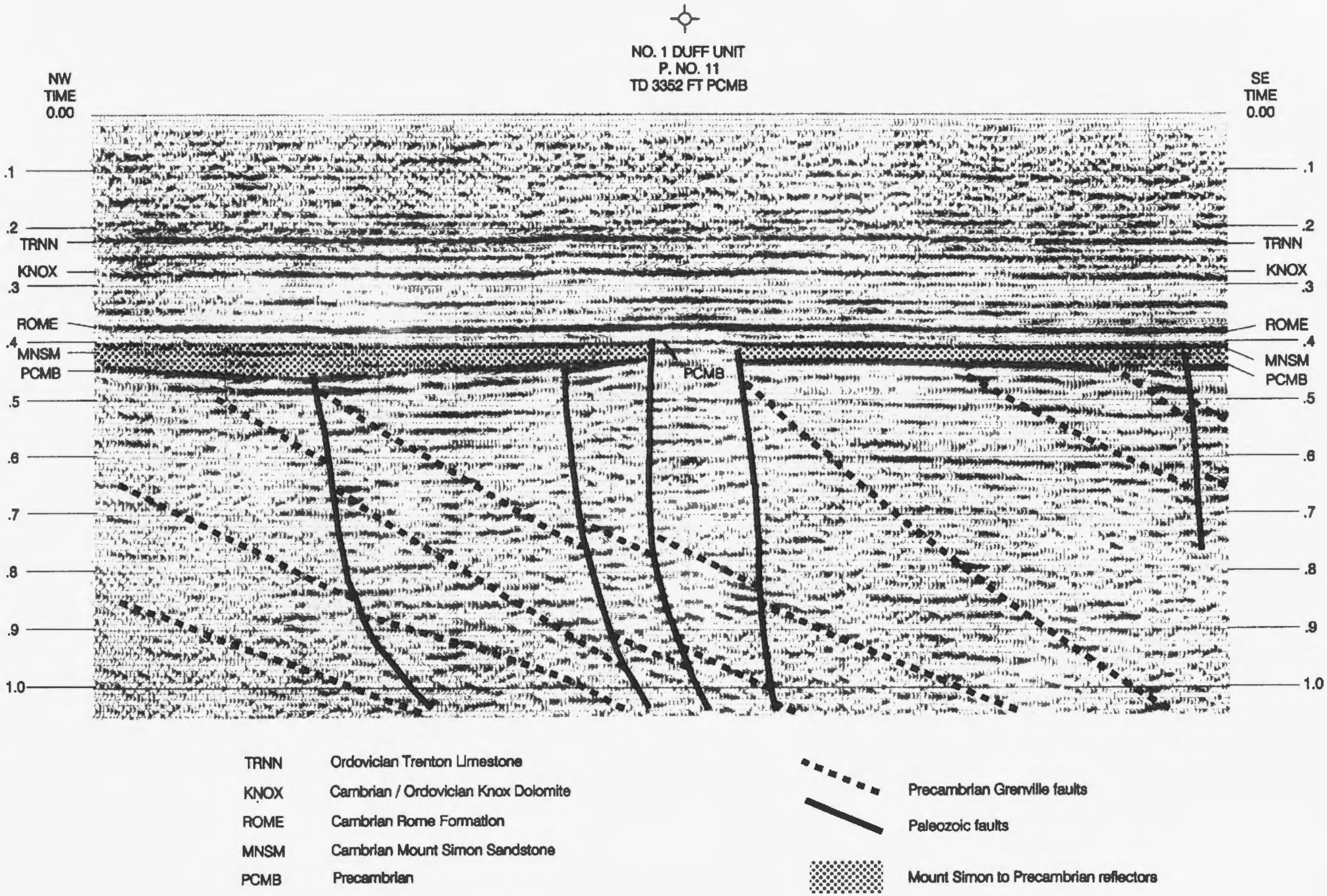

Figure 11. Seismic section from Fayette County, Ohio (dynamite source, 12-fold, migrated, with normal polarity). Note the thick Mt. Simon Sandstone adjacent to the Precambrian basement paleotopographic high at the Duff well. (Modified from Riley and others, 1993.)

extends through western West Virginia and Pennsylvania, and possibly into south-central New York (Wagner, 1976; Cardwell, 1977; Shumaker, 1986; Harper, 1989) (Fig. 5). The Rome Trough has been interpreted as a failed Cambrian continental rift basin, developing approximately 250 miles cratonward of the central area of Iapetan rifting (Harris, 1978; Ammerman and Keller, 1979; Beardsley and Cable, 1983; Keller and others, 1983; Shumaker, 1986, 1987; Thomas, 1991; Walker and others, 1991). Paleontological data and thickness of the Rome Formation indicate that maximum subsidence within the trough occurred during the Middle Cambrian (Webb, 1980). Cambrian depocenters are located along the northern rift margin in Kentucky and the southern margin in West Virginia, indicating that the rift is characterized by half-graben structures of alternate polarity. Within the trough, Cambrian gas production is related to structural closures and fracturing. Fracture porosity is commonly associated with reactivated basement faults that cut pre-Knox rocks.

The area southeast and east of the Rome Trough (eastern basin area) remained structurally higher, and separated the trough from the Iapetan rift farther east (Beardsley and Cable, 1983; Thomas, 1991). Recurrent basement faulting within this area formed broad structures in overlying Cambrian rocks. Positive structures associated with these fault blocks include the Perry, Pike, and Rockcastle Uplifts in Kentucky; the Central, Southern, and Eastern West Virginia Arches; and the South-Central and Northeastern Pennsylvania Arches (Figs. 4–5) (Ammerman and Keller, 1979; Sutton, 1981; Kulander and Dean, 1986; Black, 1986; Ryder, 1991, 1992a–b; Ryder and others, 1992).

Reservoir

Limited gas production from pre-Knox rocks makes interpretation of characteristic trap types difficult. A wide variety of structural, stratigraphic, and combination trapping mechanisms probably occur in the play. In Ontario, where Knox Group-equivalent rocks have been eroded, pre-Knox reservoirs occur as unconformity truncation traps below the post-Knox (Middle Ordovician) unconformity, and as fault closures. In deeper parts of the Appalachian Basin, potential traps include anticlinal structures, fault closures, and stratigraphic pinch outs. The complex stratigraphy and structure in the sparsely explored pre-Knox section are responsible for a wide variety of potential trapping mechanisms and reservoir types. Potential reservoirs include clastic and carbonate rocks containing intergranular, vuggy, and fracture porosity. The primary tool used by most operators to locate prospective traps in this play is seismic reflection data.

Gas production in Ontario has been attributed to both stratigraphic and minor structural trapping. The Gobles and Innerkip Fields are stratigraphic traps, resulting from erosional truncation of a sandy dolostone at the post-Knox unconformity on the flank of the Algonquin Arch (Sanford, 1968; Bailey Geological Services Ltd. and Cochrane, 1984; Powell and others, 1984). The Willey and Clearville Fields have been attributed to both structural and stratigraphic trapping (Pounder, 1964, 1967; Bailey Geological Services Ltd. and Cochrane, 1984; Powell and others, 1984). Specific trapping mechanisms include fault-related traps, truncation by the post-Knox unconformity, and small anticlinal noses.

Structural traps are the primary target in and around the Rome Trough, where basement-controlled normal faults influenced deposition and created potential structural traps during initial rifting and later reactivation. Three commercial gas wells have been reported in the Rome Trough part of the basin, and all of these accumulations are structurally influenced. The Ashland No. 1 Williams well in Johnson County, Ky. (Table 1, Fig. 2), was completed in a fractured shale interval in the Conasauga Group (Rome Formation of Kentucky). This well is near the Irvine-Paint Creek Fault System in the Rome Trough, and fracturing is thought to be related to proximity to this fault. The Exxon No. 1 McCoy well in Jackson County, W.Va., produced for about 6 months from the Belgrove Field, a probable fault-related anticlinal closure in the Rome Trough. Data are limited for the recent Carson Associates No. 1 Kazee well in Elliott County, Ky., but the well appears to be producing from a fault block trap.

Source rocks for hydrocarbons present in pre-Knox reservoirs vary with the play area. Studies of oil produced from Cambrian reservoirs in Ontario have shown distinctive geochemical characteristics that correspond to source-rock samples from the Upper Ordovician Collingwood Formation (Powell and others, 1984). Studies by Cole and others (1987) also found that oils from Knox reservoirs in Ohio were most likely from the equivalent Upper Ordovician Point Pleasant Formation. Assuming that gas and oil in Ontario have a common origin, hydrocarbons from the Upper Ordovician source presumably migrated updip and down section along the post-Knox unconformity into pre-Knox reservoirs.

Potential source rocks for pre-Knox hydrocarbons in deeper parts of the basin in Kentucky, New York, Pennsylvania, Ohio, and West Virginia are less well constrained. Stratigraphic separation of the pre-Knox interval from the Knox unconformity makes Upper Ordovician shales unlikely as a source in these areas. Oil produced from the Rome-Conasauga interval in eastern Kentucky is distinguished by high gravity (41 to 54° API), unlike mostly lower gravity oils derived from post-Knox source rocks. This suggests that both oil and gas in pre-Knox reservoirs were generated from pre-Knox or other unknown source rocks at higher thermal maturities. Ryder and others (1991) reported geochemical analyses of 22 shale samples from the Rome and Conasauga interval in three wells in the Rome Trough of West Virginia and an outcrop section in Tennessee. Total organic carbon values of these samples range from 0.05 to 0.59 percent, and the samples are considered to have low to marginal source potential (Ryder and others, 1991). Ryder and others (1991) also calculated production indices for samples with total organic carbon greater than 0.5 percent using pyrolytic yields (S_1 and S_2). Average production indices for the pre-Knox samples range from 0.4 to 0.6, indicating that the interval sampled is in the gas-generation window. Richer Cambrian source rocks may occur elsewhere in the basin, and may have undergone relatively high thermal activity, generating the characteristic gas, condensate, and high-gravity oil found in pre-Knox reservoirs.

Ontario reservoir rocks consist of either sandy dolostone or sandstone (Fig. 12). The most complete reservoir data available for southwestern Ontario are from the Innerkip and Innerkip East Fields (Bailey Geological Services Ltd. and Cochrane, 1984; Phil Mitchell, Denbridge Gas Corp., oral communication, 1994). These data are summarized in Table 2. Innerkip and Innerkip East Fields produce primarily gas, although minor associated oil is also produced from Innerkip. Gas expansion is thought to be the primary reservoir drive mechanism. The producing interval is at a depth of 2,831 to 2,917 ft. Pay thickness averages 11 ft, and the reservoir was initially underpressured, at 500 psi. Forty gas wells had been completed in Innerkip through 1994. Older wells in Ontario were typically treated with acid, but more recent wells have been hydraulically fractured to enhance production.

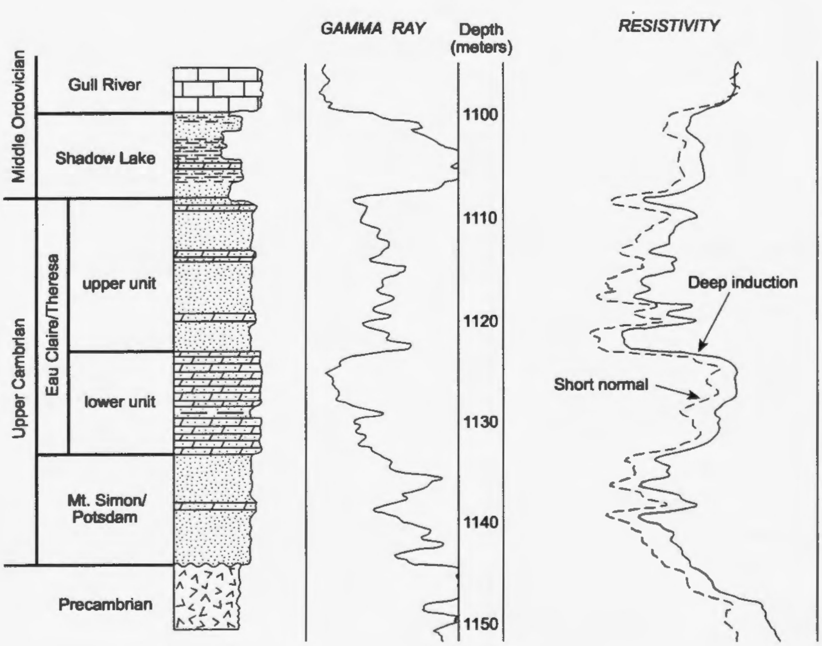

Figure 12. Typical geophysical and lithologic logs for the Cambrian and Middle Ordovician of southwestern Ontario. These data are from the Ontario Geological Survey 82-3 Yarmouth 3-9-I stratigraphic borehole. Lithologic patterns are the same as in Figure 4. (Modified from Trevail, 1990.) Used with the permission of the Ontario Petroleum Institute.

Reservoir heterogeneity in Ontario is generally moderate. Sandstones and dolostones were uniformly deposited on the flank of the Algonquin Arch (Trevail, 1990), but lateral facies changes resulted from tidal channel development and fill (Phil Mitchell, Denbridge Gas Corp., oral communication, 1994). Variations in porosity resulted from carbonate cementation and secondary dissolution of feldspars and ooids. Average log porosity for Innerkip Field is 9.5 percent. Permeability in this field averages 1 millidarcy (md). Pressure decline data from Innerkip also indicate a low-permeability reservoir (Bailey Geological Services Ltd. and Cochrane, 1984).

Potential reservoir facies in the Rome Trough consist of sandstones, carbonates, and fractured shales. Sandstones and fractured shales have been responsible for most of the production to date, but the dolostone intervals of the Conasauga Group and Shady/Tomstown Dolomite may have reservoir potential. Reservoir parameters in the Rome Trough are based on only three commercial wells, and thus should not be considered characteristic or inclusive. Depth to pay ranges from 6,250 to 14,350 ft below surface. Records on file at the Kentucky Geological Survey indicate average depth to pay is 8,953 ft below surface. Thickness of pay ranges from 10 to 100 ft and averages 41 ft. Rock pressure ranges from 2,708 to 11,710 psi and averages 6,139 psi. Initial open-flow data were available for two wells, the Exxon No. 1 McCoy and the Carson No. 1 Kazee, and were 9.2 and 11 MMcf/d, respectively. Final open flows for the Ashland No. 1 Williams and the Exxon No. 1 McCoy were 1.055 and 9.1 MMcf/d, respectively, an average of 5.1 MMcf/d. Although a final open flow of 9.1 MMcf/d was reported for the Exxon No. 1 McCoy well, production data indicate a settled production rate of 5.6 MMcf/d. Drive mechanisms may be solution gas, gas expansion, or water. Completion strategies range from acid fracturing of open-hole intervals to conventional acid treatment through perforated casing.

In the Rome Trough, reservoir heterogeneity results from a complex interplay of depositional processes and syndepositional faulting. Production to date is entirely limited to single-well pools, so an accurate evaluation of heterogeneity within a reservoir is not possible. Fracture porosity is associated with faulting and folding, and may be partially to completely crustified by mineralization in some areas. The Basal sandstone and the younger Mt. Simon Sandstone on the craton are transgressive deposits, and commonly have good porosity and permeability. They range from fine to coarse grained, are moderately to well sorted, and are commonly friable. Rome For-

Table 2. Data for the Innerkip Field, Oxford County, Ontario, Canada.

Basic reservoir data	Discovered	1961
	Depth to top of reservoir	2,800 ft
	Age of reservoir	Late Cambrian
	Formation	Potsdam/Theresa
	Producing reservoir	Potsdam/Theresa
	Lithology	sandstone
	Trap type	stratigraphic
	Depositional environment	shallow marine
	Discovery well initial potential	1,187 Mcf
	Drive mechanism	gas expansion
	No. producing wells	40
	No. abandoned wells	3?
	Area	4,000 acres
	Oldest formation penetrated	Precambrian
	Expected heterogeneity due to:	diagenesis/deposition
Reservoir parameters	Average pay thickness	11 ft
	Average log porosity	9.5%
	Minimum log porosity	3.5%
	Maximum log porosity	22%
	Average permeability	1 md
	No. data points	45
	Reservoir temperature	82.4°F
	Initial reservoir pressure	500 psi
	Producing interval depths	2,831–2,917 ft
	Present reservoir pressure	300 psi (1995)
Fluid and gas properties	Gas gravity	0.634 g/cm^3
	Gas saturation	75%
	Water saturation	25%
	Commingled?	no
	Associated or nonassociated?	nonassociated
	Btu/scf	1,110
Volumetric data	Status	producing
	Original gas in place	14,300,000 Mcf
	Original gas reserves	10,000,000 Mcf
	Production years	1961–1995
	Reported cumulative production	9,500,000 Mcf
	Remaining gas in place	4,800,000 Mcf
	Remaining gas reserves	500,000 Mcf
	Recovery factor	70%

mation sandstones have poorer reservoir characteristics, but are quite variable and difficult to predict. These sandstones are typically fine to very fine grained, micaceous, and glauconitic. Coarser grained facies may occur in proximity to major border faults. Porosity data for the three commercial pre-Knox wells in the Rome Trough are limited. The Ashland No. 1 Williams well produces from a fractured shale, and the borehole is washed out over this interval, invalidating the porosity logs (Fig. 13). The Exxon No. 1 McCoy produced for about 6 months from a 10-ft-thick porous sandstone in the Conasauga Group (Fig. 14). Average log poros-

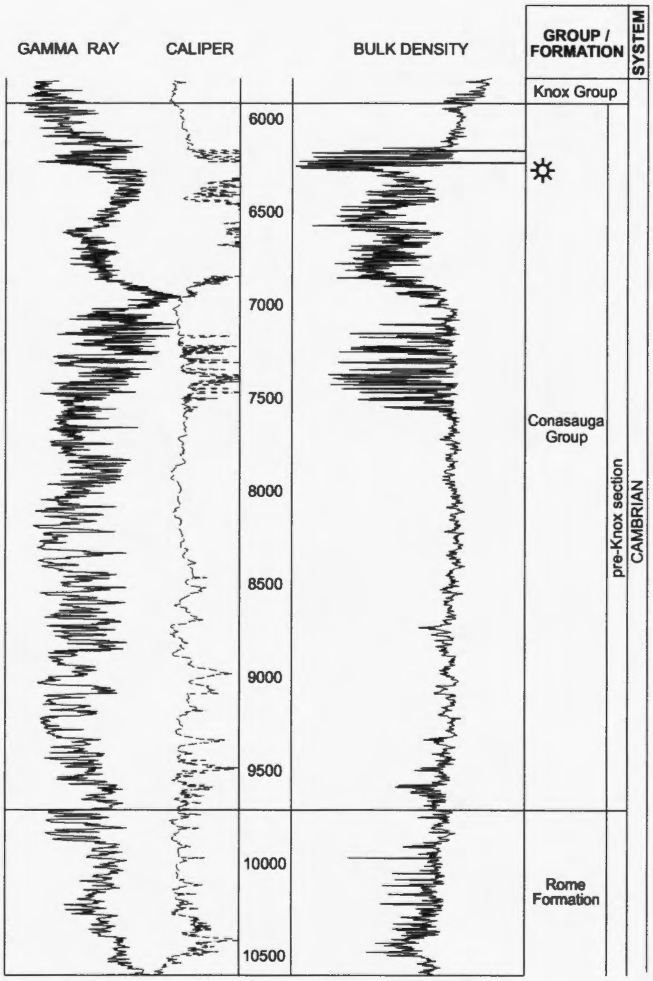

Figure 13. Gamma ray, caliper, and bulk density logs for the pre-Knox interval in the Ashland No. 1 Williams well, Johnson County, Ky. This well initially produced 1.055 MMcf/d from 6,250 to 6,350 ft in the Conasauga Group (production indicated by gas symbol). Reservoir rock is a fractured shale (note severe borehole washout indicated on caliper log). Stratigraphic correlations based on Ryder (1992a).

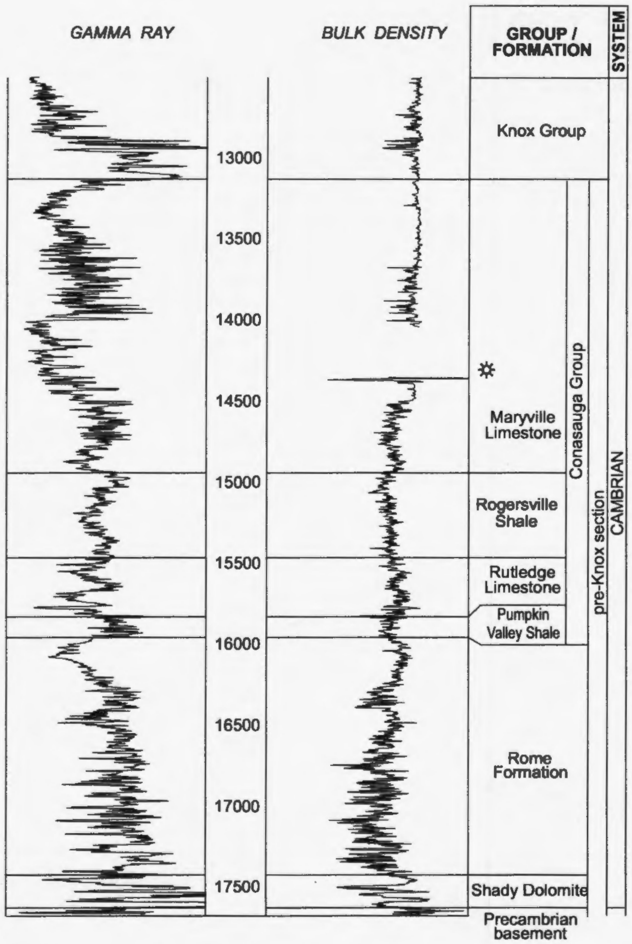

Figure 14. Gamma ray and bulk density porosity logs for the Exxon No. 1 McCoy well, Jackson County, W.Va. This well produced at a rate of 5.6 MMcf/d from 14,350 to 14,360 ft for about 6 months. Reservoir is a porous sandstone in the Conasauga Group. Stratigraphic correlations are from Ryder (1992a).

ity in this zone is 11 percent, and ranges from 3 to 15 percent. Logs from the Carson Associates No. 1 Kazee well are confidential at this time.

Gas analyses for two of the commercial wells in the Rome Trough are shown in Table 3. The Exxon No. 1 McCoy gas analysis indicates an almost pure methane composition, while the Ashland No. 1 Williams gas has heavier components, consistent with reports of some produced condensate. Both wells have Btu values of over 1,000 (Table 3). At least two wells in the western part of the Rome Trough in Kentucky, and one well on the craton in Highland County, Ohio, have had significant shows of low-Btu, non-combustible gas. Two of the wells are located in Garrard County, Ky.; tests indicate the gas was from the Rome Formation and had an average methane content of 15.9 percent and an average nitrogen content of 76.8 percent (Table 4; data from U.S. Bureau of Mines natural gas database). These wells were of interest as a possible source of helium; they averaged an unusually high 1.6 percent of the gas. Gas analyzed from the Highland County, Ohio, well was lower in nitrogen (32.6 percent) and higher in methane (60.2 percent) than the Kentucky wells, but was still noncommercial (Table 4). Helium content of gas from the Ohio well was not available. The origin of these high-nitrogen gases is not known, but Garrard County, Ky., and Highland County, Ohio, are both located near the Grenville Front, a major tectonic suture between the Precambrian Grenville Province and the Keweenawan(?) East Continent Rift Basin (Drahovzal and others, 1992). A deep-basement origin for part of this low-Btu gas is possible. The risk of low-Btu gas appears confined to the western Rome Trough/Grenville Front area, since gas produced farther east in the trough (Johnson and Elliott Counties, Ky., and Jackson County, W.Va.) is of commercial quality (Table 3).

Resources and Reserves

The variety of reservoir and trap types included in this play and the very limited commercial production to date make calculation of gas resources and reserves in most of the play area extremely speculative. Gas resources in the play area are best known for southwestern Ontario, because of its long history of gas production and more mature stage of exploration. Bailey Geological Services Ltd. and Cochrane (1984) calculated total proven gas reserves for Ontario of 16.6 Bcf as of 1981. Gross undiscovered resources, using data from both pinch-out and structural fields, were calculated by Bailey Geological Services Ltd. and Cochrane (1984) to be 152.1 Bcf, and potential recovery was 810.7 Mcf per acre-ft. Insufficient data are available to calculate proven reserves outside of Ontario.

There are essentially no production data on which to base more precisely determined resources; therefore, undiscovered resource calculations for the pre-Knox interval in the rest of the basin are largely speculative. The basin is divided into three resource calculation areas based on relative risk and estimated gas recoveries (Fig. 15, Table 5). The lowest risk area (area A, Fig. 15) consists of all areas in which shows or commercial production have been reported from the pre-Knox interval. This area covers the stable craton in parts of southwestern Ontario, Ohio, Pennsylvania, New York, and Kentucky, and the western and southern parts of the Rome Trough in West Virginia and Kentucky. A deeper, higher risk area (area B, Fig. 15) consists of the eastern and northeastern parts of the Rome Trough in West Virginia, Pennsylvania, and New York, where drilling is very sparse and no shows have been reported. The third area (area C, Fig. 15) is thought to contain the highest risk of commercial gas production. It consists of the deepest parts of the basin, east and southeast of the Rome Trough. We estimated potential undiscovered resources for these three areas by calculating the gross acreage of each area, and estimating a net pro-

Table 3. Analyses of commercial-quality gases from Cambrian reservoirs in the Rome Trough, Appalachian Basin.

Gas (mole percent)	*Ashland No. 1 Williams Johnson Co., Ky. Conasauga/Rome: 6,250–6,350 ft*	*Exxon No. 1 McCoy Jackson Co., W.Va. Conasauga: 14,350–14,360 ft*
Methane	81	97
Ethane	9	2
Propane	4	< 1
N-Butane	1	< 0.1
I-Butane	< 1	< 0.1
Pentanes	< 1	< 0.1
Nitrogen	2	1
H_2S	0	0
CO_2	1	0
Total*	99	100
Btu	1,175	1,022

*Totals do not add up to 100 percent due to rounding.

Table 4. Analyses of low-Btu, high-nitrogen gases from Cambrian reservoirs in the western Rome Trough. Unpublished data from the U.S. Bureau of Mines natural gas database.

Gas (mole percent)	*Texaco No. 1 Kirby, Garrard Co., Ky.*		*Widener No. 1 Burdette, Garrard Co., Ky.*	*Oxford Heyob, Highland Co., Ohio*
	Conasauga/Rome		*Conasauga/Rome*	*Eau Claire*
	4,546 ft (avg. of 3 samples)	*4,574 ft*	*4,450 ft*	*2,810 ft*
Methane	13.9	14.5	19.3	60.23
Ethane	2.1	2.2	4.5	3.14
Propane	0.6	0.6	0.7	1.43
N-Butane	0.3	0.3	0.5	0.46
I-Butane	0.0	0.0	0.3	0.14
N-Pentane	0.2	0.4	0.2	0.15
I-Pentane	0.0	0.0	0.1	0.06
C-Pentane	< 0.05	< 0.05	< 0.05	NA
Hexane-PL	0.2	0.2	0.1	0.1
Nitrogen	80.4	79.3	70.7	32.64
Oxygen	0.1	0.1	0.0	NA
Argon	0.4	0.4	0.5	NA
Hydrogen	0.1	0.1	0.0	NA
H_2S	0.0	0.0	0.0	NA
CO_2	0.1	< 0.05	1.8	1.63
Helium	1.62	1.81	1.32	NA
TOTAL*	100.02	99.91	100.02	99.98
Gravity	0.916	0.911	0.912	0.750
Free air	0	0	0	NA
Btu	227	240	339	723

*Totals do not add up to 100 percent due to rounding.

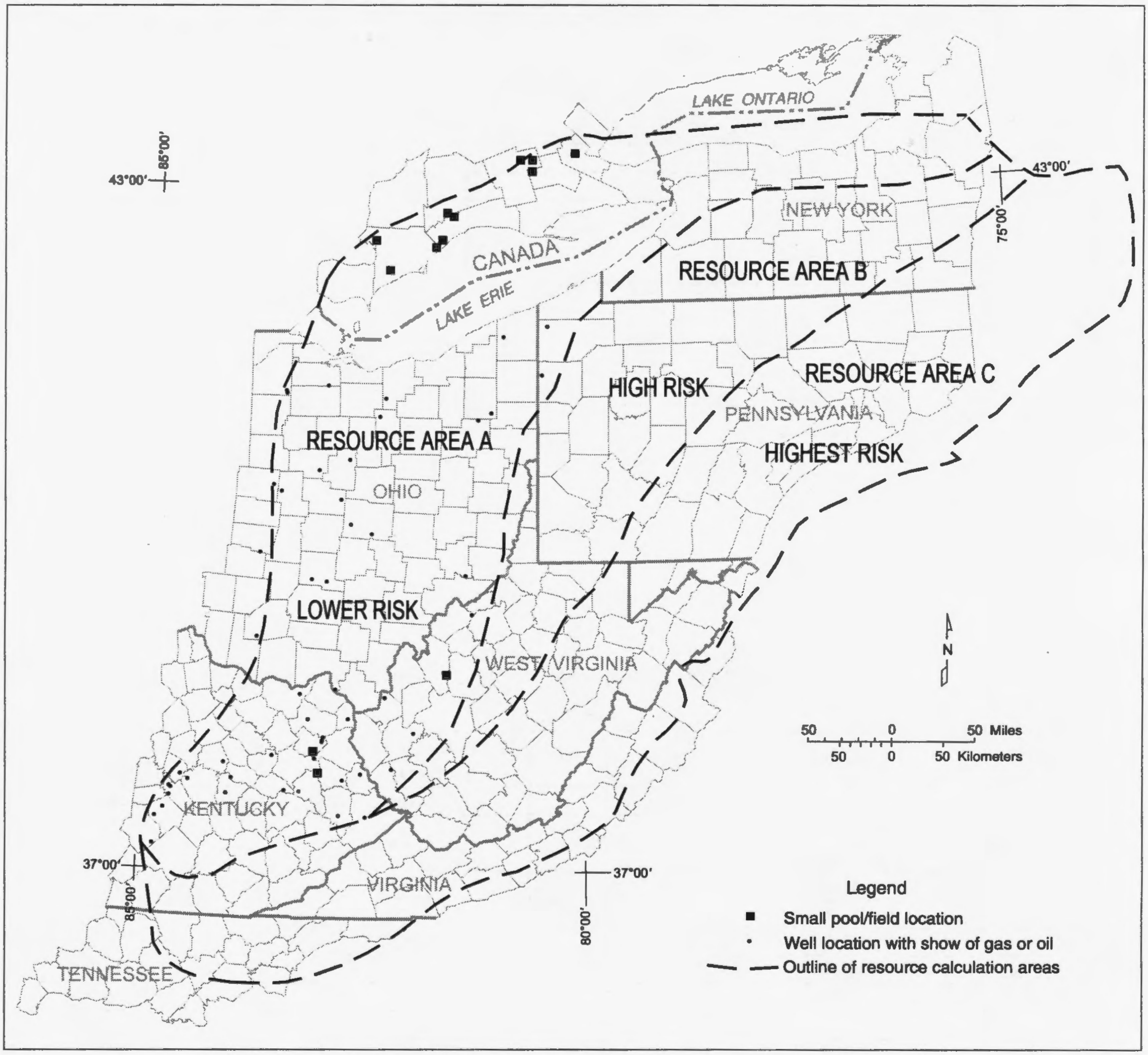

Figure 15. Risk areas for reserve calculations for the Cambrian pre-Knox play. Area A: gas shows and production to date. Area B: lacks shows, but covers the sparsely drilled part of the Rome Trough. Area C: highest risk of commercial gas because of burial depth and thermal maturity. Gas resources calculated from these areas are shown in Table 5.

Table 5. Gas resource estimates for the Cambrian pre-Knox play in the Appalachian Basin.

Resource Area	*Gross Area (acres)*	*Estimated Ratio of Productive Area to Gross Area*	*Estimated Net Productive Area (acres)*	*Estimated Gas Recovery per Acre (Mmcf)*	*Estimated Recoverable Gas Resources (Bcf)*
A	46,000,000	0.002	92,000	5.0	460
B	21,700,000	0.001	21,700	2.5	54
C	41,700,000	0.0005	20,850	1.0	21

ductive area for each risk area using ratios that reflect the relative exploration risk (Table 5). Using estimates of gas recovery per acre for reservoirs of similar age and depth from Geomega, Inc. (1983), we then calculated estimated recoverable gas resources (Table 5).

Future Trends

The pre-Knox interval in the Appalachian Basin has potential for future gas exploration. Much of the section has been sparsely drilled, and thick untested intervals remain in parts of the Rome Trough and eastern deep basin areas. Viable structural and stratigraphic prospects are possible in many areas. Fault closures and fractured prospects associated with the Rome Trough remain the highest priority targets. In addition, stratigraphic traps within the Rome Trough, although of higher risk, are potential reservoirs. Sandstones (including turbidite fans) (Drahovzal, 1994) and carbonates in the Conasauga, Rome, and Shady intervals are possible reservoirs in the trough. In Ontario, structures downdip from the mature unconformity truncation play may be prospective. On the craton in Ohio, western Pennsylvania, and New York, subtle stratigraphic and structural anomalies indicated on seismic profiles should be tested. The deep basin east of the Rome Trough is poorly drilled in the pre-Knox interval. Reservoirs in this deep area are largely unknown, but are likely to be of moderate to poor quality. Potential source rocks may be low in organic matter. Additional geochemical work and structural analyses are warranted.

Successful exploration in this play will require additional geologic interpretation. Organic geochemistry studies should be expanded to determine hydrocarbon sources and maturity profiles. Depositional models should be refined with available well and seismic data to allow prediction of favorable reservoir trends. A better understanding of the structural history of the eastern deep basin and Rome Trough, using seismic data, is crucial for recognizing traps and their relative sequence of formation. The relative timing of trap formation and hydrocarbon migration, derived from geochemical and subsidence studies, should be resolved.

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