ROME TROUGH CONSORTIUM

FINAL REPORT AND DATA DISTRIBUTION

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Chapter 1.

Introduction, Goals, Conclusions, Project Data, Production History, Previous Work, Acknowledgements

D. C. Harris,
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Introduction

This report contains the results of research conducted by the Rome Trough Consortium, a partnership of three state geological surveys, several energy industry companies and the U.S. Department of Energy. The Consortium was headed by the Kentucky Geological Survey, University of Kentucky, Lexington, Ky. Research was also conducted by the Ohio Department of Natural Resources, Division of Geological Survey in Columbus, Ohio and the West Virginia Geological and Economic Survey in Morgantown, W. Va.. Members of the consortium are listed in Table 1-1. This consortium was formed to gain a better understanding of the geology and deep hydrocarbon potential of the Rome Trough, a Cambrian-age depositional basin located in eastern Kentucky, northern West Virginia, and southeastern-most Ohio. The Consortium was initiated in January 1999, and research lasted 2 years, with a final project review and core workshop on January 24, 2001 at the Kentucky Geological Survey in Lexington, Ky. At this meeting members decided to continue research on core material that arrived near the end of the project. This report documents all research done through mid-2002. Significant new research resulted from the extra time allowed to continue this work.

Data Confidentiality

As agreed in the original Consortium proposal, this report and all project data (with the exception of some geochemical data contributed by the U.S. Geological Survey) will be held confidential to Consortium members for a period of 2 years. The anticipated release date for these data is August 1, 2004.

Goals

The original goals of the Rome Trough project are listed below.

1) Correlate regional stratigraphic units and illustrate with cross sections. Because of the variety of stratigraphic nomenclature used for the Cambrian rocks in the study area, the first goal was to produce a regional stratigraphic framework for the sub-Knox Group rocks using consistent well log correlations. These regional correlations were used to build cross sections using digitized well logs, showing stratigraphic relationships in and around the Rome Trough.
2) Compile stratigraphic tops database. Stratigraphic formation tops collected during regional correlation were entered into a computer database, to allow the data to be manipulated electronically.
3) Describe available cores. Description and interpretation of cores from sub-Knox Group rocks in the study area. The originally proposed well cuttings work was changed to core studies after numerous cores from the Rome Trough were made available.

4) Homer Field study. This part of the study involved a detailed interpretation of the Homer field, a Rome gas field in Elliott County, Ky.
5) Generate regional maps of sand distribution and paleogeography/lithofacies in the sub-Knox interval. Log-derived lithologic data was used to map clastic and carbonate trends in the trough.
6) Compile a hydrocarbon geochemistry database. Originally planned as a simple compilation of available data, this part of the project grew substantially. With the help of the U.S. Geological Survey, a significant amount of new geochemical data was collected for source rocks and hydrocarbons in the Rome Trough.

The data collected and results of the project have far exceeded these original goals. Several opportunities that were unforeseen at the start of the project added significantly to the deliverables in this report.

Major Conclusions and Summary

1. Cambrian stratigraphy has been revised in Ohio and eastern Kentucky. The Conasauga Group and its component formations have been correlated into Kentucky and Ohio. The recognition of these units allows a more accurate interpretation of the depositional history of the Rome Trough and surrounding area.

2. Stratigraphic formation tops have been collected on 761 Knox and deeper wells in the 3-state study area. These data have been compiled in a Microsoft Access database, with as many as 50 tops per well.

3. The Rome Formation is not recognized north of the bounding faults of the Rome Trough, and the use of the term Rome in northern Kentucky and Ohio (Janssens, 1973) is discouraged. While we are not formally proposing new stratigraphic nomenclature at this time, rocks previously correlated as the Rome and Conasauga Formations in north-central and northeastern Kentucky and Ohio are interpreted as Maryville Limestone, Nolichucky Shale, and Maynardville Limestone of the Consauga Group.

4. Stratigraphic correlations in the Conasauga Group have revealed the presence of a westward prograding carbonate ramp and distal intrashelf shale basin in the Rome Trough of Kentucky. The Conasauga Group formations record several cycles of progradation and transgression from east to west. These cycles correspond to cycles in the Conasauga Group and an intrashelf basin in the outcrop belt in eastern Tennessee, thus extending the mapped extent of these units.

5. Regional stratigraphic interpretations are documented in a series of 13 structural and stratigraphic cross sections. The cross sections utilize digital well log plots and lithology data calculated from the log data.

6. Stratigraphic and lithofacies interpretations are also presented in a series of 5 paleogeographic maps. These maps document the distribution of rock units and general depositional environments for 5 time intervals.

7. Cambrian cores from 19 wells were described for the study. The Consortium was able to obtain important core donations from Texaco and Exxon to greatly enhance the project.

8. Hydrocarbon reservoir development is most likely to occur in sandstones within the Rome Formation and the Maryville Limestone of the Conasauga Group. Highest potential for Rome reservoirs occurs along the Irvine-Paint Creek shelf in eastern Kentucky. Sandstones within the Maryville Limestone occur primarily in Kentucky and Ohio, with more limited distribution in West Virginia. Current gas production occurs from both the Rome Formation and Maryville Limestone in Elliott, Johnson, and Lawrence Counties, Ky. The basal Cambrian sandstones in the basin (Mt. Simon Sandstone in northern Kentucky and Ohio, and the basal sandstone in the Rome Trough) have reservoir potential but are less attractive targets due to other concerns (primarily hydrocarbon charge).

9. Porosity in Rome and Conasauga sandstones is common, and widely distributed in Kentucky and Ohio. Porosity development in sandstones is not considered a major risk factor in prospect evaluation in these areas. Permeability distribution in sandstones was not addressed in this study, but is a concern in some areas. Porosity development in Rome and Conasauga limestones and dolomites is rare, and carbonates are not considered an attractive exploration target. There is potential for fractured reservoirs, both in carbonates and shales, but this reservoir type is much higher risk. One well in Johnson County, Ky. currently produces from fractured Conasauga shale. Potential also exists for hydrothermal, fault-related dolomitization in Rome/Conasauga carbonates. However, no evidence of fault-controlled dolomitization has been seen to date in these rocks.

10. Geophysical logs from 157 wells were digitized or compiled for the project. These digital logs were used for interactive correlation and cross section construction. For the 109 wells with sufficient log curves, the digital data was used to calculate lithologies using a 4 mineral model (sandstone, limestone, dolomite, shale (and porosity). The sandstone component of the lithology data was then mapped by formation to generate sand percentage maps. These maps indicate the percentage of gross and net sandstone in the Rome and Maryville Limestone across the study area.

11. Current production from the Rome/Conasauga interval in the Rome Trough is from structural traps. These fields are fault-related, with the largest field (Homer) lying on a buried fault that was not reactivated in post-Pennsylvanian time, unlike other parts of the Kentucky River and Irvine-Paint Creek fault systems. Such buried faults have a lower risk of being breached by recurrent movement along the trapping fault than faults that have evidence of more recent reactivation (such as surface expression).

12. Detailed study of the Homer Field in Elliott County, Ky. has indicated the presence of 5 sandstone reservoir zones within the field, in the Rome, Conasauga, and Ordovician St. Peter Sandstone. Cambrian production occurs on the upthrown side of a north-south trending growth fault, on the Irvine-Paint Creek shelf. Significant facies changes occur across this fault in Cambrian and Ordovician zones. Monthly production data for the Homer Field has been compiled and provided in digital format for the years 1997 through 2000.

13. Cambrian sub-Knox hydrocarbon source rocks have been identified for the first time in the Rome Trough area. Shales with total organic carbon high enough to generate commercial amounts of hydrocarbons occur from the western end of the trough in Jessamine County, Ky. to Wayne County, W. Va. in both the Rome Formation and Conasauga Group. The Rogersville Shale of the Conasauga Group contains a significant thickness of high-TOC shales that have generated hydrocarbons. Hydrocarbon extracts from these shales are geochemically similar to produced condensate in the Homer Field in Elliott County, Ky.

14. Cambrian oil (condensate) samples from the Homer Field in Elliott County, Ky. have a geochemical signature similar to known Ordovician and Cambrian-sourced oils. While an Ordovician source cannot be ruled out, geological constraints suggest the likely source rocks occur below the Knox Group, in the Cambrian Conasauga and Rome intervals. The proximity of shales with sufficient TOC and thermal maturity to have generated hydrocarbons in the Rogersville Shale in the Exxon 1 Smith well also supports a Cambrian source for these hydrocarbons.

Study Area

The study area is shown in Plate 1, and includes eastern Kentucky, northwestern West Virginia and southern Ohio. To extend correlations into Tennessee and Virginia, one well from each of those states was also included. The study area was defined to cover the extent of the Rome Trough and adjacent areas to the northwest and southeast. While the Rome Trough probably extends into Pennsylvania and New York, data in those states is very limited, and these areas were not included in the study.

Project Data

Geologic data available for the project included a total of 761 wells, covering parts of 5 states. Criteria for wells selected for use in the project varied by state. In Kentucky, all wells penetrating the Cambrian Copper Ridge Dolomite (Knox Group) were included. In addition, all wells penetrating the top of the Knox Group (Beekmantown Dolomite) with in the Rome Trough boundaries were included. Outside of the trough in Kentucky, the number of Beekmantown wells was reduced by selecting wells with the best available data in areas of dense control. This process resulted in a total of 648 wells in Kentucky. In Ohio, all wells penetrating sub-Knox Group rocks in the study area were included, plus one additional Beekmantown Dolomite well, for a total of 89 wells. In West Virginia, due to the limited well control, all Knox Group and deeper penetrations were included, along with 5 Trenton-Black River wells, for a total of 22 wells. In addition, two wells, one in Campbell Co., Tennessee and one in Russell County, Virginia were included into order to extend stratigraphic correlations toward the Cambrian outcrop belt in the Appalachian Mountains. Stratigraphic data for the 761 project wells is included in the project database on the accompanying CD-ROM, in Microsoft Access and Excel file formats.

Data used in the project consisted primarily of geophysical well logs and driller's logs. Commercial sample descriptions (Geolog, Inc.) were utilized when available. No seismic data were interpreted as part of the project, We did collaborate with T. White, a graduate student at the Department of Geological Sciences, University of Kentucky during her seismic study of the Rome Trough.

Digital Well Log Data

Geophysical well logs from key deep wells were digitized from scanned images using Neuralog software. All Precambrian wells were digitized, and other wells were selected based on their location and log quality. The distribution of digital well log data is shown in Plate 17. A total of 157 wells were either digitized during the project or compiled from contributions from consortium members and other industry sources. All digitized logs are included on the project CD-ROM in Log ASCII Standard (LAS) format. These are ASCII text files that can be viewed in a text editing program such as Microsoft Wordpad. The LAS format is the industry standard for well log data, and many log analysis and mapping programs will import LAS files. Files are named with the API number of the well. All digital log data is documented in a Microsoft Access

database table in the project database file. This table identifies which curves were digitized in each well, with start and stop depths included. The number of curves and footages digitized per well varies, and not all curves were digitized in every well. In some of the deep wells, logs were only digitized from the top of the Knox down. The LAS files also contain new data that was calculated from the original log curves. This data includes calculated lithology fractions for wells with sufficient data to do these calculations. A listing of wells with digitized well logs is included in Chapter 5 of this report.

Core Data

Other data included cores from 19 wells in Kentucky, Ohio and West Virginia. These cores were used for depositional interpretation and hydrocarbon source rock analyses. Core descriptions are included in Appendix B.

Potential Fields Data

Although not an original part of the project proposal, we compiled public domain gravity and magnetic data for the study area. These data were not interpreted as part of the project, but are provided on the CD-ROM in the form of ESRI ArcView GIS shape files. There is also an ArcView project file that can be opened to load and view the data.

Geological software

This project made extensive use of geologic interpretation software produced by Terrasciences, Inc. The TerraStation program was used for log-based lithology calculations, mapping and well log cross-sections. All of the project data is available in TerraStation format if consortium members are using this software. We would like to acknowledge and thank Terrasciences for providing this software to KGS.

Production History and Previous Work

Hydrocarbon exploration in Cambrian age rocks in Kentucky, West Virginia and Ohio dates back to the 1940's when better drilling technology allowed deeper targets to be tested. Shows of oil and gas were reported from some of these older wells, but no commercial production was established. For a complete list of wells with reported Cambrian sub-Knox hydrocarbon shows, see Harris and Baranoski (1996). The development of improved seismic reflection techniques in the early 1960's helped to encourage deep exploration in the late 1960's and 1970's. Numerous deep tests were drilled by several major companies, and medium-sized independents. Seven wells have been drilled to depths greater than 15,000 ft, with the deepest well reaching 20,222 ft (the Exxon 1 Gainer-Lee well, Calhoun Co., W. Va.).

The first commercial production from Cambrian sub-Knox rocks occurred during this period with completion of the Inland Gas 529 White well in Boyd Co., Ky. in 1967. This well is reported to have produced about 30,000 bbl of oil. In 1975 Exxon completed the No. 1 McCoy well in Jackson County, W. Va. with an initial open flow of 9.2 MMcf gas per day (MMcf/d). This was the first commercial gas well in the Rome Trough, and produced a total of 427 MMcf gas at a rate of 5.6 MMcf/d for approximately 6 months (Harris and Baranoski, 1996). This well produced from a sandstone in the Conasauga Group (Maryville Limestone). This well was plugged after 6 months due to increasing water production. About 10 years later Ashland Exploration completed a deep test in the Minefork Field in Johnson County, Ky. The Ashland 1 Williams well reported an initial open flow of 1.055 MMcf/d from fractured Nolichucky Shale at 6,250-6,350. According

to Kentucky Geological Survey (KGS) records this well has not been plugged, and is assumed to still be producing as of 2002.

In 1994, a second major phase of deep drilling to Cambrian targets in eastern Kentucky began after the discovery of gas in the Carson Associates 1 Kazee well in Elliott County, Ky. This discovery well for what was later named the Homer Field initially flowed 11 MMcf/d from a sandstone in the Maryville Limestone of the Conasauga Group. This well produced at a rate of 500 Mcf/d (thousand cubic feet per day) for an unknown period of time. When visited in 1999 for gas sampling, the well had declined sufficiently to be converted for use as a domestic gas supply. The Homer field has been successfully developed with additional drilling since its discovery in 1994, and is discussed in greater detail in Chapter 6 of this report.

Carson Associates made one additional gas discovery in the Rome Trough in Lawrence County, Kentucky in 1998. The Carson Associates 1 Ray well produces gas and condensate from the Conasauga Group (Maryville Limestone). This well had not been offset at the time of this report.

Additional sub-Knox exploration since the Homer Field discovery has resulted one additional discovery in Lawrence County, and numerous dry holes being reported. These include deep tests in Carter, Johnson, Morgan, Wolfe, Powell, and Elliott Counties, Ky. Data from wells drilled through the end of 2000 were used in interpretations for this study. No recent drilling to Cambrian sub-Knox targets has been reported in West Virginia.

Previous Research

Harris and Baranoski (1996) summarized much of the previous research on the Rome Trough. Key Cambrian regional studies for each state include McGuire and Howell (1963) for Kentucky, Janssens (1973) for Ohio and Cardwell (1977) for West Virginia. Key dissertation research studies include Webb (1980), Cable (1984), and Cable and Beardsley (1984). An excellent stratigraphic reference for the Rome Trough is a series of 6 stratigraphic cross sections published by Bob Ryder and colleagues at the U.S. Geological Survey (Ryder,1991; Ryder, 1992a; Ryder 1992b; Ryder and others, 1992, Ryder and others, 1996; Ryder and others, 1997). These cross sections utilize well data for the Ordovician and Cambrian, and they formed the basis for revised stratigraphic correlations in this project. Several new abstracts and papers have been published since the Appalachian Basin Gas Atlas (Harris and Baranoski, 1996). These include Earle and others (1997) who discuss the Blue Ridge Group #1 Greene well in Elliott County, Ky. Lynch and others (1999) published an important abstract on the area around the Homer Field. This paper describes the Isonville Fault, which traps the Homer Field.

Two papers on the structure and subsidence history of the Rome Trough were published in 2000 (Gao and others, 2000 and Wilson, 2000). The Gao and others (2000) paper is discussed more fully in Chapter 2.

White (2002) has just completed recent research on structure and faulting interpreted from seismic data. This is a MS thesis completed at the University of Kentucky. Some of the results of this work have been published as abstracts (White and Drahovzal, 2000; 2001, 2002). They have some interesting new interpretations on Rome Trough faulting.

A interesting paper was published in 1999 by Rodvelt and others (1999) on stimulation of Rome sandstone reservoirs. This paper discusses permeability problems in Rome sandstones, and their fluid sensitivities. A case history of a CO_2 foam fracture stimulation is discussed in detail.

Finally, Rome Trough source rock quality and hydrocarbon geochemistry were discussed in Ryder and others (1998). This paper summarizes data collected in the 1980's and early 1990's for Cambrian and Ordovician source rocks. This paper is discussed more fully in Chapter 7.

Report Format

This report consists of eight chapters, two appendices, 31 plates, and a data CD-ROM. Plates 4A–16B are rolled in a separate tube. Authorship credit is listed in each chapter. References are listed separately for each chapter.

Acknowledgements

We would first like to acknowledge the financial support of the four industry partners, and the U.S. Department of Energy (under contract DE-AF26-98FT02147), who funded this study. Without this funding, the project would have never been done. We appreciate the collaboration of the Ohio and West Virginia Geological Surveys on this research, and have benefited greatly from this interaction.

Various companies contributed important data to the project. We appreciate the willingness to share data shown by the industry participants, and Monte Hay and Dan Wells. Equitable Resources provided key digital logs, geochemical data, and cores from the Homer Field. Columbia Natural Resources provided log and core data from several wells. Exxon and Texaco contributed important cores to the project, which will now be housed permanently at the respective state surveys.

Our collaboration with the U.S. Geological Survey in the geochemical part of the study resulted in important new conclusions on Cambrian source potential. We appreciate the help of Bob Ryder, Bob Burruss, and Bob Milici of the U.S.G.S.

M.C. Noger of the Kentucky Geological Survey provided valuable help with stratigraphic problems and regional geology.

TerraSciences, Inc. of Littleton, CO provided the TerraStation computer software used to perform many of the tasks and make most of the products for this study. We appreciate the continued support of TerraSciences.

Finally we would like to thank Tina White, Collie Rulo and Terry Hounshell for their help with drafting and assembling the final report.

Table 1-1. Rome Trough Consortium member companies and organizations. One copy of the final report is being sent to the contact person listed for each company.

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Chapter 2.

Regional Structure and Tectonics

J.B. Hickman, Kentucky Geological Survey

Introduction

The Rome Trough is an Early to Middle Cambrian age extensional graben that extends from northern Tennessee, northeastward through central and eastern Kentucky, West Virginia, into southwestern Pennsylvania (Woodward, 1961; McGuire and Howell, 1963; Drahovzal and Noger, 1995), and possibly into southern New York (Wagner, 1976). It is a portion of the eastern North American interior rift system that formed in conjunction with the opening of the Iapetus-Theic Ocean (Harris, 1978; Thomas, 1991). Although there is evidence of reactivation as recent as the post-Pliocene (VanArsdale and Sergeant, 1992), the majority of the extension (normal fault movement) within the Trough occurred during the Middle to Late Cambrian Period.

All of the major boundaries and structures within the Trough are created, either directly of indirectly, by basement rooted faults. These faults are all high angle normal faults, although there is evidence of some reactivated reverse motion during Appalachian tectonic compression (White, 2002). Except for a small portion in southern Boyle and northern Casey Counties in Kentucky (which overlies the East Continent Rift Basin), the vast majority of the Rome Trough overlies the Late Proterozoic metamorphic “basement” rocks of the Grenville allochthon (Keller and others, 1981; Drahovzal and Noger, 1995). Based upon well data in this project, the structural relief on the top of basement between the northern edge and the deepest part of the Trough is over 13,000 feet. Seismic data suggests that the relief upon the basement along the southern boundary is up to 4,400 feet (White, 2002). Overall, the top of basement within the Trough is shallower in central Kentucky, and deepens eastward along strike into central West Virginia. Although not documented by drilling data, previous interpretations of seismic data (Gao, et al., 2000) suggest that the basement deepens to over 24,000 feet below sea level in Kanawha Co.,

W.Va. The deepest basement top from well data within this project is 18,836 feet below sea level in Calhoun Co., W.Va.

Trough Border Faults

The Rome Trough is bordered by several basement faults. These include the Lexington Fault System to the west, the Kentucky River and Ohio River fault systems to the north and northwest, and the Rockcastle River fault system and the "East Margin Fault" of Gao et al. (2000) to the southeast (see Fig. 2-1).

The Lexington Fault system trends NNE from southern Casey Co. through Bourbon Co., Kentucky. This fault system directly overlies the Grenville Front, the western edge of the Grenville metamorphic basement complex. It appears that the portion of this high angle reverse fault, south of the Kentucky River fault system in Jessamine Co., was reactivated in the Early to Middle Cambrian. This normal fault motion (down to the east) along the front then created the western edge of the Rome Trough.

The Kentucky River fault system trends roughly west-to-east through central Kentucky (Figure 2-1). Unlike the Lexington fault system to the west however, only about half of its length is exposed at the surface. Although later movements within this fault system have been interpreted (based on river terrace deposits) to be as recent as the post-Pliocene (VanArsdale and Sergeant, 1992), the majority of movement (which totaled at least 1,200 to 1,800 ft) occurred during the Middle Cambrian. This time corresponds to the deposition of the lower portion of the Rome Formation.

The Ohio River fault system in West Virginia is not exposed at the surface, but is visible on seismic data (Gao, et al., 2000) and from dramatic changes in the depth to basement observed in local wells. This fault system trends northeast, approximately from the end of the Kentucky River fault system near the Kentucky state border, through western West Virginia, and into southwestern Pennsylvania. Due to the lack of deep wells or available seismic data within this portion of Pennsylvania, the configuration of

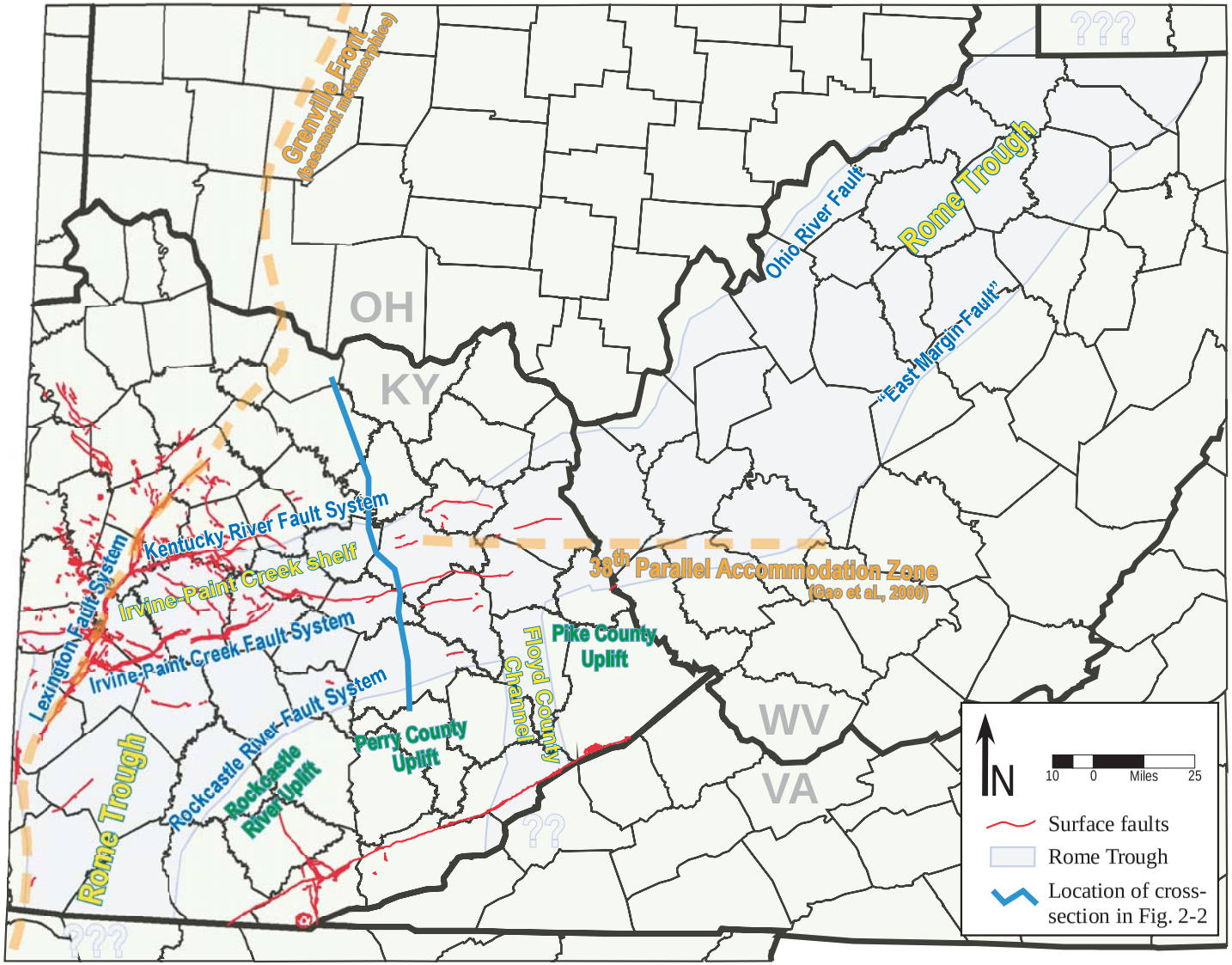

Figure 2-1: Major structural features and trough boundaries within the study area mentioned in the text.

this fault system, and of the whole Rome Trough structure in this area is poorly understood. However, the location and orientation of the Ordovician and Upper Cambrian aged Olin Basin (Wagner, 1976) in western Pennsylvania and southern New York suggest that these basement normal faults may continue northeast into this area. In West Virginia, movement along this fault system was similar in age to that along the Kentucky River fault system, with more than 1,000 ft of down-to-southeast movement occurring during the Early-Middle Cambrian.

None of the southeastern border faults of the Rome Trough are exposed, although there is evidence of localized deformation in the form of surface anticlines along the Rockcastle Uplift. In Kentucky, the Rockcastle River fault system separates the Trough from the Rockcastle River and Perry County Uplifts to the south (see Fig. 2-1). Based on stratigraphic thicknesses, the motion along these faults began around the same time as those within the Kentucky River fault system, but lasted until the Upper Cambrian. This corresponds to the time of deposition of the Shady Dolomite, the Rome Formation, and the Conasauga Group. Total vertical offset occurring through this time interval across the fault system increases to the east from around 1,000 ft for the Rockcastle River Uplift, to 1,800 ft or more along the Perry Co. Uplift, to more than 3,600 ft along the Pike County Uplift. The Floyd County Channel separates the Perry Co. Uplift from the Pike Co. Uplift to the east. This is a more than 2,000 ft deep graben that trends roughly north-south (see Fig. 2-1) from the center of the Rome Trough and continues at least as far as the Virginia border.

Unfortunately, no wells have been drilled deeper than the Upper Cambrian Knox Group in West Virginia southeast of the “East Margin Fault” of Gao et al. (2000). This makes direct measurement of basement offset across the fault impossible, but the displacement has been estimated from seismic data to be as much as 6,500 ft (Gao et al., 2000). The age of this movement appears to be the same as that for the Rockcastle River fault system, Early through Late Cambrian (Shady Dolomite to the top of the Conasauga Group).

Interior Structures

Basement faults also bisect the Trough's interior. In central and eastern Kentucky, the Irvine-Paint Creek fault system delineates an internal boundary between the shallower, northern section of the Trough and the deeper region to the south. The strike of the Irvine-Paint Creek Fault System is nearly identical to the strike of the Kentucky River fault, ~20 miles north (see Fig. 2-1). Both of these fault zones offset strata down to the south. The surface exposure of the Irvine-Paint Creek Fault System extends east from Lincoln County to Johnson County, Kentucky. Interpretations within this report, as well as those of Lynch et al. (1999) however, suggest that in the deep subsurface, the strike of the Irvine-Paint Creek fault system changes near the Morgan/Magoffin County line. From here the system (via the buried Isonville Fault) strikes north-northeast through eastern Elliott County, Kentucky. It is motion along this fault that later created the Paint Creek Uplift (Hudnal, and Browning, 1949). This may have been caused by localized inversion through a reactivation of the fault in a reverse motion due to lateral tectonic loading during the Alleghenian and/or Acadian orogenies.

Based on stratigraphic evidence studied in this project, there appears to have been a transfer of displacement during the Middle Cambrian between the Kentucky River fault system and the Irvine-Paint Creek fault system. Before that time, the extension forming the northern and southern boundaries of the Rome Trough in Kentucky was being created along the Kentucky River and Rockcastle River fault systems. Sometime during the deposition of the middle portion of the Rome Formation however, the movement along the Kentucky River faults stopped (or slowed dramatically) and extension began along the Irvine-Paint Creek fault system. Movement along the Rockcastle River faults during this time appears to have continued at approximately the same rate without interruption. This tectonic movement led to the formation of the shallower Irvine-Paint Creek shelf along the northern border of the Trough between the Kentucky River and Irvine-Paint Creek fault systems (see Fig. 2-2). South of this zone, the Trough extends down to the full depth, similar to that within West Virginia. Because of this, a major unconformity

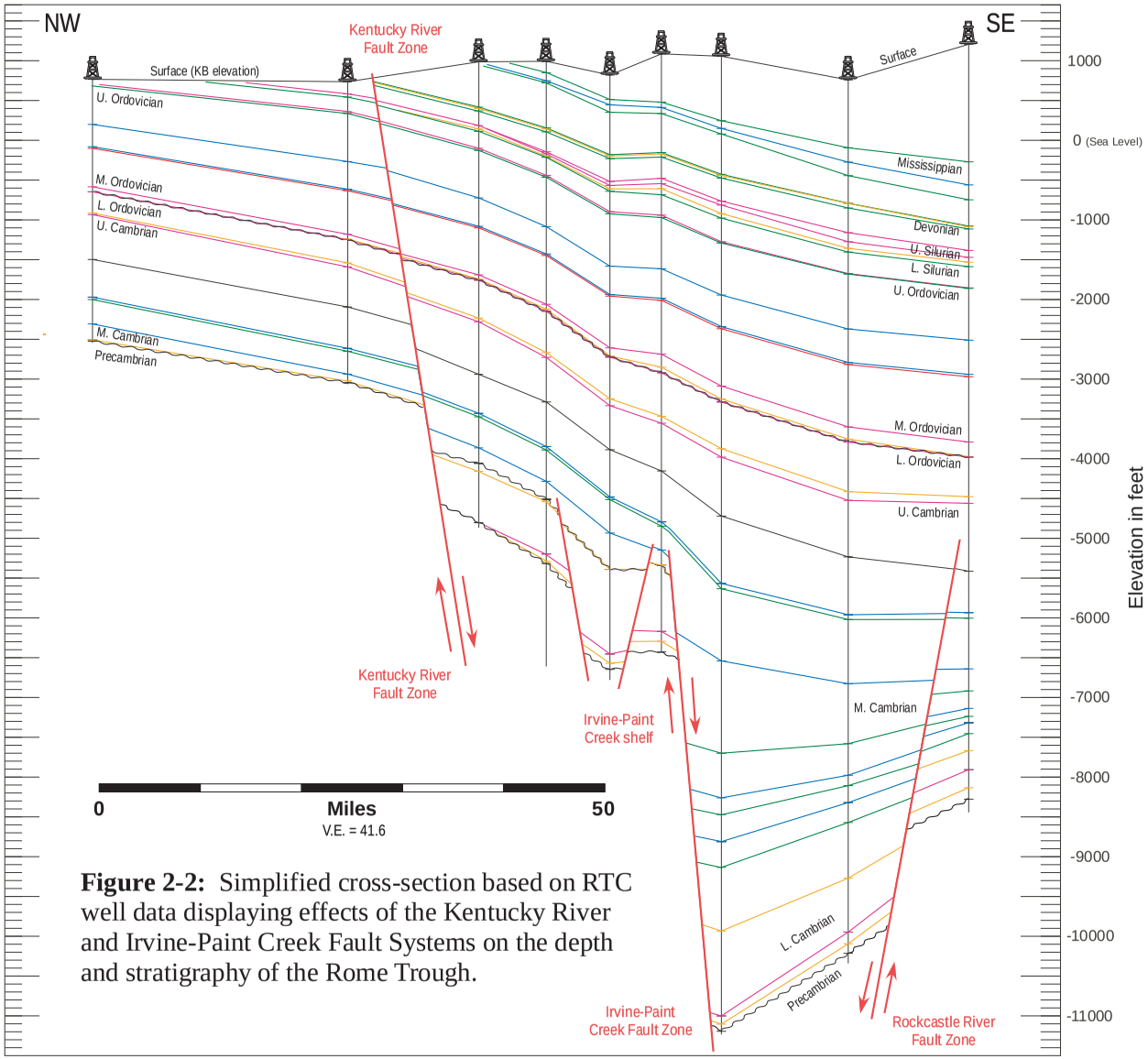

Figure 2-2: Simplified cross-section based on RTC well data displaying effects of the Kentucky River and Irvine-Paint Creek Fault Systems on the depth and stratigraphy of the Rome Trough.

exists between the lower-middle Rome Formation and the Maryville Limestone of the Conasauga Group within the shallower northern zone. Within the deeper, southern Kentucky zone, a nearly continuous record of sedimentation exists from the top of the Grenville aged metamorphic basement, until the Middle Ordovician Knox unconformity (Figure 2-2).

Several fault blocks in local horst-and-graben or half-graben configurations achieved the mechanical extension that formed the Rome Trough. Due to the type of data used in this project (point data at well locations), the precise size and placements of most of these blocks are difficult to determine. What appears to be the trend in eastern Kentucky is that the vertical movements along the Irvine-Paint Creek faults are greater than that along the Rockcastle River faults. This has lead to an asymmetrical graben type structure that dips to the north (see Fig. 2-2). This type of orientation reverses however, near the southern border of West Virginia. Around what has been called the 38th Parallel Accommodation Zone by Gao et al. (2000), the dip of the top of basement changes to southeast (see Fig. 2-1). In southwestern West Virginia, the basement offset of the Ohio River Fault is dramatically less than that of the East Margin Fault. This leads to an overall southeastward dip of the basement, with the deepest portion of the Rome Trough along the East Margin Fault. This agrees with published magnetic intensity map from King and Zietz (1978). This places a significant magnetic intensity low near the borders of Logan, Boone, and Lincoln Counties in West Virginia that extends northeastward adjacent to the East Margin Fault (based on seismic data published within Gao et al., 2000).

Later structures

The Rome Formation and most of the Conasauga Group strata were formed through syn-tectonic sedimentation within the Rome Trough rift valley. By the time the upper portions of the Nolichucky Shale (Middle Cambrian Conasauga Group) were deposited, the majority of the fault motion that created the Rome Trough had ended. Stratigraphic thickening over the Trough however, continued until the Middle

Ordovician. Although minor fault reactivations may have assisted this growth to a lesser extent, this sag basin was primarily formed from compaction of the several thousand feet of clastic sediment within the Trough. The formation of this sag basin appears to have ceased by the Upper Ordovician (post-Knox unconformity).

During the Alleghenian orogeny of the Appalachians to the east, compressional tectonic forces extended all the way into the mid-continent. This caused some of the normal faults that were created during the extension and formation of the Rome Trough to be reactivated in a reverse motion. This fault movement caused minor inversion structures during the Mississippian in West Virginia (Shumaker and Wilson, 1996) and the Mississippian and Pennsylvanian periods in Kentucky. One notable inversion structure in eastern Kentucky attributed to this fault reactivation is the Paint Creek Uplift in Elliott and Morgan Counties. This local uplift, first mapped and described by Hudnal and Browning (1949), is due in part to a reactivation of the buried Isonville Fault. Its significance to this project is its contribution to the formation of the Homer Field. The deformation and upward movement of the hanging-wall of this fault within the Paint Creek Uplift, created the hydrocarbon trap that would later become a very productive deep oil and gas field in southern Elliott County, Kentucky. For more details about the structure of this field, see the *Homer Field Study* in chapter 6 of this report.

Conclusion

The creation of the Rome Trough, and the smaller structures both within and surrounding it, were due to the regional tectonics affecting this area of the craton from the late Precambrian until the Plio-Pleistocene. The effects of these tectonics are as varied as the time scale that they occur across. Normal fault movement along an ancient thrust boundary (Grenville front) creates the Lexington Fault system and the western edge of the Trough. A major transfer of displacement causes the Trough in central Kentucky to have a bi-level basement horizon in the Middle Cambrian. And more recently, reverse reactivations of Cambrian normal faults created inversion structures in the Pennsylvanian and Mississippian aged strata. This complex history has led to one of the deepest and

least explored basins in the US. The purpose of this project is to compile and examine all available data in order to yield an organized and comprehensive model of this complex system.

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Chapter 3.

Regional Stratigraphy and Depositional History

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M.T. Baranoski, Ohio Geological Survey
Brandon C. Nuttall, Kentucky Geological Survey (database expertise)

A main goal of this project was regional stratigraphic correlation in the 3 state study area using a consistent set of formation picks and names. Historically subsurface Cambrian stratigraphy in Ohio, Kentucky, and West Virginia was a confusing mixture of formation names extrapolated from outcrop sections, which were often far removed from the Appalachian Basin. In addition, drillers' terminology had been mixed with formal stratigraphic names. The results of this study have improved stratigraphic correlations and relationships in the 3 states, but we are not proposing new stratigraphic names at this time. Much of the confusing terminology is used in Ohio, where Janssens (1973) applied the Rome and Conasauga Formations to rocks which are not equivalent to those formations elsewhere in the basin. This problem and recommended usage is discussed more fully in Chapter 4.

The regional Cambrian stratigraphy that was presented in Harris and Baranoski (1996) has been refined as the result of this project. Figure 3-1 is a modification of the stratigraphic correlation chart for the central Appalachian Basin in Harris and Baranoski (1996). Key changes to this interpretation follow:

1) The Conasauga Group and its member formations, as defined in the outcrop belt in eastern Tennessee are correlated into eastern Kentucky. Much of the interval now interpreted as Conasauga was previously called Rome in Kentucky.
2) The Rome Formation is confined to the Rome Trough and south, and does not extend north of the Kentucky River Fault Zone in Kentucky and the Ohio Fault Zone in eastern Ohio/W.Va.
3) The oldest 3 formations in the Conasauga Group (Pumpkin Valley Shale, Rutledge Limestone, and Rogersville Shale) are confined to the deeper parts of the Rome Trough in eastern Kentucky and West Virginia. These units are largely absent on the shallower Irvine-Paint Creek shelf, where the Maryville Limestone unconformably overlies the Rome Formation. This unconformity is named the pre-Conasauga unconformity. The Conasauga Group transgressively onlaps older rocks to the north, with only Maryville Limestone, Nolichucky Shale, and Maynardville Limestone present in Ohio.
4) The Mt. Simon Sandstone is time-equivalent to the lower Maryville Limestone to the east and south.

Figure 3-1 retains the original position of the Middle-Upper Cambrian boundary from Harris and Baranoski (1996). This boundary may be revised upward in Ohio and Kentucky to the top of the Maryville Limestone. This change is based on recent work on

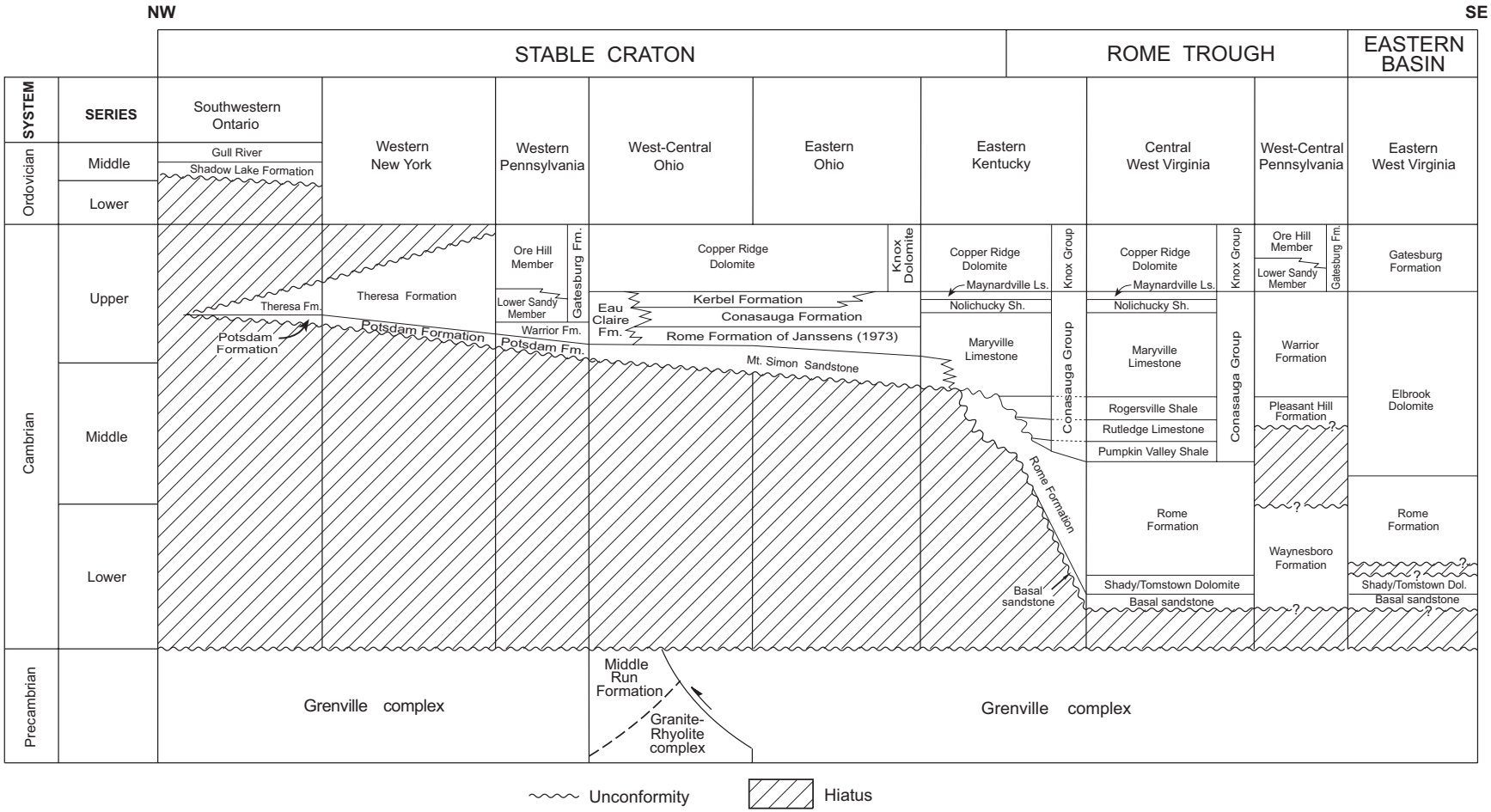

Figure 3-1. Stratigraphic correlation chart for Cambrian rocks in the Rome Trough study area. Modified from Harris and Baranoski (1996).

Maryville fossils in southwestern Ohio. These interpretations will be discussed in more detail below.

Stratigraphic Tops and Database

Stratigraphic tops were correlated for 761 wells in the study area. Formation picks agreed on by the Consortium are listed in Table 3-1, and most are shown on the type geophysical log (Plate 2). Stratigraphic tops are recorded in 2 digital file formats on the project CD-ROM. A Microsoft Access database file was built by Brandon Nuttall at the Kentucky Geological Survey. This database file has a formed designed to view the header and tops data for each file. The data are also stored in a Microsoft Excel spreadsheet on the CD-ROM. Either file format can be used to export data to other programs for mapping or interpretation.

Stratigraphic Cross Sections

To help with regional correlations and illustrate the stratigraphic framework of the basin, as series of 13 cross sections were constructed across the Rome Trough. These cross sections are included as Plates 4–16. Nine dip oriented sections were made, running roughly NW–SE across the Rome Trough. These sections are named dip sections 1-9 (Plates 4–12). Four strike-oriented sections run parallel to the Trough, in a NE–SW direction. These sections are strike A–B. Cross sections are presented with both a structural datum (sea level) and a stratigraphic datum (top of the Copper Ridge Dolomite of the Knox Group), giving a total of 26 sections. Plates are labeled A (structural datum) and B (stratigraphic datum). Formation tops are correlated between wells, and are labeled on each side of the section. Major structural features (faults, uplifts) are located along the bottom of the sections

The cross sections were built using digitized well log data. A legend is included in the title block of each section explaining the curves displayed. The structural cross sections were plotted at a larger vertical scale (1in = 500 ft) and include as much of the shallower post-Knox Group section as possible. The stratigraphic sections were plotted at a smaller vertical scale (1 in = 300 ft)to increase detail in the sub-Knox Group section. The structural sections have the gamma ray curve shaded with the major lithology component when available (see Chapter 5). Wells without the color lithology data did not have sufficient log data to model lithologies. The stratigraphic sections add another track with all the lithologic component fractions plotted. Engineering data, cored intervals, hydrocarbon shows and perforated intervals are shown in the log depth track for wells with this data available. Both versions of the sections have a horizontal scale of 1 in. = 10 miles measured between the log edges.

Full scale plots of the 26 cross sections are included with this report, rolled in a separate tube. Digital versions of these plots are also included on the project CD-ROM in Adobe Acrobat Portable Document Format (PDF files). The Adobe Acrobat viewer software is required to view and print these files. This free viewer is included on the CD-ROM for Microsoft Windows operating systems. These cross sections can be printed full scale to a

large-format plotter, or to a page-size printer by selecting the “Fit to Page” command in the printer dialog box. For quick review and reference, we have included smaller versions of each cross section in Appendix A. These versions are difficult to read, but were intended mainly as a reference to the full-scale versions. These small sections were printed with the fit-to-page option, which scales each section differently depending on its original size. Because they were scaled to fit an 11x17 inch sheet, the reduced sections do not have a consistent vertical or horizontal scale.

Biostratigraphy

Biostratigraphic correlation was not possible in the basin due to lack of data. Ryder (1992a) provides the best biostratigraphic summary of Cambrian sub-Knox rocks in the Rome Trough, and available data is presented on his series of cross sections (Ryder,1991; Ryder, 1992a; Ryder 1992b; Ryder and others, 1992, Ryder and others, 1996; Ryder and others, 1997). Plate 2 indicates geologic ages of most of the units in the study. One new development is the recognition of probable Middle Cambrian strata in the ODNR DGS 2627 corehole in Warren County, Ohio. Previously pre-Knox rocks in Ohio were thought to be entirely Late Cambrian in age. Babcock (1994) has identified trilobites of probable Middle to Upper Cambrian age in this well. Babcock interpreted the Mt. Simon Sandstone and lower Eau Claire Formation to be Middle Cambrian age. This is discussed further in Chapter 4.

For the purposes of this study, the basal sandstone and Shady Dolomite are considered Early Cambrian age. The Rome Formation, and lower part of the Conasauga Group are considered Middle Cambrian (including the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, and Maryville Limestone. On the platform in Ohio, the Mt. Simon Sandstone and lower Eau Claire formation are considered Middle Cambrian based on Babcock (1994). Units considered to be Upper Cambrian in age include the Nolichucky Shale and Maynardville Limestone of the Conasauga Group, the Kerbel Formation in Ohio, and the Copper Ridge Dolomite of the Knox Group.

The large amount of sub-Knox core material donated to the project provides an excellent opportunity to enhance our biostratigraphic data in the Rome Trough. These cores should be sampled for fossils and interpreted to provide additional age control in the basin. Such data would improve the lithostratigraphic correlations done in this project. Exxon and Texaco may have collected biostratigraphic data when these cores were originally drilled. We will continue to try and obtain these data from these companies.

Lithostratigraphy

Stratigraphic correlations made in this project were primarily lithostratigraphic, although in some cases correlations were carried across lithologic changes if we were confident of facies equivalents. Detailed stratigraphic picks are shown on the regional cross sections (Plates 4-16). The correlations on the sections match the digital tops data on the CD-ROM. In addition a series of paleogeographic maps have been drawn to illustrate the regional distribution of stratigraphic units (Plates 18–22). These maps illustrate general

depositional facies and lateral relationships. Structural or isopach mapping of the sub-Knox units was not an objective of this project.

The stratigraphic framework used in this study is very similar to that employed by Ryder (1992a). This study extends and refines these correlations to more wells in Kentucky and Ohio. For more detail on specific stratigraphic units, the reader is referred to Ryder (1992a) for a more in-depth discussion.

Precambrian Unconformity

The top of Precambrian basement was picked where possible, and for most of the study area this basement consists of metamorphic rocks of the Grenville Province. This surface is a major unconformity, resulting from deep erosion of the Grenville orogenic belt. The western side of the study area, west of the Grenville Front (see Chapter 2) is underlain by the East Continent Rift Basin, a Precambrian rift basin composed of sedimentary and volcanic rocks (basalts, Middle Run Formation) (see Drahovzal and others, 1992). Drahovzal and Noger (1995) have published a preliminary top of basement structure map. This Precambrian surface is broken by numerous Cambrian-age faults, which may be reactivated Grenville structures in some areas (Cable and Beardsley, 1984).

Basal Sandstone and Shady Dolomite

The basal sandstone is an informal term for a sand and shale sequence directly overlying Precambrian basement. This interval represents the initial Cambrian transgressive deposits on basement rocks, and is interpreted to be Early Cambrian in age (Ryder, 1992a). This interval is absent in some basement wells, and ranges up to 313 thick feet in the Texaco Perkins well in Madison County, Ky. The sandstones are commonly arkosic, which affects the gamma ray log, giving a more shaly appearance.

The basal sandstone is interpreted as a pre-rift sequence, since its distribution and thickness are not influenced by the major Rome Trough faults. The basal sandstone is restricted to areas south of the northern boundary fault of the Rome Trough (the Kentucky River and Ohio Fault Systems). The present limit is likely not the original depositional extent of the basal sandstone. It may have been eroded from areas north of the boundary faults after later fault movement, creating an erosional edge coincident with the faults. The basal sand is not present in Ohio or northern Kentucky, where the oldest sedimentary units are the younger Eau Claire Formation or Mt. Simon Sandstone.

The basal sandstone was cored in the Exxon Banks well in Wolfe County, Ky. The cores consist of red and green shales and siltstones, with nodular evaporites. This is indicative of very shallow subtidal to intertidal environments, with restricted marine circulation.

The Shady Dolomite is a limestone, dolomite and shale interval overlying the basal sandstone in most of the study area. The unit typically has a lower and upper carbonate sequence separated by a shale-dominated zone (see Plate 2, type log). The Shady thickens to the southeast in the study area, reaching a thickness of 373 feet in the Gulf Price well

in southwest Virginia. The Shady thickens to 400-600 meters in Tennessee and Virginia (Read, 1989a), so the study area contains only a thin edge of this unit. The distribution of the Shady is slightly different than for the basal sandstone, but in general they occur south of the major bounding faults of the Rome Trough. The distribution of the Shady Dolomite is mapped on Plate 18. Like the basal sandstone, the present northwest edge of the Shady may represent an erosional subcrop, after extension and uplift of areas to the northwest. The upper contact is possibly unconformable with the overlying Rome Formation (Ryder, 1992a; Read, 1989a). Both the Shady and basal sandstone are thought to be Early Cambrian age.

Rome Formation

Both Ryder (1992a) interprets the Rome Formation to possibly unconformably overlie the Shady Dolomite. Read (1989a) shows the 2 units to be conformable, and we have not seen any evidence in this study to support or disprove either interpretation. The Rome Formation is generally interpreted to be Middle Cambrian age (Ryder, 1992a).

The Rome Formation records the greatest movement and growth across the normal faults that created the Rome Trough. Extension and possible strike-slip motion along these faults was most active during Rome deposition, and variations in the thickness of the Rome reflect differential subsidence. A more quantitative treatment of subsidence and fault movement in the Trough can be found in Wilson (2000).

The Rome Formation is confined to the Rome Trough, and does not extend beyond the boundary faults of the basin. Ample evidence (Chapter 5) suggests that sediments were transported into the trough from the north, across the Kentucky River and Irvine-Paint Creek Faults. Facies equivalents north of the Kentucky River fault are not preserved, and may have been removed or reworked by transgression onto the craton during Conasauga time. The Rome Formation contains a complex sequence of shales, siltstones, sandstones, and carbonates. Three major units within the Rome were correlated in this project. The lower Rome units and middle Rome units are clastic-dominated, consisting of deeper water shales, siltstones and thin sandstones in the center of the trough, south of the Irvine-Paint Creek Fault System. The lower unit consists of alternating thin shales and sandstones, while the middle unit is a more consistent shale-dominated sequence. Red beds are commonly reported from the Rome Formation elsewhere (Read, 1989a), but in Kentucky and West Virginia the rocks are predominately green-gray marine facies.

Toward the north side of the Rome Trough sand content increases dramatically in the middle and lower Rome units. On the Irvine-Paint Creek shelf, between the two fault systems, the thickness and number of sandstone beds increases. Cores from wells in these area have been interpreted in this study as shallow marine shelf and delta front and distributary channel/bar sand bodies (see core descriptions).

Middle Rome paleogeography is interpreted in Plate 19. This map shows a distal clastic shelf or ramp, with limited sandstone deposition. Between the Irvine-Paint Creek and Kentucky River Fault Systems, is a shallower structural platform dominated by delta

front and shallow marine shelf deposits, with sand supplied by fluvial systems to the north. This area has the highest exploration potential due to the abundance of potential reservoir sandstones with porosity.

A third unit of the Rome Formation was correlated and mapped in the project. This unit, the upper Rome limestone is a thick carbonate ramp sequence. It's placement with the Rome Formation follows the classification of Ryder (1992a). This Rome carbonate unit is present in the deeper parts the trough in Kentucky and West Virginia, but is absent on the Irvine-Paint Creek shelf in Kentucky, and near the northwest edge of the trough in West Virginia. Like all of the Rome units, the upper carbonate was not deposited in Ohio. It is best developed south of the Irvine-Paint Creek Fault, in wells such as the Exxon Banks (Wolfe Co.), Ashland Cable (Lee Co.) and the Signal Elkhorn (Johnson Co.). Several of the dip cross sections (dip 4, dip 5) show the termination of this unit at the Irvine-Paint Creek Fault. On strike line C, the upper Rome carbonate thins to the west, along strike. It shales out in south-central Kentucky, or is possibly truncated against an unconformity. This relationship is interpreted as a carbonate ramp that prograded east to west into a deeper intrashelf basin in south-central Kentucky. This interpretation is shown on Plate 20, which is a paleogeographic map for upper Rome time. The deeper Rome Trough is occupied by a carbonate ramp that possibly developed to the east and south of the trough in southern West Virginia and Virginia. Our initial interpretation is that this prograded into the trough to the north and west. A deeper water intrashelf basin is interpreted in south-central Kentucky, based on the few wells drilled there. This is thought to be a precursor to a younger Conasauga-age intrashelf basin in the same area (discussed next). The upper Rome carbonate is limestone to dolomitic limestone, and has low reservoir potential. No porosity has been seen associated with this unit.

To summarize, the Rome Formation is an overall transgressive sequence, with clastics sourced from the north and west. Large thickness changes occur within the Rome Trough as the result of synsedimentary fault movement. The sequence culminates with a carbonate ramp that was possibly prograding from the south and east into the basin, with a deeper intrashelf basin in south-central Kentucky. The Irvine-Paint Creek shelf in eastern Kentucky has the greatest sandstone reservoir potential. Sandstones may have been deposited in deeper water areas as gravity flow deposits (turbidites), no evidence for this has been seen in this project. Such deposits have been interpreted on the basis of seismic data (Drahovzal, 1994).

Conasauga Group

Five formations within the Conasauga Group have been correlated in this study area. In addition, two formations time-equivalent to the Conasauga are interpreted in the western part of the study area. The Conasauga Group consists of the following formations, in ascending order: Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. As previously discussed the Pumpkin Valley through Maryville units are considered to be Middle Cambrian in age, while the Nolichucky and Maynardville units are Upper Cambrian age.

Like the Rome, the Conasauga Group shows dramatic stratigraphic changes across faults bordering and within the Rome Trough, indicating that fault movement was still active. Like the upper Rome carbonate unit, the oldest Conasauga formations are restricted to the deeper parts of the Trough. The Pumpkin Valley, Rutledge Limestone and Rogersville Shale are not present on the Irvine-Paint Creek shelf, north of the Irvine-Paint Creek Fault, and in shallower parts of the trough in West Virginia. These units are also absent in northern Kentucky and Ohio. Dip cross sections 3-9 illustrate this relationship. North of the Irvine-Paint Creek Fault, the oldest Conasauga Group formation is the Maryville Limestone, which rests on Rome Formation. Because of the missing section, this contact is interpreted as an unconformity. The age of this unconformity is post-Rome, and pre-Conasuaga, and is referred to as the pre-Conasauga unconformity in this report. The Rome and Consauga are thought to be conformable in the deeper parts of the Trough, a correlative conformity in sequence stratigraphy terminology. The unconformity is present on shallower structural blocks in the basin, which were uplifted and exposed while deposition of the older Conasauga units continued deeper in the Rome Trough. The pre-Conasauga unconformity is indicated with a wavy line on all cross sections where it occurs. This interpretation explains the dramatic thickening of the Conasauga across major faults such as the Irvine-Paint Creek and the Isonville Fault. Higher fault blocks were not flooded until Maryville time, which was a major transgression across northern Kentucky and Ohio.

The pre-Conasauga unconformity interpretation is different than Ryder's (1992a and other cross sections) interpretation of the Rome/Conasauga interpretation. Ryder interprets Maryville Limestone on top of Rome sandstones on the Irvine-Paint Creek shelf (Ryder and other, 1997), but shows an intertonguing facies relationship between the Maryville and Rome sandstones on his sections, with no unconformity. He also shows lateral facies changes between the Rome and lower Conasauga formations on several cross sections. The abrupt change in stratigraphy across major faults led us to favor the unconformity interpretation. The pre-Conasauga unconformity has not been cored in wells to date. Additional biostratigraphic or seismic data would help to further interpret this relationship.

The Conasauga formations have been interpreted as a series of transgressive (shales) and regressive (carbonates) forming thick depositional cycles in the outcrop belt in eastern Tennessee (Fig. 3-2). Outcrop studies by a number of workers in the Valley and Ridge Province has helped to understand the origin of the Conasauga in the Rome Trough area. These studies include Markello and Read (1981; 1982), Hasson and Haase (1988), Read (1989b), Srinivasan and Walker (1993), Rankey and others (1994), and Glumac and Walker (1998; 2000). The models resulting from these studies shows the Conasauga Group as 3 major cycles, with the shale formations comprising the lower, deeper water transgressive part of the cycle, with the carbonate units forming the upper regressive (progradational) part of the cycle (Fig. 3-2). The carbonates prograded from a platform in eastern Tennessee and southwestern Virginia to the northwest, *toward* the craton. This landward progradation filled an intrashelf basin (Fig. 3-3). This intrashelf basin is now extended into south-central Kentucky on the basis of this study, a much larger area than shown in Figure 3-3.

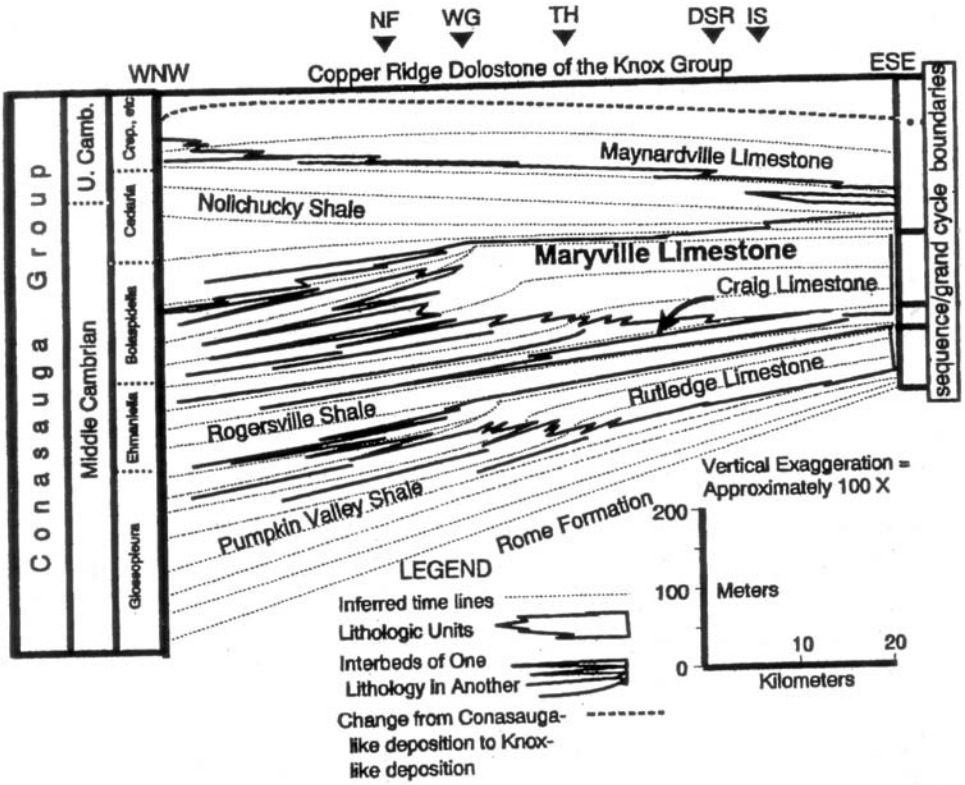

Figure 3-2. Stratigraphic model for Conasauga Group in the outcrop belt in eastern Tennessee. Three major transgressive/regressive cycles are present, composed of a lower shale formation and upper carbonate formation. The minor cycle involving the Craig Limestone has not been observed in the Rome Trough area. Note the progradation direction is *toward* the craton, into an intrashelf basin, shown in Figure 3-3. From Rankey and others, 1994.

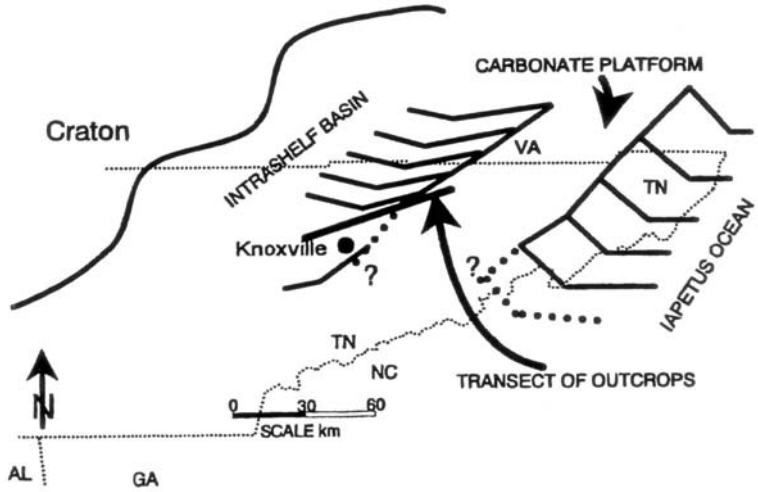

Figure 3-3. Middle Cambrian paleogeography in northeast Tennessee and southwestern Virginia. A Conasauga carbonate platform existed in this area, characterized by cyclic progradation to the northwest (cratonward) into Kentucky. The shale-carbonate cycles have been correlated into the Rome Trough, and the location of the intrashelf basin shown here has been reinterpreted to the west, in south-central Kentucky (see Plate 21). From Srinivasan and Walker (1993).

The Conasauga Group cycles have been correlated into the Rome Trough in West Virginia and Kentucky. The carbonate parts of the cycles thin to the west–southwest in the Trough, grading into shale. In south-central Kentucky, the Conasauga is composed of a thick sequence of shale, and the individual formations cannot be recognized. The term Conasauga Shale is used in this area for all of the Conasauga. The lateral gradation of the Conasauga carbonates into the Conasauga Shale is shown well on strike section C (Plate 15B, Copper Ridge datum). This section runs SW down the center of the Rome Trough, and shows the westward thinning and shaling-out of the Conasauga carbonates into the intrashelf basin. Conasauga shales have potential as hydrocarbon source rocks, and good source rock quality has been identified in the Rogersville Shale in the Exxon 1 Smith well in Wayne County, West Virginia (see Chapter 7).

The Maryville Limestone prograded out of the Trough, into northern Kentucly and Ohio. The Mt. Simon Sandstone is laterally equivalent to the Maryville, and is the basal sandstone in Ohio and northeastern Kentucky. Stratigraphic relationships in Ohio are discussed in more detail in Chapter 4. The Maryville interval contains significant sandstones on the Irvine-Paint Creek shelf, and north of the trough in Ohio. These sandstones have been mapped using log data, and these results are presented in Chapter 5. The Maryville is carbonate-dominated to the east in Ohio, and is a mixed carbonate-sandstone unit in south-central Ohio and northeastern Kentucky. To the west, the Maryville section above the Mt. Simon grades laterally into shales mapped as the Eau Claire Formation. The Eau Claire Formation is equivalent to the upper Maryville, Nolichucky Shale, and Maynardville Limestone (see Chapter 4). Plate 21 is a paleogeographic map showing facies relationships in upper Maryville time. This map indicates the location of areas interpreted as Eau Claire Formation shales (northwest), and the Conasauga Shale intrashelf basin in south-central Kentucky. The Maryville carbonate ramp system lies to the east in Kentucky, West Virginia and Ohio. A north-south band of sandstone-rich Maryville Limestone is mapped in northeastern Kentucky, and along the Irvine-Paint Creek shelf to the west, and north into southern Ohio. Maryville sandstones in this area have reservoir potential, and form pay zones in Elliott and Lawrence Counties, Kentucky (see Chapter 5).

The Nolichucky Shale and Maynardville Limestone comprise the final Conasauga depositional cycle, and were deposited across most of the study area. These units show little thickness variation across the trough, indicating that movement on the boundary faults had largely stopped. The Maynardville paleogeography is shown in Plate 22. This shallow water carbonate has a depositional pinchout in the northeast part of the study area, in eastern Ohio and northern West Virginia. Shales of the Eau Claire Formation grade into the Maynardville Limestone in western Ohio and northern Kentucky. The Maynardville Limestone lacks significant sandstones, and has limited reservoir potential. The Maynardville is conformably overlain by the Copper Ridge Dolomite of the Knox Group.

Figure 3-4 is a chronostratigraphic diagram which attemps to summarize the rather complex facies relationships in various parts of the study area in Kentucky. The diagram runs from the northwest part of the study area in northern Kentucky, to eastern Kentucky

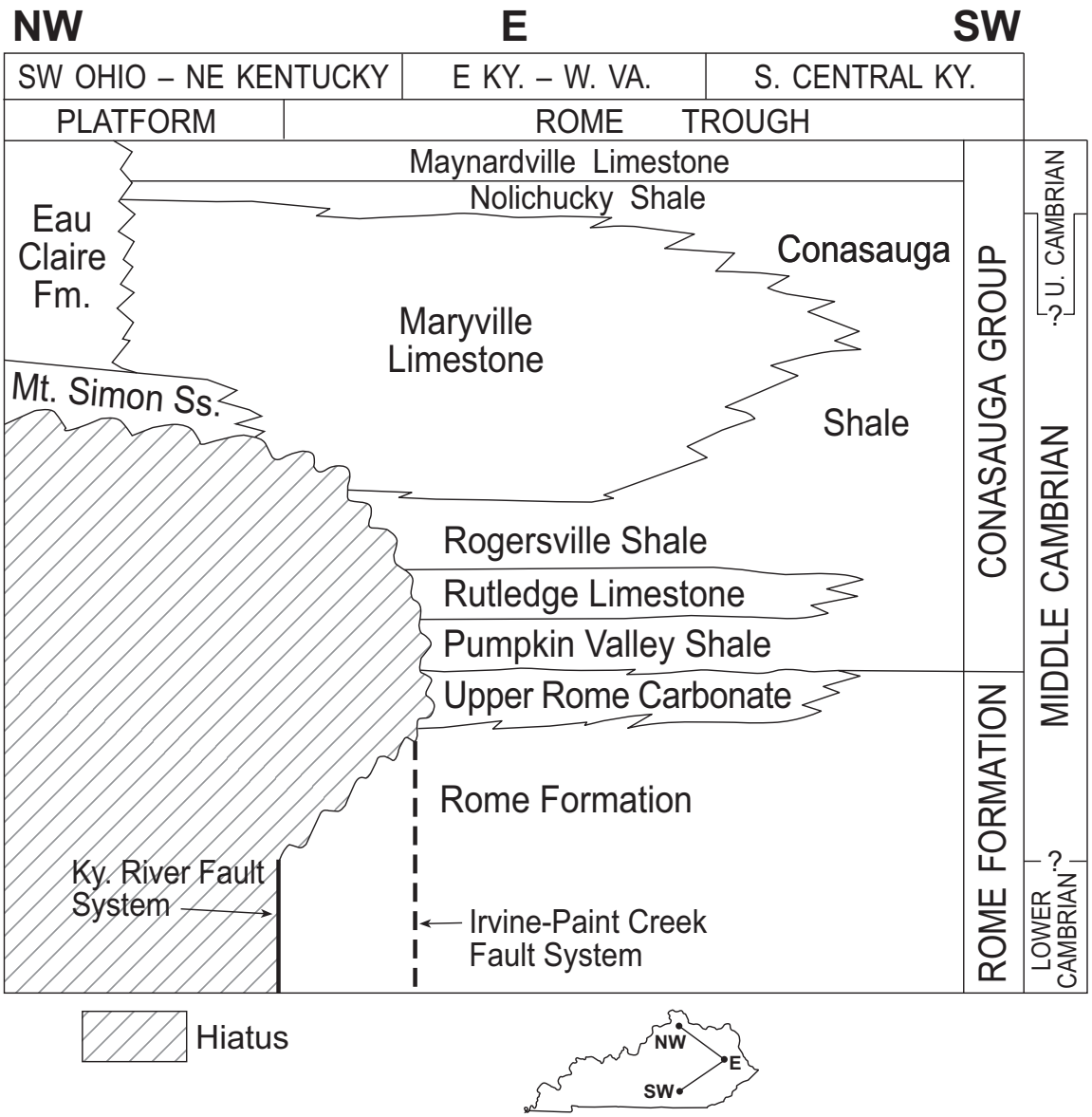

Figure 3-4. Chronostratigraphic diagram for the Rome Formation and Conasauga Group in Kentucky, based on stratigraphic correlations interpreted in this study. The diagram includes three general areas, north-central Kentucky outside of the trough (NW), eastern Kentucky in the Rome Trough (E), and south-central Kentucky inside the trough (SW). The location of the Kentucky River and Irvine-Paint Creek Fault Systems is shown. The upper Rome carbonate and lower Conasauga units are absent on the shelf between these faults, due to a pre-Conasauga unconformity. Deeper in the trough, a full Rome section is present. The upper Rome carbonate grades laterally into shale in an interpreted intrashelf basin in south-central Kentucky (SW). The Conasauga Group formations represent transgressive-regressive cycles that prograded to the west and northwest into the Rome Trough. The Conasauga carbonates grade laterally into the Conasauga Shale in south-central Kentucky, into a deeper intrashelf basin. The Maryville and younger formations transgressed across northern Kentucky and Ohio, and grade laterally into the Mt. Simon Sandstone and Eau Claire Formation in western Ohio and north-central Kentucky.

(in the Rome Trough), then back to south-central Kentucky in the southwestern part of the study area. The location of the Kentucky River and Irvine-Paint Creek Fault Systems is shown. The upper Rome carbonate and lower Conasauga units are absent on the shelf between these faults, due to the pre-Conasauga unconformity. Deeper in the trough, a full Rome section is present. The upper Rome carbonate grades laterally into shale in an interpreted intrashelf basin in south-central Kentucky (SW). The Conasauga Group formations represent transgressive-regressive cycles that prograded to the west and northwest into the Rome Trough. The Conasauga carbonates grade laterally into the Conasauga Shale in south-central Kentucky, into a deeper intrashelf basin. The Maryville and younger formations transgressed across northern Kentucky and Ohio, and grade laterally into the Mt. Simon Sandstone and Eau Claire Formation in western Ohio and north-central Kentucky.

Table 3-1. List of stratigraphic tops included in the tops database. Not all tops were picked in all areas due to stratigraphic changes.

Age	Database Code	Formation Name	Area
Mississippian	332PNGT	Pennington Gp	Ky., W. Va.
	332LTLM	“Little Lime”	Ky.
	332PCCV	“Pencil Cave Sh”	Ky.
	332BIGL	“Big Lime” (Newman Ls)	Ky., W. Va.
	333SLWW	Salem Ls/Warsaw Fm (undif)	Ky.
	337FTPN	Ft. Payne Fm	Ky.
	337BRDN	Borden Fm	Ky., W. Va.
	339SNBR	Sunbury Sh	All
	339BRBD	Berea Ss/Bedford Sh (undif)	All
Devonian	341OHIO	Ohio Sh	All
	344CORN	“Corniferous”	All
	344BOYL	Boyle Ls	Ky.
	344ONDG	Onondaga Ls	All
	347ORSK	Oriskany Ss	All
	347HDBG	Helderberg Ls	All
Silurian	351SALN	Salina Fm	All
	355LCKP	Lockport Dol	All
	355BGSX	“Big Six Sd” (Keefer Ss)	All
	357CBOC	Crab Orchard Fm (Clinton)	All
	357TCRR	Tuscarora Ss	All
	357BRSF	Brassfield Dol	All
Ordovician	361ODVCU	Ordovician, Upper (undif)	All
	361MRBG	Martinsburg Fm	Ohio, W. Va.
	365LXTN	Lexington Ls (Trenton)	All
	365TRNT	Trenton Ls.	Ohio
	365HGBG	High Bridge Gp (Black River)	All
	365PCAV	Pencil Cave Bentonite	All
	365HGBGL	High Bridge Gp, lower part	All
	365WLCK	Wells Creek Fm	All
	365STPR	St. Peter Ss	All
	368KNOX	Knox Gp	All
	368BKMN	Beekmantown Dol	All
	368RSRN	Rose Run Sd	All
Upper Cambrian	372CPRG	Copper Ridge Dol	All
	372CPRGL	Copper Ridge Dol, lower unit	All
	372KRBL	Kerbel Fm	Ohio
	375CNSG	Conasauga Gp	All
	375CNSGS	Conasauga Sh	Ky.
	375ECLR	Eau Claire Fm	Ohio, Ky.
	375MDVL	Maynardville Ls	All
	375NCCK	Nolichucky Sh	All
Middle Cambrian	375MTSM	Mt. Simon Ss	Ohio, Ky.
	375MRVL	Maryville Ls	All
	375RGRV	Rogersville Sh	W. Va., Ky.
	375RLDG	Rutledge Ls	W. Va., Ky.
	375PPKV	Pumpkin Valley Sh	W. Va., Ky.
	375PCNUF	“Pre-Conasauga Unconformity”	Ky., W. Va.
	375ROME	Rome Fm.	W. Va., Ky.
	375ROMEU	Rome Fm, upper part	W. Va., Ky.

	375ROMEM	Rome Fm, middle part	W. Va., Ky.
	375ROMEL	Rome Fm, lower part	W. Va., Ky.
Lower Camb	375SHDY	Shady Dolomite	W. Va., Ky.
	375BASL	“Basal Sand”	W. Va., Ky.
Precambrian	400PCMB	Precambrian basement	All
	400GRVB	Grenville basement	All
	400ARKS	“Arkose”	Ohio
	400BSLT	Precambrian basalt	Kentucky
	400GRRY	Precambrian Granite-Rhyolite	Ohio, Kentucky
	400MDLR	Middle Run Fm	Ohio, Kentucky

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Chapter 4.

REPORT OF THE OHIO DIVISION OF GEOLOGICAL SURVEY TO THE ROME TROUGH CONSORTIUM

by
Mark T. Baranoski
July 2002

Project Contractors: Kentucky Geological Survey, Ohio Division Of Geological Survey, and West Virginia Geological and Economic Survey

Project funded by Belden & Blake, Columbia Natural Resources, Equitable Oil & Gas, Robert Fox, and U.S. Department of Energy
Subcontract No. UKRF 4-62517-99-131, Ohio Department Of Natural Resources

INTRODUCTION

The Ohio Division of Geological Survey has been pleased to work with the Kentucky and West Virginia Geological Surveys and sponsors on the Rome Trough Consortium. This joint government-industry consortium was formed to gain a better understanding of the structural and stratigraphic framework of the deep Rome Trough and its production potential. The Kentucky Geological Survey served as the primary contractor to the sponsoring parties and, in turn, subcontracted the geologic interpretations to the respective states. The subcontract to the Ohio Division of Geological Survey required the following tasks: (1) collect subsurface stratigraphic-formation tops for 44 selected wells in Ohio and provide data to the Kentucky Geological Survey; (2) provide any existing digital geophysical-log data from these wells in an electronic format to the Kentucky Geological Survey; (3) assist the Kentucky Geological Survey with stratigraphic correlation and cross-section generation.

Stratigraphic units were interpreted for 88 wells in Ohio. A second set of 44 pre-Knox wells were added to the original data set of 44 wells in order to cover a larger area and to tie into a continuously cored hole (Division of Geological Survey core DGS 2627) in Warren County, Ohio. Thirty-seven geophysical-log suites were provided to the Kentucky Geological Survey in either digital or hard-copy format. Hard-copy logs were digitized by the Kentucky Geological Survey. The Ohio Division of Geological Survey has worked closely with the Kentucky Geological Survey and the West Virginia Geological and Economic Survey throughout the project on cross sections, correlations, and mapping.

METHODS USED BY THE OHIO DIVISION OF GEOLOGICAL SURVEY

To establish consistency in correlations, the three state geological surveys constructed a cross-section network across the study area, which includes eastern Kentucky, southern Ohio, and northwestern West Virginia (Plate 3). The cross-section network roughly follows the interpreted WSW-ENE structural trend of the Early to Middle Cambrian-age Rome Trough. This structural

trend is at an oblique angle to the present-day north-south trend of this portion of the Appalachian Basin.

Janssens (1973) defined most of the currently used nomenclature for Cambrian units in Ohio (Fig. 4-1). Janssens' correlations to deeper portions of the Appalachian Basin were performed at a time when very few deep wells were available for study, especially within the Rome Trough. It has been evident for some time that certain Ohio Cambrian units were not correlative with their deeper basin namesakes (Ryder, 1992; Riley and others, 1993); for example, Ohio's Rome Formation is correlative with part of the Conasauga Group, not the Rome Formation of the Rome Trough. Pre-Knox Cambrian correlations and facies relationships are the focus of an ongoing Ohio Division of Geological Survey investigation; some of our results are presented here. However, this report is not an attempt to revise Ohio's Cambrian stratigraphic nomenclature at this time.

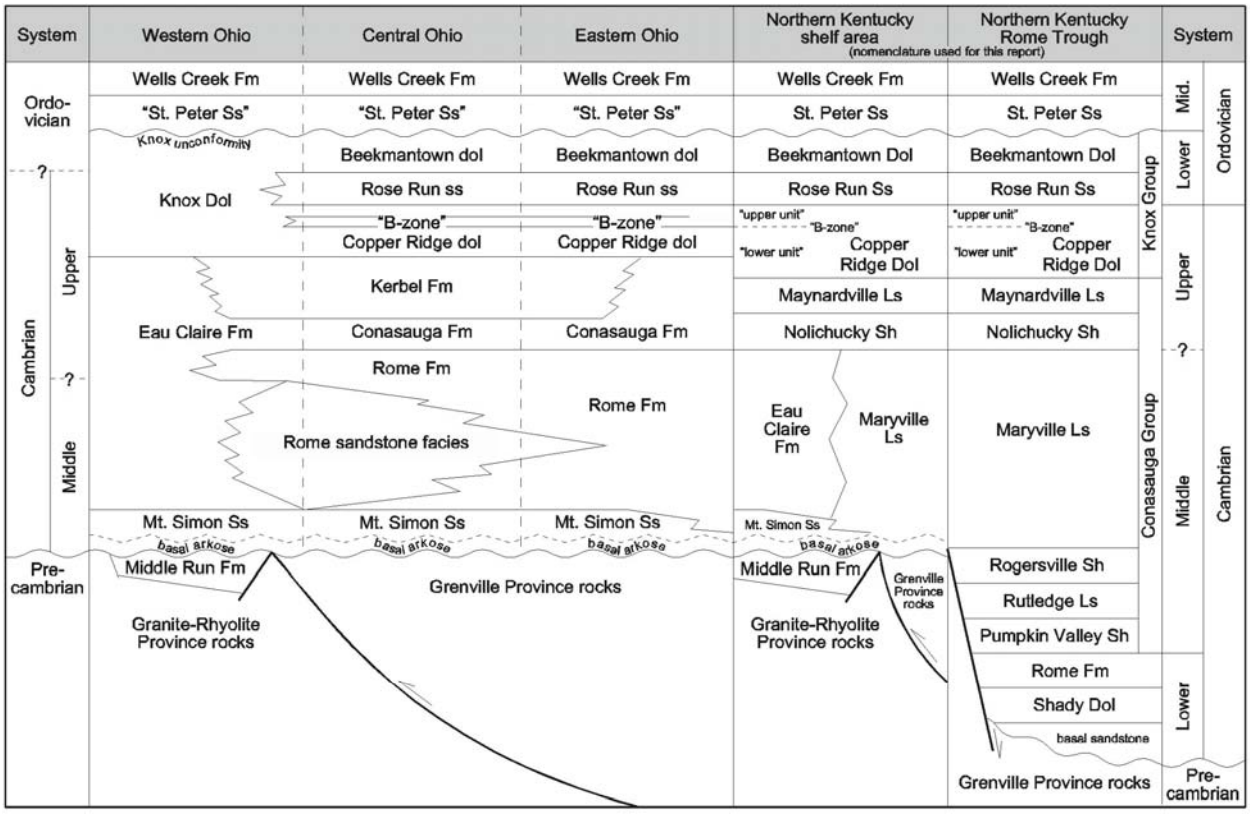

Figure 4-1. Stratigraphic nomenclature and relationships for the Rome Trough Consortium project area. Ohio nomenclature modified from Janssens (1973). Quotation marks indicate drillers' terms.

This report on Ohio will be included as a separate chapter in the final report for the Rome Trough Consortium. Therefore, correlations of the Knox and deeper units were made across the region using Kentucky Geological Survey stratigraphic nomenclature (Figs. 4-1, Plate 13B) except as noted below. Using one set of nomenclature resulted in more accurate definition of the lateral extent of specific mappable units and eliminated differences in interpretation and nomenclature used by earlier workers. The two exceptions to using Kentucky Geological Survey stratigraphic nomenclature for Cambrian units in Ohio are: (1) the use of the Kerbel Formation (Janssens, 1973), which occurs only in Ohio, and (2) the use of the Eau Claire Formation, which is present in western Ohio and over much of the northern Midcontinent. Geologic units in the

Rome Trough beneath the Maryville Limestone are not discussed in this study as they have not been correlated into Ohio.

Plate 13B is a cross section striking parallel to the Rome Trough and illustrates changes in Cambrian stratigraphy from north-central Kentucky through southern Ohio to West Virginia. Geologic tops used in this report for the Knox Group units and the Wells Creek Formation are taken in part from an earlier report on correlative units by Riley and others (1993). Geologic tops of units below the Knox Group were interpreted specifically for this study.

Four strike lines (A-D, Plates 13-16) and nine dip lines (1-9, Plates 4-12) cover the project area (Plate 3). Work in Ohio concentrated on strike line A (Plate 13), most of strike line B (Plate 14), and Dip lines 2 through 9 (Plates 5-12). Hard-copy geophysical logs were used for the correlation work in Ohio. Ohio pre-Knox wells were correlated to geologic units defined by the Kentucky Geological Survey specifically for this project. The method of correlation was based primarily on lithostratigraphic interpretation of the geophysical logs. Where possible, density and photoelectric curves were used to distinguish dolomite, limestone, shale, and sandstone. Sample-cuttings descriptions by Janssens (1973) as well as descriptions on open file at the Ohio Division of Geological Survey also were used in some cases. Correlations were made on consistent lithostratigraphic surfaces, interpreted as largely marine to marginal-marine depositional-facies boundaries. Exceptions to these surfaces are major regional unconformities at the top of the Knox Group, at the base of the Mount Simon Sandstone or the Maryville Limestone, and the basal arkose on top of the Precambrian. All boundaries were tied directly to the correlations made by the Kentucky Geological Survey on the cross-section network. Wells not on the line of cross section were systematically correlated in multiple directions to maintain consistency between lines.

In cases where the boundary of the unit changed laterally due to pinch-out or facies change, a correlation pick, designated as “C,” was added to the top value in the database (for example, “C4500”). The correlation pick was used because the Cambrian-age units in Ohio were deposited on an extensive platform where abrupt lateral facies changes are not common. In contrast, very rapid lateral changes occur within the Rome Trough (Riley and others, 1993, Fig. 24). Correlation of older, deeper Cambrian units of the Rome Trough to the shallow platform area to the north remains problematic. Nevertheless, correlations were extended as far as possible until the correlation surfaces pinched out or disappeared. This method helped identify truly abrupt lateral facies changes and eliminated apparent anomalies due to widely spaced well control. This method also eliminated “state line” faults due to erroneous correlations and addressed the problems with stratigraphic nomenclature from state to state.

If the boundary of the unit was not present, a “0” was entered as the top in the database. A blank entry indicates that either the well was not drilled deep enough or was not geophysically logged through the interval. Well API number 3414570003 is a deviated (non-vertical) hole, so tops were not entered in the database. Data were entered by well API number into a computer spreadsheet, and isopach values were calculated then loaded into a computer contour-mapping program to check for data errors or anomalies.

GENERALIZED DESCRIPTIONS OF LITHOSTRATIGRAPHIC UNITS

The focus of this study was to correlate wells in southern Ohio drilled deeper than the Knox Group to very deep wells drilled in the Rome Trough of Kentucky and West Virginia. The Knox and deeper units of Ohio were deposited on a broad shelf; these deposits were first described by Sloss and others (1949) informally as the Sauk Sequence. The Sauk Sequence is considered to be a complex transgressive assemblage of clastic and carbonate rock units. The sequence generally becomes thinner northward across Ohio as it onlaps onto a broad shelf and then onto the Canadian Shield. It is bounded at the bottom by the Precambrian unconformity and at the top by the Knox unconformity. For geologic simplicity, the informal term “Ohio shelf” is used to refer to this broad Cambrian depositional region northwest of the Rome Trough.

Accurately defining the Cambrian System boundaries in Ohio has always been problematic owing to the paucity of biostratigraphic data from deep wells. Numerous previous workers generally have assumed that Upper Cambrian rocks were the oldest Paleozoic units in Ohio (Riley and others, 1993). This assumption was based largely on regional correlations to the Cambrian outcrops in the upper Mississippi Valley and the southern Appalachians. In examining a deep continuous core from southwestern Ohio (Ohio Division of Geological Survey core DGS 2627, API number 3416522627), Babcock (1994) discovered fragments of Middle to Late Cambrian trilobites in the Eau Claire Formation. This discovery allowed Babcock to infer a Middle Cambrian age for the lower part of the Eau Claire Formation and the Mount Simon Sandstone of southwestern Ohio. Hence, Ohio’s Cambrian units can now be placed in a less ambiguous regional biostratigraphic context.

The structural complications characteristic of the Early to Middle Cambrian-age Rome Trough are largely absent on the Ohio shelf. Faulting parallel to a linear segment of the Ohio River in Lawrence County, Ohio (Calvert, 1974; Baranoski and Riley, 1988), is thought to be due to minor influence of the Rome Trough. Calvert (1974) called this fault the Ohio River Fault (Fig. 4-2). Calvert’s (1974, Fig. 4A) isopach map of the Maynardville to Precambrian interval shows a thin area north of the Ohio River Fault in Ohio and adjacent West Virginia. This thin area suggests a broad basement high on the edge of the Ohio shelf related to the Rome Trough. Other deep subsurface structures in the study area are depicted on Figure 4-2. Structures exposed at the surface include the Serpent Mound disturbance and the nearby Plum Run Quarry Fault. Interpretation of seismic data over the Serpent Mound disturbance indicates localized facies changes and significant stratigraphic thinning in the Cambrian (Baranoski, 1993).

Summerson (1962) discussed the relationship of fault systems to patterns of sedimentation and suggested that faults in the Precambrian basement influenced overlying Paleozoic sedimentation, especially in northern Kentucky and western Ohio. Later workers (Cable and Beardsley, 1984; Riley and others, 1993) speculated that Cambrian facies variations observed in Ohio are related to reactivated Precambrian fault systems along boundaries separating Precambrian provinces and along regional changes in the gradients on gravity and magnetic maps. Localized paleotopographically high Precambrian areas occur rarely in southern Ohio. Janssens’ (1973) Mount Simon Sandstone is absent due to nondeposition over these basement highs (Fig. 4-2). Riley and others (1993, Fig. 26) show a highly faulted area in Fayette County, Ohio, that has a

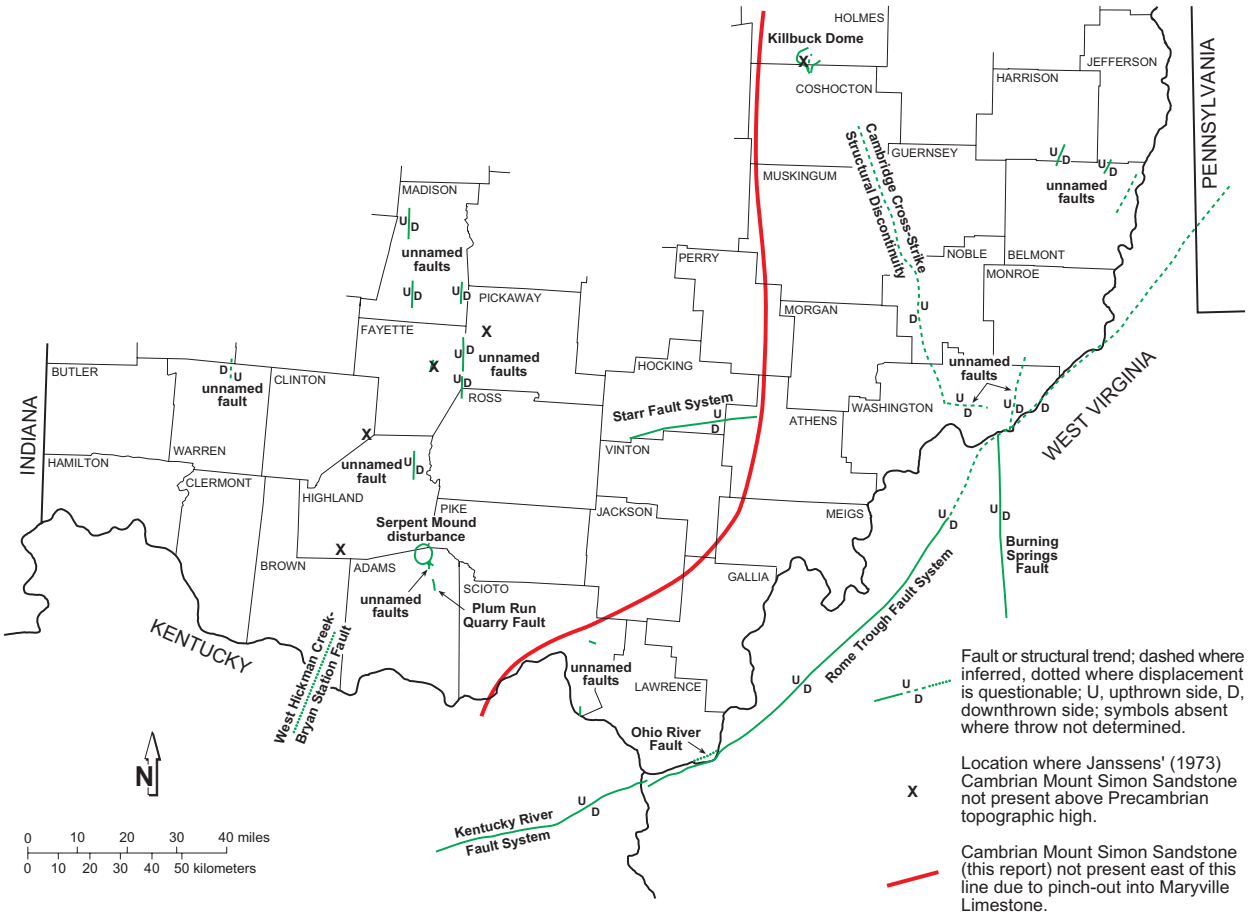

Figure 4-2. Major structures in the southern Ohio study area (modified from Baranoski and Wickstrom, 1991) and area of pinch-out of the Mount Simon Sandstone (as used in this study; see text).

thick accumulation of Cambrian sediments adjacent to a basement high. Well API number 3404720010 was drilled into this basement high.

PRECAMBRIAN

Precambrian basement rocks of south-central and eastern Ohio consist predominantly of granite gneiss, schist, amphibolite, and marble of the Grenville Province (Bass, 1960). In western Ohio, lithic arenite and basalt/andesite of the East Continent Rift Basin or a complex assemblage of intrusive and extrusive igneous rocks of the Granite-Rhyolite Province underlie the Mount Simon (Drahovzal and others, 1992). Drahovzal and others (1992) estimate that the East Continent Rift Basin contains sequences of sedimentary and volcanic rocks greater than 20,000 feet thick in areas adjacent to the Grenville Province. The rocks of the East Continent Rift Basin were deposited unconformably on the Granite-Rhyolite Province. Summerson (1962) and later workers interpreted the north-south-trending ridgelike boundary separating the Grenville Province from western provinces as a resistant paleotopographic ridge.

The upper contact of the Precambrian is unconformable with the overlying basal arkose of the Mount Simon Sandstone or the Maryville Limestone. This contact is highly weathered in some areas. In rare instances, wells in Ohio have penetrated localized, topographically high, erosional/structural Precambrian remnants, which may have as much as 500 feet of relief and upon which the Mount Simon may be entirely or partially absent (Wicks, 1996). Figure 4-2 indicates areas where the Mount Simon is absent.

BASAL ARKOSE

The difficulty in recognizing the top of the Precambrian surface using sample cuttings has been discussed by Summerson (1962) and Janssens (1967). Summerson (1962) noted the difficulty in "distinguishing arkosic sediments and weathered or fresh granite" to determine the top of the Precambrian in Ohio. Top and base elevations of the basal arkose were entered in the database for wells in which it is present and distinct from the lithologically "cleaner" overlying Mount Simon Sandstone. This basal arkosic sandstone is clayey and hematitic in some wells. The basal arkose typically contains higher amounts of feldspar and other grains than overlying sedimentary units; these higher amounts are probably derived from the underlying weathered Precambrian surface. Higher gamma ray counts on geophysical logs in general indicate greater amounts of feldspar and other potassium minerals or radioactive minerals. Very little is known about the provenance and depositional history of the unit, which represents an extended period of weathering of the Precambrian surface prior to the deposition of the Mount Simon. The basal arkose typically is less than 20 feet thick (Plate 13B, Fig. 4-3).

MIDDLE CAMBRIAN MOUNT SIMON SANDSTONE

The Mount Simon Sandstone consists of fine- to coarse-grained sandstone and siltstone. Janssens (1973) included dolomite and dolomitic sandstone in the upper part of the unit he mapped as the Mount Simon (particularly in south-central and eastern Ohio). These lithologies were not included in the Mount Simon in this investigation to maintain lithostratigraphic consistency throughout the study area (Plate 13B, Figs. 4-3, 4-4.). Examination of cores from Warren, Fayette, and Scioto Counties, Ohio, indicates that the Mount Simon is predominantly a nonmarine sandstone.

The Warren County deep core (core DGS 2627, API number 3416522627) (Shrake and others, 1990) indicates that the Mount Simon is a nonmarine, massive, cross-bedded, white to pink to purple quartz arenite. Bioturbated bedding and a pinkish hue interpreted as diagenetic feldspar are noticeably absent from the Mount Simon, in contrast to the overlying Eau Claire Formation. The unit is fine to coarse grained and locally conglomeratic. Hematitic staining, some of which is mottled, and large-scale cross-bed sets are common throughout the core of the Mount Simon.

The gamma ray response of the Mount Simon Sandstone is relatively lower than the Eau Claire Formation and the Maryville Limestone (Plate 13B, Fig. 4-3). Quartz-rich arenite beds of the Mount Simon decrease in thickness and eventually pinch out in eastern Ohio through an intertonguing relationship with the Maryville Limestone. The thickness of the Mount Simon ranges from zero to 300 feet and generally increases to the west. The Mount Simon is locally absent over Precambrian paleotopographic highs (see Fig. 4-2). The upper contact of the Mount

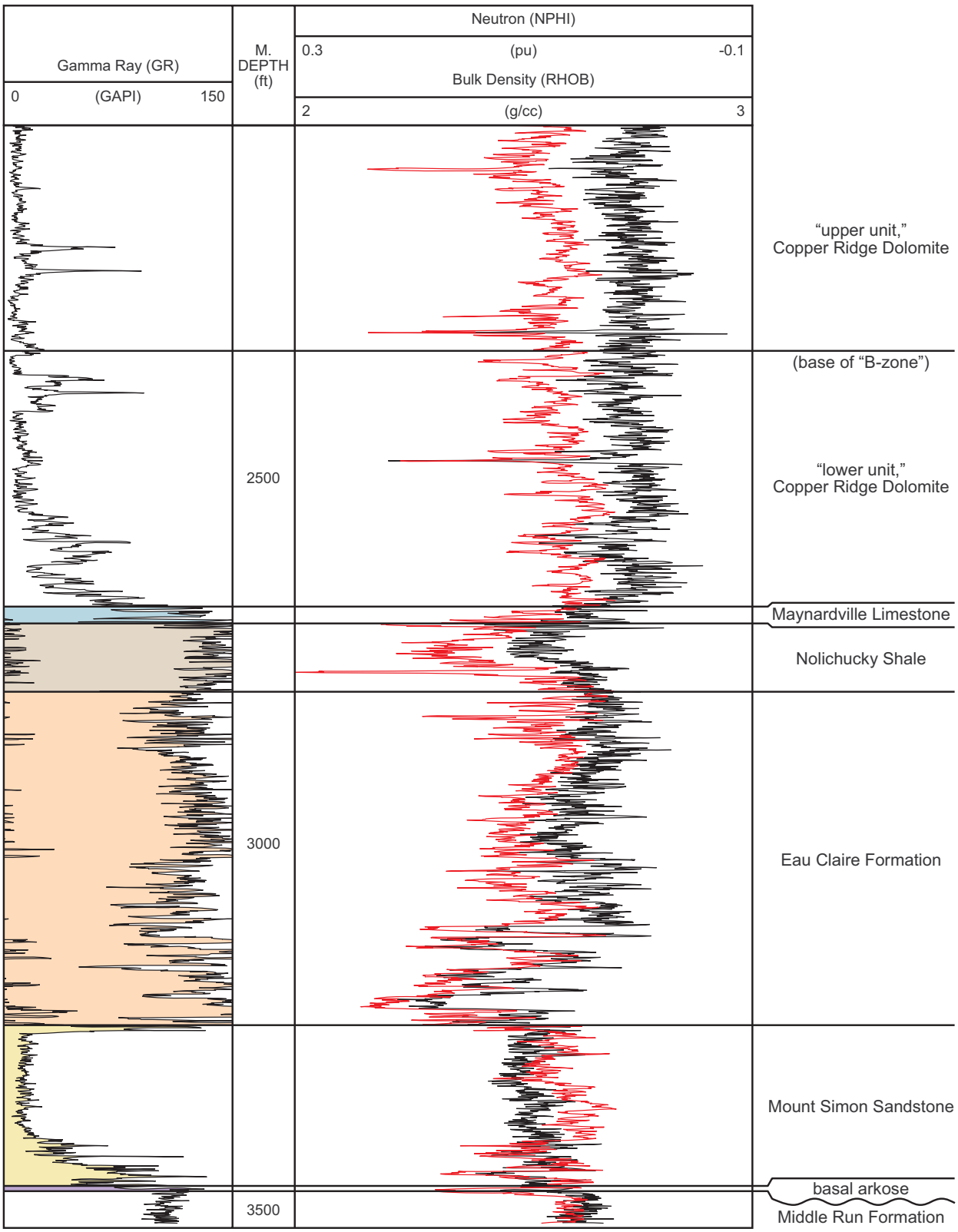

Figure 4-3. Geophysical log of DGS core 2627 (API number 3416562627) from Warren County, Ohio, and stratigraphic nomenclature used for the study.

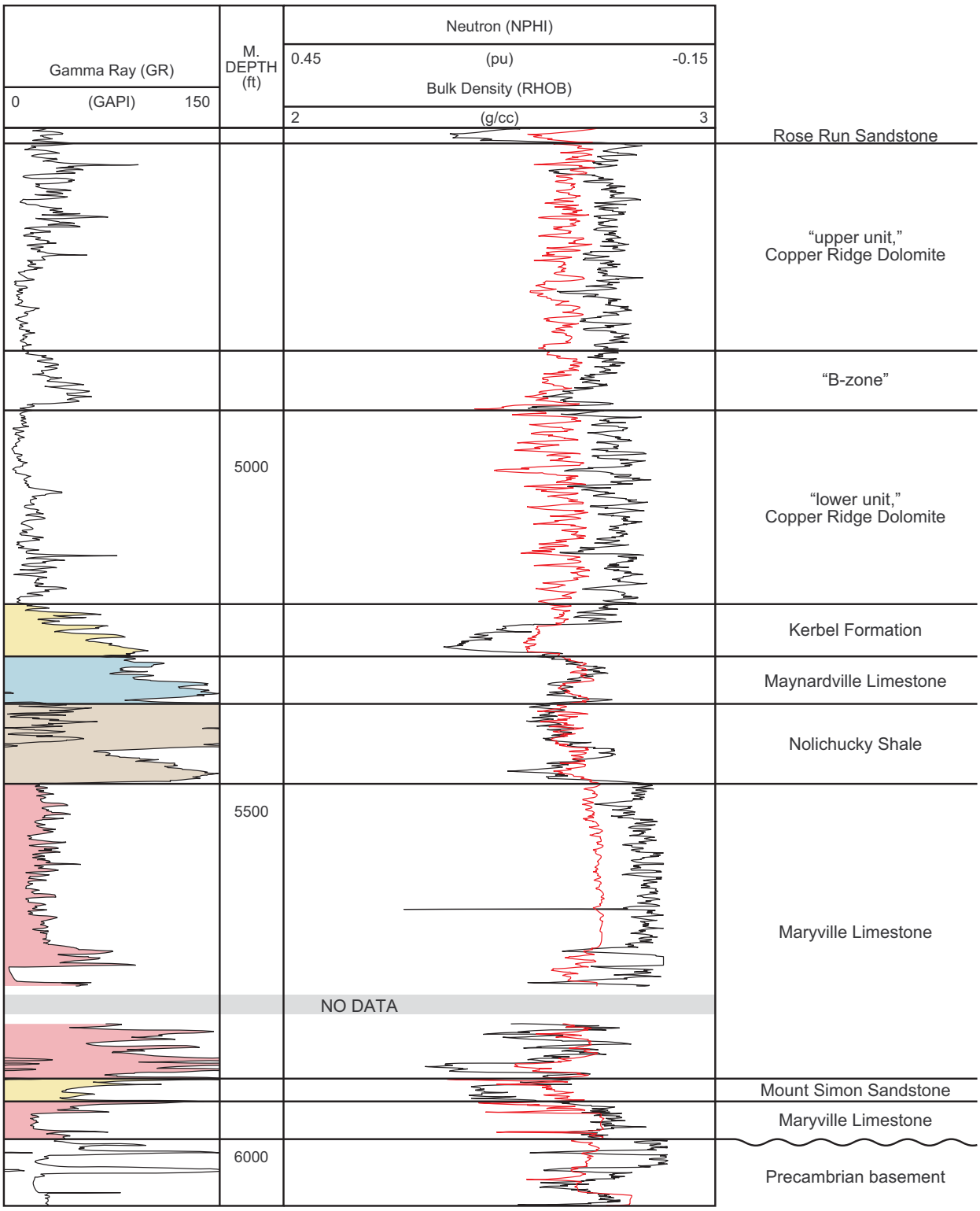

Figure 4-4. Geophysical log of well (API number 3407920102) from Jackson County, Ohio, and stratigraphic nomenclature used for this study.

Simon is interpreted as gradational and conformable with the overlying Eau Claire Formation in western Ohio and the Maryville Limestone in eastern Ohio.

MIDDLE AND UPPER CAMBRIAN EAU CLAIRE FORMATION

The Eau Claire Formation is present in western Ohio and consists of interbedded glauconitic and micaceous sandstone, siltstone, and shale and lesser amounts of dolomite (Janssens, 1973). Examination of the Warren County deep core indicates that the Eau Claire is a bioturbated pink (feldspathic) sandstone interbedded with siltstone. Glauconite zones and thin beds of micaceous gray to black shale are present throughout. The amount of laminated shale increases toward the top of the unit.

In southeastern Ohio, the Eau Claire has a facies relationship with the Maryville Limestone and Nolichucky Shale of the Conasauga Group (Figs. 4-3, 4-4). Higher gamma ray counts on geophysical logs from south-central Ohio indicate greater amounts of shale, mica, feldspar, and glauconite, which make it difficult to distinguish the dominantly clastic-rich Eau Claire from feldspathic and arenaceous dolomite of the Maryville on logs. Sample descriptions were used to determine wells in which clastic lithologies dominate carbonates.

The Eau Claire increases in thickness to the west and southwest and ranges from zero to 400 feet thick. The higher gamma ray response of the clastic lithology of the Eau Claire forms a stair-step profile upward into the overlying Nolichucky Shale and disappears eastward where the unit intertongues with lower gamma ray response dolomite of the Maryville Limestone (Plate 13B). The upper contact of the Eau Claire is gradational and conformable with the overlying Nolichucky Shale.

MIDDLE AND UPPER CAMBRIAN CONASAUGA GROUP (MARYVILLE LIMESTONE, NOLICHUCKY SHALE, AND MAYNARDVILLE LIMESTONE)

The Conasauga Group is subdivided into the following units, in ascending order: Maryville Limestone, Nolichucky Shale, and Maynardville Limestone (Figs. 4-1, Plate 13B). The Maryville Limestone consists of dolomite and fine- to coarse-grained sandstone; it is equivalent to the Rome Formation of Janssens (1973). The Maryville is dominantly dolomitic sandstone in south-central Ohio, where a thicker north-south-trending sandstone facies intertongues with the Eau Claire Formation (Plate 13B).

Examination of the Fayette County, Ohio, deep core (core DGS 779, API number 3404720001) indicates that part of the Maryville Limestone is a cross-bedded, dolomitic, bioturbated, pink (feldspathic) sandstone. Several zones of glauconite and anhydrite-filled vugs within brecciated zones, which are interpreted as paleosols, were observed in the lower portion of the Maryville in core DGS 779.

The Maryville Limestone ranges from approximately 350 feet thick in western Ohio to more than 800 feet thick in eastern Ohio, where the unit is primarily dolomite. The upper contact of the Maryville is gradational and conformable with the overlying Nolichucky Shale.

The Nolichucky Shale in southern Ohio consists of dominantly medium- to dark-brown shale interbedded with lesser amounts of siltstone, sandstone, limestone, and dolomite. It is equivalent to the lower portion of the Conasauga Formation of Janssens (1973). The unit is clastic rich in central and western Ohio on the basis of high gamma ray log response and core and sample descriptions. The Nolichucky increases in thickness in western Ohio, where it becomes gradational with clastic facies of the Eau Claire Formation. The unit decreases in thickness to the northeast until it disappears laterally (Plate 13B). In the northeastern portion of the study area (between wells API numbers 3412727110 and 3411927076 on strike line A, Plate 13B), the Nolichucky becomes very clastic poor, on the basis of low gamma ray response and sample descriptions, and is a dolomite that is difficult to separate from the Maryville Limestone and the Copper Ridge Dolomite. Thickness of the Nolichucky Shale ranges from 180 feet in western Ohio to 70 feet in eastern Ohio. The unit increases in thickness in southern Ohio toward the Rome Trough; it is 130 feet thick in Scioto County, Ohio. The upper contact of the Nolichucky is interpreted as gradational and conformable with the overlying Maynardville Limestone, where it is present.

The Maynardville Limestone consists of interbedded shale, siltstone, sandstone, limestone, and dolomite. It is equivalent to the upper portion of the Conasauga Formation of Janssens (1973). The upper contact of the unit is gradational with the overlying Kerbel Formation, where that unit present, or merges completely into the Copper Ridge Dolomite (Plate 13B). The thickness of the Maynardville Limestone ranges from 50 feet in southern Ohio to zero in central Ohio.

UPPER CAMBRIAN KERBEL FORMATION

The Kerbel Formation consists of fine- to coarse-grained sandstone, siltstone, and dolomite (Janssens, 1973). Janssens (1973) interpreted the Kerbel Formation as a broad, north-south-trending, lobate, deltaic deposit extending from northern to southern Ohio. The Kerbel is 90 feet thick in central Ohio but pinches out in southern Ohio and does not extend into Kentucky. The upper contact of the Kerbel Formation, where present, is interpreted as gradational and conformable with the overlying Knox Group (Figs. 4-1, Plate 13B).

UPPER CAMBRIAN-LOWER ORDOVICIAN KNOX GROUP (COPPER RIDGE DOLOMITE, ROSE RUN SANDSTONE, BEEKMANTOWN DOLOMITE)

Using Kentucky nomenclature, the Knox Group is subdivided, in ascending order, into the Copper Ridge Dolomite and the Rose Run Sandstone of Late Cambrian age and the Beekmantown Dolomite of early Ordovician age. The Copper Ridge Dolomite consists predominantly of dolomite but includes localized thin beds of fine-grained sandstone and siltstone; it is equivalent to the informal Copper Ridge dolomite of Janssens (1973). The Copper Ridge is divided into an “upper unit” and a “lower unit” on the basis of a distinct break on geophysical logs (Plate 13B) called the “B-zone.” The “B-zone” consists of thin beds of fine-grained dolomitic sandstone and siltstone (Janssens, 1973). The “B-zone” separates light-colored dolomite of the lower part of the Copper Ridge from overlying darker dolomite of the upper part of the Copper Ridge. The top of the “lower unit” of the Copper Ridge (base of the “B zone”) is an informal mappable surface for this project. The upper contact of the Copper Ridge Dolomite is gradational with the overlying quartz arenite beds of the Rose Run Sandstone or, where the

Rose Run is absent, is unconformable beneath the Ordovician Wells Creek Formation. Where the Rose Run is absent in central Ohio, the Copper Ridge forms an extensive regional subcrop beneath the Knox unconformity. Thickness of the Copper Ridge Dolomite ranges from 160 feet in eastern Ohio to more than 1,000 feet in southwestern Ohio.

The Rose Run Sandstone consists of interbedded fine- to coarse-grained dolomitic sandstone and dolomite (Janssens, 1973; and Riley and others, 1993). This unit is present throughout eastern Ohio and adjacent areas of Kentucky and West Virginia. The Rose Run forms an extensive regional subcrop at the Knox unconformity in southern and eastern Ohio; this subcrop does not extend into Kentucky (Riley and others, 1993). The upper contact of the Rose Run is gradational with the overlying Beekmantown Dolomite, where that unit is present, or forms a sharp erosional contact with units above the Knox unconformity (Plate 13B). Thickness of the Rose Run Sandstone ranges from 125 feet in eastern Ohio to zero where the unit has been eroded at the subcrop or where it changes laterally into dolomite in southwestern Ohio.

The Beekmantown Dolomite consists of massive, bedded, microcrystalline to crystalline dolomite, which may contain desiccation features and is locally vuggy (Janssens, 1973; Riley and others, 1993). The Beekmantown forms an extensive regional subcrop in southern and eastern Ohio, which extends into Kentucky (Riley and others, 1993). The top of the unit is a sharp erosional contact with units above the Knox unconformity. Thickness of the Beekmantown ranges from more than 600 feet in eastern Ohio to zero where the unit has been eroded at the subcrop of the Knox unconformity. The Beekmantown and the Copper Ridge cannot be consistently separated in southwestern Ohio unless the Rose Run Sandstone is present (Plate 13B).

MIDDLE ORDOVICIAN ST. PETER SANDSTONE

The St. Peter Sandstone is a fine-grained quartz arenite deposited on the Knox unconformity. Its presence is spotty throughout southern Ohio, where its thickness ranges from zero to 10 feet.

MIDDLE ORDOVICIAN WELLS CREEK FORMATION

The Wells Creek Formation consists of dolomite, argillaceous and arenaceous dolomite, dolomitic shale, siltstone, and sandstone (Janssens, 1973). The unit ranges in thickness from zero on paleotopographically high erosional remnants on the Knox unconformity to more than 120 feet in eastern Ohio. The upper contact is gradational and interbedded with micritic limestone and calcareous shale of the overlying High Bridge Group.

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Chapter 5.

Digital Well Log Data, Computer Lithology Modeling and Sandstone Mapping

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Digital Well Log Files and Database

One of the major accomplishments of this project is the creation and compilation of digitized wireline logs for 157 deep wells in the project. Through a joint effort on the part of all the consortium members, digital logs were either donated, or paper logs were digitized to create this database of LAS-format (log ASCII standard) log data. We gratefully acknowledge the contributions of log data by Columbia Natural Resources, Equitable Resources, and Hay Exploration for the project. A database table is included in the project database that contains details on the digitized curves available for each well.

For the many paper logs, the Kentucky Geological Survey used the Neuralog digitizing software to semi-automatically trace log curves from scanned images. The West Virginia Geological Survey digitized most of the deep wells in West Virginia for the project. In general, logs were digitized from the top of the Knox Group and below. When time allowed, or original service company files were available, the entire well is available in digital format.

The locations of wells that have digital log data are shown shown in Plate 17. All Precambrian wells with logs available and most pre-Knox wells in the trough were digitized. Wells selected for digitizing were chosen on the basis of location and log quality. Shallower wells, only penetrating the top of the Knox were digitized for use on the cross sections in a few areas where deeper control was not available. A list of wells with digital well log data is included as Table 5-1.

In many cases not all log curves for a given well were digitized. Spontaneous potential (SP), resistivity, and induction logs were not digitized unless they were the only available curves for the well. The emphasis in this project was on stratigraphic correlation and lithology interpretation, rather than fluid saturations. Thus only the log curves that were important for these uses were digitized. In general, the following log curves were digitized, if available for a well:

Gamma ray
Density
Neutron porosity
Sonic
Photoelectric effect (PE)
Caliper

Density porosity curves were not digitized- but were later generated from the bulk density data using appropriate matrix values. In most cases logs were digitized with a vertical resolution of 0.5 feet.

The LAS files are included on the project CD-ROM. Each file is named with the 10-digit API number for the well. These API numbers are included in the main well database. A database table listing the digital log data available for each well is included in the main project database (Microsoft Access file). The type and depth range of digitized curves can be viewed by clicking the "Digitized Log Curves" tab on the main well data display form. The database can be used to search for wells with specific curves.

The LAS files also contain curves that were not digitized, but calculated from other curves. An example of these kind of data are the lithologic fractions for sandstone (SS), limestone (LS), dolomite (DOL), shale (SH), and porosity (POR) calculated during the lithology modeling discussed below. In cases where the original digitized curves were changed, the original data is preserved. An example of this is when old log data was converted to modern units. Both the original data (commonly in counts per second) and the standardized data is included in the LAS file.

The digital wireline log data became the "backbone" of this study. These data were used for:

- Interactive correlation of rock units on computer
- Log display on the regional structural and stratigraphic cross sections
- Input data for lithologic modeling
- Sandstone percentage mapping of lithology data

Lithology Modeling

The significant amount of digital wireline log data compiled for this project provided an excellent opportunity to attempt to model and map lithologies utilizing computer software. This approach was of interest in the Cambrian section in and around the Rome Trough due to the thin-bedded and complex lithologic nature of much of the sequence. The Rome Formation, and in some areas, the Conasauga Group rocks are poorly represented in well cuttings, due to bed thicknesses much less than the average 10 foot cuttings sample interval. The advantage of log based lithology calculations is the greater vertical resolution (limited only by the logging tool's resolution). Computer-based lithologic determinations are also much faster than manual methods, and can be run over thousands of feet of section in a relatively short time. Computer techniques can also incorporate a large number of well logs to use as input, many more than is feasible in a manual calculation.

There are several methods of computer-based lithologic modeling available in commercial software packages. Rider (1996, Chapter 11) and Doveton (1994, Chapter 3) provides a good overview of the various approaches to lithology modeling from multiple well logs. They can be grouped into two general categories: petrophysical and statistical. Petrophysical techniques are primarily concerned with solving simultaneous linear equations in order to determine lithology and eventually pore volume and fluid content. Statistical methods use a probabilistic model to calculate lithologic components. This project tried both approaches to model lithology in the Cambrian. The statistical method

worked much better for this project, and all lithology data included in the LAS files was generated with StatLith, the statistical lithology modeling program in TerraStation. A summary of the StatLith technique is quoted below from TerraSciences:

> *In statistical lithology, also known as probabilistic petrophysics, measurements from a suite of logging tools are modeled by a corresponding set of response equations. These equations use an appropriate group of formation mineral and fluid volumes plus their log-response parameters to predict each measurement in the logging suite. Optimum values for the formation volumes are calculated from the model using statistical methods. These optimum values will produce the most likely match between the suite of actual log measurements and the suite of measurements predicted by the response equations of the model. The quality of the solutions can be monitored, depth by depth, by several diagnostic statistics. The formulation of the model is primarily the interpreter's responsibility. The model is based on your knowledge of the formation environment to be analyzed. The ingredients of a model that you must pre-set are:*
>
> • *The suite of logs for the linear response equations.*
> • *The linear response coefficients.*
> • *The nonlinear response equations, if any.*
> • *The mineral and fluid components.*
> • *Lower and upper bounds on the component volumes.*
> • *Weights or uncertainties for each log response.*
>
> *Besides the bounds constraining the component volumes, the volumes are also constrained by the unity equation (i.e. the component volumes must add up to one). The unity equation effectively turns the volumes into proportions. The optimization of the component volumes is achieved by minimizing the objective function of the model, subject to the component constraints. The objective function is the sum of the squared weighted log errors, where a weighted log error equals (actual log value - predicted log value) / uncertainty. Once the model has been set up,* ***StatLith*** *will perform the optimization, depth by depth, over the entire depth interval you selected. At any given depth, logs with missing values are eliminated from the model. The optimization uses only the remaining non-missing logs.*

Methods

For the Cambrian rocks in the Rome Trough, a 4 mineral plus porosity model was built. The minerals used were quartz (sandstone), calcite (limestone), dolomite, and clay (shale). This model worked well, since other sedimentary minerals (halite, anhydrite, gypsum) are absent or a very minor component of the rocks. This model was also used for the Knox Group and overlying formations in some of the wells where log data permitted. The model worked well in these post-Cambrian rocks also.

The model required the presence of 3 log curves for a solution. If fewer than 3 curves were present, then lithologies were not computed. This resulted in some wells not being

modeled, and gaps in others where log data was insufficient. Of the 157 wells with digital log data, lithology modeling was possible on 109 wells. These wells are indicated with a check mark in the lithology data column in Table 5-1.

In attempting to model lithology using well logs, the first problem encountered was that of the wide range of log vintages and quality. Due to differences in the logging tools and service companies, many logs had to be converted from old logging units (counts per second, ug Ra equiv./ton, etc.) to modern API standard units. These conversions were done with published equations using the TerraStation petrophysics software. The conversion of older units to modern units may not result in identical log values. This is one source of error that must be considered.

Initially, well-to-well variability in log responses was thought to be a problem in modeling lithology using a single model. Differences in absolute log readings were seen in the same interval in different wells due to poor tool calibration, variability between logging companies, or different vintages of logging tools. We initially tried to correct for this variability by normalizing the log responses. This resulted in unacceptable smoothing of the log data and reduction of the data range. We felt that the lithology calculations would suffer from using normalized data. We decided to use the original un-normalized data, and wells with abnormally high or low log responses were recalculated individually to obtain a better match.

One important factor influencing the quality of lithology models is the quality of the original log data. The Rome Trough area in general is known for less than ideal borehole conditions. The Rome and Conasauga shales tend to cave, and borehole washouts and breakouts are common in some parts of the section. Borehole rugosity affects the density and sonic logs the most. The volume of log data included in the project was too large to attempt to edit or correct for hole problems. Editing of density or sonic data in intervals of bad data would improve results, but was not possible in the time available.

Another problem in lithology calculations was the presence of minerals other than clay that affect the gamma ray response. Some of the Rome and Conasauga sandstones are arkosic or contain glauconite. Feldspars and glauconite contain potassium which is naturally radioactive, and affects the gamma response. These minerals make the gamma curve appear more “shaly.” Ideally, if other log curves are indicating sandstone, the lithology will be interpreted as sandstone, even with a high gamma ray response. This may result in sandstones being interpreted in zones with high gamma response that look like shales.

The problems of old log data, well-to-well log response variability, and borehole problems all have an effect on the resulting lithology calculation. In many cases the lithology result is inaccurate because of the problems above. We devoted a great deal of time in “tweaking” the model parameters to achieve the best possible result. Nevertheless, problems still remain in some of the wells. Changing parameters to correct problems in a limestone interval often has detrimental effects in an adjacent sandstone interval. Overall, a good level of accuracy was achieved in the lithology models. Results were checked against sample descriptions and adjusted if necessary. An example of the results of the lithology model is shown in Figure 5-1 for part of a well in the Homer field. This display is the same as used on the stratigraphic cross sections, with the gamma ray shaded with the major lithologic component, and all of the lithologic fractions plotted in

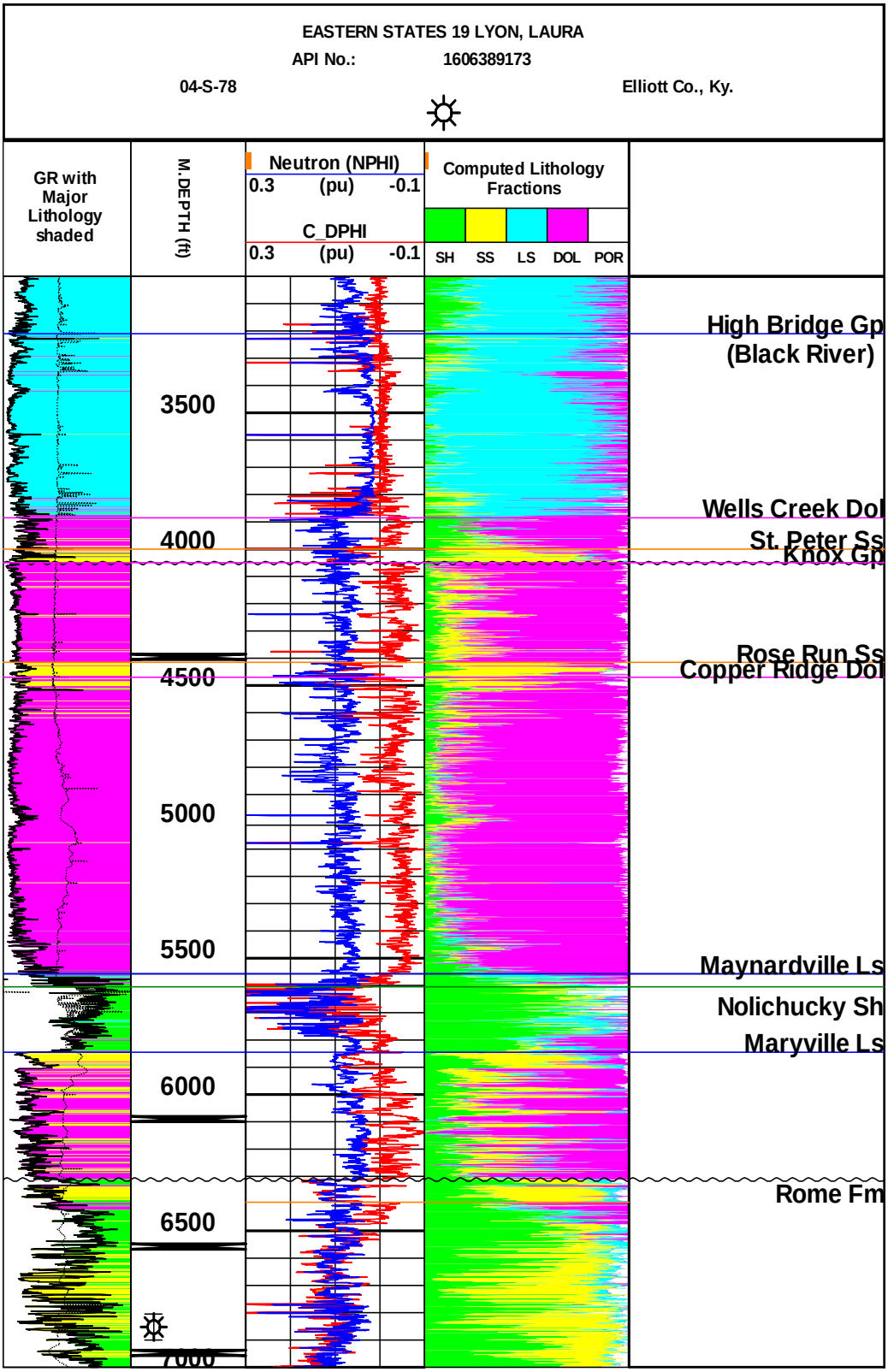

Figure 5-1. Geophysical log plot showing results of lithologic calculations for formations of varying lithology. The gamma ray curve in the left track is shaded with the major lithology. Individual lithologic fractions are plotted in the 4th track from the left.

the far right track. This well has a good quality, complete and modern log suite, and the results are very good. As log quality decreases or as fewer log curves are available, the lithologic results are not as good.

As stated previously, all of the calculated lithology data is included in the LAS files. It is stored as 5 curves as a decimal number. For each depth step, the sum of SS, LS, DOL, SH and POR equals 1.

Sandstone Mapping

One of the main reasons for performing the lithology modeling was to use the data to map sandstone trends across the study area. Two intervals were chosen for mapping because of their sandstone reservoir potential, the Rome Formation and the Maryville Limestone of the Conasauga Group. The Maryville Limestone is a carbonate unit in most of the study area, but does contain significant sandstones in Kentucky and Ohio, and is a reservoir zone in the Homer Field.

Initially we chose the entire Conasauga Group (6 formations) for a sandstone mapping interval, but soon realized that log quality problems in parts of this interval were giving bad lithology results, and overestimating sandstone percentages. This was particularly true in the Nolichucky Shale due to caving and washout of the shales. Sandstone data for the whole Conasauga was inconsistent, and difficult to interpret because of these log problems. The Maryville Limestone was the primary Conasauga Group formation with significant sandstone, and sandstone mapping was limited to it. The formations laterally equivalent to the Maryville Limestone, the Eau Claire Formation and the Conasauga Shale, were also included in the Maryville maps to complete coverage over the whole project area.

TerraStation software was used to add the footage of each formation where the sandstone component was ≥ 0.4 (40%). With the 4 mineral model, this value resulted in the best approximation of sandstone vs. non-sandstone. Initial mapping of sandstone feet in each formation was ambiguous because of the great variation in thickness of each formation. Thick intervals that were sandstone-poor would give values similar to thinner intervals that were sand-rich. To avoid this problem sandstone *percentages* were mapped. The sandstone percentage was calculated by dividing the total feet of sandstone by the total thickness of the formation. Percentages proved to be a better measure of sandstone distribution in the Rome and Conasauga, where thicknesses varied significantly.

Two maps for each unit were made at a scale of 1:1,000,000. The gross sandstone percentage maps show the percentage of the formation where the sandstone fraction was ≥ 0.4. This map was contoured by hand using a 20% interval. The net sandstone percentage maps used the same value for the sandstone fraction, but only counted sands with calculated porosity ≥ 4%. The net sandstone maps are contoured with a 10% interval. The Rome Formation maps are included as Plate 23A (gross sandstone) and 23B (net sandstone). The Maryville Limestone maps are included as Plate 24A (gross sandstone) and Plate 24B (net sandstone).

Sandstone percentage maps for the Rome Formation include both wells that went completely through the formation, and wells that only partially penetrate it. Partial

penetration data points are shown with a + symbol, and because they are not representative of the whole formation like the other points, they were not always honored by contouring. They were included to provide additional control in some areas.

There were very few partial penetrations of the Maryville, and these data points were not used for sandstone mapping. All of the data points on the Maryville/Eau Claire/Consauga Shale maps were derived from complete sections. Because three laterally-equivalent formations were included on the Maryville sandstone maps, the formations are coded by the well symbol.

Interpretation of Sandstone Distribution

Interpretation of the sandstone maps must be made in light of the potential data quality issues discussed above. These maps are valuable for illustrating trends in sandstone content and distribution, but absolute values must viewed with the underlying log quality and lithologic modeling in mind. The data mapped out in a consistent and geologically reasonable pattern, which greatly increased our confidence in the validity of the technique.

Rome Formation Sandstone Maps

The Rome Formation sandstone percentage data mapped out very consistently. Plate 23A, the Rome gross sandstone map shows a maximum value of 93% in Carter County. Sandstone percentage is highest in the trough south of the Kentucky River Fault System. South of the Irving-Paint Creek Fault System sandstone percentage decreases significantly in most areas. This north to south decrease in sandstone content is interpreted to reflect sand transport from the north, across the Kentucky River Fault System.

The Rome gross sandstone map shows 2 areas of high sandstone percentage, which were locations of high sand transport into the trough from the north. The western lobe, centered in Garrard, Jessamine, and Madison Counties, Ky. immediately southeast of the Kentucky River and Lexington Faults, has values as high as 78% sandstone. The sand-rich Rome in this area was drilled in several Texaco wells, and Webb (1980) referred to this area as a delta (the Garrard County delta). The highest sandstone percentages are located next to the faults, and decrease away from them. The 20% contour extends south of the Irvine-Paint Creek Fault, beyond a well in Jackson County, with no control in the area between. Whether this entire area contains greater than 20% sandstone is speculative. The map suggests there was a major sand source in this part of the basin during Rome time. Sand was transported from north to south across the faults, into the delta front and subtidal shelf area between the Kentucky River and Irvine-Paint Creek fault systems.

The eastern lobe of high sand also lies along the Kentucky River Fault System, from Menifee County east to Carter and Boyd Counties, Ky. A sandstone-rich area lies in Menifee and Morgan Counties, with somewhat lower values in Elliott County. The Homer Field in Elliott County lies in the 20-40% sandstone area on this map. Sandstone values increase northeast of Elliott County, along the fault into Carter and Boyd Counties. In the Morgan-Menifee County area, the whole shelf between the Kentucky

River Fault System and the Irvine-Paint Creek Fault System is sand-rich, with values over 20%.

A broad low between the two high-sandstone areas, is defined by the 20% gross sandstone contour in Powell and Estill Counties, Ky. This reentrant is defined by 2 points, one of which is a partial penetration value of 11%. Better data is needed to fully define this feature, but it is tentatively interpreted as an area of lower sandstone content between the Garrard-Jessamine County area to the west and the higher sandstone area to the east along the Kentucky River shelf. This area may have been somewhat deeper during Rome deposition, with finer-grained deposits (shales) predominating. It is interesting to note the presence of NW-SE trending surface faults parallel with this feature, and a deflection in the trend of the Irivine-Paint Creek fault in this area. Assuming these are deep basement-related faults, they could have been active during Rome time, forming a NW-trending graben, with deeper, more shale-prone depositional environments.

Farther east in West Virginia, lithology data is limited to 2 points. The Exxon McCoy well in Jackson County has a 31% value, and the 20% and 30% contours were tentatively extended into this area. Other Rome wells in this part of West Virginia, could not be used for mapping because of insufficient log curves to calculate lithologies. Manual estimates of sandstone percentages in this area would improve the confidence in this part of the map.

Areas south of the Irvine-Paint Creek Fault in the center of the trough in Kentucky are largely low in sandstone. Values range from 2% to 7% sandstone. These areas were located in deeper water environments, removed from active sand supply points. Sandstone percentages do increase in south-central Kentucky within and on the southern rim of the trough in Pulaski and Laurel Counties (52, 41, and 38% sandstone). This indicates a southern or southwestern sand source may have been active in Rome time. The upthrown side of the Rockcastle River Fault has good sandstone content in Laurel County, but a low value in Perry County, suggesting the southern rim of the trough was not a major sand source. An isolated high sandstone value (38%) occurs in Johnson County, on the edge of the Pike County uplift. A well immediately north of this point in the trough is much lower (6%). This may indicate higher energy depositional environments on the northern edge of this structure than to the south in Pike County (2%) or within the trough to the north.

The Rome Formation *net* sandstone percentage map (Plate 23B) shows sandstone percentages with calculated porosity ≥ 4%. The map is very similar to the gross sandstone map in overall pattern, indicating that porous sandstones occur throughout the Rome Trough. The fact that sandstones with porosity ≥ 4% occur across the study area indicates that porosity is not a major risk factor in this formation. Porous sandstones occur in both of the major sand depocenters on the northern shelf of the trough. While this map shows sandstones with porosity are common in the Rome, it does not indicate permeability in the sandstones. Permeability may be an issue in some areas of the Rome Trough, and is discussed in the exploration recommendations section.

Maryville Limestone, Eau Claire Formation and Conasauga Shale Sandstone Maps

The Maryville Limestone, Eau Claire Formation and Conasauga Shale are lateral equivalents, and were mapped together on the sandstone percentage maps (Plates 24A, 24B). For simplicity, this interval will be referred to as Maryville in this discussion. This interval was chosen because it contains important sandstone reservoirs in Elliott and Lawrence Counties, Ky., and in Jackson County, W. Va. The Maryville gross sandstone percentage map (Plate 24A) shows a distinctly different pattern than the Rome maps. As Cambrian seas transgressed across the craton, the Maryville and equivalents were deposited well to the north of the Rome Trough, across southern Ohio. The predominant trend of sand deposition runs north-south from Clinton County, Ohio to Menifee and Rowan Counties, Ky. Areas to the west, in the Eau Claire Formation, are shale-dominated, with much lower sandstone percentages. Areas to the east are much higher in carbonate, where the Maryville Limestone consists of limestone, dolomite, and minor clastics. As mapped from the log data, a Maryville sandstone depocenter exists in Menifee and Rowan Counties, Ky., where sandstone percentages of 62 and 65 were calculated. Relatively high sandstone values occur to the north into Ohio, allowing the data to be contoured in a linear north-south pattern. Sandstone values remain high between the Kentucky River and Irvine-Paint Creek faults in this area, but fall significantly south of the Irvine-Paint Creek Fault, as seen for the Rome Formation sandstones. This suggests that these faults were still active during Maryville time, and influenced depositional patterns.

The main north-south sandstone pattern mapped from Ohio to the Rome Trough is parallel to facies trends published by Janssens (1973) (Fig. 5-2 in this report). Janssens shows a north-south trending pattern in approximately the same area, mapped as sand-prone. This pattern continues north through west-central Ohio to Michigan. The more quantitative sandstone mapping in this study supports Janssens trends.

A smaller area of significant sandstone in the Maryville occurs in the western end of the trough, in the Garrard, Jessamine, and Madison County, Ky. area. Values here reach 24% sandstone. This area overlies a sandstone-rich zone in the Rome Formation seen on Plate 23A, and suggests this area was still a focus for sand deposition.

Farther east, in West Virginia sandstone percentages are consistently low. Note that an anomalous value of 45% in Lincoln County, W. Va. is due to a poor lithology calculation (see log plot on cross section dip 7). This value is included on the map, but is not contoured.

Several wells in eastern Ohio have gross sandstone percentages of 20%, and these wells were connected to form a linear NE-SW zone parallel to the northwest boundary fault of the Rome Trough. This area may be somewhat more sand-rich due to higher energy depositional environments on the upthrown side of this fault zone.

As with the Rome, the Maryville *net* sandstone map is similar to the gross sandstone map. The main north-south trend is present, indicating sandstones with porosity ≥ 4% are present, and are thus potential reservoir targets. The eastern Ohio trend is not apparent from the data on the net sandstone map, and that area appears to have little porosity development in the sandstone facies. The western Rome Trough area in Jessamine and Garrard Counties, Ky. also has some porosity development, with one well with a 10% net sandstone value. Other parts of the Rome Trough have lower net sandstone values for the

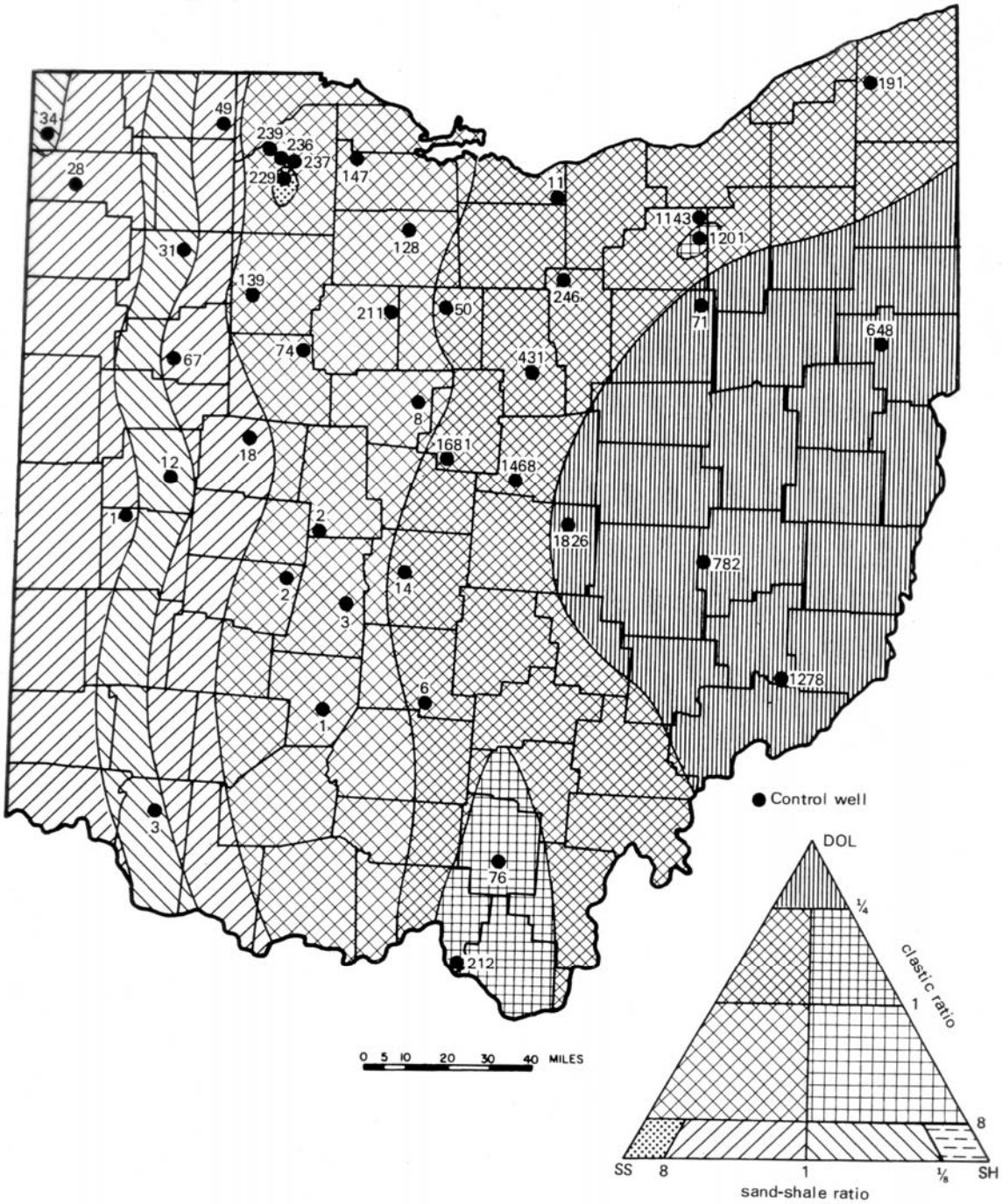

Figure 5-2. Lithologic percentage map for post-Mt. Simon, pre-Knox rocks in Ohio from Janssens (1973). Note similarities in trend of Janssens' lithologic boundaries to sandstone percentages mapped in this project shown on Plates 24A and 24B. Highest sandstone percentage is in west-central Ohio, and trends north-south into Kentucky.

Maryville, including the Homer Field area in Elliott County. These areas all map as less than 10% net sand.

Summary

Maps of sandstone percentage for the Rome Formation and the Maryville/Eau Claire/Conasauga Shale intervals show 2 different trends. The best sand development in the Rome occurs on the structural shelf between the Kentucky River and Irvine-Paint Creek faults. Two sand depocenters have been mapped on this shelf. One occurs in the far western end of the Rome Trough, in Jessamine, Garrard and Madison Counties and is bounded to the north and west by faults. Sand percentages are highest immediately adjacent to the faults, and decrease to the south and east. Farther east, Rome sandstones are well-developed between the Kentucky River and the Irvine-Paint Creek Fault zones from Menifee and Morgan Counties, eastward through Elliott County to Boyd County, Ky. Again, sandstones are most abundant immediately adjacent to the Kentucky River Fault Zone, and decrease in abundance to the south. A less sand-prone reentrant is mapped on limited data in Estill and Powell Counties between the two sandstone-rich areas. This area coincides with NW-SE trending cross faults, which may have formed a structural graben during the Cambrian. Rome Formation sandstones have good porosity development throughout the area, as indicated on a map of net sandstone containing porosity ≥ 4%.

The younger Maryville/Eau Claire/Conasauga Shale interval shows a different sandstone distribution. A north-south pattern is present from Menifee and Morgan Counties, Ky. northward into southern Ohio. This sandstone-prone belt coincides with facies maps done by Janssens (1973) using different methods and data. Sandstone percentages in the Maryville are lower in eastern Ohio, but an area with about 20% sandstone occurs on the upthrown edge of the trough, west of the boundary fault.

Sandstone distribution maps indicate the best potential reservoir development in the Rome Formation occurs in 2 areas along the structural shelf between the Kentucky River and Irvine-Paint Creek faults in Kentucky. This trend may continue along the north bounding fault into West Virginia, but data quality there is poor. The Maryville Limestone of the Conasauga Group contains higher sandstone content in a north-south trend from the Rome Trough in Kentucky into Ohio, with best potential reservoir quality in Menifee and Rowan Counties. High sandstone percentages in the Rome and Maryville are superimposed in Menifee, Morgan, and Elliott Counties, Ky, and in the far west end of the Rome Trough in Jessamine, Garrard and Madison Counties, Ky. Opportunities for multiple pay zones exist in these areas where Rome and Maryville sand highs coincide. In addition to sandstone and porosity trends, permeability in these sandstones needs to be considered. Permeability was not evaluated in this study, but may be an issue in parts of the Rome Trough.

Table 5-1. List of wells with digitized geophysical logs included on project CD-ROM. Wells with calculated lithology data are checked in the right column.

API No. (LAS file name)	County	St.	Well_Name	Lith. Data
1601119092	BATH	KY	QUASAR 1 PREWITT, C & M	✓
1601300000	BELL	KY	UNITED FUEL GAS 8801A KNUCKLES, J	✓
1601500001	BOONE	KY	FORD, F M 1 CONNER, CECIL	
1601920459	BOYD	KY	INLAND GAS 533 INLAND GAS CO	
1601920876	BOYD	KY	INLAND GAS 535 MCKEAND, S	✓
1601921652	BOYD	KY	INLAND GAS 537 FANNIN, C	✓
1601927870	BOYD	KY	INLAND GAS 551 SMALLRIDGE, EVA	✓
1602500000	BREATHITT	KY	UNITED FUEL GAS 8613T WILLIAMS, S	
1603718051	CAMPBELL	KY	ASHLAND OIL & REFINING 1 WILSON, H	✓
1604129557	CARROLL	KY	MINEX 1 ROBINSON, JOHN	
1604300000	CARTER	KY	UNITED FUEL GAS 8807T STAMPER, L	
1604316235	CARTER	KY	ASHLAND OIL & REFINING 11-1 STAPLETON	✓
1604322935	CARTER	KY	INLAND GAS 538 INLAND GAS CO	✓
1604325730	CARTER	KY	INLAND GAS 546G MCDAVID, E	✓
1604326995	CARTER	KY	INLAND GAS 547 DUNCAN, T	✓
1604534578	CASEY	KY	CITIES SERVICE OIL A1 GARRETT, A	✓
1604588047	CASEY	KY	SCOTT, BENNY DRILLING 1 KING, V	
1604918142	CLARK	KY	ASHLAND OIL & REFINING 1 MILLER, M	✓
1604922398	CLARK	KY	TEXACO 1 WILLIAMS, JOE	
1605114386	CLAY	KY	ALGONQUIN PETROLEUM 1 HUBBARD, B	✓
1605145279	CLAY	KY	WORLD WIDE ENERGY 1 JOHNSON, W	✓
1606300000	ELLIOTT	KY	UNITED FUEL GAS 8802T LITTON, J	
1606323542	ELLIOTT	KY	MONITOR PETROLEUM 1 ISON, CECIL	✓
1606367748	ELLIOTT	KY	ASHLAND EXPLORATION 1 KAZEE	✓
1606385783	ELLIOTT	KY	CARSON ASSOCIATES 1 KAZEE, G	✓
1606386988	ELLIOTT	KY	BLUE RIDGE GROUP 1 GREENE, J	✓
1606387820	ELLIOTT	KY	CARSON ASSOCIATES 33 LAWSON, E	✓
1606388019	ELLIOTT	KY	CARSON ASSOCIATES 57 PRICHARD HEIRS	✓
1606388290	ELLIOTT	KY	CARSON ASSOCIATES 50 OLIVER, GARY	✓
1606388355	ELLIOTT	KY	CARSON ASSOCIATES 18 BLAIR, IRENE	✓
1606388869	ELLIOTT	KY	COLUMBIA NATURAL RES. 23063T ISON	✓
1606389000	ELLIOTT	KY	EASTERN STATES 40 KAZEE, GEORGE HEIRS	✓
1606389173	ELLIOTT	KY	EASTERN STATES 19 LYON, LAURA	✓
1606389760	ELLIOTT	KY	CARSON ASSOCIATES 25 LYONS, DELTA	✓
1606389762	ELLIOTT	KY	CARSON ASSOCIATES 77 ISON, O D	✓
1606390457	ELLIOTT	KY	EASTERN STATES 35 GILLIAM, C	✓
1606390472	ELLIOTT	KY	EASTERN STATES 34 KAZEE, CARL	✓
1606390473	ELLIOTT	KY	EASTERN STATES 39 FANNIN, ALICE	✓
1606521865	ESTILL	KY	TEXACO 1 TIPTON, GLYN	
1607127524	FLOYD	KY	SIGNAL OIL & GAS 1 HALL, M	
1607921048	GARRARD	KY	TEXACO 1 KIRBY, LEONARD	✓
1607921674	GARRARD	KY	CLINTON OIL & GAS 1V HALE, C	✓
1607922875	GARRARD	KY	PATRICK PETROLEUM 1 BROADUS C C & E	
1608921256	GREENUP	KY	COMMONWEALTH GAS 1 NEWELL, D	
1610929847	JACKSON	KY	MONITOR PETROLEUM 1 NEELEY, S	✓
1611318114	JESSAMINE	KY	TEXACO 1 SHERRER, THOMAS	✓
1611320747	JESSAMINE	KY	TEXACO 1 WOLFINBARGER, P	✓

1611526311	JOHNSON	KY	U S SIGNAL 1 ELKHORN COAL	✓
1611526604	JOHNSON	KY	COLUMBIA GAS TRANSMISSION 9784T EVANS	✓
1611539121	JOHNSON	KY	ARCO EXPLORATION 1 KY/WV GAS	✓
1611560712	JOHNSON	KY	ASHLAND EXPLORATION 1 MCCARTY, J	
1611567526	JOHNSON	KY	ASHLAND EXPLORATION 1 TACKETT, A J	
1611567549	JOHNSON	KY	ASHLAND EXPLORATION 1 WILLIAMS, E	✓
1612179689	KNOX	KY	G & M OIL 1 GARLAND, JERRY	✓
1612520438	LAUREL	KY	HOWARD SOBER 3 CUMBERLAND MINERALS	
1612724502	LAWRENCE	KY	INLAND GAS 542 YOUNG, W	✓
1612789172	LAWRENCE	KY	CARSON ASSOCIATES 1 RAY, BALLARD	✓
1612960010	LEE	KY	ASHLAND EXPLORATION 1 CABLE, M	✓
1613100000	LESLIE	KY	UNITED FUEL GAS 8437T FORDSON COAL	
1613500000	LEWIS	KY	THOMAS, RALPH 1 ADAMS, DAISEY	
1613502579	LEWIS	KY	UNITED FUEL GAS 9060 SHEPHARD, A	
1613521132	LEWIS	KY	ASHLAND OIL & REFINING 1 WOLFE, D	✓
1613700000	LINCOLN	KY	CALIFORNIA 1 SPEARS, A R	
1613722948	LINCOLN	KY	ROME OIL & GAS 1 FOSTER-MORROW UNIT	
1614787114	MCCREARY	KY	EASTERN AMERICAN ENERGY 2 COFFEY HEIRS	✓
1615121905	MADISON	KY	TEXACO 1 PERKINS, B	✓
1615133878	MADISON	KY	TEXAS WEST BAY 1 HAMILTON, W J	✓
1615900000	MARTIN	KY	UNITED FUEL GAS 8610T JASPER, J	
1616103990	MASON	KY	UNITED FUEL GAS 9061T RAWLINGS, W	✓
1616518101	MENIFEE	KY	UNITED FUEL GAS 9380 BROWN, F	✓
1616529846	MENIFEE	KY	MONITOR PETROLEUM 1 CAMPBELL, A	✓
1617311507	MONTGOMERY	KY	FERGUSON & BOSWORTH 16-1 POTTER, A	
1617521871	MORGAN	KY	ASHLAND OIL & REFINING 1 LEE CLAY PROD.	✓
1617524194	MORGAN	KY	MONITOR PETROLEUM 1 ISON, F & E	✓
1617527544	MORGAN	KY	MONITOR PETROLEUM 1 BLANTON, B	✓
1617528019	MORGAN	KY	MONITOR PETROLEUM 1 STACY HEIRS	✓
1617588839	MORGAN	KY	CARSON ASSOCIATES 15-M KIMELTON	✓
1617589986	MORGAN	KY	EASTERN STATES 1 SMITH, NORMA	✓
1618130197	NICHOLAS	KY	UNION LIGHT HEAT 200 MYNEAR, J	✓
1618780234	OWEN	KY	KINOSHITA, GILBERT 1 COBB, J	✓
1619344492	PERRY	KY	ARCO EXPLORATION 1 DUFF, J	✓
1619524577	PIKE	KY	SIGNAL OIL & GAS 1 STRATTON, H	✓
1619787816	POWELL	KY	CUMBERLAND HARLAN EXPL. 1 SHUMATE HEIRS	✓
1619922393	PULASKI	KY	AMERADA PETROLEUM 1 EDWARDS, R	✓
1619922670	PULASKI	KY	AMERADA HESS 1 DAULTON, H & M	✓
1620351133	ROCKCASTLE	KY	OHIO OIL & GAS EXPL. 1 SINGLETON	✓
1620514647	ROWAN	KY	PENNZOIL 1 JONES, CARMIA	✓
1620522478	ROWAN	KY	PETER HENDERSON 1 BAILEY, W	
1620525356	ROWAN	KY	KENTUCKY CENTRAL 1 PERKINS, R	✓
1620974609	SCOTT	KY	OHIO KENTUCKY OIL 1 RAMSEY CREEK OIL	✓
1623132644	WAYNE	KY	REYNOLDS & VINCENT 1 STEARNS COAL	✓
1623553298	WHITLEY	KY	DELTA-MIKE 1 OHLER HEIRS	✓
1623584852	WHITLEY	KY	ALPHA GAS DEVELOPMENT 1 COBB, C	✓
1623730520	WOLFE	KY	EXXON 1 BANKS, ORVILLE	✓
1623789379	WOLFE	KY	MILLER OIL & GAS 1 BAILEY, G & L	✓
1623790214	WOLFE	KY	MILLER OIL & GAS 1 CHICHESTER	✓
1623921801	WOODFORD	KY	PHILLIP AGRIOS EXPL. 1 GAINES	✓
3400120004	ADAMS	OH	CABOT 1-A BAILEY, A	
3400120005	ADAMS	OH	COMMONWEALTH GAS 1 COVERT, G	✓

3400120011	ADAMS	OH	OXFORD OIL 1 RUSSELL & TENER	
3401520006	BROWN	OH	SPENCER PETROLEUM 1 GRIFFITH	✓
3401770004	BUTLER	OH	ARMCO STEEL 1 ARMCO STEEL	✓
3402520003	CLERMONT	OH	CONTINENTAL OIL 1 WIKOFF, C	✓
3402720010	CLINTON	OH	STOCKER & SITLER 1 COY	✓
3402920648	COLUMBIANA	OH	MANAGEMENT CONTROL 3 MURRAY, F	✓
3402921476	COLUMBIANA	OH	TPI 21750 AQUILA SOLOMON	✓
3403122053	COSHOCTON	OH	TATUM, BOB 1 LEE, EDWIN	✓
3403124118	COSHOCTON	OH	POMSTONE CORP 1 BURRELL, J	
3404720001	FAYETTE	OH	KEWANEE OIL 1 HOPKINS, E	
3404720009	FAYETTE	OH	OXFORD OIL 1 HANAWALT, B	
3405920782	GUERNSEY	OH	LAKE SHORE PIPELINE 1 W MARSHALL COMM	
3406120001	HAMILTON	OH	CONTINENTAL OIL 1 BRISBIN, W	✓
3406720737	HARRISON	OH	RED HILL DEVELOPMENT 1 ZECHMAN, T	✓
3407120001	HIGHLAND	OH	KEWANEE OIL 1 PAVEY, H & F	
3407120007	HIGHLAND	OH	OHIO VALLEY OIL & GAS 1 COURTNEY, O	
3407321222	HOCKING	OH	DUNIGAN, E J 1 HOCKMAN, M & H	✓
3407323421	HOCKING	OH	COLUMBIA NATURAL RES. 22915 ZEISLER	✓
3407920076	JACKSON	OH	WORTHINGTON OIL 1 WOOD, G & I	✓
3407920102	JACKSON	OH	NUCORP ENERGY 1 TREPANIER, F & C	✓
3408720174	LAWRENCE	OH	GOLDBERG, J STANLEY 1 PAYNE, A	✓
3409720003	MADISON	OH	AMERADA PETROLEUM 1 HUME, J	
3409720007	MADISON	OH	COLUMBIA NATURAL RES. 1 IMMELL	✓
3411927076	MUSKINGUM	OH	RSC ENERGY CR400 CONSOLIDATION COAL	✓
3411927892	MUSKINGUM	OH	CLINTON OIL 2 MURRAY, D UNIT	✓
3412121278	NOBLE	OH	AMOCO 1 ULLMAN, R	✓
3412726595	PERRY	OH	POLING, R C 1 RUSH CREEK PARTNERS	✓
3412727110	PERRY	OH	RED HILL DEVELOPMENT 11 KIMBLE, F	✓
3412920020	PICKAWAY	OH	MINUTEMAN EXPLORATION 1 HIGGY, P & R	✓
3412920024	PICKAWAY	OH	RAMCO OIL & GAS 1 KERNS, M	✓
3413120036	PIKE	OH	ORWIG OIL 1 FRICK, L	
3414120007	ROSS	OH	WELL SUPERVISION 1 OYER, M	
3414120008	ROSS	OH	WELL SUPERVISION 1 IMMELL, M	
3414120021	ROSS	OH	OXFORD OIL 1 IRVINE, R	
3414520257	SCIOTO	OH	ADOBE OIL & GAS 1 SMITH, H	✓
3414570212	SCIOTO	OH	USS CHEM./US STEEL 1 USS CHEMICALS	
3416562627	WARREN	OH	ODNR DGS 2627 AMERICAN AGGREGATES	✓
4101320188	CAMPBELL	TN	COLUMBIA NATURAL RES. 823959 BEGLEY LUMB	✓
4516720256	RUSSELL	VA	GULF OIL 1 PRICE, W	✓
4701100537	CABELL	WV	CYCLOPS 1 KINGERY, E	
4701302503	CALHOUN	WV	EXXON 1 GAINER-LEE	
4702900080	HANCOCK	WV	HUMBLE OIL & REFINING 1 MINESINGER	✓
4703501366	JACKSON	WV	EXXON 1 McCOY (STALNACKER)	✓
4704301469	LINCOLN	WV	EXXON 1 McCORMICK, D E	✓
4704900244	MARION	WV	PHILLIPS PETROLEUM A-1 FINCH, R	✓
4705100539	MARSHALL	WV	McCORMICK/OCCIDENTAL 1 BURLEY, J	✓
4705300069	MASON	WV	UNITED FUEL GAS 1 ARRINGTON, G	
4705300297	MASON	WV	UNION DRILLING 1 JIVIDEN, R	✓
4705900805	MINGO	WV	COLUMBIA GAS 9674T MINERAL TRACT 10	
4705900879	MINGO	WV	COLUMBIA GAS 20500T HUNTINGTON REALTY	
4707100006	PENDLETON	WV	UNITED FUEL GAS 1 SPONAUGLE, R	
4708300103	RANDOLPH	WV	HOPE NATURAL GAS 2 WV BOARD OF CONTROL	✓

4709900465	WAYNE	WV	UNITED FUEL GAS 42 CALDWELL, F	
4709901572	WAYNE	WV	EXXON 1 SMITH, J P	
4710700351	WOOD	WV	HOPE NATURAL GAS 1 POWER OIL	
4710700756	WOOD	WV	EXXON 1 DEEM, H H	✓

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Chapter 6.

Homer Field Study

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Location

The Homer Field is located in the southern portion of Elliott County, Kentucky. It consists of layered structural traps associated with faulting and growth along the Isonville Fault and Kentucky River Fault Zone at the northern edge of the Rome Trough (see Plate 25).

Production History

The discovery well for the Homer Field was the Carson Associates 1 Kazee, George Heirs (API 1606385783). This well had an initial estimated flow of 11,000 thousand cubic feet of gas per day (MCF/D) through a blowout from what would be later called the Kazee sands (within the Maryville Limestone of the Conasauga Group) in July 1994. Unfortunately, the reservoir was apparently damaged from this blowout (and the subsequent use of a saline "kill" fluid), and is now plugged back to the Upper Ordovician for domestic gas use (at 100 psi).

After the production from the damaged zone in the #1 Kazee well ended, the Carson Associates 57 Prichard Heirs (API 1606388019) was the first well to begin prolonged production from the pre-Knox section of the Homer Field in January 1997. Production from this well had a peak rate of 16,076 MCF for the month of February 1997 (an average of 574 MCF/D), see Figure 6-1a. The 57 Prichard well produces from what would be called the Prichard sand, within the lower unit of the Rome Formation. A total of eight wells have since reported production from sandstone units within the Conasauga Group (Kazee sands 1 & 2) and the lower Rome Formation (Prichard and Lawson sands). A fourth sandstone and possible reservoir unit within the lower Rome Formation, the Oliver sand (from the Carson Associates 50 Oliver well) that was tested but not produced from, has also been mapped within this study.

A total of seven wells producing from post-Knox units have been reported, four from the Upper Ordovician and Trenton fractured limestones, and three from the St. Peter Sandstone. The Carson Associates 1 Kazee, (discovery well mentioned above) and the Carson Associates 50 Oliver (API 1606388290) were deep wells that were later plugged back to the Upper Ordovician (Garrard Siltstone?). Also producing from that section are two twin wells specifically targeting petroleum shows recorded while drilling the original deep wells; the Carson Associates 50(T-2) Oliver and T-1 Lawson wells. The two St. Peter wells are the Carson Associates 25 Lyons (API 1606389760) and the Carson Associates 18 Blair (API 1606388355). The 18 Blair well has reported the highest production (as of 12/00) for the Homer Field at a peak of 39,919 MCF in May 1997 (an

average of 1,288 MCF/D). The deepest production is from the Lawson sands at 7000 feet depth in the Eastern States 39 Fannin well.

The total reported gas production (net) from the Homer Field was 559.8 MMCF in 1997, 337.4 MMCF in 1998, 469.5 MMCF in 1999, and 451.3 MMCF in 2000. The total net oil production from the field was 293 barrels of oil and condensate in 1998, 3,944 barrels in 1999, and 3,394 barrels in 2000 (1997 and earlier oil production reports were not required by the State). The bulk of the 1999, and all of the 2000 year oil production came from the Lawson sands in the Eastern States 39 Fannin well (see Fig. 6-1b).

Stratigraphy

The Homer Field involves four different reservoir zones: Upper Ordovician fractured shales and limestones, Middle Ordovician St. Peter Sandstone, Upper Cambrian Conasauga Group (Kazee sands 1 & 2), and the Middle Cambrian Rome Formation (Prichard and Lawson sands). The origin of these reservoirs' names comes from the usage of the discovery well names by the well operators to define the zones. This informal nomenclature is used within this report for simplicity. Further details on the stratigraphy and geology of the pre-Knox section (Conasauga Group and Rome Formation) can be found in Chapter 3 of this report.

The Upper Ordovician section in this area contains around 800 feet of alternating shale, siltstone, and limestone. It conformably overlies the Upper Ordovician Lexington Limestone, and is unconformably overlain by the Lower Silurian Brassfield Dolomite. Porosity and hydrocarbon production appears to be related to fractures within the Garrard Siltstone. The four wells producing from this section in this field are low rate oil (condensate) and gas producers.

The St. Peter Sandstone is a dolomite-cemented quartz arenite, which unconformably overlies the Lower Ordovician Beekmantown Dolomite of the Knox Group, and is conformably overlain by the Wells Creek Dolomite (Humphreys and Watson, 1996). Due to faulting that was active during deposition, the thickness of the St. Peter Sandstone varies greatly in the Homer Field, from 23 feet in the Carson Associates 57 Prichard Heirs well to 150 feet thick in the Carson Associates 1 Kazee well. Porosities calculated from well log readings average 6%, but rise as high as 20%. One of the two wells completed in the St. Peter (Carson Associates 18 Blair) has the highest gas production rate reported to date.

The Kazee sands occur in the central portion of the Maryville Limestone member of the Upper Cambrian Conasauga Group. These total about 20-25 feet of sandstone in two roughly equal units 40-65 ft. apart, differentiated in this study as "Kazee 1" and "Kazee 2". This study has mapped the lateral extent of the Kazee sands out of the Homer Field and into the surrounding area, (see Plate 31). It was from this zone that the discovery well had a gas blowout in 1994 (see above). Porosities calculated from log readings range from near 0 to 12%.

Figure 6-1a: Homer Field Net Gas Production

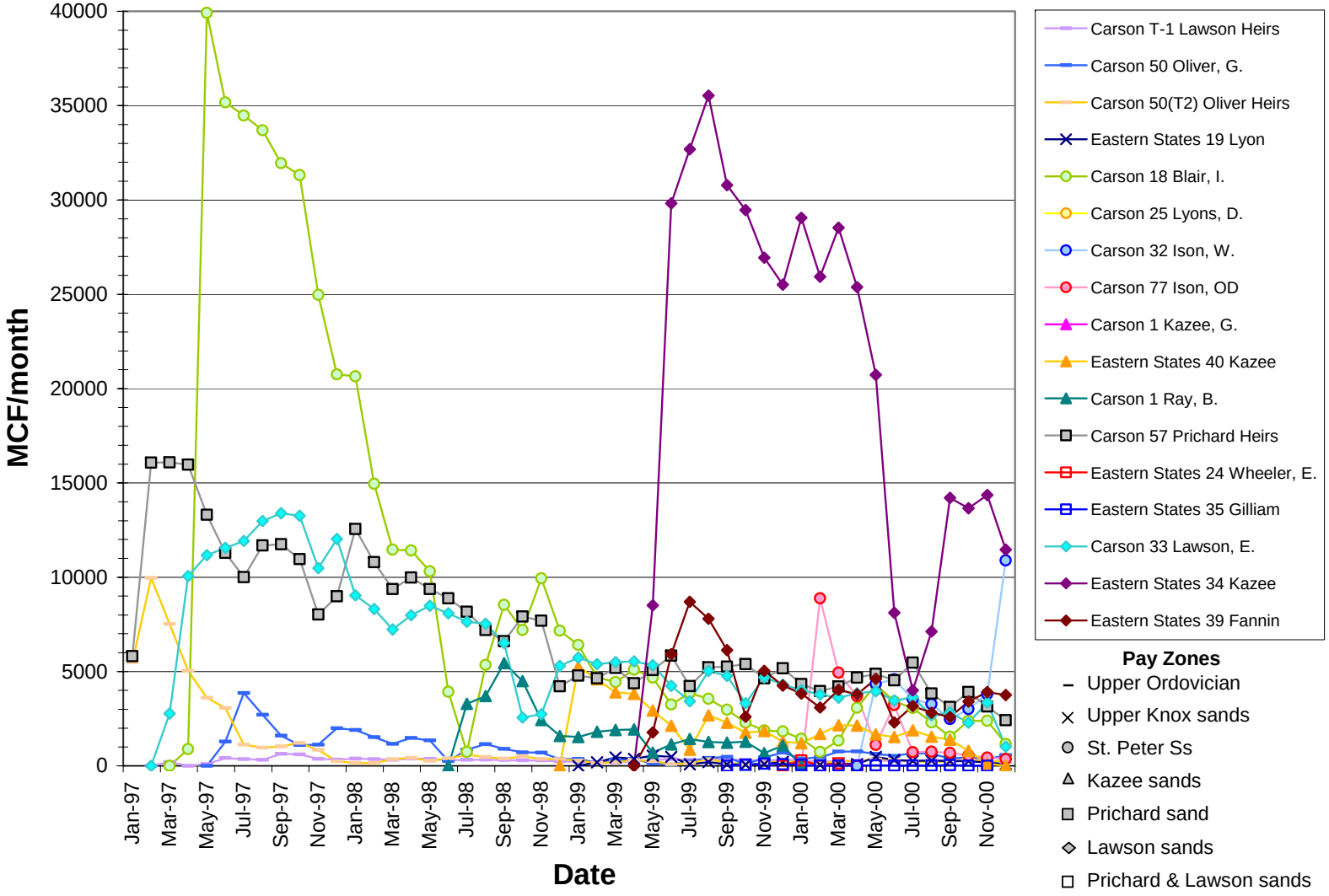
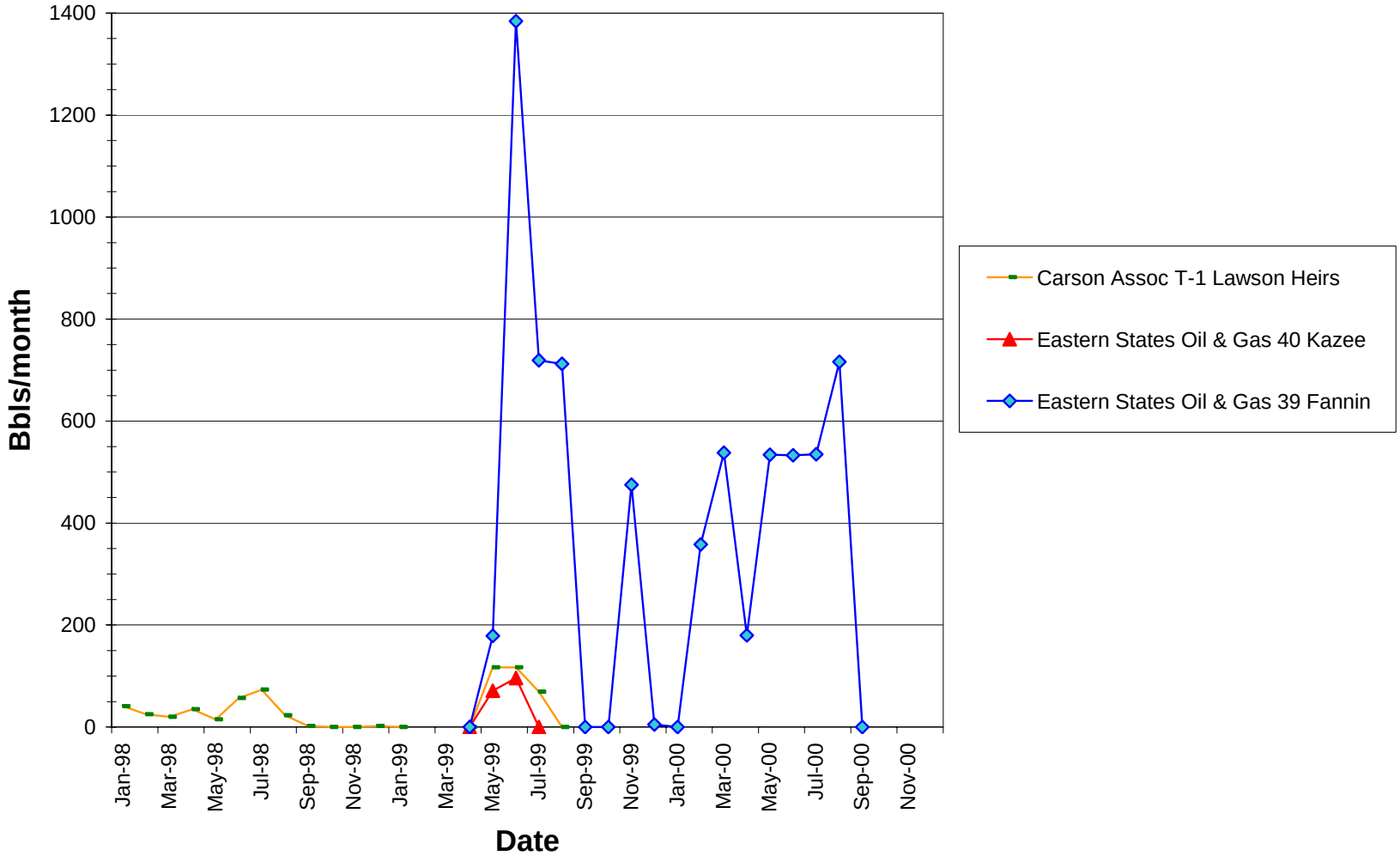


Figure 6-1b: Homer Field Net Oil Production



The Prichard sand, Lawson sands, and Oliver sand (informal) are found in the lower unit of the Middle Cambrian Rome Formation. The Prichard sand is 15-20 ft. of shaly sandstone, 60-80 ft. below the top of the Rome Formation lower unit. Porosities calculated from density and neutron logs range from near 0 to 5%.

About 275-300 feet below the Prichard sand are the Lawson sands. These are a series of alternating clean and shaly sandstones. This unit ranges in thickness from about 65 to 85 feet. Porosities calculated from log readings range from near 0 to 10%.

The Oliver sand is found about 300-325 ft. below the base of the Lawson sands. This unit consists of 10 to 15 feet of sandstone with a calculated porosity of 0-8%. No wells reported production from this zone, but the Carson Associates 50 Oliver well had gas shows though this interval and it may prove to be an economic reservoir elsewhere in this field at a later date.

Structure

The structure of the Homer Field is characterized by southeast regional dip, dissected by two different trends of normal faults and their associated folds. One set of faults strikes roughly east-west and is offset down to the south. This trend of faults includes the Little Sandy Fault, which has been mapped at the surface (Englund and DeLaney, 1966, 1966a, Outerbridge, 1977) and delineates the northern limit of the Rome Trough in western Elliott County (see Plate 25). The second set of faults strike NNE-SSW and offset down to the east. The easternmost of these two faults (as yet unnamed) only appears to affect only the Rome Formation and deeper section, but the other fault in this trend (named the “Isonville Fault” by Lynch, et al., 1999) effects the stratigraphy from the Middle Ordovician Wells Creek Dolomite downward. This fault controls the extent and trapping mechanisms of the Homer field.

The Isonville Fault follows closely to the axis of the Trench Anticline within Paint Creek Uplift, as described by Hudnall and Browning (1949). The theory that a N-S oriented fault at depth caused the creation of the Paint Creek uplift has been noted (Drahovzal and Noger, 1995), but until now there existed very little well data to support it. This anticline was probably created by either block rotation of the footwall upward, away from the fault, or more likely, localized inversion caused by a later reactivation of the fault in a reverse motion due to lateral tectonic loading from the Alleghenian and/or Taconic orogenies. The trap forming the Homer Field occurs within the subsurface expression of this anticline, immediately adjacent to the west of this fault. The production from the St. Peter Sandstone is from the downthrown hanging wall, where the thickened sandstone unit traps has structural closure down dip of the fault (see Figure 6-5). To the west, the limb of the Trench Anticline merging with the southeast regional dipping strata creates the Briar Fork Basin.

The Isonville Fault dramatically affected the deposition of the Cambrian section. To the west of the fault, a large unconformity places the middle Conasauga Group (Maryville Limestone or Rogersville Shale) on top of the middle or lower unit of the Rome Formation. This represents a calculated 2500 to 3000 feet of missing section, probably due to non-deposition. To the east of the Isonville Fault this unconformity does not exist, allowing a complete Conasauga section to be deposited (see Figures 6-2 and 6-4). A similar abrupt thickening during the Middle Cambrian has also been documented across the Irving-Paint Creek fault zone to the southwest in Morgan, Wolfe, Powell, Estill, Madison, and Garrard

Counties, Ky. (Drahovzal and Noger, 1995). Although deep well data is sparse in Lawrence and Johnson Counties, Ky., the data present, along with the recent Homer Field wells, support the connection of the Isonville Fault with the master fault of the Irving-Paint Creek system as proposed by Lynch, et al., 1999. This would suggest that the northern edge of the Rome Trough, the Kentucky River Fault system, was actively faulting throughout the early Rome Formation deposition (Early-Middle Cambrian). Soon after the top of the Rome lower unit was deposited, the major faulting along the Kentucky River Fault system ended, and the continuing displacement was transferred to the Irving-Paint Creek Fault zone and the Isonville Fault. This created a relatively elevated, elongated-rhomboid shaped fault block that extended from central Elliott Co. west to central Lincoln Co., Ky., within the northern half of the trough. The fault motion continued along the southern and eastern edges of this plateau-like structure until at least the Upper Cambrian, with probable intermittent reactivation afterward (Donaldson and Shumaker, 1981).

The Isonville Fault continues north, crossing the Little Sandy Fault before curving eastward into the southern portion of Carter County, Ky. Due to this ~ 60° change in strike, some transtensional strike-slip motion has most likely occurred along the northern, east-west segment of this fault, but without cross-cutting features or detailed seismic data, the magnitude of this strike-slip motion is unknown. This structure appears to agree with the strike slip accommodation zone centered along the 38t^{h} Parallel Lineament proposed by Gao, et al., 2000.

See Plates 25 through 31 and Figures 6-2 through 6-5 for a more detailed illustration of this structure.

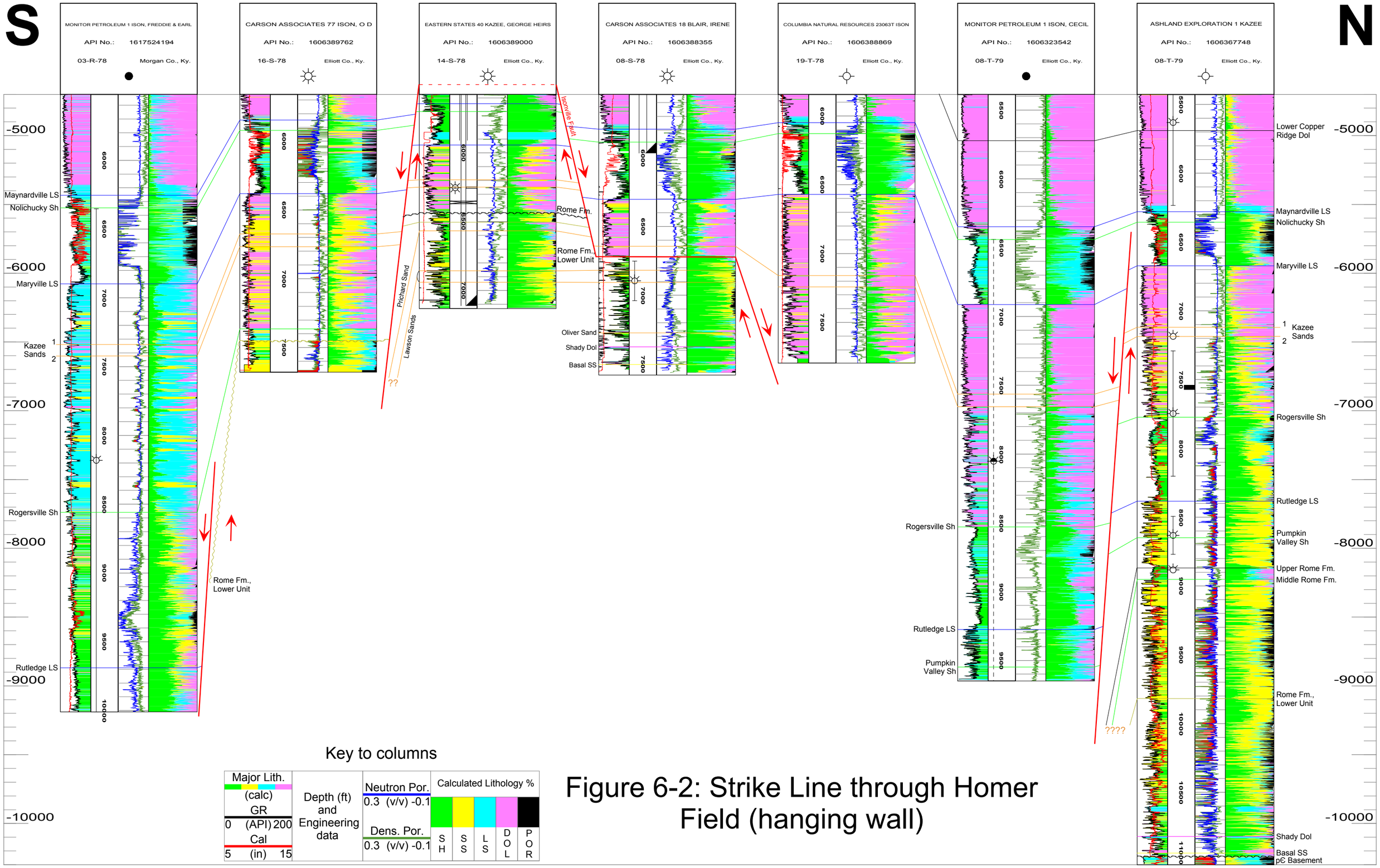


Figure 6-2: Strike Line through Homer Field (hanging wall)

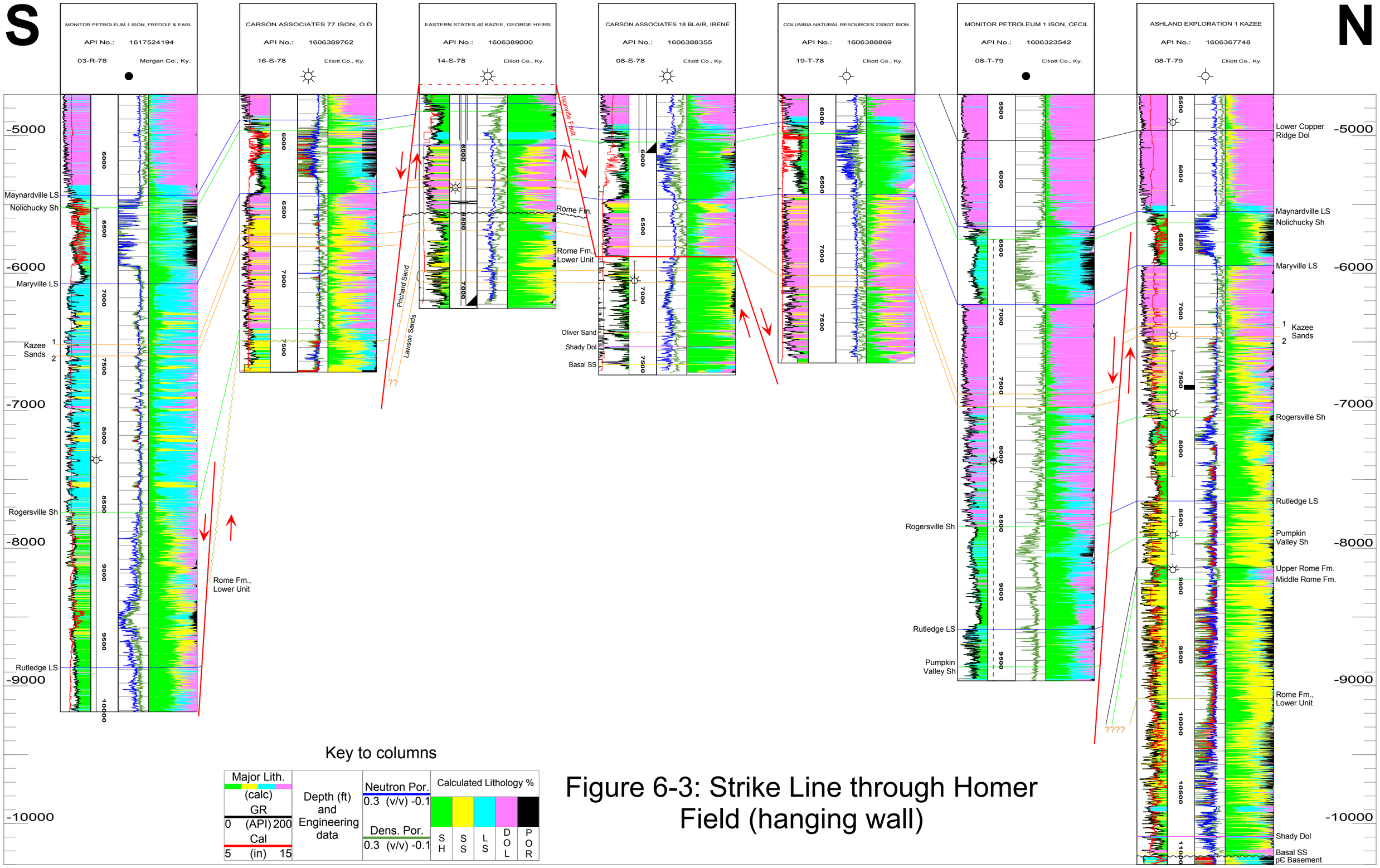


Figure 6-3: Strike Line through Homer Field (hanging wall)

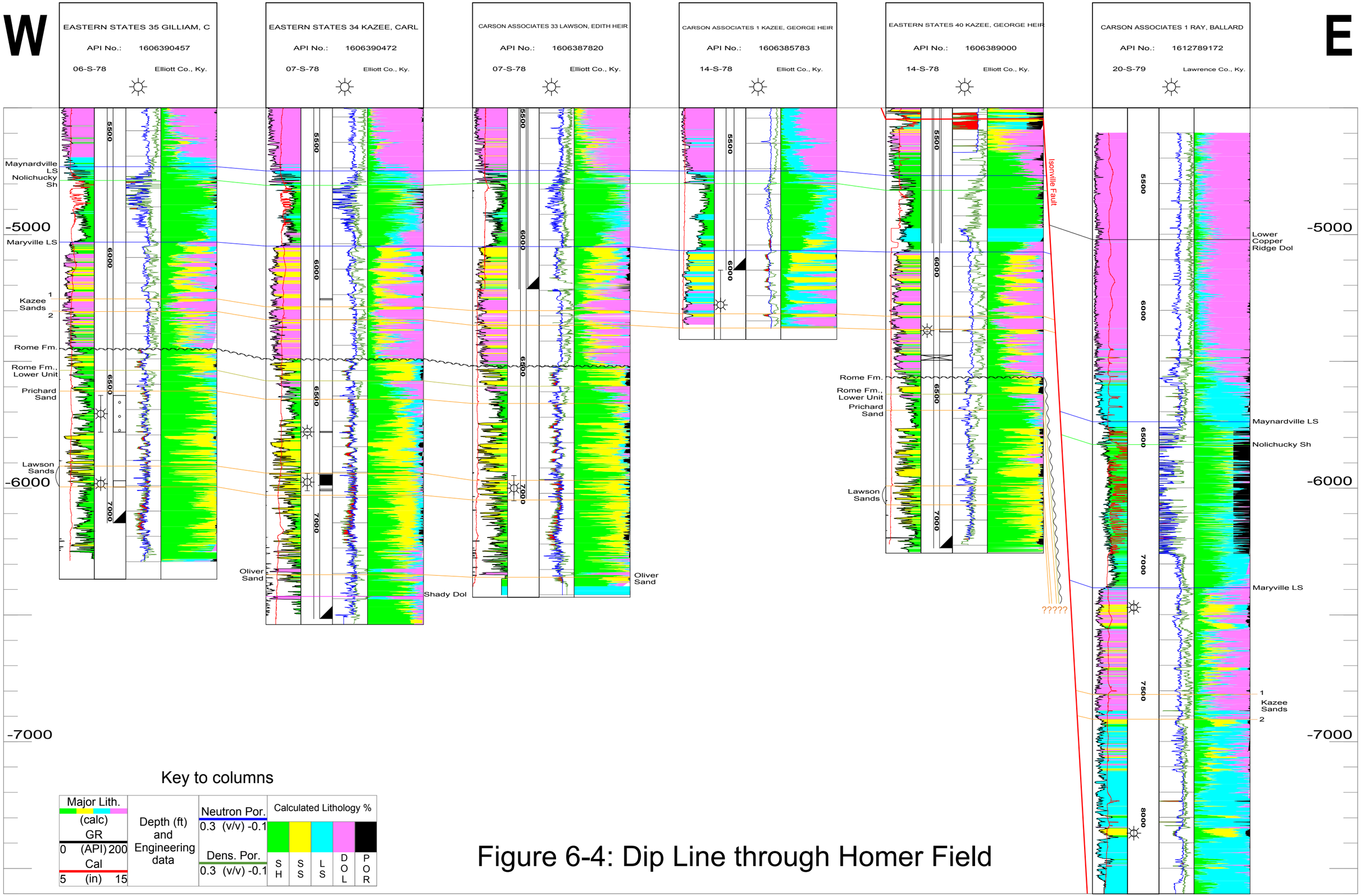


Figure 6-4: Dip Line through Homer Field

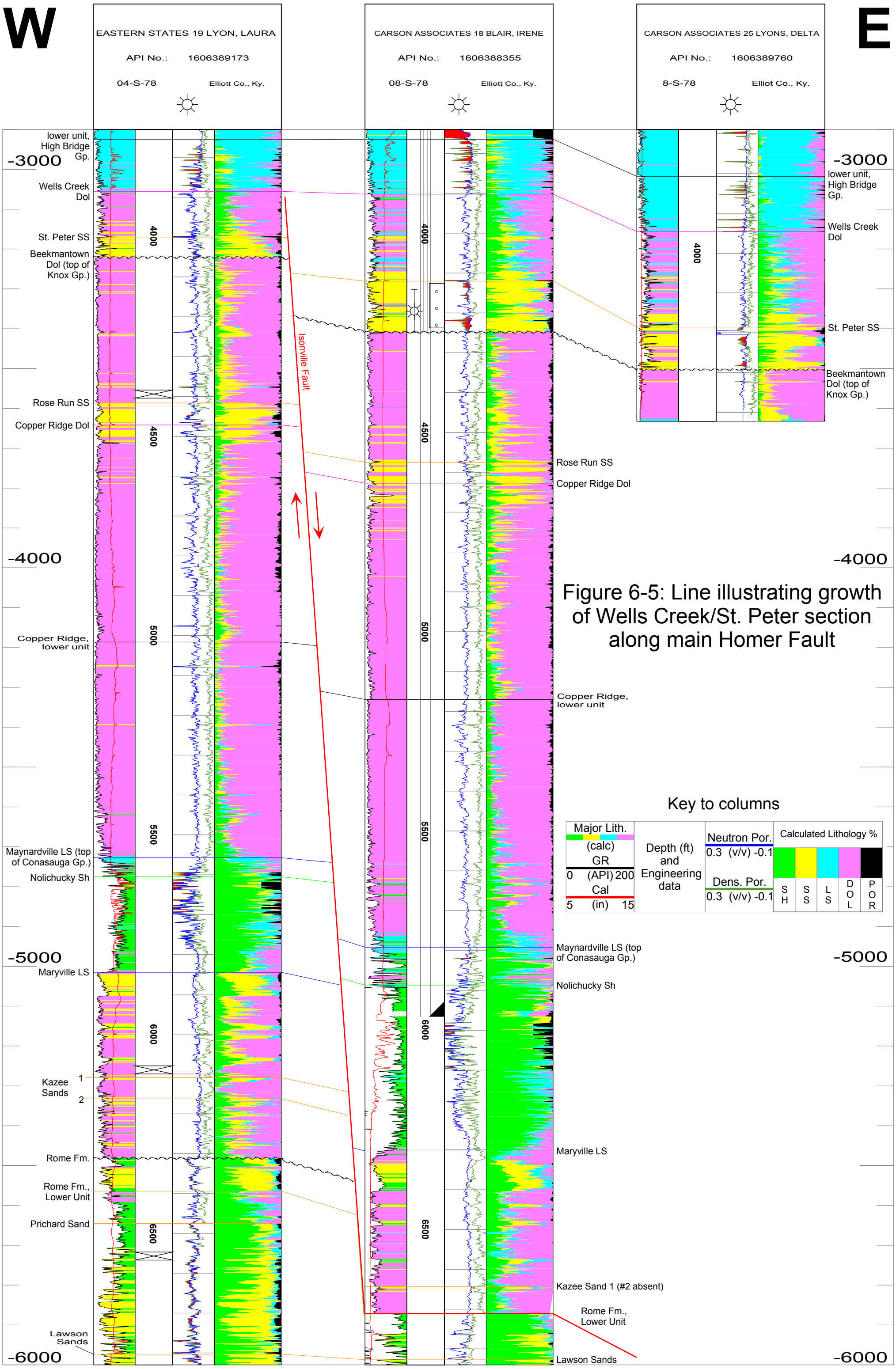


Figure 6-5: Line illustrating growth of Wells Creek/St. Peter section along main Homer Fault

Reservoir

The trapping mechanisms for each set of reservoirs in the Homer Field are slightly different, but probably all are related to the motion on the Isonville Fault. For the sandstone intervals within the Conasauga and Rome, the trapping occurs within the Trench Anticline in the footwall at depths of 6109 - 7163 feet. The gas accumulates in whichever horizon (Kazee sands, Prichard sand, or Lawson sands) lies along the anticlinal axis at that point in the field.

Although similar data for other horizons is not available, the Kazee sands (from the Carson Associates 1 Kazee, George well) were estimated to have a porosity of 12%, and a permeability of 1.9md. It is assumed that the producing sandstones within the Rome have similar characteristics. Other reservoir data is summarized in Table 6-1.

Porosity and permeability data are available for conventional core from the Eastern States 34 Kazee well, and are included in Table 6-2. Porosity and permeability data from sidewall cores taken in the Carson Associates 1 Ray well in Lawrence County are included in Table 6-3 (from Rodvelt et al., 1999). Permeability varies widely for a given porosity, indicating possible diagenetic controls on permeability distribution in the reservoir.

Well treatment and completion has proven difficult in the pre-Knox section due to the susceptibility of the sandstones to water imbibition and brine damage from both drilling fluids and from nearby water-bearing intervals (Rodvelt et al., 1999). The use of CO_2 foam as a fracturing fluid has proved effective in dewatering the formation and helping (with acid treatment) to remove drilling damage near the wellbore (Rodvelt et al., 1999). Before pumping the fluid and proppant, a retrievable packer is set with 2 $^{7}/_{8}$ inch tubing within the wellbore just above the reservoir. This isolates the completion zone and prevents damage to the casing, or to non-reservoir formations within an openhole section (Rodvelt et al., 1999; Monte Hay, personal communication, 1999).

The St. Peter reservoir is trapped downdip of the Isonville Fault, placing the thickened (from synsedimentary faulting) sandstone unit juxtaposed against the underlying Beekmantown Dolomite, at depths of 4120-4293 feet.

The Upper Ordovician section produces out of fractures, possibly caused by the creation of the Paint Creek Uplift and the related motion along the Isonville Fault. For all of these units, overlying shaly carbonates with little or no porosity seal the producing zones.

Table 6-1: Homer Field reservoir data.

Basic Reservoir Data	**Field Name**	Homer	Homer	Homer
	Discovered	1996	1997	1994
	Depth to top reservoir (ft)	2700?	4120	6109
	Age of reservoir	Upper Ordovician	Middle Ordovician	Middle Cambrian
	Formation	Upper Ordovician	St. Peter Sandstone	Maryville Ls. and Lower Rome Fm.
	Producing reservoir	Garrard Siltstone	St. Peter Sandstone	Kazee, Prichard, and Lawson Sands
	Lithology	fractured siltstone	sandstone	sandstone
	Trap type	structural-fracture	structural	structural
	Depositional environment	shallow marine	marine-shoreline	shallow marine
	Discovery well IP (Mcf)	1,516	7,500	11,000
	Drive mechanism	water?	water	water?
	No. producing wells	2	3	6
	No. abandoned wells	0	0	1
	Area (acreage)	unknown	850, estimated	3600, estimated
	Oldest Formation penetrated	Lexington Ls.	Beekmantown Dol.	Rome Fm.
Reservoir Parameters	**Average pay thickness (ft)**	50?	125	100
	Average completion thickness (ft)	50	112	75
	Average porosity-log %	5	6	8
	Minimum porosity-log %	1	0.1	2
	Maximum porosity-log %	11	20	12
	No. data points	1	3	7
	Porosity feet		25	12
	Reservoir temperature (*F)			112
	Initial reservoir pressure (psi)	750	1620	2708
	Producing interval depths (ft)	2650-2850	4120-4293	6109-7026
Fluid and Gas Properties	**Gas gravity (g/cc, avg)**	0.676	0.610	0.656
	Gas saturation (%)			80?
	Water saturation (%)			20
	Commingled	no	no	no
	Associated or nonassociated	nonassociated w/ condensate	nonassociated	nonassociated w/ condensate
	Btu/scf (avg)	1125	1037	1112
Volumetric Data	**Status (producing, abandoned, storage)**	producing	producing	producing
	Production years	1997-current	1997-current	1997-present
	Reported cumulative production (Mcf)	77,690 (as of 12/98)	364,752 (as of 12/98)	433,836 (as of 12/98)
	No. wells reported	2	3	7
	Initial open flow (Mcf/d)	2,700	7,500	11,000 (disc. well)
	Final open flow (Mcf/d)	11 (as of 12/98)	231 (as of 12/98)	197 (disc. well)

Table 6-2. Core analysis data for the Eastern States No. 34 Kazee well, Homer Field, Elliott County, Ky. Cored formation is the Rome Formation. Samples ending with "V" are vertically-oriented samples.

Sample ID	*Sample Depth Feet*	*400 psi Air Permeability MD*	*Helium Porosity %*	*Pore Volume Saturation Oil %*	*Pore Volume Saturation Water %*	*Gas Vol %*	*Grain Density gm/cc*	*Core Lithology*
1	6809.5	127.	7.0	0.0	50.3	3.5	2.66	Ss fg slty scalc no flu
1V	6809.2	233.		0.0				
2	6809.9	87.8	7.0	0.0	50.3	3.5	2.65	Ss fg slty scalc no flu
2V	6809.6	137.		0.0				
3	6810.5	5.00	5.5	0.0	33.3	1.8	2.66	Ss fg slty no flu
3V	6810.2	18.4		0.0				
4	6810.8	0.023	7.8	0.0	61.6	7.8	2.63	Ss vfg slty sshy stkd no flu
4V	6810.6	0.021		0.0				
5	6813.8	*3.10	2.9	0.0	82.7	0.5	2.68	Ss vfg vslty vshy lam no flu
5V	6813.5	*0.330		0.0				
6	6817.5	0.063	6.5	0.0	61.7	2.5	2.67	Ss f-vfg slty sshy no flu
6V	6817.2	0.022		0.0				
7	6818.8	0.117	6.2	0.0	60.7	2.4	2.67	Ss f-vfg slty sshy no flu
7V	6818.6	0.117		0.0				
8	6820.2	0.095	5.8	0.0	51.7	2.8	2.64	Ss f-vfg vslty no flu
8V	6819.9	0.066		0.0				
9	6824.1	0.024	4.3	0.0	38.9	2.6	2.68	Ss f-vfg slty sshy no flu
9V	6823.8	0.057		0.0				
10	6824.4	0.027	6.9	0.0	20.9	5.5	2.67	Ss f-vfg slty sshy no flu
10V	6824.1	0.019		0.0				
11	6825.3	0.051	3.1	0.0	52.9	1.5	2.65	Ss f-vfg slty sshy scalc no flu
11V	6825.1	0.049		0.0				
12	6826.6	*1.02	1.9	0.0	77.5	0.4	2.66	Ss vfg vslty shy lams no flu
12V	6826.4	0.018		0.0				
13	6828.8	0.024	2.1	0.0	44.4	1.2	2.66	Ss f-vfg vslty no flu
13V	6828.9	< 0.01		0.0				
14	6830.5	< 0.01	1.7	0.0	64.7	0.6	2.64	Ss f-vfg vslty sshy sfoss no flu

14V	6830.3	< 0.01		0.0				
15	6836.2	0.056	3.5	0.0	71.1	1.0	2.66	Ss f-vfg slty sshy stks sfoss no flu
15V	6836.3	< 0.01		0.0				
16	6839.9	0.038	5.8	0.0	67.4	1.9	2.65	Ss f-vfg slty sshy stks no flu
16V	6839.6	0.012		0.0				
17	6842.5	0.063	3.5	0.0	81.4	0.7	2.65	Ss vfg slty sshy stks no flu
17V	6842.7	0.016		0.0				
18	6845.4	0.038	7.3	0.0	55.2	3.3	2.64	Ss vfg slty sshy stks no flu
18V	6845.0	0.021		0.0				
19	6846.4	1.23	7.6	0.0	68.3	2.4	2.63	Ss vfg slty sshy stks no flu
19V	6846.9	0.060		0.0				
20	6847.8	0.081	7.4	0.0	73.5	2.0	2.64	Ss vfg slty sshy stks no flu
20V	6847.5	0.046		0.0				
21	6850.6	4.29	7.6	0.0	29.2	5.4	2.65	Ss f-vfg slty no flu
21V	6850.5	1.02		0.0				
22	6851.2	18.1	6.8	0.0	39.2	4.1	2.66	Ss fg slty no flu
22V	6851.0	12.2		0.0				
23	6851.6	11.5	7.0	0.0	40.5	4.2	2.66	Ss fg slty no flu
23V	6851.8	2.78		0.0				
24	6852.3	9.33	7.1	0.0	33.5	4.7	2.65	Ss fg slty no flu
24V	6852.0	3.09		0.0				

***Indicates fractured permeability**

Table 6-3. Porosity and permeability data for sidewall cores from the Carson Associates #1 Ray well, Lawrence County, Ky. Samples are from sandstones in the Maryville Limestone interval of the Conasauga Group. Data is from Rodvelt et al. (1999).

Depth	Porosity (%BV)	Permeability to gas (md)
7166.0	7.7	0.17
7175.0	8.0	0.43
7178.0	9.9	---
7180.0	8.9	0.29
7224.0	9.2	0.36
7242.0	7.7	0.33
7248.0	6.3	0.05
7414.0	8.2	0.63
7415.0	7.9	0.56
7620.0	8.7	0.69
7626.0	8.3	0.57
7810.0	8.2	0.11
7997.0	5.0	0.01
8055.0	9.5	2.23
8058.0	7.7	0.65
8061.0	7.7	0.42
8064.0	8.5	1.49
8067.0	9.3	1.94
8070.0	8.6	1.40

Future Trends

Possible future areas for exploration exist locally near or along the subsurface faults. For the St. Peter Sandstone reservoir, the Trench Anticline follows the Isonville Fault as it curves to the northeast, possibly causing a similar trap within the thickened hanging wall. Although limited deep well data to the south in Morgan County makes the exact location of the Isonville Fault difficult to determine, similar structures may be present there as well.

For the pre-Knox units (Kazee, Prichard, Lawson, and Oliver sands), possible locations for hydrocarbon traps exist along the edges of the upthrown footwalls in the four east-west striking faults (see Plate 31), as well as the other NNE striking fault to the east of the Isonville Fault (see Plate 30).

An additional location for possible exploration in the Kazee sands exists in western Elliott County, near the terminus of the exposed Little Sandy Fault. This would include the Carter Section 21-T-76 and the southern halves of 22 and 23-T-76, to the south and southeast of the United Fuel Gas 8802T Litton, J. well. If the Kazee sands extend this far northwest, they would probably terminate updip against this fault, creating a trap for oil or gas to migrate into.

Detailed reflection seismic data of the deeper section would greatly assist in locating and verifying all of the possible targets listed here.

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Chapter 7.

Cambrian and Ordovician Hydrocarbon Geochemistry

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Introduction

The presence of hydrocarbon source rocks in Cambrian sub-Knox Group sedimentary rocks of the Appalachian Basin has been debated for years. Numerous shows of oil and gas in sub-Knox Group rocks have suggested that mature source rocks exist, but the lack of commercial production left doubt as to whether source rocks were rich enough to have formed significant accumulations. Limited production in the 1970's and 1980's, and more significant commercial production from the Homer Field in Elliott County, Ky. and a nearby well in Lawrence County, Ky. in the 1990's indicate that economic Cambrian reservoirs are present in the Appalachian Basin, outside of Ontario, Canada. Data available for the Homer Field from 1997 through 2000 indicate a minimum of 1.8 BCF of gas has been produced (this number does not include data for the first 3 years of production).

Natural gas and condensate in Conasauga/Rome reservoirs is most easily explained as being derived from Cambrian source rocks, but previous studies did not identify source rocks with significant organic content (Ryder and others, 1998). An alternative model would involve downward or lateral migration of hydrocarbons from more deeply buried Ordovician post-Knox source rocks or from the Knox Group, from deeper in the Appalachian Basin to the east. through several thousand feet of carbonates. There is no evidence to suggest that downward or long-range lateral migration has occurred. Organic matter in sufficient abundance to generate commercial hydrocarbons is known to occur in Cambrian and even Precambrian rocks in other basins. Examples include the Precambrian Nonesuch Formation in Michigan (Elmore and Daniels, 1988) and the Cambrian Deadwood Formation reservoirs in the Williston Basin.

Previous studies in the Appalachian Basin have documented probable hydrocarbon source rocks of Late Ordovician age, but indicated lean, low organic content in Cambrian rocks (Ryder and others, 1998). Webb (1980, p. 28) reported poor source quality, with total organic content ranging from 0.9 to 1.5 mg/g (0.09 to 0.15%) for the Cambrian Nolichucky Shale in the Rome Trough area. The source of Webb's data is unknown, and details on the type of analysis and location of the samples were not given.

The goal of the geochemical part of this study was to compile a database of published and unpublished geochemical analyses of Cambrian pre-Knox Group rocks and produced hydrocarbons. Very little geochemical data has been published for the Cambrian in the Appalachian Basin, consisting primarily of work by the U.S. Geological Survey (Ryder and others, 1991; 1998). These data have been compiled in a computer spreadsheet file (Microsoft Excel format). We had hoped to also include data contributed from industry

sources, and requested data from Texaco and Exxon, two of the larger companies that drilled Cambrian wells in the Rome Trough. Neither company responded to requests for this type of data. As a result we were only able to include published data from Ryder and others (1998), Harris and Baranoski (1996), Cole and others (1987), and Webb (1980).

Although not originally planned as a part of this project, we were able to obtain a number of new geochemical analyses though our collaboration with Bob Ryder, Bob Burruss, and Robert Milici at the U.S. Geological Survey (Reston). This work included analysis of natural gas and condensate samples from the Homer Field (Elliott County, Ky.), and a one-well field in Lawrence Co., Ky. The data also include Rock Eval pyrolysis of potential source rock samples from various Cambrian cores in the study area. The Elliott and Lawrence County gas and condensate samples were collected in June 1999, by Bob Burruss and Bob Ryder of the USGS, along with Dave Harris and Jim Drahovzal of KGS. Equitable Resources subsequently gave permission for the USGS to release this data to the consortium. In addition, a few samples were analyzed for vitrinite reflectance, to provide data on thermal maturity. Figure 7-1 shows the location and type of geochemical data collected. All of the new data collected by the USGS is included in the geochemical data file included on the project CD. This includes numerical Rock Eval and gas analysis data, and scanned images of all gas chromatograms from the condensate samples.

SOURCE ROCK DATA

While studies of Ordovician hydrocarbons and source rocks from a variety of areas have been published (Reed and others, 1986; Cole and others, 1987; Longman and Palmer, 1987; Fowler, 1992; Guthrie and Pratt, 1995; Obermajer and others, 1999), data from Cambrian rocks, particularly from the Rome Trough are limited. For this report we have included data published by Ryder and others (1998), and Cole and others (1987). These data are summarized in Table 7-1.

Published Data

The quality of potential hydrocarbon source rocks is commonly determined using a pyrolysis technique called Rock-Eval. Peters (1986), Tissot and Welte (1978) and Hunt (1996) give good overviews of this technique. We have also included a document from Humble Geochemical, Inc. that discusses the interpretation of Rock-Eval data on the project CD-ROM. This file is in Adobe Acrobat format (PDF). Rock-Eval involves analysis of a whole rock sample, and is faster than other methods that involve isolation of organic matter from the rock. Rock-Eval involves heating a powdered sample through a range of temperatures up to 550ºC. During this process, any hydrocarbons already present in the sample are volatilized and measured as the S_1 peak. Heating the sample to higher temperatures results in pyrolysis of kerogen in the sample to produce hydrocarbons (measured as the S_2 peak) and CO_2 (measured as the S_3 peak). S_1 and S_2 are measured in milligrams of hydrocarbon per gram of sample, and S_3 is milligrams of CO_2 per gram of sample. These units are equivalent to kilograms per metric ton. The temperature at which

maximum S_2 hydrocarbons are produced is known as T_{max}. T_{max} is primarily an indicator of thermal maturity.

Ryder and others (1998) primarily studied Ordovician source rock quality in the Appalachian Basin, but also analyzed 20 Cambrian pre-Knox samples from 3 Rome Trough wells. All of the Rome Trough samples had low total organic carbon (TOC), ranging from 0.08 to 0.84 weight %, with an average of 0.37%, indicating poor to marginal hydrocarbon source potential (Table 7-2). Ryder concluded that Cambrian pre-Knox shales analyzed would have only limited source potential in localized areas, and cannot be considered regional source rocks. Ryder's data is also included on the spreadsheet file on the CD-ROM.

Cole and others (1987) analyzed 46 Cambrian pre-Knox rocks from the subsurface of Ohio. 26 samples of the Conasauga and Kerbel Formations averaged 0.18 weight % TOC, and 20 samples of Mt. Simon Sandstone averaged 0.15%. Complete data is included in Table 7-2 and in the geochemical spreadsheet file on the CD-ROM. Cole and others (1987) considered the Cambrian pre-Knox samples to have marginal to nonsource hydrocarbon potential.

Both of these published studies found very poor hydrocarbon source potential in the pre-Knox samples they analyzed. However, the known hydrocarbon shows and commercial production in the Rome Trough strongly suggest that a Cambrian source exists. The difficulty that previous studies have had in locating rich source rocks indicates there is probably not a widespread regional source, but rather discontinuous, localized organic-rich zones.

New Source Rock Pyrolysis Data

The availability of numerous cores from Cambrian pre-Knox formations presented a unique opportunity to collect additional source rock data in the Rome Trough. There was not funding available in this project for this type of work, but through collaboration with the U.S. Geological Survey, we were able to have 35 samples analyzed using Rock-Eval pyrolysis. We would like to acknowledge this contribution to the project, and thank Bob Ryder, Bob Burruss, and Bob Milici for their help in getting these samples analyzed.

Source rock samples were obtained from cores from 11 pre-Knox wells, primarily from Kentucky and West Virginia. Shales were sampled for analysis, with darker colored shales selected from the cored intervals. There is some bias in the samples, as only intervals cored in the well were sampled. Well cuttings could be used for more complete stratigraphic coverage, but this was beyond the scope of this project. The detailed Rock-Eval data are listed in Table 7-2 and the geochemistry spreadsheet file, and summarized by formation in Table 7-1. A histogram plot of sample frequency vs. TOC by formation is shown in Fig. 7-3. This plot includes only the new data collected in this study, and illustrates the distribution of TOC by formation.

The Rock-Eval data contain some very surprising and encouraging results. Most of the formations sampled had low total organic carbon (TOC) values, commonly less than 1%, with most below 0.5%. These low values are not considered to be capable of generating commercial amounts of hydrocarbons (Peters, 1986). However two wells had samples with significantly higher TOC values (highlighted in bold in Tables 7-1 and 7-2). These samples were from the Rome Formation in the Texaco 1 Kirby well, in Garrard County, Ky., and the Rogersville Shale of the Conasauga Group in the Exxon 1 Smith well, Wayne County, W. Va. These wells are discussed in more detail below.

Texaco Kirby pyrolysis data

Cores of the Rome Formation from the Texaco Kirby well are almost entirely sandstone, but several thin shale beds are present and these were sampled for Rock-Eval analysis. The 4,576 ft sample had low TOC (0.28%), but the sample from 4,628 feet had a TOC of 3.26% (Table 7-2). After this analysis was done, a second sample at 4,628.8 ft (just below the first) was analyzed to determine the extent of the high-TOC shale. The 4,628.8 ft sample was much lower in TOC, with 0.70%. The shale at 4,628 ft is volumetrically small, but does indicate the presence of organic-rich source rocks capable of generating hydrocarbons in the Rome Formation. To characterize the type of organic matter (kerogen) in these samples, hydrogen (HI) and oxygen (OI) indices were calculated from the Rock-Eval data, and plotted on an HI-OI cross plot (Fig. 7-2). While not definitive, the HI-OI plot is useful for initial screening of kerogen types. The plot has several lines that mark the midpoints of the typical spread of data for the various kerogen types. The lines indicate trends of increasing thermal maturity toward the origin (0,0). As Figure 7-2 indicates, the Texaco Kirby samples fall in an area characteristic of both type 1 and 2 kerogen (oil or mixed oil/gas prone) with moderate thermal maturity. In this case, the Rock-Eval data cannot distinguish the exact kerogen type.

Thermal maturity of these rocks can also be determined in several other ways. T_{max}, the temperature during Rock-Eval pyrolysis when maximum hydrocarbons are generated is an indication of the thermal maturity of the source rock. T_{max} values for the Kirby samples were very similar at 444° and 446°C, which indicates the rocks reached the top of the oil window (which ranges from 430 to 470°C). The Rock-Eval data can also be used to calculate the production index (PI), which is S1/(S1+S2). The Kirby samples have PI values of 0.11 and 0.04, which fall just within and below the oil window (PI=0.08–0.5). This is consistent with the T_{max} data.

A third technique for determining thermal maturity is vitrinite reflectance. This involves the systematic change in reflectance of vitrinite, an organic maceral derived from land plants, with increasing temperature. The terrestrial source of vitrinite typically this limits the use of this technique to Silurian and younger rocks (Buchardt and Lewan, 1990). But vitrinite-like macerals have been reported from rocks as old as Cambrian (Buchardt and Lewan, 1990). The origin of this Cambrian vitrinite-like material is not known, but it does exhibit similar changes in reflectance with thermal maturity. Two samples from the Texaco Kirby well were processed to extract kerogen, and examined for vitrinite by Humble Geochemical for the U.S. Geological Survey. Vitrinite-like macerals were

identified in both samples, and reflectance (%R_o) was measured. Mean %R_o for the 2 samples was 0.43 and 0.45 (Fig. 7-11,7-12 and data in spreadsheet file). These values are just below the start of the oil window at 0.50% (Hunt, 1996). However, because these samples are hydrogen-rich, with HI's of 356 and 417, a correction for suppression of vitrinite reflectance in hydrogen-rich kerogen may need to be made (Lo, 1993). R_o values reported here are uncorrected.

Vitrinite reflectance data is also included for three samples from the Texaco 1 Tipton well in Estill Co., Ky. Although these samples have low TOC values, some vitrinite-like material was recovered and analyzed. The samples are deeper than those in the Kirby well, around 6,400 ft. R_o values for this material is slightly higher than the Kirby samples, with mean R_o values of 0.49, 0.51, and 0.53 (Figs. 7-13, 7-14, 7-15).

In summary, the cored interval in the Texaco Kirby core contains thin shales with TOC values high enough to serve as a source of hydrocarbons. The exact type of organic matter cannot be determined from the Rock-Eval data, but it is hydrogen-rich, either oil or oil/gas prone. Thermal maturity is fairly low, just above or at the top of the oil window. Well site core descriptions mention bleeding oil adjacent to the shale bed sampled, possibly indicating that some oil was generated in-situ in this interval. Other intervals in the Kirby well may contain shales with similar geochemical characteristics, but due to the low maturity, oil or gas generation was probably limited in this part of the basin.

Exxon 1 Smith pyrolysis data

The highest quality hydrocarbon source rock in this study was found in the Exxon 1 Smith well, in Wayne Co., W. Va. Nine core samples from the Rogersville Shale of the Conasauga Group and the Rome Formation in the Smith well were analyzed using Rock-Eval pyrolysis. Shales from the Rome Formation in this well were consistently low in TOC (0.13–0.22%), but all 4 samples from the Rogersville Shale contained significant TOC, ranging from 1.20–4.40%. These TOC values fall in the good to very good source potential classification of Peters (1986). Other Rock-Eval data for these samples indicate good hydrocarbon source quality, with higher thermal maturity than the Texaco Kirby samples discussed previously.

The T_{max} values for the Smith samples range from 414-477° C. The single low value of 414° may be anomalous, since heavy free hydrocarbons included in the S_2 peak can result in low T_{max} values (D. Jarvie, Humble Geochemical, personal comm., 2001). Other evidence that heavy hydrocarbons are present in these samples is discussed further below. The other T_{max} values range from 460-477°C, falling in the gas generation window. Assuming a type II, oil and gas prone kerogen, the oil window occurs from T_{max} values of 425–450°C (Espitalie *et al*., 1985, cited in Humble Geochemical Services, unpublished).

An additional indicator of thermal maturity is the production index, PI: $S_1/(S_1+S_2)$. This ratio reflects the conversion of kerogen into free hydrocarbons. PI values for the Smith samples range from 0.51 to 0.58. Values >0.50 fall in the gas window, which is

consistent with the T_{max} and hydrogen index data (discussed below). Vitrinite reflectance data has not been measured for the Smith samples yet. We hope to add this data in the future.

S_1 values for the Smith samples indicate all 4 whole rock samples contain free extractable hydrocarbons. This is verified by the one extracted rock sample, in which all free hydrocarbons were removed by solvents. The S_1 hydrocarbons in the extracted sample are almost negligible, at 0.08. The data table includes a ratio of S1 to TOC (S_1*100/TOC). This ratio is interpreted by Jarvie and Baker (1984) as a show indicator. This ratio for these samples in the range of 50-100, which they indicate as "possible staining, show; mature, tight source rock." These S1 hydrocarbons indicate that oil has been generated in-situ from organic matter in the Rogersville Shale.

S_2 values for the 4 Smith samples indicate the present-day source potential of the rock. These are the hydrocarbons that are generated from cracking of kerogen and high molecular weight hydrocarbons during pyrolysis. S_2 values are lower for the Smith samples than for the Kirby samples. This is most likely a reflection of higher thermal maturity for these samples, with much of the kerogen having already generated hydrocarbons. As noted in the spreadsheet, these samples had a low-temperature shoulder on the S_2 peak during during pyrolysis. This is typically either due to contamination by drilling fluids, or the presence of free heavy natural hydrocarbons that remain behind after the S_1 hydrocarbons are extracted. Since the Smith well was not drilled with oil-based mud, and the samples are from core, contamination can likely be ruled out. The low temperature S_2 peak in these samples is interpreted to come from heavy oil generated in the shale. The extracted rock sample at 11,161.5 ft confirms the presence of hydrocarbons in the sample. The extracted rock analysis shows a lower TOC and S_2, and a much lower S_1, as would be expected from removal of oil in the sample.

The Exxon Smith samples are included in the HI-OI plot in Figure 7-2. Due to their much lower HI values than the Texaco Kirby samples, the Smith samples fall much lower on the HI-OI plot. This is interpreted to reflect the higher thermal maturity of these rocks, which is consistent with their greater depth of burial, higher T_{max} and PI values. The HI-OI plot can sometimes be used to help constrain the type of kerogen in the source rock. The Smith samples likely contain type 1 or type 2 kerogen because of their position on the HI-OI plot. The maturation pathways for types 1 and 2 kerogen merge at lower values of HI, making it impossible to distinguish them on this plot. Type 3 kerogen (woody, terrestrial-sourced kerogen) is not indicated by the HI-OI plot, nor is it geologically reasonable due to the pre-Silurian age (pre-land plants) of the rocks.

OIL AND NATURAL GAS DATA

Published Data

Very few published natural gas analyses from Cambrian reservoirs the Rome Trough were located. Published data was previously compiled by Harris and Baranoski (1996) in the Cambrian pre-Knox play description in the Appalachian Basin gas atlas. We have

also included analyses of Ordovician gases from Central Kentucky in the Trapp and Furnace fields (McGuire and Howell, 1963), one Ordovician gas analysis from the Big Sinking Field, Lee Co., Ky. (B. Miller, pers. comm.), and data from the U.S. Bureau of Mines natural gas database. These published analyses are included in Table 7-3 and in the spreadsheet file. While some of these fields produce from the shallower Ordovician St. Peter Sandstone, the gas composition may have significance to the deeper Cambrian reservoirs in that area.

Gas Quality

The data available from the Rome Trough prior to this study (Table 7-3) show a wide variety in Cambrian gas quality, with total BTU content ranging from 227 to 1175. All of the low-BTU gases are from the western end of the Rome Trough and southwestern Ohio (Garrard and Rockcastle Cos., Ky. and Highland Co., Oh., Fig. 7-1). The low-BTU gases are commonly high in nitrogen, ranging from 27% in Rockcastle Co., Ky. to 80% in Garrard Co., Ky. Carbon dioxide (CO_2) is low in these wells, with a maximum of 1.6% in the Highland County well. Wells farther east in the Trough (Johnson Co., Ky. and Jackson Co., W.Va.) have produced commercial-quality gas. The low-quality gas in the western Rome Trough is also unusual in its higher than normal helium content. Helium ranges from 0.6 to 1.8% in the samples where it was measured. This helium content was significant enough that the U.S. Bureau of Mines included these wells in its inventory of strategic helium reserves. These data are now maintained by the National Technical Information Service run by the U.S. Dept. of Commerce (www.ntis.gov).

An important exploration constraint in the Rome Trough is the extent of low-BTU gas in the basin. Limited drilling and few geochemical analyses of gas shows in the western Rome Trough make it difficult to delineate the boundary of non-commercial gas. High nitrogen gas is known to occur in Cambrian reservoirs in Garrard County, Ky. and Highland County, Ohio. Gas analyses are also available from the Middle Ordovician Sunnybrook (Trenton) and Lower Ordovician Knox in the Hunt's Natural Resources 1 Livesay well (permit 75242), Rockcastle County, Ky. (Table 7-3). Both zones in this well produce gas with 27% nitrogen, 66% methane, negligible CO_2, and 0.6% helium, with a BTU content of around 800. While better quality than the Cambrian reservoirs in nearby Garrard Co., this gas has a significant nitrogen and helium content, and may be derived from a similar source.

Non-commercial gas has also been reported in Estill and Powell Counties, Ky., from the Ordovician St. Peter Sandstone in the Furnace Field (Table 7-3) (McGuire and Howell, 1963). However, the composition of this gas differs from the deeper high nitrogen Cambrian gas. Gas in the Furnace Field contains high CO_2 (26–42%), but low nitrogen (1.4–2.3%). The source of this St. Peter gas is not known, but its composition suggests that it may have a different origin than the Cambrian high-nitrogen gas.

The presence of nitrogen and helium in natural gas can be explained by one of several models. Nitrogen can be derived from atmospheric sources, chemical reactions with red beds, and deep mantle outgassing (Hunt, 1996, p. 230-231). The depth of these nitrogen

reservoirs makes atmospheric contributions unlikely, and the analyses show negligible oxygen, which commonly indicates contamination. Red beds can form nitrogen when iron oxides react with ammonia or nitrogen-bearing organic compounds from thermal alteration of organic matter. While red beds have not been found in significant quantities within the Cambrian sediments in the Rome Trough, there is a thick sequence of Precambrian red beds on the western boundary of the Trough, across the Lexington Fault System. In this area, red sandstones and shales of the Precambrian Middle Run Formation are in fault contact with Cambrian Rome Trough sediments. Thus a red bed origin cannot be ruled out, although there is a limited area along the fault plane for oxidation of ammonia to nitrogen to occur. Middle Run sandstones presently have very low porosity and permeability, so movement of large volumes of ammonia-rich pore fluids through these red beds is unlikely.

Perhaps a more likely model to explain high nitrogen gas is mantle outgassing. The association of nitrogen with higher than average helium is also an indication of a crystalline basement source (Hunt, 1996, p.232). Helium can also be generated by radioactive decay of uranium in sedimentary rocks, but there is no evidence to suggest this has occurred in the Rome Trough. Isotopes of helium (^{3}He and ^{4}He) can be used to determine its source, but there is no isotopic data currently available from these wells. ^{4}He is generated almost entirely by radioactive decay in sedimentary rocks, while ^{3}He is associated with mantle sources. Future isotopic analysis of this helium-rich gas could help to constrain its origin.

Mantle outgassing as a source for the nitrogen and helium gas in the western Rome Trough is geologically reasonable due the proximity to the Grenville Front, a major Precambrian fault. The Grenville Front marks the western edge of the Grenville Province, a metamorphic terrane which was thrust westward over the East Continent Rift Basin (Drahovzal and others, 1992). The Grenville Front is a major thrust fault zone in the Precambrian, and could have provided a pathway for mantle-derived gases to migrate upward into porous Cambrian sandstones. It is worth noting that the Garrard/Rockcastle County area in Kentucky and Highland County in Ohio, where high-helium gases have been reported all lie on or near the Grenville Front (Fig. 7-1).

New Natural Gas and Oil Data

Although not originally a part of the goals of this study, we were able to obtain a number of new gas, condensate, and source rock analyses from ongoing work by the U.S. Geological Survey. The natural gas and condensate analyses were done by the USGS in collaboration with Statoil Energy (now Equitable Resources) from producing wells in the Homer Field, Elliott County, Ky. and an unnamed one-well field in Lawrence County. These data were donated to the Rome Trough Consortium, and should be held confidential to consortium members until published by the USGS. The new source rock data were obtained by the USGS at KGS's request from core material collected during this project. These data should also be held confidential until published by the USGS. Because these data were collected with USGS funds, and were not part of the original consortium work plan, we cannot hold the data confidential with the other project data.

Oil Analyses

In addition to the source rock analyses, Equitable Resources and the USGS provided the consortium with analyses of condensate samples from Homer Field in Elliott County, and from source rock extracts from Garrard County, Ky and Wayne County, W. Va. These data consist of preliminary gas chromatographs of the condensate samples collected from the Elliott County, Ky. gas wells, and 2 extracted samples from the higher TOC source rock in the Texaco 1 Kirby and Exxon 1 Smith wells. The gas chromatographs (GC's) are included as scanned images in this report (Figs. 7-4 through 7-10), and in the geochemistry data file. It is important to note that these are preliminary data, and USGS plans to conduct additional analyses on these samples.

A primary question pertaining to these Cambrian-reservoired hydrocarbons is whether they were sourced from sub-Knox rocks (Cambrian) or younger post-Knox rocks. This distinction is made possible by unique geochemical characteristics of known Ordovician-sourced hydrocarbons. These geochemical characteristics are due the nature of the marine organic matter present during the Ordovician, before the evolution of land plants. While both bacteria and algae contributed to organic matter in Ordovician source rocks, the unique geochemical characteristics are thought to result from an abundance of the microfossil *Gloeocapsomorpha prisca (G. prisca)* (Fowler, 1992). There is debate as to what type of organism *G. prisca* was. Interpretations include a non-photosynthetic, benthic prokaryote that formed mats; a chemosynthetic autotroph, to a phototropic, planktonic, eukaryotic alga (Fowler, 1992). Regardless of its exact affinity, *G. prisca* seems to have been an important organic component in Ordovician and possibly Cambrian sediments.

Much of the published data pertains to Ordovician oils. Data for Cambrian hydrocarbons is more limited, but some researchers feel that the Ordovician characteristics may apply to Cambrian oils and source rocks (Wielens and others, 1990; Fowler, 1992). Oils derived from Ordovician source rocks have distinctive characteristics (Reed and others, 1986; Fowler, 1992; Guthrie and Pratt, 1995):

- a predominance of odd carbon number normal paraffins in the C_{11}–C_{19} range
- low abundance of high molecular weight normal paraffins ($>C_{20+}$)
- very low concentrations of acyclic isoprenoids (pristane and phytane) and polycyclic alkanes
- relatively high concentration of monocyclic alkanes

The most distinctive characteristic of Ordovician oils is the dominance of odd-carbon parraffins from C_9 through C_{19}. The concentration of pristane and phytane varies, but is typically low in Ordovician oils. These compounds are thought to be derived from chlorophyll, and when abundant, suggest a photosynthetic organism was the organic source (Fowler, 1992). A lack of pristane and phytane may indicate that photosynthetic organisms did not contribute to the organic material, and has been noted in oils derived from organic matter rich in *G. prisca*, suggesting that it may have been a non-photosynthetic organism. (Reed and others, 1986; Guthrie and Pratt, 1995).

Since this project has focussed on Cambrian rocks and hydrocarbons, a key question is whether these Ordovician oil characteristics also apply to Cambrian-sourced hydrocarbons. Cambrian oils with characteristics similar to Ordovician oils have been documented by Wielens and others (1990). In addition, alginite similar to *G. prisca* has been identified in rocks as old as Middle Cambrian in the Northwest Territories of Canada (Wielens and others, 1990).

Rome Trough Oils

Eight wells producing from the Cambrian were sampled for gas and condensate. Five preliminary gas chromatographs were run on the condensates by the USGS, and released to the consortium by Equitable Resources. Copies of these GC's are included as Figures 7-4 through 7-8. In addition, GC's were run on extracted hydrocarbons from the higher TOC shales sampled in the Exxon 1 Smith and Texaco 1 Kirby wells by Humble Geochemical (Figs. 7-9, 7-10). The 5 GC's run by USGS on the Elliott County, Ky. oils are preliminary data, and additional analyses are planned by Ryder and Burruss. A more detailed interpretation is necessary before any firm conclusions can be made from these oils.

The Elliott County oils (Figs. 7-4 to 7-8) were collected from stock tanks and gas separators at each well location. Condensate stock tanks were open to the atmosphere, and some of the more volatile components may have been lost due to evaporation. Three of the samples run by USGS were produced from the Cambrian Rome Formation. The other 2 samples are from Ordovician reservoirs in the field, one from the Trenton Limestone, and the other from the St. Peter Sandstone.

Gas chromatographs from the Rome Formation condensates are variable. Two of the three show a predominance of odd carbon normal paraffins in the C_{11} to C_{19} range (Figs. 7-4, 7-5). These samples also have very small abundances of normal paraffins above C_{20} and no significant pristane and phytane peaks. These GC's are similar to published Ordovician-sourced oils, and are likely derived from source rocks as old as Ordovician, and possibly Cambrian. The other Rome sample (Fig. 7-6) differs in that it has no odd carbon normal paraffin dominance, but rather a steep uniform decline in normal paraffins from C_{11} to C_{17}. This sample, from the Carson Associates 1 Pritchard Heirs well, is strongly depleted in the higher weight paraffins. This oil will require further analysis to determine it's origin. Also, the sample from the Carson Associates 40 Kazee well (Fig. 7-4) is slightly contaminated with Tretolite, a chemical used to treat a paraffin problem in this well. The influence of this contaminant is not known in this preliminary analysis.

The two oils produced from Ordovician reservoirs in the field are shown in Figs. 7-7 and 7-8. The Trenton Limestone oil sample from the Carson Associates T-1 Lawson Heirs well (Fig. 7-7) has the typical Ordovician odd carbon number dominance in the C_{11}-C_{19} range, but differs slightly in the small, but observable phristane and phytane peaks. This oil is much darker in color than the deeper Rome oils, but whether this is due to a different source is not known. The condensate sample from the St. Peter Sandstone reservoir in the field is shown in Fig. 7-8. This sample shows a sharp decline in the

heavier normal alkanes (C_{14}-C_{20}), and does not show an odd carbon-dominance in the C11-C20 range. A full interpretation of this sample will have to wait until more work is done by USGS.

Finally, gas chromatographs were run on 2 extracted oils from potential source rocks in the Exxon 1 Smith and Texaco 1 Kirby wells discussed previously (Figs. 7-9, 7-10). These chromatographs were interpreted by Dan Jarvie of Humble Geochemical in Houston, Texas. His interpretation follows below:

"We extracted the two samples from the Exxon Smith and Texaco Kirby wells and ran GC fingerprints (Figs. 7-9 and 7-10). They are very similar in that they both have n-C_{17} and n-C_{19} predominance with odd predominance from C_{11}-C_{19} and are composed primarily of normal alkanes. You will note that the isoprenoid content, e.g., what we think are pristane and phytane, is very low; this is also typical of the Ordovician oils. The C_{17} and C_{19} predominance is seen in Ordovician oils derived from *G. prisca* sources. However, these oils are a bit more waxy than typical Ordovician oils having relatively high abundance of alkanes extending into the C_{30} range. Ordovician oils usually die around C_{20}, although some Ordovician oils do have a slightly more waxy fingerprint. The Kirby extract is slightly different from the Smith extract in that it is more waxy and has slight C_{21} predominance. It also contains more light hydrocarbons but this could be a sample preparation artifact. Please note that all peak identification are tentative based on retention times and being a homologous series. While I have compared these to Ordovician oils, this is by no means conclusive as I would expect Cambro-Ordovician oils to be somewhat similar based on the limited biomass available to generate these oils. Thus, I certainly would not attempt to rule out a Cambrian source either. These oils are somewhat similar to the White Pines Precambrian oil recovered from a copper mine seep in Wisconsin (mostly n-alkanes, limited compositional variation) and even the Cambrian Deadwood oil, although it contains abundant pristane and phytane. All these oils look virtually like a saturate fraction GC even though these are whole extract fingerprints.

The extracted rock from the Smith well contains lower S_1 and S_2 after extraction as I suspected based on the presence of a low temperature S_2 shoulder in the whole rock pyrogram."

Thus based on the preliminary analyses done to date, extracted hydrocarbons from Cambrian source rocks in 2 wells match the GC fingerprint of produced condensate from the Homer Field in Elliott Co., Ky. This correlation will be refined with additional work by the USGS.

Rome Trough Gas Analyses

Natural gas and condensate were sampled from 8 Cambrian sub-Knox producing wells. Seven of these wells are within the Homer Field in Elliott County, Ky. The other well (Carson Associates 1 Ray) produces from a separate structure in Lawrence Co., Ky. Gas was sampled at the separator, and condensate samples were obtained either from the separator or from stock tanks. All of the wells were flowing gas when sampled, with the

exception of the Carson Associates 18 Blair well in the Homer Field. This well produces from the Ordovician St. Peter Sandstone, and was temporarily shut-in. This well and other St. Peter Sandstone producers in the area have reported small concentrations of H_2S (5-30 ppm, M. Hay, personal comm., 2001), but H_2S was not included in the analyses done by the USGS. There have been no reports of H_2S from Cambrian zones in the Homer Field.

Composition and isotope data from 8 gas samples are included in the spreadsheet, and are summarized in Table 7-4. The analyses were done by Isotech Laboratories, Inc., Champaign, Il. The Cambrian gas contains varying amounts of condensate, and most of the gas can be classified as wet (> 0.3 gallons of liquids per MCF). Production data obtained in the field for one of the higher producing wells, the Eastern States 34 Kazee, indicated a daily rate of 1,248 MCFG with 29 bbl. condensate.

All of the Cambrian gas sampled is of commercial quality, with an average BTU content of 1098 (Table 7-4). Methane averages 87%, and nitrogen and CO_2 are low, averaging 3.5% and 0.09% respectively. These gases differ significantly from those in the western Rome Trough discussed previously. This could be explained by their distance from the Grenville Front (assuming that is the source of the high nitrogen gas). The producing area is also deeper and more thermally mature, lying closer to the deepest parts of the Rome Trough. This might also explain why this area has commercial quality gas, while the western Rome Trough does not.

The USGS data also includes carbon isotopic analyses for various gas constituents. These data are included in the spreadsheet, but have not been interpreted by us.

SUMMARY AND CONCLUSIONS

The geochemistry part of this study has resulted in several important new findings. First, potential hydrocarbon source rocks of Cambrian age have been documented for the first time in the Appalachian Basin. The extent of these source rocks is widespread, but the distribution is not likely to be uniform. High TOC shales were found in Garrard County, Ky. and Wayne County, W. Va. in the Rome Formation and Conasauga Group (Rogersville Shale). The volume of these organic-rich shales in the Rome Trough is not currently known. The Garrard County shales are thin and volumetrically small. The Rogersville Shale interval in the Exxon 1 Smith well in Wayne County, W. Va. is thick enough to map based on geophysical log characteristics. Future work should attempt to determine the extent of this source interval.

Analysis of Cambrian oils (condensates) from wells in Elliott County, Ky. shows characteristics of Ordovician or older sources. These characteristics include a predominance of odd-carbon normal alkanes in the C11–C20 range, low abundance of high molecular weight normal paraffins ($>C_{20+}$), and low abundance of pristane and phytane. Additional work needs to be done on these oils by the USGS, but the preliminary data matches known Ordovician and older oils fairly well. The oils also match gas chromatograms run on hydrocarbons extracted from the high TOC source

rocks in Garrard Co., Ky. and Wayne Co., W. Va. This match indicates that the Elliott County hydrocarbons could have been sourced from Cambrian shales within the Rome Trough.

Cambrian natural gas quality varies significantly across the study area, with low-BTU, high nitrogen gas encountered in the western part of the study area (Garrard and Rockcastle Counties, Ky. and Highland County, Ohio). . High-BTU, commercial quality Cambrian gas occurs in Elliott, Lawrence, and Johnson Counties, Ky, and in Jackson Co., W. Va. The exact boundary for non-commercial gas in the Rome Trough is not well-constrained, but exploration risk probably increases west of Estill Counties, Ky. where gas high in CO_2 occurs in Ordovician reservoirs. It is not known if the Cambrian high-nitrogen gas is related to the Ordovician high-CO_2 gas. Risk of high nitrogen in Cambrian reservoirs increases with proximity to the Grenville Front, a Precambrian fault zone. A correlation of high nitrogen in Cambrian wells near the Grenville Front has been observed in Kentucky and Ohio, suggesting a deep basement source of nitrogen (and associated anomalous helium in these wells). Commerical-quality gas is produced from the Knox and overlying Ordovician High Bridge/Lexington carbonates (Black River/Trenton equivalents) in Clay County, Ky. along the Rockcastle River uplift.

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Table 7-1: Summary of Rock-Eval data for Cambrian rocks in the study area. Numbers in bold print indicate samples with higher TOC values. New data in this study was contributed by the USGS.

Study	Formation	Number of samples	Total Organic Carbon (%)			S_2 Yield (kg/ton)		
			Ave.	High	Low	Ave.	High	Low
Cole et al. 1987	Conasauga/ Kerbel	26	0.18	0.67	0.00	0.19	2.03	0.00
Cole et al. 1987	Mt. Simon Ss.	20	0.15	0.45	0.00	0.11	0.65	0.00
Ryder et al. 1998	Conasauga/ Rome	20	0.37	0.84	0.08	0.14	0.41	0.00
This study (USGS)	Nolichucky Shale	9	0.12	0.15	0.10	0.12	0.22	0.01
This study (USGS)	Maryville Limestone	4	0.61	1.12	0.24	0.31	0.65	0.12
This study (USGS)	Rogersville Shale	**5**	**2.73**	**4.40**	**1.20**	**1.49**	**2.58**	**0.75**
This study (USGS)	Rome Fm.	17	0.40	**3.26**	0.08	1.02	**13.61**	0.01

Table 7-2: Detailed Rome Trough Rock-Eval pyrolysis data. Numbers in bold indicate samples with higher TOC. Table continued on next page. New data was contributed to this study by the USGS.

API No.	Well	Location	Formation	Depth	TOC	T_{max}	HI	OI	S1	S2	S3	S1*100 /TOC	S2/S3	PI	Source
n/a	average of 26 samples	Ohio	Conasauga Gp and Kerbel Fm.	N/a	ave=0.18	n/a	n/a	n/a	n/a	ave=0.19	n/a	n/a	n/a	n/a	Cole et al., 1987
n/a	average of 20 samples	Ohio	Mt. Simon Ss	N/a	ave=0.15	n/a	n/a	n/a	n/a	ave=0.11	n/a	n/a	n/a	n/a	
4710700351	Hope Nat. Gas 9634 Power Oil	Wood Co., WV	Rome Fm	13,128.0	0.18		246	155	0.31	0.39	0.28	172	1.39	0.44	Ryder et al. 1998
4710700351	Hope Nat.Gas 9634 Power Oil	Wood Co., WV	Rome Fm	13,133.0	0.18		0	127	0	0	0.23	0		0.00	
4710700351	Hope Nat. Gas 9634 Power Oil	Wood Co., WV	Rome Fm	13,139.8	0.08		12	337	0	0.01	0.27	0	0.04	0.00	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Maryville Ls	13,985.5	0.34		20	97	0.03	0.07	0.33	9	0.02	0.30	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Maryville Ls	14,136.0	0.36		19	88	0.04	0.07	0.32	11	0.02	0.40	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Maryville Ls	14,364.5	0.19		26	200	0.02	0.05	0.38	11	0.02	0.33	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Maryville Ls	14,380.5	0.59		18	54	0.13	0.11	0.32	22	0.04	0.54	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Maryville Ls	14,386.5	0.25		40	112	0.09	0.1	0.28	36	0.03	0.50	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Maryville Ls	14,400.5	0.51		29	86	0.12	0.15	0.44	24	0.07	0.46	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Rogersville Sh	14,660.0	0.57	425	33		0.11	0.19		19		0.37	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Rogersville Sh	15,530.0	0.53	392	68		0.49	0.36		92		0.57	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Rogersville Sh	15,532.0	0.29		48	86	0.13	0.08	0.25	45	0.02	0.50	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Rutledge Ls	15,560.5	0.33		15	115	0.03	0.07	0.38	9	0.03	0.37	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Pumpkin Valley Sh and Rome Fm	15,830.0	0.74	426	41		0.19	0.3		26		0.38	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Rome Fm	16,310.0	0.84	428	49		0.23	0.41		27		0.36	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Rome Fm	16,461.0	0.09		88	177	0.05	0.08	0.16	56	0.01	0.42	
4703501366	Exxon 1 McCoy et.al.	Jackson Co., WV	Rome Fm	16,493.0	0.11		63	190	0.05	0.07	0.21	45	0.01	0.42	
4705900805	Columbia Gas 9674T Mineral Tract 10	Mingo Co, WV	Rome Fm	16,233.5	0.15		33	180	0.04	0.05	0.27	27	0.01	0.50	
4705900805	Columbia Gas 9674T Mineral Tract 10	Mingo Co, WV	Rome Fm	16,235.5	0.51		15	54	0.12	0.08	0.28	24	0.02	0.60	
4705900805	Columbia Gas 9674T Mineral Tract 10	Mingo Co, WV	Rome Fm	16,239.5	0.58		15	46	0.15	0.09	0.27	26	0.02	0.62	
1611567549	Ashland 1 Williams	Johnson Co., KY	Nolichucky Sh	6,270.6	0.12	494	158	258	0.06	0.19	0.31	50	0.61	0.24	USGS/ RTC (This study)
1611567549	Ashland 1 Williams	Johnson Co., KY	Nolichucky Sh	6,275.0	0.13	421	69	146	0.05	0.09	0.19	38	0.47	0.36	
1611567549	Ashland 1 Williams	Johnson Co., KY	Nolichucky Sh	6,280.0	0.15	444	147	187	0.04	0.22	0.28	27	0.79	0.15	
1611567549	Ashland 1 Williams	Johnson Co., KY	Nolichucky Sh	6,285.5	0.1	506	470	230	0.03	0.17	0.23	30	0.74	0.15	
1611567549	Ashland 1 Williams	Johnson Co., KY	Nolichucky Sh	6,292.0	0.12	500	83	125	0.04	0.1	0.15	33	0.67	0.29	
1607921048	Texaco 1 Kirby	Garrard Co, KY	Maryville Ls (equiv.)	4,576.0	0.28	438	232	107	0.05	0.65	0.3	18	2.17	0.07	

API No.	Well	Location	Formation	Depth	TOC	T_{max}	HI	OI	S1	S2	S3	S1*100 /TOC	S2/S3	PI	Source
1607921048	Texaco 1 Kirby	Garrard Co, KY	Rome Fm	4,628.0	**3.26**	**444**	**417**	**11**	**0.55**	**13.61**	0.35	17	38.89	0.04	
1607921048	Texaco 1 Kirby	Garrard Co, KY	Rome Fm	4,628.8	**0.70**	**446**	**356**	**16**	**0.30**	**2.49**	0.11	43	22.64	0.11	USGS/ RTC (This study)
1606521865	Texaco 1 Tipton	Estill Co, Ky	Rome Fm	6,375.5	0.17	448	53	76	0.01	0.09	0.13	6	0.69	0.10	
1606521865	Texaco 1 Tipton	Estill Co, Ky	Rome Fm	6,385.0	0.16	450	31	19	0	0.05	0.03	0	1.67	0.00	
1606521865	Texaco 1 Tipton	Estill Co, Ky	Rome Fm	6,389.5	0.12	447	75	17	0	0.09	0.02	0	4.50	0.00	
4703501366	Exxon 1 McCoy	Jackson Co., WV	Black River Gp	9,294.8	0.88	392	16	28	0.24	0.14	0.25	27	0.56	0.63	
4704301469	Exxon 1 McCormick	Lincoln Co., WV	Maryville Ls	13,650.0	0.79	400	15	8	0.15	0.12	0.06	19	2.00	0.56	
4704301469	Exxon 1 McCormick	Lincoln Co., WV	Maryville Ls	13,661.0	1.12	348	20	10	0.23	0.22	0.11	21	2.00	0.51	
4704301469	Exxon 1 McCormick	Lincoln Co., WV	Rome Fm	16,255.0	0.83	299	8	18	0.15	0.07	0.15	18	0.47	0.68	
4704301469	Exxon 1 McCormick	Lincoln Co., WV	Rome Fm	16,906.0	0.13	392	46	46	0.1	0.06	0.06	77	1.00	0.63	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rogersville Sh	11,150.5	**2.83**	**460**	**61**	**13**	**1.79**	**1.72**	0.36	63	4.78	0.51	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rogersville Sh	11,161.5	**4.40**	**469**	**59**	**6**	**2.71**	**2.58**	0.27	62	9.56	0.51	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rogersville Sh	11161.5 (extract)	**3.16**	**477**	**40**	**10**	**0.08**	**1.26**	0.32	3	3.94	0.06	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rogersville Sh	11,180.5	**1.20**	**414**	**63**	**23**	**0.81**	**0.75**	0.27	68	2.78	0.52	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rogersville Sh	11,195.5	**2.08**	**465**	**55**	**12**	**1.60**	**1.15**	0.25	77	4.60	0.58	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rome Fm	12,440.3	0.15	475	13	100	0.03	0.02	0.15	20	0.13	0.60	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rome Fm	12,478.5	0.22	361	32	50	0.03	0.07	0.11	14	0.64	0.30	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rome Fm	12,497.0	0.14	299	7	50	0.03	0.01	0.07	21	0.14	0.75	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rome Fm	13,710.5	0.13	319	38	85	0.03	0.05	0.11	23	0.45	0.38	
4709901572	Exxon 1 Smith	Wayne Co., WV	Rome Fm	13,734.5	0.21	299	43	48	0.04	0.09	0.10	19	0.90	0.31	
1604534578	Cities Service 1 Garrett	Casey Co., KY	Rome Fm	7,242.0	0.18	423	33	28	0.03	0.06	0.05	17	1.20	0.33	
1606390472	Eastern States 34 Kazee	Elliott Co., KY	Rome Fm	6,814.5	0.12	449	142	50	0.03	0.17	0.06	25	2.83	0.15	
1606390472	Eastern States 34 Kazee	Elliott Co., KY	Rome Fm	6,828.0	0.15	435	127	67	0.05	0.19	0.10	33	1.90	0.21	
1606390472	Eastern States 34 Kazee	Elliott Co., KY	Rome Fm	6,835.0	0.13	477	154	54	0.04	0.20	0.07	31	2.86	0.17	
1606390472	Eastern States 34 Kazee	Elliott Co., KY	Nolichucky Sh	5700-5800	0.15	420	127	160	0.07	0.19	0.24	47	0.79	0.27	
1606390472	Eastern States 34 Kazee	Elliott Co., KY	Maryville Ls	5970-6000	0.24	431	104	75	0.16	0.25	0.18	67	1.39	0.39	
1615121905	Texaco 1 Perkins	Madison Co., KY	Rome Fm	4,770.0	0.08	450	25	125	0.02	0.02	0.10	25	0.20	0.50	
1623730520	Exxon 1 Banks	Wolfe Co., KY	Nolichucky Sh	7,341.5	0.10	338	10	80	0.03	0.01	0.08	30	0.13	0.75	
1623730520	Exxon 1 Banks	Wolfe Co., KY	Nolichucky Sh	7,377.0	0.10	299	50	120	0.02	0.05	0.12	20	0.42	0.29	
3414560141	Aristech Chemical 4 Monitor Well	Scioto Co., OH	Nolichucky Sh	5,137.8	0.12	299	50	92	0.03	0.06	0.11	25	0.55	0.33	

Table 7-3: Published and contributed natural gas analyses from Ordovician and Cambrian reservoirs in the study area.

API No.	Well	Location	Producing Zone	BTU	He	N	CO_2	Methane	Ethane	Propane	Iso-butane	N-bu-tane	Iso-pen-tane	N-pen-tane	H_2S	Source
1604905543	Smith 1 Chambers	Clark Co., KY	Ord. St. Peter Sandstone	955	nd	5.96	2.96	88.25	1.66	0.19	0.20	0.27	0.17	0.18	0.15	McGuire and Howell, 1963
1604908246	Melcher 1 Shephard	Clark Co., KY	Ord. St. Peter Sandstone	952	nd	5.76	3.18	88.36	1.62	0.37	0.14	0.15	0.06	0.07	0.15	
1604908448	Melcher 1 Barrett	Clark Co., KY	Ord. St. Peter Sandstone	953	nd	6.07	2.67	88.74	1.71	0.30	0.13	0.13	0.12	0.1	0.00	
1606500489	Petroleum Exploration 1 McIntosh	Estill Co., KY	Ord. St. Peter Sandstone	758	nd	1.44	25.54	69.93	1.79	0.70	0.10	0.25	0.09	0.07	nil	
1606500490	Petroleum Exploration 1 Newkirk	Estill Co., KY	Ord. St. Peter Sandstone	646	nd	2.04	37.6	57.88	1.14	0.42	0.07	0.14	0.12	0.13	nil	
1606500492	South Central Petroleum 3 Garrett	Estill Co., KY	Ord. St. Peter Sandstone	764	nd	nd	18.2	67.45	nd	nd	nd	nd	nd	nd	nil	
1606500492	South Central Petroleum 3 Garrett	Estill Co., KY	Ord. St. Peter Sandstone	643	nd	nd	34.9	59.05	nd	nd	nd	nd	nd	nd	nil	
1606500492	South Central Petroleum 3 Garrett	Estill Co., KY	Ord. St. Peter Sandstone	572	nd	nd	40.9	54.00	nd	nd	nd	nd	nd	nd	0.5	
1606500492	South Central Petroleum 3 Garrett	Estill Co., KY	Ord. St. Peter Sandstone	566	nd	nd	41.95	53.04	nd	nd	nd	nd	nd	nd	0.55	
1619700491	Carpenter 1 Wise	Powell Co. KY	Ord. St. Peter Sandstone	n/a	nd	2.28	41.04	54.68	0.95	0.23	0.04	0.10	0.04	0.01	0.56	
1607921048	Texaco 1 Kirby	Garrard Co, KY	Camb. Rome Formation	227	1.62	80.4	0.01	13.90	2.1	0.60	0.00	0.30	0	0.2	nd	Harris and Baranoski, 1996
1607921048	Texaco 1 Kirby	Garrard Co, KY	Camb. Rome Formation	240	1.81	79.3	<.05	14.50	2.2	0.60	0.00	0.30	0	0.4	nd	
1607925811	Widener 1 Burdette	Garrard Co, KY	Camb. Rome Formation	339	1.8	70.7	0	19.30	4.5	0.70	0.50	0.70	0.1	0.2	nd	
1611567549	Ashland No.1 Williams	Johnson Co, KY	Camb. Nolichucky Sh	1175	nd	2		81.00	9	4.00	<1	1		<1	nd	
3407120016	Oxford Heyob-Coyne-West Unit	Highland Co, OH	Camb. Eau Claire Fm	723	nd	32.64	1.63	60.23	3.14	1.43	0.14	0.46	0.06	0.15	nd	
4703501366	Exxon No.1 McCoy	Jackson Co, WV	Camb. Conasauga Gp	1022	nd	1		97.00	2	<1	<.01	<.01		<.01	nd	
1612960010	Ashland 1 Cable, Millard	Lee Co., KY	Ord. Beekmantown/ Rose Run Ss	869	nd	4.86	14.42	75.00	3.52	1.34	0.13	0.37	0.08	0.07	nd	Bretagne GP.
1620375242	Hunt's Natural Resources 1 Livesay	Rockcastle Co., KY	Ord. Trenton Limestone	801	0.6	27	<0.05	66.60	3.8	1.20	0.40	0.20	0.1	0	nd	NTIS Database
1620375242	Hunt's Natural Resources 1 Livesay	Rockcastle Co., KY	Ord. Knox Group	796	0.6	27.7	0.1	65.60	3.9	1.20	0.30	0.30	0.2	0	nd	

Table 7-4: New natural gas analyses from Cambrian reservoirs in the Homer Field in Elliott Co., Ky. and an unnamed field in Lawrence Co., Ky. Data was contributed by the USGS and Equitable Resources, and is confidential to the Rome Trough Consortium.

API No.	Well	Location	Produc-ing Fm.	BTU	Me-thane	Etha ne	Pro-pane	N-Bu-tane	Iso-Bu-tane	N-Pen-tane	Iso-Pen-tane	Hex-anes+	N	CO_2	H	Ar	He
1612789172	Carson Associates 1 Ray	Lawrence Co., KY	Camb. Cona-sauga	1066	92.84	3.31	1.09	0.34	0.18	0.13	0.12	0.23	1.38	0.31	0.005	0.0094	0.053
1606388019	Carson Associates 57 Prichard Heirs	Elliott Co., KY	Camb. Rome Fm	1087	89.95	4.05	1.64	0.61	0.19	0.25	0.14	0.41	2.62	0.01	0.028	0.018	0.081
1606390473	Eastern States 39 Fannin	Elliott Co., KY	Camb. Rome Fm	1150	82.71	7.33	3.6	1.21	0.044	0.33	0.25	0.25	3.76	0.01	0.0091	0.021	0.072
1606389000	Carson Associates 40 Kazee	Elliott Co., KY	Camb. Rome Fm	1087	92.13	3.63	1.23	0.47	0.19	0.2	0.15	0.43	1.41	0.07	0.031	0.011	0.053
1606387821	Carson Associates T-1 Lawson Heirs	Elliott Co., KY	Ord. Trenton Ls	1125	81.64	7.81	3.54	0.92	0.35	0.2	0.17	0.23	4.75	0.06	0.19	0.013	0.13
1606388355	Carson Associates 18 Blair	Elliott Co., KY	Ord. St. Peter Ss.	1037	90.98	3.29	0.97	0.29	0.12	0.1	0.078	0.21	3.58	0.17	0.06	0.032	0.1
1606390472	Eastern States 34 Kazee	Elliott Co., KY	Camb. Cona-sauga/ Rome	1114	83.13	6.86	2.74	0.9	0.34	0.33	0.24	0.32	5	0.01	0.011	0.025	0.094
1606387820	Carson Associates 33 Lawson	Elliott Co., KY	Camb. Rome Fm	1120	81.83	6.61	2.9	1.02	0.35	0.43	0.29	0.53	5.85	0.04	0.0065	0.041	0.1
			Average	**1098**	**86.90%**	**5.36%**	**2.21%**	**0.72%**	**0.22%**	**0.25%**	**0.18%**	**0.33%**	**3.54%**	**0.09%**	**0.04%**	**0.02%**	**0.09%**

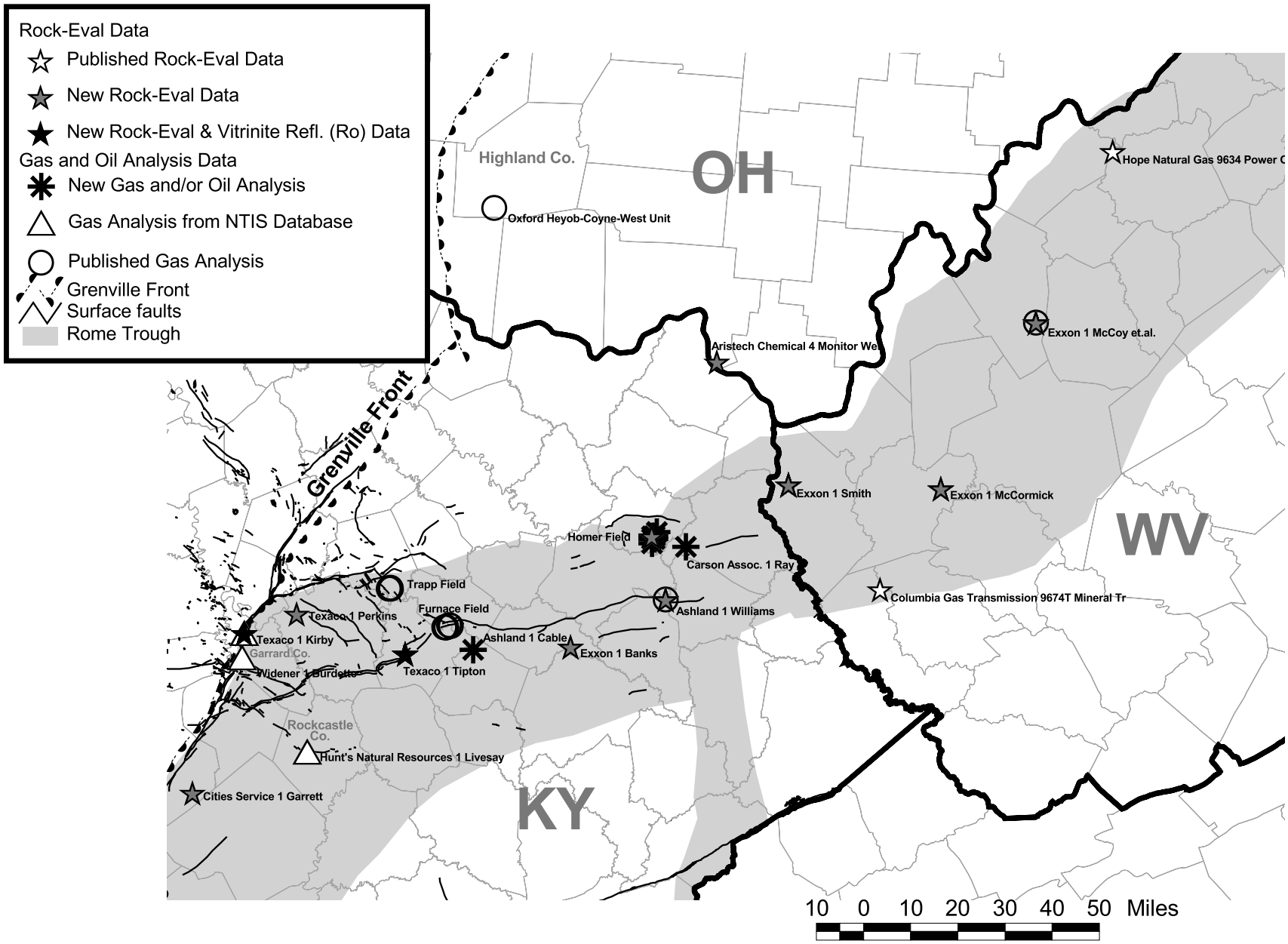


Figure 7-1. Map of Rome Trough study area showing distribution of new and previously published geochemical and thermal maturity data.

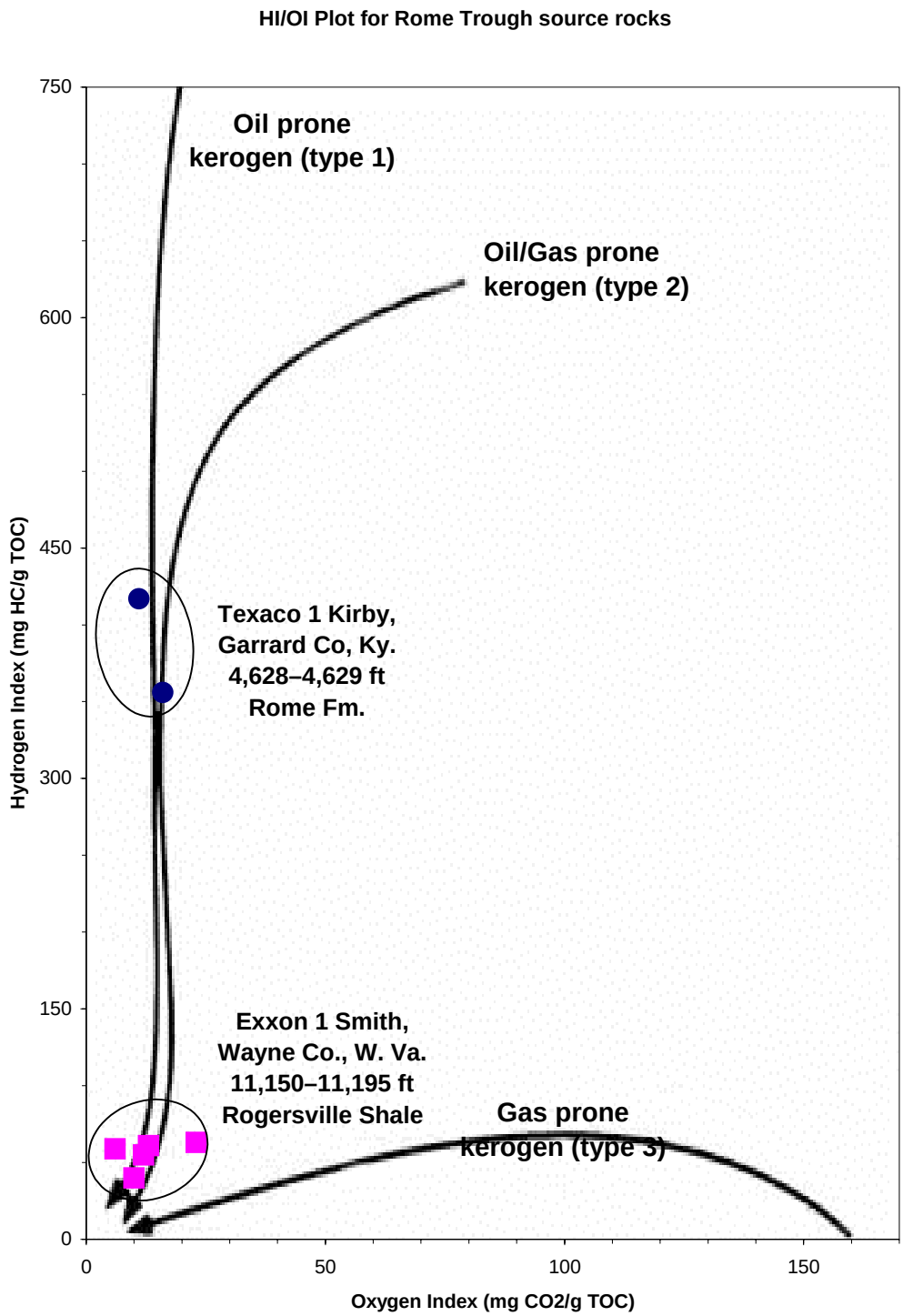


Figure 7-2. Plot of hydrogen index vs. oxygen index for samples with significant total organic carbon content. Thermal maturity of the kerogen increases from upper right to lower left. Samples from Garrard Co., Ky. are less thermally mature and plot higher on the hydrogen axis than the deeper samples from Wayne Co., W. Va. This type of plot is sometimes useful for determining the type of kerogen present, but is not diagnostic for these samples.

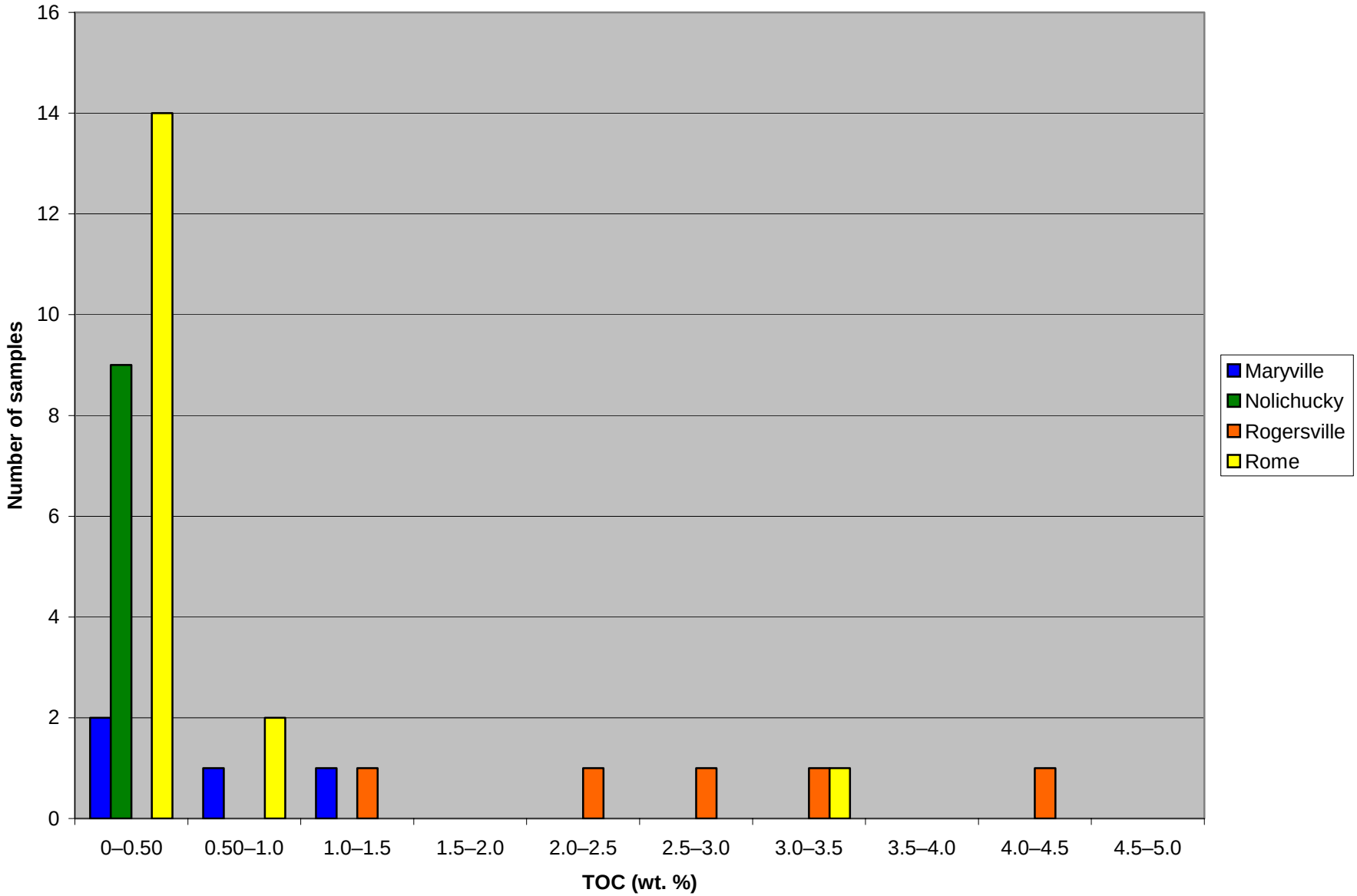


Fig. 7-3. Histogram showing range of total organic carbon (TOC) for Rome and Conasauga core samples analyzed in this study (n=35). The majority of samples are lean to very lean in TOC, but potential source rocks were identified in the Rogersville Shale and Rome Formation.

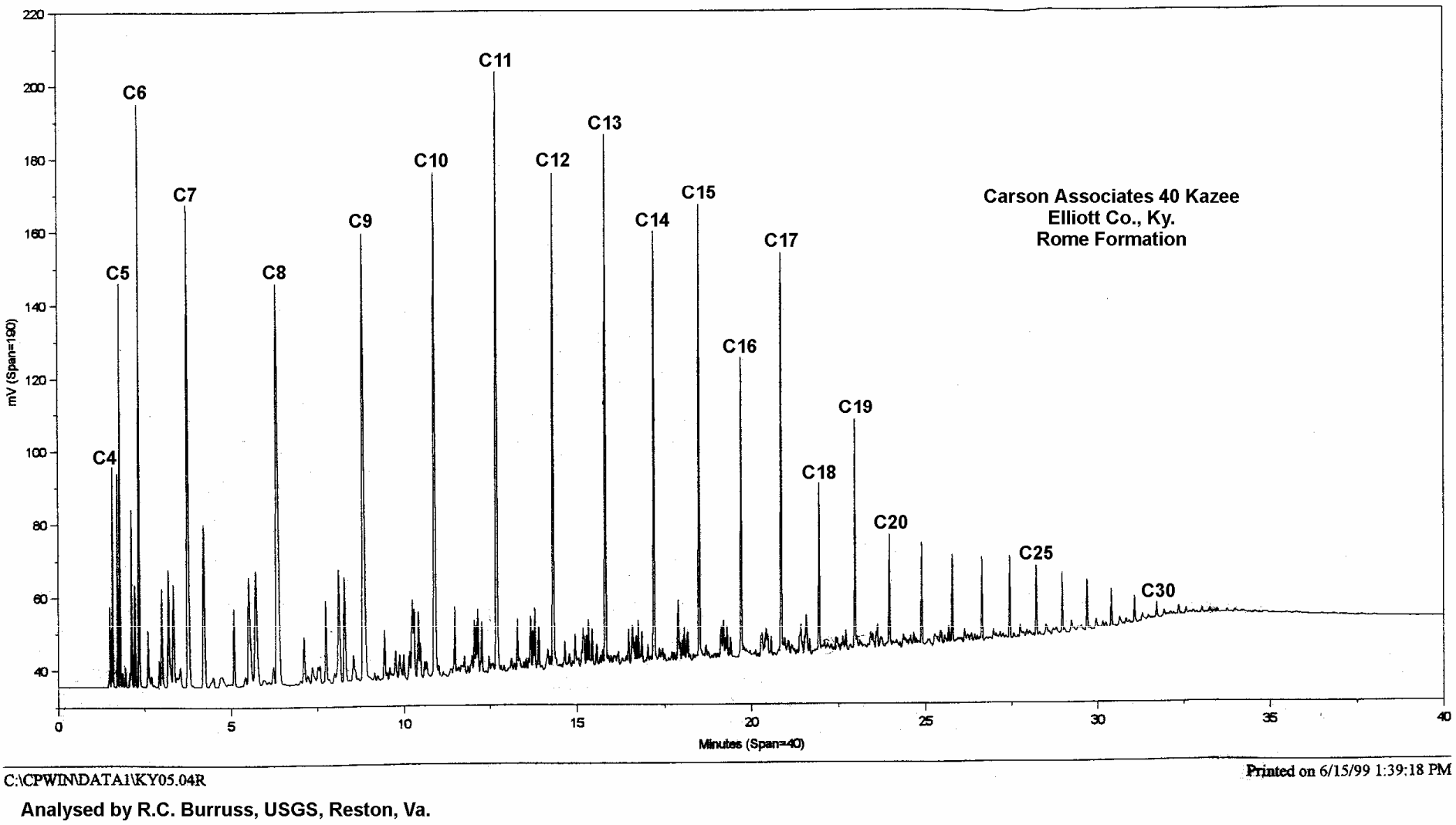


Figure 7-4. Preliminary gas chromatograph analysis for Rome Formation condensate from the Carson Assoc. 40 Kazee well, Elliott Co., Ky. Carbon number of hydrocarbons identified are labeled. Note the predominance of odd-carbon number compounds in the C11-C19 range, and absence of pristane and phytane peaks. These are characteristics of Ordovician (and possibly Cambrian) sourced hydrocarbons. Data courtesy of USGS and Equitable Resources (confidential).

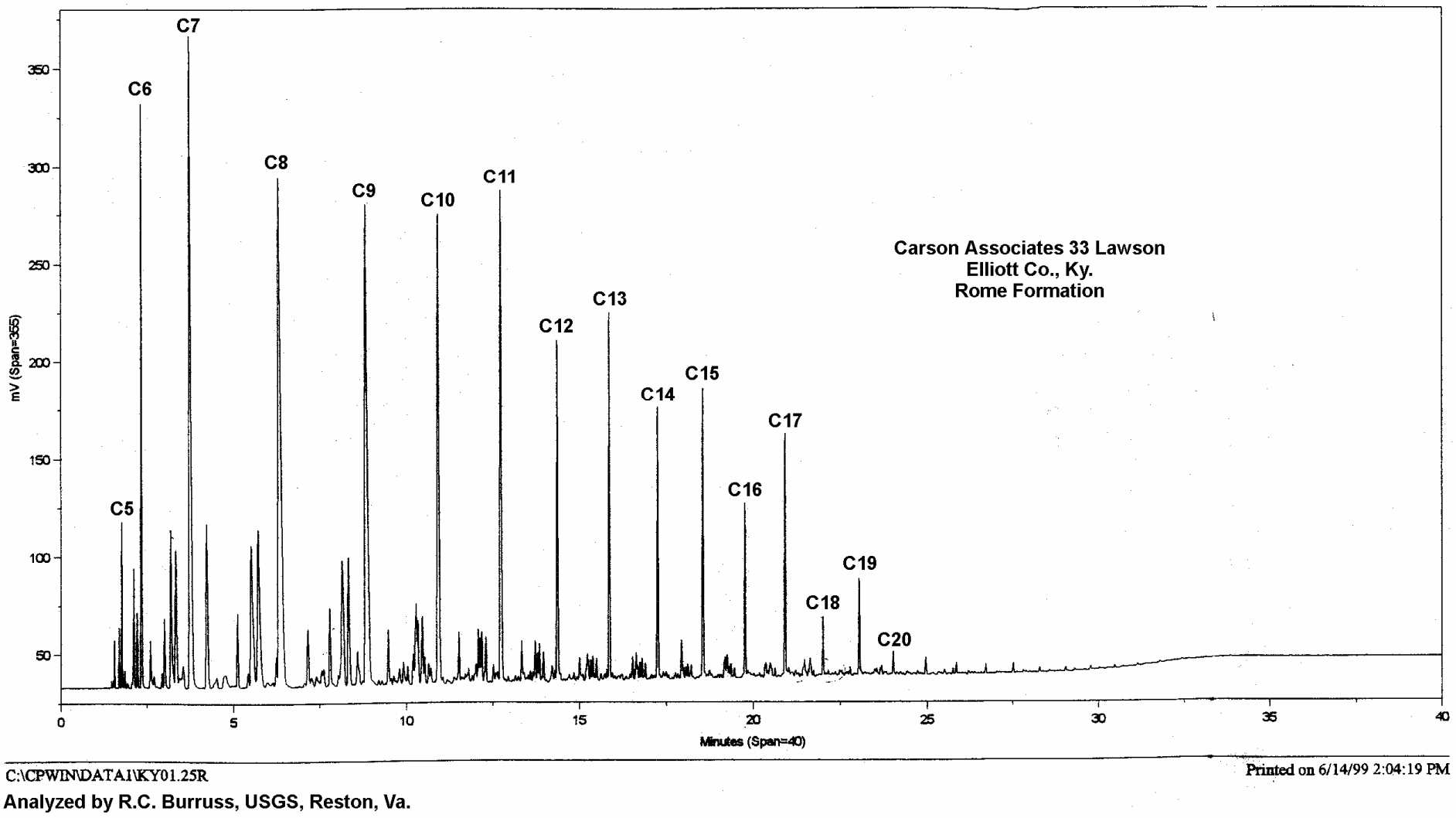


Figure 7-5. Preliminary gas chromatograph analysis for Rome Formation condensate from the Carson Assoc. 33 Lawson well, Elliott Co., Ky. Carbon number of hydrocarbons identified are labeled. Note predominance of odd-carbon number compounds in the C11-C19 range, and absence of pristane and phytane. These are characteristics of Ordovician (and possibly Cambrian) sourced hydrocarbons. Data courtesy of USGS and Equitable Resources (confidential).

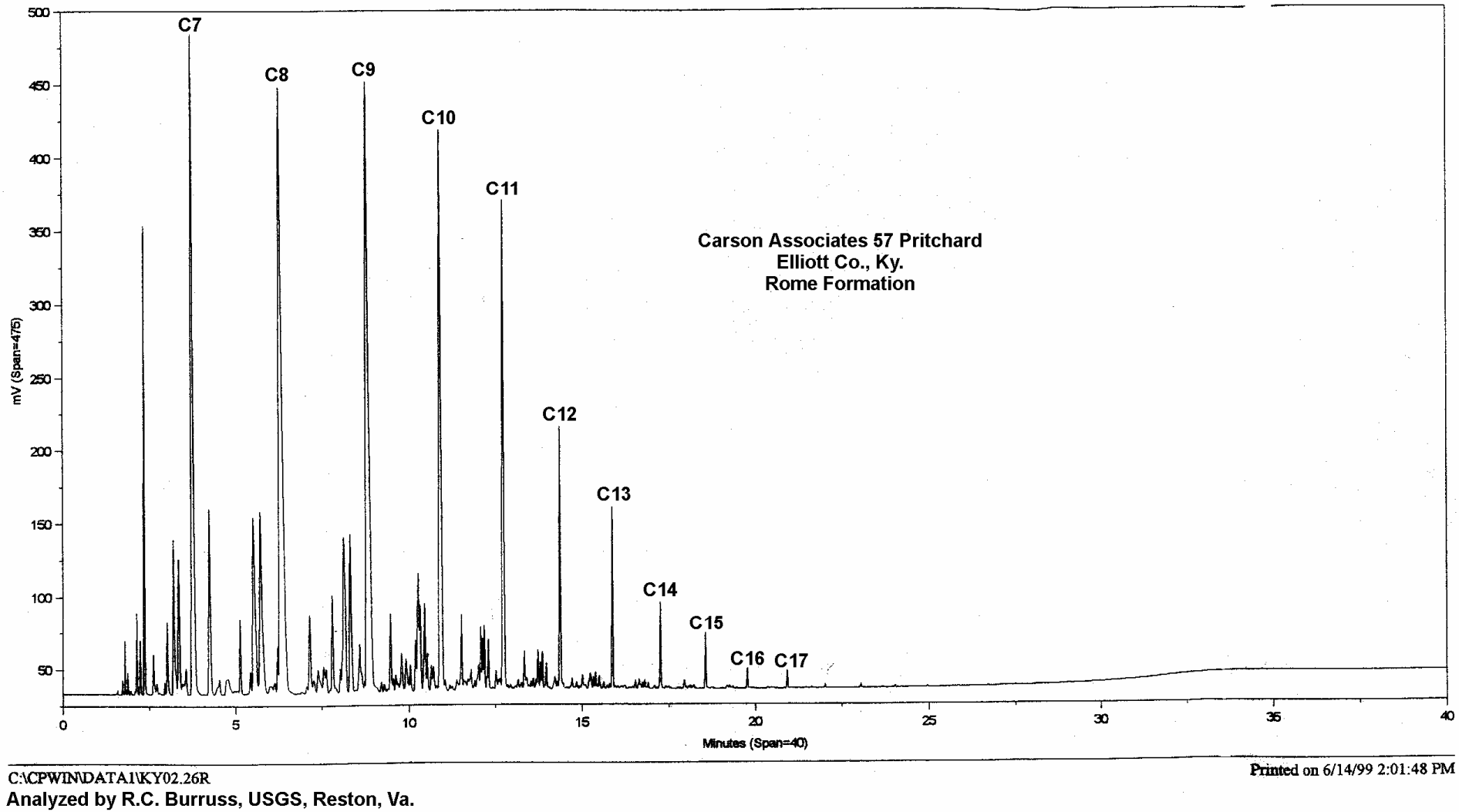


Figure 7-6. Preliminary gas chromatograph analysis for Rome Formation condensate from the Carson Assoc. 57 Pritchard well, Elliott Co., Ky. Carbon number of hydrocarbons identified are labeled. Odd-carbon number predominance is not apparent in this sample, but due to the lack of heavier hydrocarbons, this sampled needs further analysis. Data courtesy of USGS and Equitable Resources (confidential).

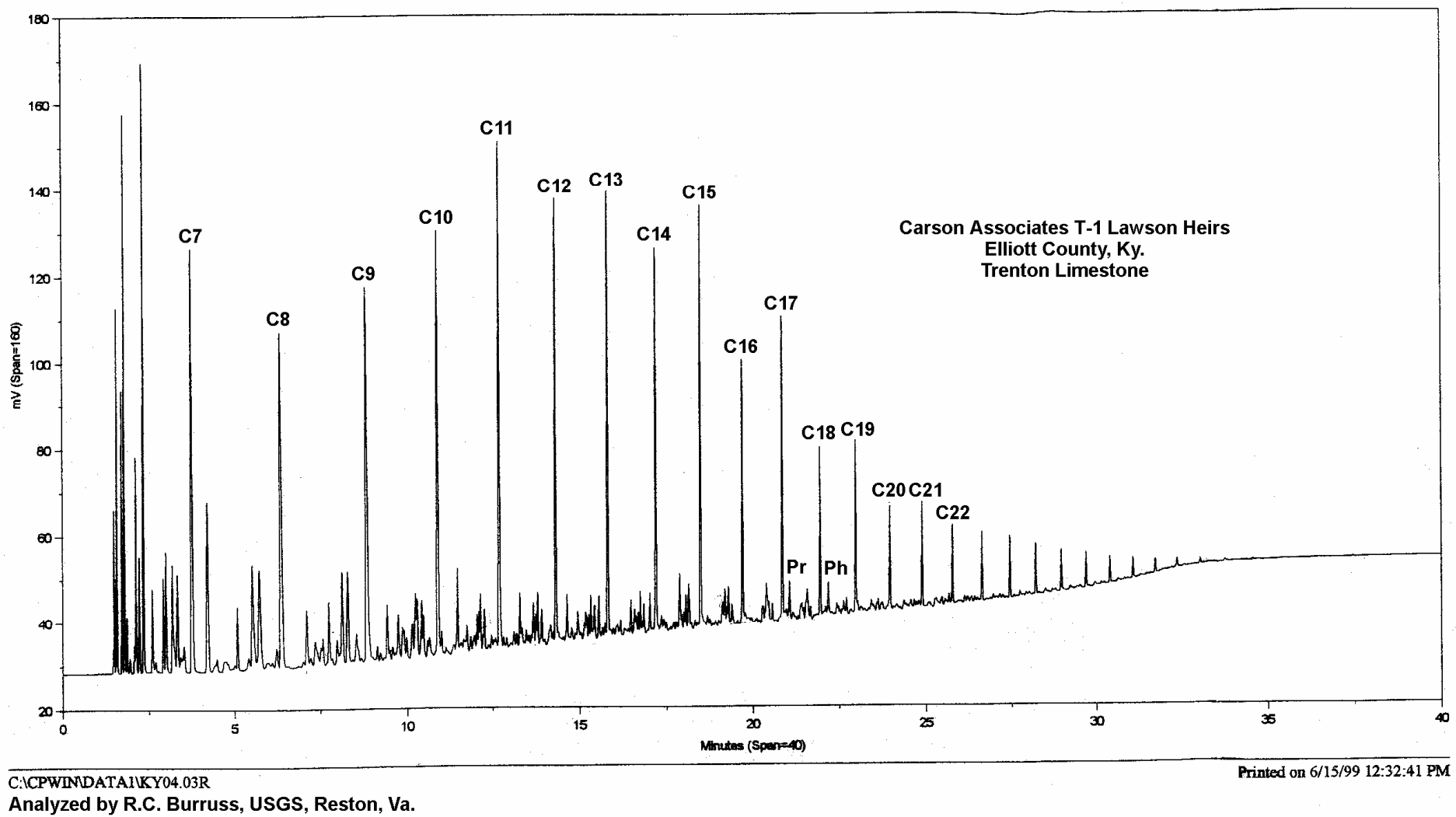


Figure 7-7. Preliminary gas chromatograph analysis for Trenton Limestone condensate from the Carson Assoc. T-1 Lawson Heirs well, Elliott Co., Ky. Carbon number of hydrocarbons identified are labeled. Note the predominance of odd-carbon number compounds in the C11-C19 range. Minor peaks for pristane and phytane are labeled. These are characteristics of Ordovician (and possibly Cambrian) sourced hydrocarbons. Data courtesy of USGS and Equitable Resources (confidential).

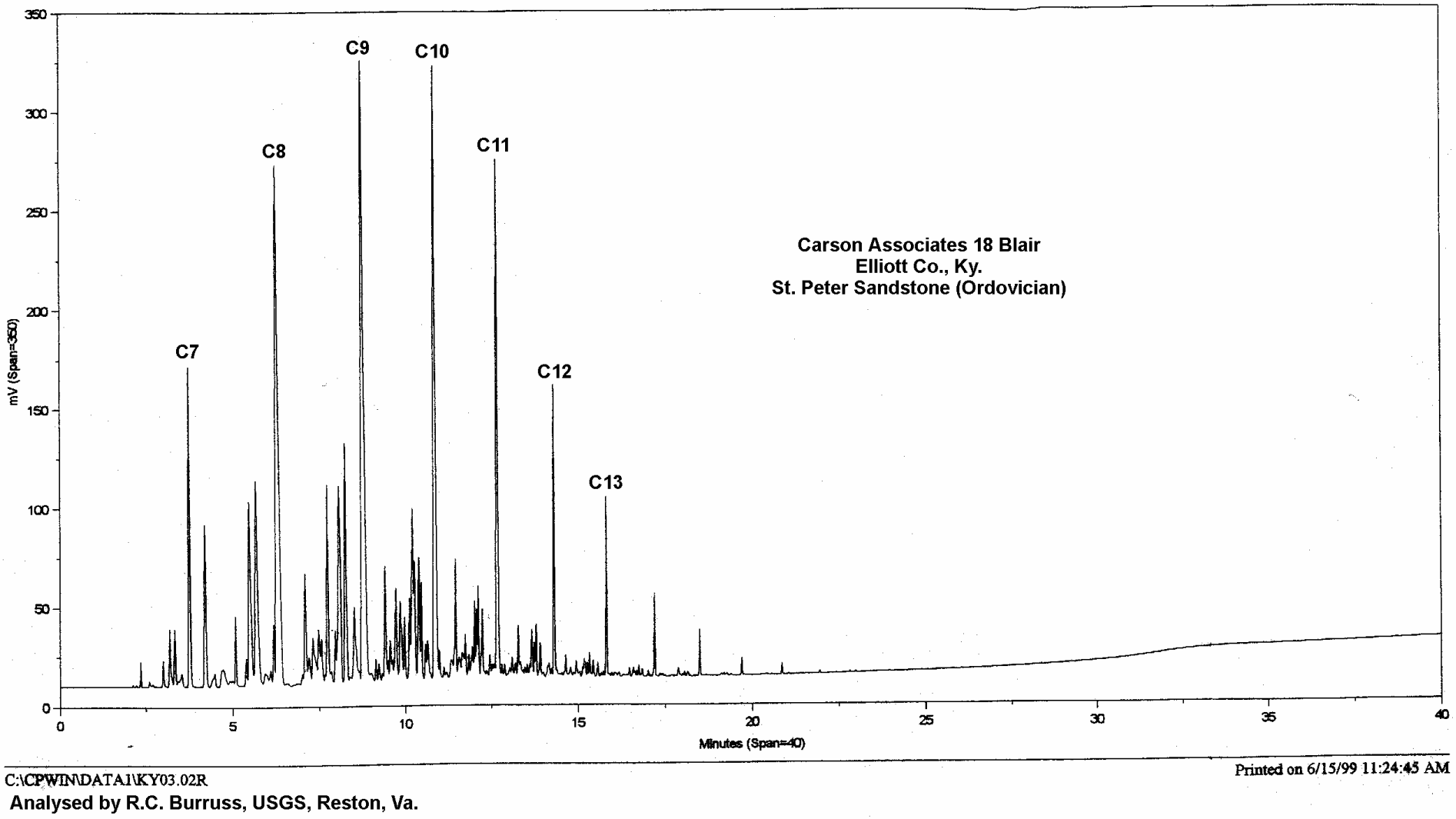


Figure 7-8. Preliminary gas chromatograph analysis for Ordovician St. Peter Sandstone condensate from the Carson Assoc. 18 Blair well, Elliott Co., Ky. Carbon number of hydrocarbons identified are labeled. Data courtesy of USGS and Equitable Resources (confidential).

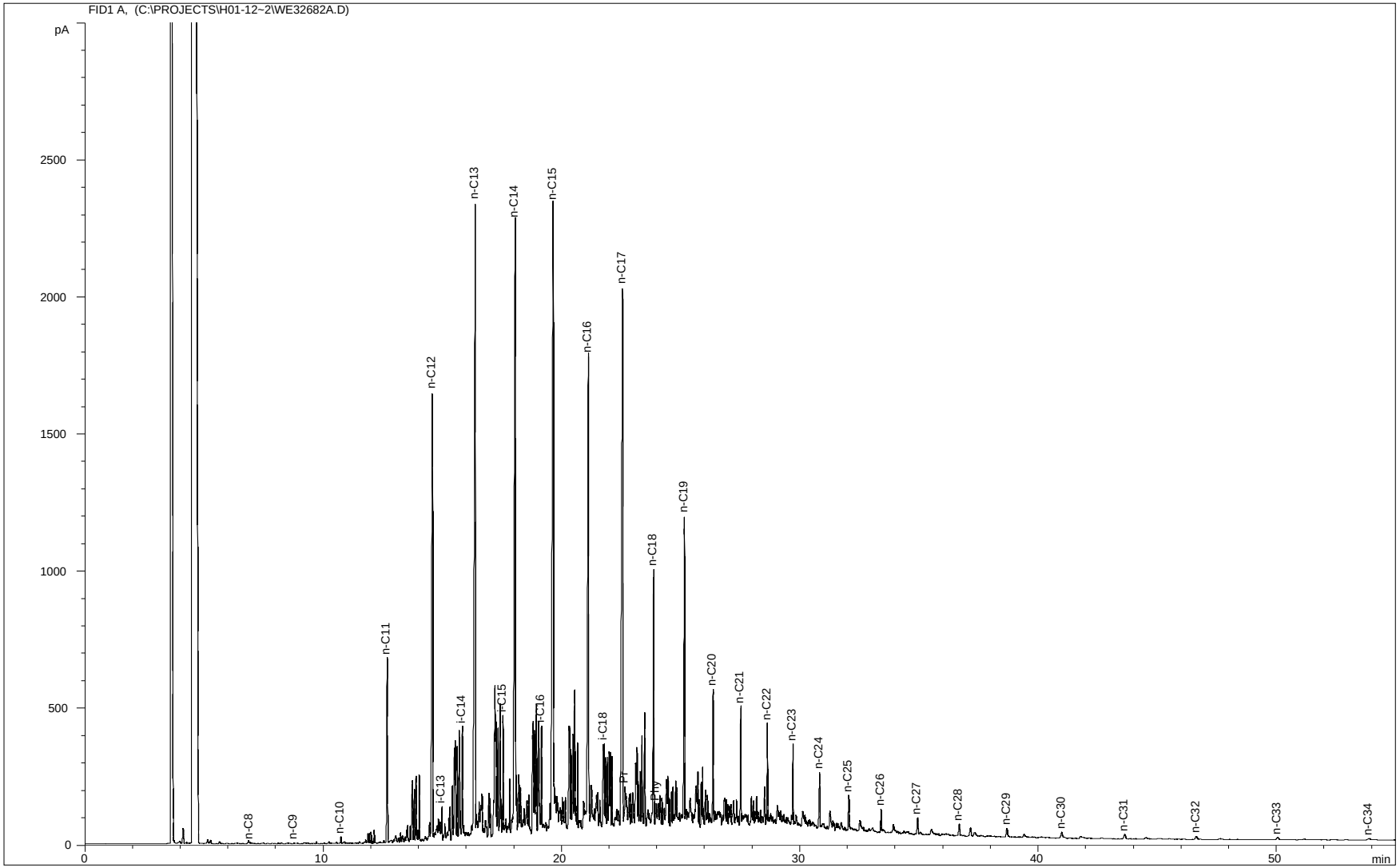


Figure 7-9. Whole extract gas chromatographic fingerprint from core sample of Rogersville Shale in the Exxon 1 Smith well at 11,161.5 ft. Note the predominance of odd-carbon number hydrocarbons, and small pristane (Pr) and phytane (Phy) peaks, characteristic of Ordovician and possibly Cambrian sourced oils. Data from Humble Geochemical, Houston, Tx., courtesy of USGS.

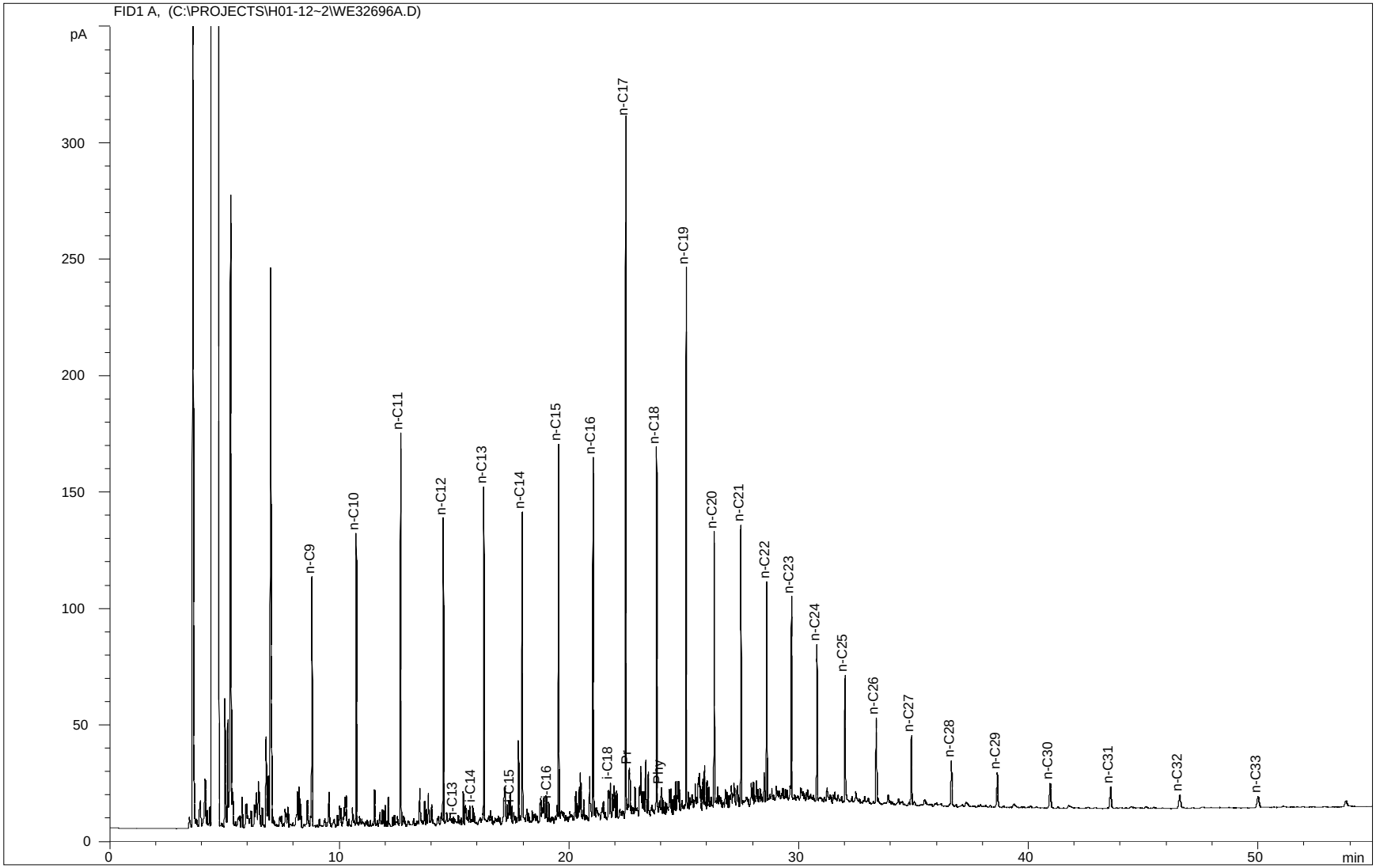
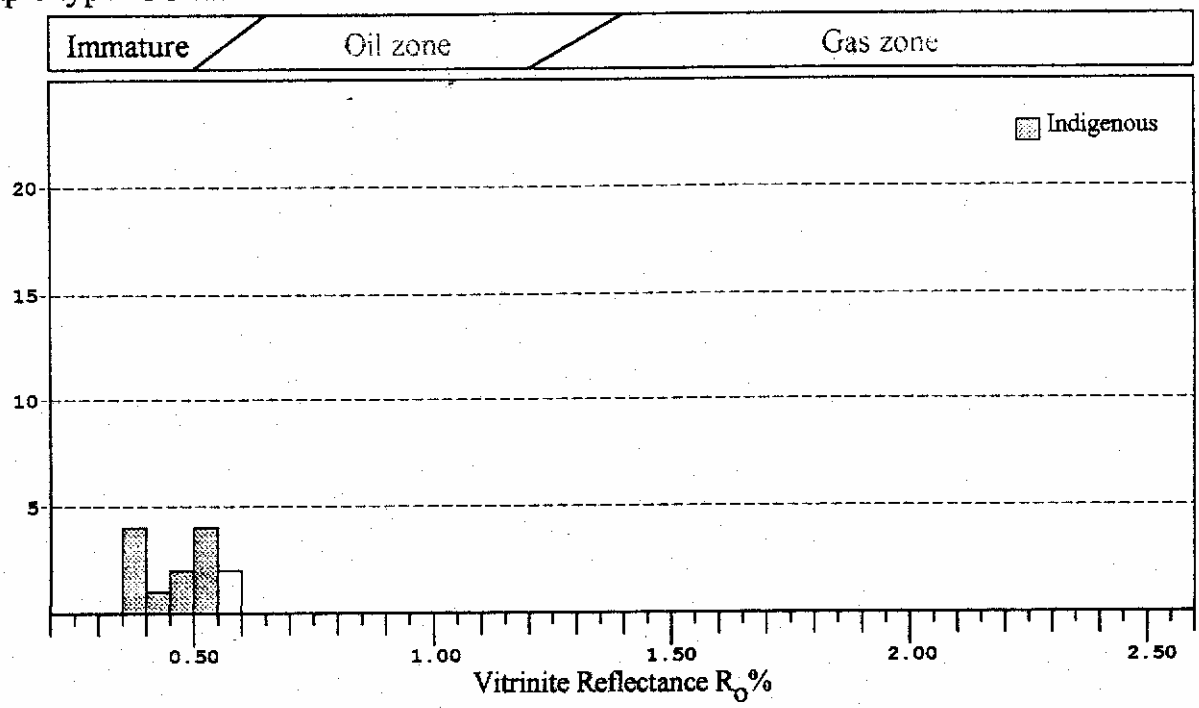


Figure 7-10. Whole extract gas chromatographic fingerprint from a core sample in the Texaco 1 Kirby well at 4,628.8 ft. Note the predominance of odd-carbon number hydrocarbons, and small pristane (Pr) and phytane (Phy) peaks, characteristic of Ordovician and possibly Cambrian sourced oils. Data from Humble Geochemical, Houston, Tx., courtesy of USGS.

Customer: ***USGS***
Well name: ***TEXACO #1 KIRBY, GARRARD, KY***
Sample ID: ***016-079-21048***
Mean depth (ft): ***4576***
Sample type: ***CORE***



Indigenous population statistics

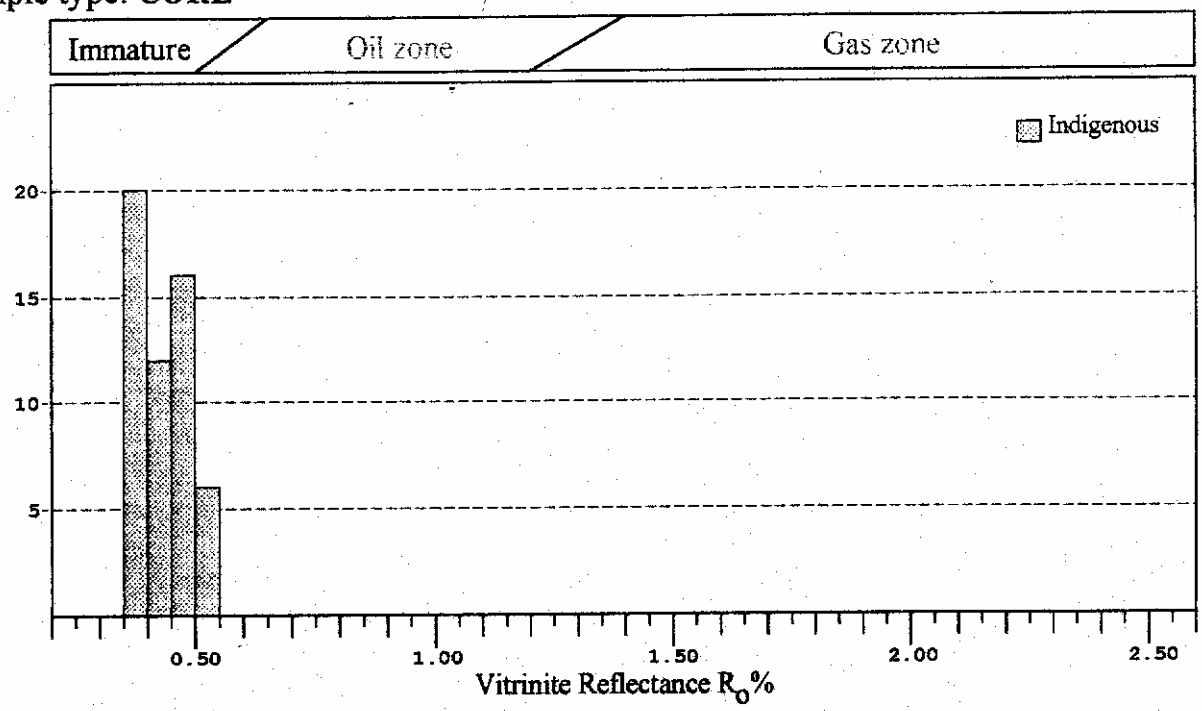
Mean: 0.45 Min: 0.35 Max: 0.54 Std. Dev.: 0.08 Count: 11

Total population statistics

Mean: 0.47 Min: 0.35 Max: 0.56 Std. Dev.: 0.08 Count: 13

Figure 7-11. Vitrinite reflectance histogram of "vitrinite-like" material from Rome Formation core at 4,576 ft in the Texaco 1 Kirby well, Garrard Co., Ky. Thermal maturity is immature, with a mean R_o of 0.45. The origin of the material measured is unknown, but it is not true vitrinite due to the age of the sample. Data courtesy of USGS.

Customer: ***USGS***
Well name: ***TEXACO #1 KIRBY, GARRARD, KY***
Sample ID: ***016-079-21048***
Mean depth (ft): ***4628***
Sample type: ***CORE***



Indigenous population statistics

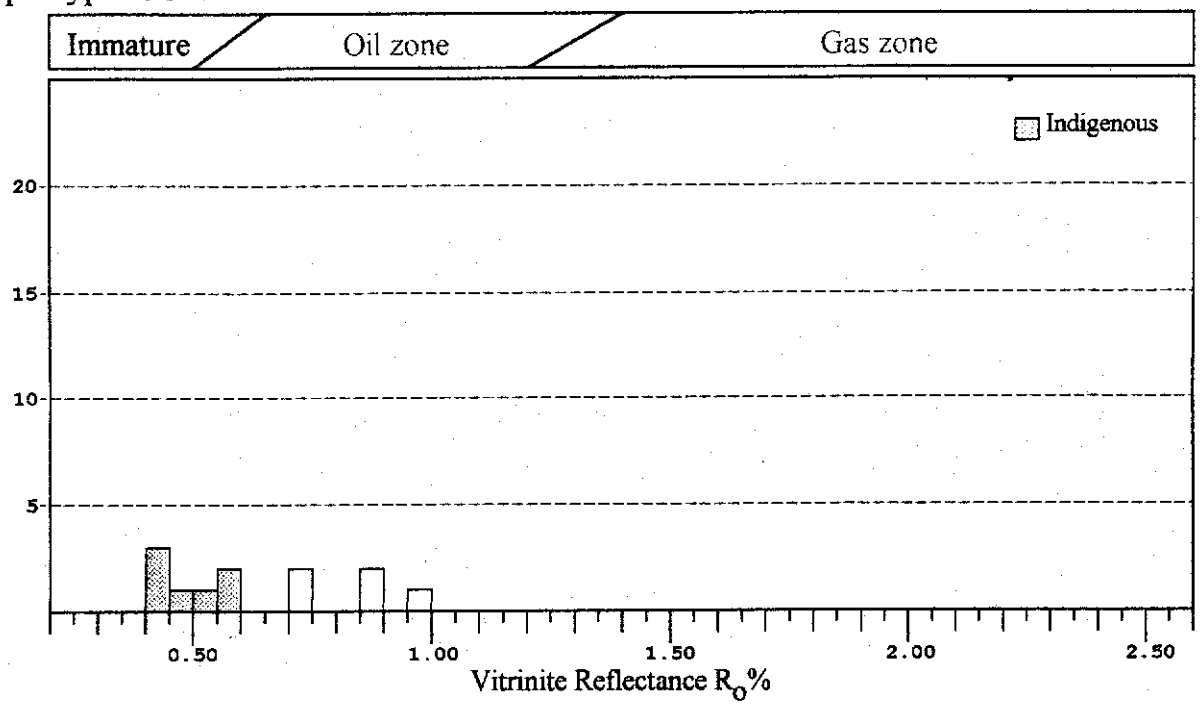
Mean: 0.43 Min: 0.36 Max: 0.52 Std. Dev.: 0.05 Count: 54

Total population statistics

Mean: 0.43 Min: 0.36 Max: 0.52 Std. Dev.: 0.05 Count: 54

Figure 7-12. Vitrinite reflectance histogram of "vitrinite-like" material from Rome Formation core at 4,628 ft in the Texaco 1 Kirby well, Garrard Co., Ky. Thermal maturity is immature, with a mean R_o of 0.43. The origin of the material measured is unknown, but it is not true vitrinite due to the age of the sample. Data courtesy of USGS.

Customer: ***USGS R. RYDER***
Well name: ***TEXACO NO. 1 TIPTON***
Sample ID: ***6375.5***
Mean depth (ft): ***6375.5***
Sample type: ***CORE***



Indigenous population statistics

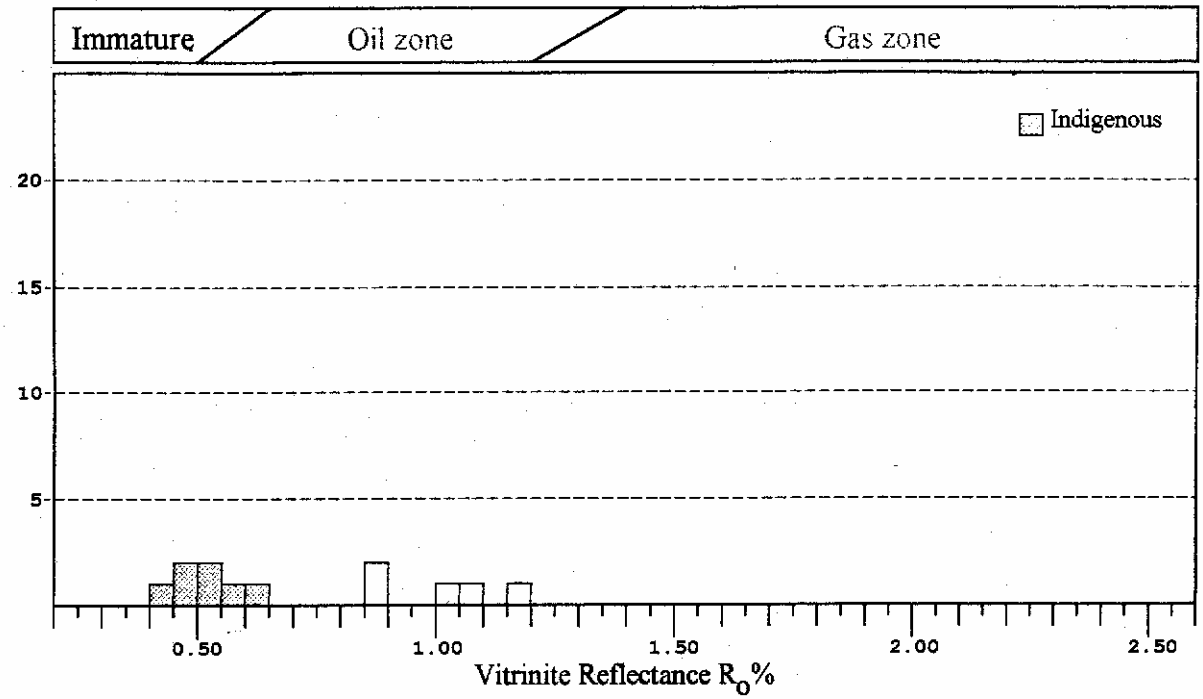
Mean: 0.49 Min: 0.44 Max: 0.56 Std. Dev.: 0.06 Count: 07

Total population statistics

Mean: 0.63 Min: 0.44 Max: 0.97 Std. Dev.: 0.19 Count: 12

Figure 7-13. Vitrinite reflectance histogram of "vitrinite-like" material from Rome Formation core at 6,375.5 ft in the Texaco 1 Tipton well, Estill Co., Ky. Thermal maturity is immature to possibly the lower oil window, with a mean R_o of 0.49. The origin of the material measured is unknown, but it is not true vitrinite due to the age of the sample. Data courtesy of USGS.

Customer: ***USGS R. RYDER***
Well name: ***TEXACO NO. 1 TIPTON***
Sample ID: ***6385***
Mean depth (ft): ***6395***
Sample type: ***CORE***



Indigenous population statistics

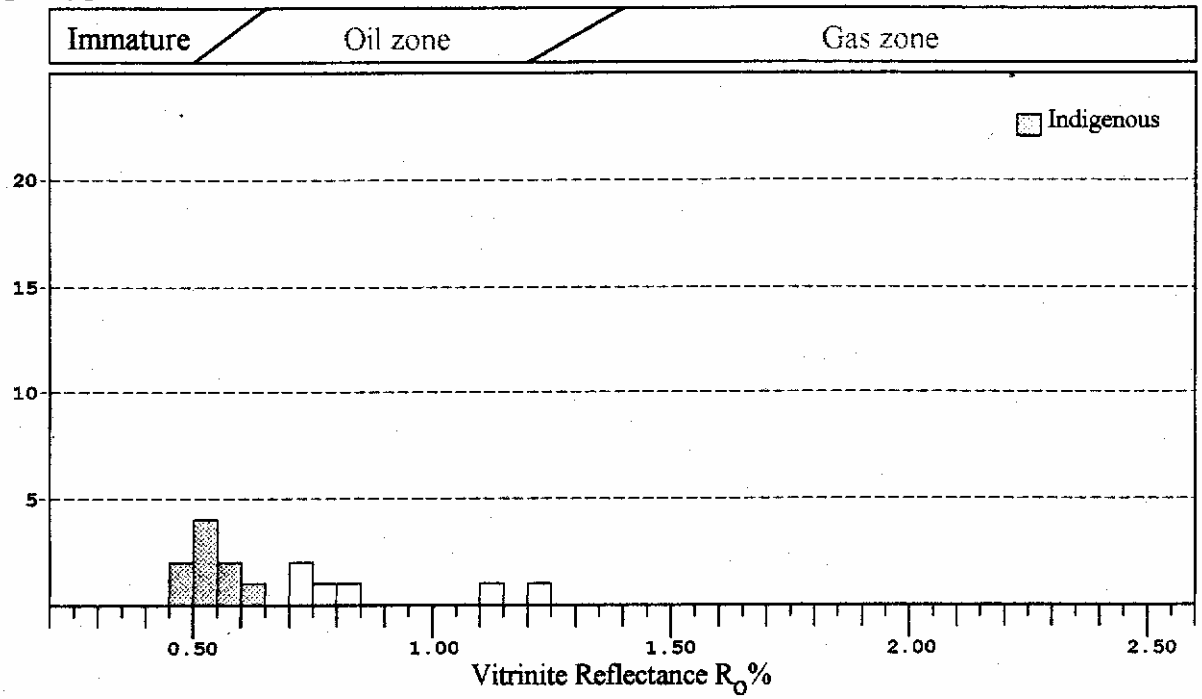
Mean: 0.51 Min: 0.44 Max: 0.60 Std. Dev.: 0.06 Count: 07

Total population statistics

Mean: 0.71 Min: 0.44 Max: 1.17 Std. Dev.: 0.27 Count: 12

Figure 7-14. Vitrinite reflectance histogram of "vitrinite-like" material from Rome Formation core at 6,395 ft in the Texaco 1 Tipton well, Estill Co., Ky. Thermal maturity is immature to possibly the lower oil window, with a mean R_o of 0.51. The origin of the material measured is unknown, but it is not true vitrinite due to the age of the sample. Data courtesy of USGS.

Customer: ***USGS R. RYDER***
Well name: ***TEXACO NO.1 TIPTON***
Sample ID: ***6389.5***
Mean depth (ft): ***6389.5***
Sample type: ***CORE***



Indigenous population statistics

Mean: 0.53 Min: 0.45 Max: 0.63 Std. Dev.: 0.06 Count: 09

Total population statistics

Mean: 0.68 Min: 0.45 Max: 1.20 Std. Dev.: 0.23 Count: 15

Figure 7-15. Vitrinite reflectance histogram of "vitrinite-like" material from Rome Formation core at 6,389.5 ft in the Texaco 1 Tipton well, Estill Co., Ky. Thermal maturity is immature to possibly the lower oil window, with a mean R_o of 0.53. The origin of the material measured is unknown, but it is not true vitrinite due to the age of the sample. Data courtesy of USGS.

Chapter 8.

Conclusions and Exploration Recommendations

D. C. Harris, Kentucky Geological Survey

Major conclusions that were listed in the introduction are repeated below. Several exploration recommendations follow the conclusions.

1. Cambrian stratigraphy has been revised in Ohio and eastern Kentucky. The Conasauga Group and its component formations have been correlated into Kentucky and Ohio. The recognition of these units allows a more accurate interpretation of the depositional history of the Rome Trough and surrounding area.

2. Stratigraphic formation tops have been collected on 761 Knox and deeper wells in the 3-state study area. These data have been compiled in a Microsoft Access database, with as many as 50 tops per well.

3. The Rome Formation is not recognized north of the bounding faults of the Rome Trough, and the use of the term Rome in northern Kentucky and Ohio (Janssens, 1973) is discouraged. While we are not formally proposing new stratigraphic nomenclature at this time, rocks previously correlated as the Rome and Conasauga Formations in north-central and northeastern Kentucky and Ohio are interpreted as Maryville Limestone, Nolichucky Shale, and Maynardville Limestone of the Consauga Group.

4. Stratigraphic correlations in the Conasauga Group have revealed the presence of a westward prograding carbonate ramp and distal intrashelf shale basin in the Rome Trough of Kentucky. The Conasauga Group formations record several cycles of progradation and transgression from east to west. These cycles correspond to cycles in the Conasauga Group and an intrashelf basin in the outcrop belt in eastern Tennessee, thus extending the mapped extent of these units.

5. Regional stratigraphic interpretations are documented in a series of 13 structural and stratigraphic cross sections. The cross sections utilize digital well log plots and lithology data calculated from the log data.

6. Stratigraphic and lithofacies interpretations are also presented in a series of 5 paleogeographic maps. These maps document the distribution of rock units and general depositional environments for 5 time intervals.

7. Cambrian cores from 19 wells were described for the study. The Consortium was able to obtain important core donations from Texaco and Exxon to greatly enhance the project.

8. Hydrocarbon reservoir development is most likely to occur in sandstones within the Rome Formation and the Maryville Limestone of the Conasauga Group. Highest potential for Rome reservoirs occurs along the Irvine-Paint Creek shelf in eastern Kentucky. Sandstones within the Maryville Limestone occur primarily in Kentucky and Ohio, with more limited distribution in West Virginia. Current gas production occurs from both the Rome Formation and Maryville Limestone in Elliott, Johnson, and Lawrence Counties, Ky. The basal Cambrian sandstones in the basin (Mt. Simon Sandstone in northern Kentucky and Ohio, and the basal sandstone in the Rome Trough) have reservoir potential but are less attractive targets due to other concerns (primarily hydrocarbon charge).

9. Porosity in Rome and Conasauga sandstones is common, and widely distributed in Kentucky and Ohio. Porosity development in sandstones is not considered a major risk factor in prospect evaluation in these areas. Permeability distribution in sandstones was not addressed in this study, but is a concern in some areas. Porosity development in Rome and Conasauga limestones and dolomites is rare, and carbonates are not considered an attractive exploration target. There is potential for fractured reservoirs, both in carbonates and shales, but this reservoir type is much higher risk. One well in Johnson County, Ky. currently produces from fractured Conasauga shale. Potential also exists for hydrothermal, fault-related dolomitization in Rome/Conasauga carbonates. However, no evidence of fault-controlled dolomitization has been seen to date in these rocks.

10. Geophysical logs from 157 wells were digitized or compiled for the project. These digital logs were used for interactive correlation and cross section construction. For the 109 wells with sufficient log curves, the digital data was used to calculate lithologies using a 4 mineral model (sandstone, limestone, dolomite, shale (and porosity). The sandstone component of the lithology data was then mapped by formation to generate sand percentage maps. These maps indicate the percentage of gross and net sandstone in the Rome and Maryville Limestone across the study area.

11. Current production from the Rome/Conasauga interval in the Rome Trough is from structural traps. These fields are fault-related, with the largest field (Homer) lying on a buried fault that was not reactivated in post-Pennsylvanian time, unlike other parts of the Kentucky River and Irvine-Paint Creek fault systems. Such buried faults have a lower risk of being breached by recurrent movement along the trapping fault than faults that have evidence of more recent reactivation (such as surface expression).

12. Detailed study of the Homer Field in Elliott County, Ky. has indicated the presence of 5 sandstone reservoir zones within the field, in the Rome, Conasauga, and Ordovician St. Peter Sandstone. Cambrian production occurs on the upthrown side of a north-south trending growth fault, on the Irvine-Paint Creek shelf. Significant facies changes occur across this fault in Cambrian and Ordovician zones. Monthly production data for the Homer Field has been compiled and provided in digital format for the years 1997 through 2000.

13. Cambrian sub-Knox hydrocarbon source rocks have been identified for the first time in the Rome Trough area. Shales with total organic carbon high enough to generate commercial amounts of hydrocarbons occur from the western end of the trough in Jessamine County, Ky. to Wayne County, W. Va. in both the Rome Formation and Conasauga Group. The Rogersville Shale of the Conasauga Group contains a significant thickness of high-TOC shales that have generated hydrocarbons. Hydrocarbon extracts from these shales are geochemically similar to produced condensate in the Homer Field in Elliott County, Ky.

14. Cambrian oil (condensate) samples from the Homer Field in Elliott County, Ky. have a geochemical signature similar to known Ordovician and Cambrian-sourced oils. While an Ordovician source cannot be ruled out, geological constraints suggest the likely source rocks occur below the Knox Group, in the Cambrian Conasauga and Rome intervals. The proximity of shales with sufficient TOC and thermal maturity to have generated hydrocarbons in the Rogersville Shale in the Exxon 1 Smith well also supports a Cambrian source for these hydrocarbons.

Exploration Recommendations

Several recommendations for continued exploration in the Rome Trough area can be made based on the results of this work.

Reservoir Trends

The Rome Formation and Maryville Limestone of the Conasauga Group contain sandstones commonly showing 6-10% porosity. Porosity development does not appear to be a risk in the high sandstone percentage areas. Two areas have the best probability for encountering porous sandstones, as shown on the sandstone percentage maps made in this study. For the Rome Formation, the structural shelf between the Kentucky River Fault System and the Irvine-Paint Creek Fault System has the highest sandstone percentages mapped. Sandstones increase toward the north against the Kentucky River Fault. This trend narrows east of the Isonville Fault, into Carter and Boyd Counties, but is still prospective. South of the Irvine-Paint Creek Fault System and in the deeper part of the Trough in West Virginia, sand quantity decreases dramatically. Reservoir risk is much higher in these areas due to lack of reservoir. Evidence for deeper water sandstones has not been seen in this study, but they cannot be ruled out.

For the Maryville interval, a north-south sandstone trend has been mapped from the Rome Trough north into Ohio. These sandstones are also porous, and have reservoir potential (and already produce in the Homer Field). An area in the center part of the Irvine-Paint Creek shelf contains both Rome and Maryville sandstone percentage highs. The stacking of good sandstone quality in this area increases the chances of multiple pays.

This study has greatly refined the stratigraphic framework of the Rome Trough, identifying areas with low sandstone potential (deeper intrashelf basins, deeper parts of the trough), and high sandstone potential. This is key data for developing prospects in this basin.

More work needs to be done to determine the controls on permeability in Rome and Conasauga sandstones. Sandstones with adequate porosity often have very low permeability. Recent dry holes drilled to Cambrian targets are thought to be unsuccessful at least partially due to low permeability. This issue was not examined in this study, and deserves more work. The known sensitivity of Rome sandstones to completion fluids (Rodvelt and others, 1999) suggests that pore-filling clay minerals may be reducing permeability in some of these sandstones, but this is speculation at this point. Thin section work on the Eastern States 34 Kazee core would be a good place to start.

Cambrian carbonates are thought to have a low potential for reservoir development. No porous carbonates were observed in this study, even in dolomitized zones. Hydrothermal; dolomites similar to those in Ordovician carbonates have not been observed. Fractured carbonates could have potential for reservoir development, but are considered high risk. Fractured Nolichucky shales produce in a well in Johnson County, Ky., but this reservoir type is also high risk. The abundance of porous sandstones at reasonable drilling depths on the Irvine-Paint Creek shelf make this the most attractive reservoir target in the Trough.

Trap Types

Structural fault traps like the Homer Field are the most likely trap style. Stratigraphic traps, while certainly possible, remain high risk due to lack of closely-spaced well control. Seismic data will be an essential tool in locating potential prospects.

Gas Quality

High amounts of nitrogen in Cambrian reservoirs and CO_2 in Ordovician reservoirs in the western end of the Rome Trough are a major exploration constraint (see Chapter 7). While the exact boundary is not known, it may be related to the Grenville Front, a basement fault zone. The distribution of this low-BTU gas needs to be considered in exploration programs.

Source Rocks

This project has identified the first good quality Cambrian hydrocarbon source rocks in the Appalachian Basin. While this reduces the risk of charging reservoirs, the volume and distribution of these source rocks is still unknown. Future work should include mapping of the high TOC rocks in the Exxon Smith well based on log character to determine their distribution. The U.S. Geological Survey is planning additional geochemical work on these source rock and hydrocarbon samples to better characterize the source material.