DEADLINE EXTENDED TO May 1, 2014

Berea Sandstone Consortium
Berea Sandstone Petroleum System—A Proposal to Understand the Distribution of Oil and Gas
Kentucky Geological Survey, University of Kentucky, Lexington

March 7, 2014

Executive Summary

Shallow horizontal drilling activity targeting the Upper Devonian Berea Sandstone has increased dramatically in the last two years in northeastern Kentucky. To better understand this new Berea oil play, the Kentucky Geological Survey, U.S. Geological Survey, and Ohio Department of Natural Resources–Division of Geological Survey are proposing a study of the Berea and related hydrocarbon source rocks in eastern Kentucky and southeastern Ohio. This project has been conceived to better understand the Berea oil play, but has broader applications in evaluating the oil and gas potential of low-maturity source rocks in other areas. Specific questions to be investigated include:

1) *Why does the Berea produce oil and gas in areas where the prospective source rocks—the over- and underlying Sunbury and Ohio Shales, respectively— are interpreted to be thermally-immature with respect to the hydrocarbon phase produced?* We will evaluate the thermal maturity, total organic carbon, and hydrocarbon generation potential of the Ohio and Sunbury Shales across the entire range of apparent thermal maturity in eastern Kentucky and immediately adjacent states.
2) *In light of questions about thermal maturity, is oil and gas produced from the Berea in northeast Kentucky sourced from shales in the immediate area, or has it migrated from deeper in the Appalachian Basin?* We will sample organic-rich shales and Berea oil and gas to geochemically tie the hydrocarbons to their source. This will also help to define the limits of the Berea source generation kitchen.
3) *How are pay zones, porosity, and permeability distributed within the Berea?* We will interpret the detailed stratigraphy and structure of the Berea in northeastern Kentucky using numerous cores, logs and outcrops to characterize the Berea in the oil producing area. This work will provide the stratigraphic and structural framework needed to successfully plan and drill horizontal wells in the Berea interval.

This project is scheduled to start on June 2, 2014 (or earlier) and last for 18 months. It will be funded by industry, with KGS providing a 20% match. Participation is open to all companies interested in the Berea play and the broader thermal maturity questions to be addressed.

Details of the proposed project are outlined in the attached proposal. The total project budget is approximately $263k, with KGS contributing approximately $56k in personnel costs. The industry share will be divided approximately evenly by the number of companies participating. We are anticipating that 8–10 companies will participate at a cost of $20–25k per company. Since we will not have an exact cost until we know the number of participants, companies electing to participate in the project should indicate the maximum amount of funds they are willing to commit to fund the work. Companies will be contacted with a final number of companies and cost after the decision deadline. **We request that companies wanting to participate reply by ~~April 11, 2014~~ EXTENDED TO MAY 1, 2014.** A project commitment form is included below. If sufficient funds are obtained, we will consider partial in-kind contributions of data or services from companies not able to fully fund the project.

Questions on the proposed project should be directed to Marty Parris or Steve Greb, principal investigators, at the Kentucky Geological Survey. Their contact information is listed below.

Thank you for your interest, and we look forward to working with you on this project.

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Kentucky Geological Survey

Berea Sandstone Consortium
Kentucky Geological Survey

Intent to Participate

Based on the proposed work plan and deliverables outlined in the project proposal dated March 7, 2014

____(company or name)

agrees to participate in the **Berea Sandstone Consortium** at a total 18-month cost not to exceed $_________________________. The final cost of the project will depend on the number of companies that participate in the project.

By:____

Position:____

Please return this form by mail, e-mail or FAX **by April 11, 2014** to:

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UK UNIVERSITY OF KENTUCKY
Kentucky Geological Survey

Berea Sandstone Petroleum System—A Proposal to Understand the Distribution of Oil and Gas

<u>Project Lead</u>
Kentucky Geological Survey, University of Kentucky, Lexington, Ky.
<u>Research Partners</u>
U.S. Geological Survey, Reston, Va.
Ohio Department of Natural Resources, Division of Geological Survey, Columbus, Ohio

INTRODUCTION

The Upper Devonian Berea Sandstone has been a major producer of natural gas and oil in eastern Kentucky for decades. As a low permeability reservoir, the Berea Sandstone was designated a tight formation in the early 1980's under the Federal Energy Regulatory Commission's Order 99 (Avila, 1983a, 1983b). Conventional vertical drilling in the Berea, primarily for natural gas, remained steady through the 1980's and 1990's. During the late 2000's horizontal drilling technology and multistage nitrogen foam fracture stimulation was used to improve Berea gas production. During this time, at least 75 horizontal wells were completed in the Berea as gas completions in Pike County, Kentucky.

The Berea produces oil or gas across much of eastern Kentucky. The Berea shows a predominance of gas production in southeast Kentucky, whereas oil production is more common in northeastern Kentucky (Fig. 1). This distribution of hydrocarbons coincides with increasing thermal maturity of the underlying Devonian Ohio Shale, a possible source rock for Berea hydrocarbons, as it becomes more deeply buried in the basin to the southeast.

Current low natural gas prices have shifted exploration focus to shallower parts of the Berea play in northeastern Kentucky, where the reservoir is more oil-prone. Since 2011, infill development with horizontal wells and multistage hydraulic fracture stimulation is resulting in Berea oil production at rates significantly higher than earlier vertical wells, and is establishing commercial oil production in formerly gas productive fields. This new Berea horizontal oil play is of significant interest to the energy industry because of shallow drilling depths (less than 1,600 ft vertical depth), good production rates, and the current price advantage of oil versus natural gas.

SCIENTIFIC SCOPE AND ISSUES

Hydrocarbon Source and Migration

The resurgence in Berea drilling has prompted researchers at the Kentucky Geologic Survey (KGS) to more closely examine the geologic development of the Berea petroleum system. This examination has revealed a number of important unanswered scientific questions related to hydrocarbon source and migration, reservoir architecture, and the distribution of reservoir porosity and permeability. Perhaps the foremost question is the source of hydrocarbons in the Berea. Understandably, the prevailing answer has been the underlying Ohio Shale (Fig. 2), which is interpreted to have sourced hydrocarbons for many petroleum systems in the Appalachian Basin (East et al., 2012 and references therein). Geochemical analysis in Ohio by Cole et al. (1987) suggests, however, that oil in the Berea was sourced from the overlying Mississippian Sunbury Shale (Fig. 2). Thus, both the Ohio and Sunbury Shales are possible sources of Berea hydrocarbons.

As noted, the change from predominantly oil (Lawrence, Boyd, and Greenup Counties) to gas (Pike, Martin, Letcher Counties) production in the Berea coincides with increasing thermal maturity in the Ohio Shale from northwest to southeast (East et al., 2012). The specific maturity level in the Ohio Shale, however, does not correlate to the hydrocarbon phase produced in the Berea. Specifically, vitrinite reflectance data show the Ohio Shale to be thermally immature (Ro < 0.6%) in areas of Berea oil and gas production and mature for oil (Ro 0.6 to 1.3%) in most areas of Berea gas production (Fig. 1). By comparison, vitrinite reflectance measurements from shallower and stratigraphically higher Pennsylvanian coal beds are about the same or higher than those for the Ohio Shale (Hower and Rimmer, 1991; Rimmer and Cantrell, 1988; Ruppert et al., 2010).

The phenomena of Pennsylvanian coals having higher vitrinite reflectance values as compared to the underlying Devonian shales has been documented elsewhere in the Appalachian Basin (Milici and Sweezy, 2006; Ryder et al., 2013). Described as a thermal maturity inversion, Ryder et al. (2013) attributed the discrepancy to mixing of reflectance measurements on solid bitumen and vitrinite.

Understanding the causal mechanism(s) for underestimating thermal maturity with vitrinite reflectance measurements and the thermal maturity inversion is critical for an accurate assessment of thermal maturity in the Ohio Shale. This is especially true in the early mature areas (Hackley et al., 2013; Ryder et al., 2013). If reflectance measurements are made on material other than vitrinite, then “suppression” is a methods and operator artifact. This is remedied by accurate recognition of vitrinite assuming it is present in sufficient quantities. However, sparse quantities of vitrinite characterize some areas of the Devonian shale in the western part of the Appalachian basin, and this presents a challenge for robust reflectance measurements (P. Hackely, personal communication). On the contrary, if vitrinite reflectance properties are truly suppressed by geologic-geochemical factors (e.g. kinetics) inherent to the Ohio Shale in early mature areas, this would necessitate use of different thermal maturity indicators. Ryder et al. (2013) and Hackley et al. (2013), using measurements such as Rock-Eval pyrolysis, gas chromatography (GC) of whole rock extracts, and GC-mass spectrometry of extract saturate fractions, observed that vitrinite reflectance tended to under-predict thermal maturity in early mature areas for the Devonian shale in the northern Appalachian basin.

Potentially less plausible is the situation in which vitrinite reflectance measurements in the Ohio Shale do accurately represent thermal maturity levels in the area of Berea production. This would suggest that hydrocarbons were either locally sourced at lower thermal maturity levels or migrated into the shallower Berea from deeper more thermally mature areas. The former scenario implies that hydrocarbons were generated under temperatures insufficient to generate vitrinite reflectance values equal to or greater than 0.6%. Meanwhile, Cole et al. (1987) argue that the presence of mature oils in many of Ohio’s reservoirs implies the migration of hydrocarbons from deeper more mature parts of the basin. Nevertheless, long distance migration in the Berea, could be problematic given the low porosity and permeability siltstone and very fine-grained sandstone that make up the reservoir (average core porosity= 13.3%, average core permeability= 2.2 md; http://kgs.uky.edu/kgsweb/Geology/presentation_detail.asp?pid=51).

Lithofacies and Reservoir Properties

Analysis of lithofacies in the Berea Sandstone and immediately underlying and interbedded Bedford Shale in outcrop and subsurface shows significant heterogeneity. Previous regional interpretations by Pepper et al. (1954), Ettensohn and Elam (1985), and Pashin and Ettensohn (1987, 1992, 1995) provide a good regional framework for Bedford-Berea deposition in eastern Kentucky. Pashin and Ettensohn modeled the Bedford-Berea as a forced regression sequence in which storm-dominated shelf facies prograded into an oxygen-deficient basin. Structural controls on some aspects of deposition were inferred. Much of their work concentrated along the outcrop margin. More work is needed, however, in understanding the lateral distribution of facies into the subsurface and within producing fields in order to determine if certain facies within the Berea are reservoirs, and for a better understanding of potential migration pathways from either overlying or underlying source rocks.

OBJECTIVES

The Kentucky Geological Survey in partnership with the U.S. Geological Survey is proposing to form a research consortium to characterize the Berea Sandstone petroleum system. The project will largely focus on the present horizontal oil and gas play in eastern Kentucky, but will potentially include adjacent parts of Ohio and West Virginia as appropriate. We envision that knowledge generated from the consortium work will provide a better understanding of the distribution of hydrocarbons in the Berea, facilitate more efficient development, and provide further insights into unconventional hydrocarbon resource characterization and assessment beyond the immediate area of the Berea play. Within the context of the questions and issues discussed in the previous section, overall goals of the project are to:

1) Evaluate total organic content (TOC), thermal maturity, and hydrocarbon potential of the Ohio and Sunbury Shales.
2) Characterize the chemistry of bitumen extracts from the Ohio and Sunbury Shales and that of Berea reservoir fluids (oil, gas and formation water), with a focus on evaluating the source and maturity levels of hydrocarbons in the Berea.
3) Interpret Berea structure and detailed stratigraphy using data from Berea cores and outcrops, with the goal of better understanding the reservoir architecture, and distribution of porosity and permeability in the producing area.
4) Interpret influence of thermal maturity and permeability on the production and distribution of oil and gas in the Berea. The extent of this effort will depend on availability of appropriate data sets, and sufficient funding to contract with outside reservoir engineering expertise.

RESEARCH STRATEGY AND STUDY AREA

To achieve the first two goals, the work plan will involve the systematic collection of cuttings and core samples from the Ohio and Sunbury Shales; and oil, gas, and formation water samples from the Berea Sandstone along an approximately 100-mile transect extending from Greenup County in the north to Pike County in the southeast (Fig. 1). The northwest-southeast transect runs orthogonal to thermal maturity isolines defined by East et al. (2012), who mapped vitrinite reflectance and conodont alteration indices for Devonian shale in the Appalachian basin (Fig. 1). The transect thus provides the opportunity to collect samples ranging from early mature in the north to gas mature in the south. Moreover, the transect provides the opportunity to collect a range of oil, gas, and formation water samples in close proximity to the core and cuttings samples.

Analysis for this proposal shows that cores from the Berea Sandstone, and Ohio and Sunbury Shales are available in parts of the study area in eastern Kentucky and southern Ohio (Fig. 3, Table 1). For areas lacking core the KGS database shows available cuttings from some 663 oil and gas wells distributed among counties in and near the study area. The robust sample availability should mitigate contamination issues associated with analysis of cuttings. Where possible, we will strive to collect samples that allow us to leverage previous work in Kentucky and adjacent areas in neighboring states (e.g., East et al., 2012; Rimmer et al., 1993; Ryder et al., 2013).

For the stratigraphic and reservoir analysis, the study will cover the aforementioned area, but will also extend west to the Berea Sandstone and Bedford Shale outcrops in Lewis, Rowan, and Bath Counties (Fig. 3). This will allow integration of outcrop data, and numerous shallow continuous cores of the Sunbury, Ohio, and Bedford Shales, and the Berea Sandstone. While no Berea cores exist in the adjacent counties of West Virginia, Berea data from the recently completed Appalachian Basin Tight Gas Reservoirs Project by the West Virginia Geological and Economic Survey will be incorporated (http://www.wvgs.wvnet.edu/atg).

SCOPE OF WORK

As stated above, the goals will be achieved through measurements and analysis detailed in the following tasks.

Task 1.0 Assess TOC, Thermal Maturity, and Hydrocarbon Potential

Task 1.1—Compile existing vitrinite reflectance, Rock-Eval pyrolysis, and TOC data for the Sunbury and Ohio Shales in and near the study area. The compilation will serve to identify spatial and stratigraphic gaps in reflectance data and guide collection of new samples. Work to be done by KGS and USGS.

Task 1.2—Collect core and cuttings samples for Rock-Eval pyrolysis, TOC measurements, and reflectance measurements for the Sunbury and Ohio Shales. This work will provide samples for up to 10 wells with 10 to 15 samples per well. The strategy will allow us to characterize the variation in TOC content, thermal maturity, and hydrocarbon potential along the aforementioned northwest-southeast transect. Work to be done by KGS.

Task 1.3—Conduct Rock-Eval pyrolysis, TOC measurements, and reflectance measurements on samples from Task 1.2. In addition to the reflectance measurements, thermal maturity assessment will include spectral fluorescence analysis of *Tasmanites* (Ryder et al., 2013). Work to be done by KGS, USGS, and an outside lab.

Task 1.4—Assess thermal maturity and TOC measurements from Task 1.3 and integrate with published data. Important analysis will include comparison of pyrolysis results (S2 output, Tmax) with reflectance measurements. Work by Hackley et al. (2013) on Devonian shales in the northern Appalachian basin showed that Tmax values often showed higher thermal maturity as compared to reflectance measurements. The work will also provide the opportunity to compare reflectance measurements between KGS and USGS laboratories to assess consistency (i.e. precision) of measurements and the possible influence of mixed vitrinite and bitumen populations on the global reflectance measurements. Lastly, the Rock-Eval, TOC, and reflectance measurements and their variation in the study area will be used as guide for selecting samples in Task 2.0. Work to be done by KGS and USGS.

The measurements and analyses from Task 1.0 are anticipated to provide the following deliverables:

- Database of reflectance measurements for the Ohio and Sunbury Shales, which will include new measurements.
- TOC measurements will characterize the range of organic content in the Sunbury and Ohio Shales. Rock-Eval pyrolysis will characterize the types of organic matter, thermal maturity (Tmax), and production index. Moreover, the Rock-Eval measurements will provide a measure of thermal maturity to which reflectance measurements can be compared and assessed.
- Refined thermal maturity map for eastern Kentucky and adjacent areas, reflecting the information gained from the above measurements and analyses.

Task 2.0 Extract Analysis, Oil-Source Rock Correlation, and Reservoir Geochemistry

Task 2.1—Use thermal maturity and TOC results from Task 1.0 as a guide to sample and measure the bulk, isotopic, and biomarker composition of bitumen extracts in the Sunbury and Ohio Shales. Collect Berea oil samples in close proximity to some of the bitumen samples for similar measurements. Sample selection will be based on quality, quantity, thermal maturity, and stratigraphic and geographic location. It is anticipated that five extracts from up to six wells will be characterized while oil samples will be collected from six wells. Work to be done by KGS.

Task 2.2—Liquid chromatography measurements on extracts from ground shale samples and Berea oils to analyze for saturated, aromatic, and resin hydrocarbon fractions. Work to be done by an outside lab on samples collected in Task 2.1.

Task 2.3—Gas chromatography measurements on whole extracts and Berea oils to provide isoprenoid and *n*-alkane composition, which can be compared to assess source. Moreover, ratios of Pr/*n*-C17, Ph/*n*-C18, and total isoprenoid/*n*-alkanes may be used to assess thermal maturity (e.g., Hackley et al. 2103). Work to be done by an outside lab on samples collected in Task 2.1.

Task 2.4—Gas chromatography-mass spectrometry measurements on saturated and aromatic fractions in the bitumen extracts and oils to characterize biomarker compounds. The biomarker analysis provides the opportunity to assess maturity and oil-source rock correlation where processes, such as migration and change in oil composition during generation, have affected bulk oil composition (Hunt, 1996). Work to be done by an outside lab on samples collected in Task 2.1.

Task 2.5—Stable carbon isotope ($\delta^{13}C$) composition measurements on saturated and aromatic fractions in the bitumen extracts and oils. These measurements, along with the biomarker characterization, provide the opportunity to evaluate source rock-oil correlation (e.g., Ryder et al., 1998). Work to be done by an outside lab on samples collected in Task 2.1.

Task 2.6—Collect gas and formation water samples coincident with or near wells from which previous thermal maturity and extract geochemical characterization was done. The distribution of oil and gas completions shows that, notwithstanding recent oil completions, gas is the dominant hydrocarbon phase produced from the Berea (Figure 1). Consequently, characterization of gas chemistry will be important in assessing gas source and maturity. It is anticipated that formation waters and gas samples will each be collected from up to eight wells. Work to be done by KGS.

Task 2.7—Measure bulk and isotopic chemistry of natural gas (associated or non-associated). Characterization will include measurement of bulk chemistry of hydrocarbon gases (methane (C1) through hexane (C6)) and non-hydrocarbon gases, such as carbon dioxide, nitrogen, argon, and helium. The carbon ($\delta^{13}C$) and hydrogen (δD) isotopic composition will be measured on methane and potentially some of the higher molecular weight hydrocarbon gases. Isotopes will also be measured on carbon dioxide ($\delta^{13}C$, $\delta^{18}O$) and nitrogen ($\delta^{15}N$). Isotopic measurements have been used effectively to demonstrate origin of methane where $\delta^{13}C$ and δD values are a function of maturity and source composition (Schoell 1980, 1983). Carbon isotopic measurements on the higher molecular weight hydrocarbons (propane, iso-butane, and n-butane) have proved to be effective at assessing maturity, gas-source rock, and gas-gas correlations (James 1983, 1990). Work to be done by Isotech or an outside lab.

Task 2.8—Measure formation water bulk and isotopic chemistry including $\delta^{18}O$-H_2O, δD-H_2O, $\delta^{34}S$-SO_4, and $\delta^{13}C$-DIC. Formation water chemistry has been used to infer flow paths from up-dip recharge zones and nutrient sources, and, along with gas chemistry, document biogenic gas in Devonian shales (e.g., Osborne and McIntosh, 2010). The bulk chemistry data will fill critical gaps in the KGS formation water database for Devonian-Mississippian reservoirs. Water chemistry data in the brine database is used to examine basin hydrostratigraphy, reservoir compartmentalization, and wellbore integrity. Berea formation water chemistry could also be used to assess provenance of contamination in the event of out-of-zone leakage associated with fracking or improperly completed or plugged wells. Bulk chemistry work to be done at KGS and isotope chemistry at Isotech. Possible $^{87}Sr/^{86}Sr$, boron, and radium isotope measurements to be done at USGS (El Paso).

Task 2.9—Integrate and interpret geochemical data from Ohio and Sunbury Shale bitumen extracts and Berea oil, gas, and formation waters. Work to be done by KGS and USGS.

Measurements and analyses from Task 2.0 are anticipated to provide the following deliverables:

- Bulk and stable carbon isotopic composition of aromatic and saturated fractions in Ohio and Sunbury Shale bitumen extracts and Berea oils. Characterization of biomarker compounds in the extracts and oils.
- Interpretation of oil-source rock correlation and thermal maturity using extract and oil measurements.
- Bulk chemical and isotopic composition of Berea natural gas and formation water. Assessment of thermal maturity and gas provenance.

- Interpretation and summary of Berea oil, gas, and formation water geochemistry within the context of thermal maturity (Task 1.0) and stratigraphic and reservoir (Task 3.0) analyses.
- Geochemical analyses to be performed for oil, gas and brine samples:

Task and Analysis	Quantity
2.2 Extract preparation	30
2.2. Liquid chromatography bitumen extracts	30
2.2. Liquid chromatography oils	6
2.3 Gas chromatography extracts	30
2.3 Gas chromatography oils	6
2.4. Gas chromatography –mass spec extracts	30
2.4. Gas chromatography –mass spec oils	6
2.5. $d^{13}C$ IRMS Extracts	30
2.5. $d^{13}C$ IRMS Oils	6
2.7 Gas chromatography and IRMS natural gas	8
2.7 $d^{13}C$-CO_2 natural gas	8
2.7 $d^{15}N$-N_2 natural gas	8
2.8 Bulk water chemistry	8
2.8 $d^{18}O$ & dD-H_2O brine	8
2.8 $d^{13}C$-DIC brine	8
2.8 $d^{34}S$ & $d^{18}O$-SO_4 brine	8

Task 3.0 Berea Structure, Sequence Stratigraphy, Core and Outcrop Interpretation

As previously stated, there is a good regional framework for the Bedford-Berea succession in southern Ohio and eastern Kentucky (Pashin and Ettensohn, 1987, 1992, 1995). Much of the existing work, however, has been concentrated along the outcrop margin. More detailed subsurface interpretation of the Berea in northeastern Kentucky is lacking, and this work would focus on interpreting the detailed internal stratigraphy of the Berea with the goal of gaining a better understanding of the lateral reservoir continuity and heterogeneity, distribution of porosity and permeability, and lithologic controls on fluid saturations and hydrocarbon distribution. These will be key factors in designing and drilling successful horizontal wells in the Berea. The goals within Task 3.0 will be accomplished with work in the following subtasks:

Task 3.1. Maps and cross-sections: log cross sections, and structure and isopach maps will be constructed to better define the structural and stratigraphic controls on Berea oil production. Maps and cross sections will be extended to the Berea outcrop belt to the west in order to tie into key outcrops. We will attempt to make detailed correlations within the Berea within a sequence stratigraphic framework. This will allow a more predictive model of Berea deposition to be interpreted, and may help to define the play limits.

Task 3.2. Core Interpretation: cores from the Lawrence-Martin-Johnson County producing area and shallow cores near the Berea outcrop belt will be described to provide key stratigraphic data to develop the sequence stratigraphic framework, and characterize the Berea reservoirs. KGS has nine Berea cores from the Lawrence, Johnson, and Martin County producing area (Fig. 3). No Berea cores are available in Greenup or Boyd Counties. To the west, in Lewis, Fleming, Bath and Rowan Counties, KGS has 16 shallow continuous cores through the Sunbury, Berea or Bedford, and Ohio Shale. These cores were part of a large oil shale resource assessment in the 1980's. These core holes were logged, and these logs will help to calibrate log response in deeper subsurface areas.

At least 14 cores of the Berea-Bedford interval are available at the Ohio Geological Survey (Fig. 3). Most of these cores are located along the Berea-Bedford outcrop trend in Adams and Scioto Counties, but four Berea cores occur farther east in eastern Scioto and Lawrence Counties. These are the closest Berea cores to the Greenup County horizontal production. Core included in the study will be photographed for reference. Where core analysis data is available (porosity/permeability), it will be plotted with the core descriptions. Cores selected for use in the project are listed in Table 1.

Task 3.3. Berea Outcrop Characterization: There are several extensive outcrops of the Berea in Lewis County, Ky. These exposures will be documented and photographed to provide reservoir-scale analogs to producing horizons in the subsurface. There are also outcrops in adjacent counties in Ohio that will be examined. The outcrop data will be correlated with the nearby shallow continuous cores to interpret sand continuity and geometry. After the outcrops have been described KGS plans to run a field trip for the project participants.

The measurements and analyses from Task 3.0 are anticipated to provide the following deliverables:

- Structure and isopach maps for the Sunbury, Berea/Bedford, and Ohio Shale
- Log cross-sections with structural and stratigraphic datums
- Core descriptions, interpretation, and photographs
- Outcrop sections and high-resolution photographs
- Field trip for project participants after outcrop work is completed

Task 4.0 Controls on Berea Permeability, Fluid Distribution, and Reservoir Models

Horizontal Berea wells that primarily produce oil in Lawrence County, and to a lesser extent Greenup County, are being drilled and completed as infill wells among older vertical wells that predominantly produced natural gas. Thus, the horizontal wells and/or production over time appear to have changed the relative permeability of oil versus gas in the reservoir, thereby decreasing the gas-oil ratio. Controls on gas, oil, and water saturation in the Berea horizontal play are not well-understood. Gaining a better understanding of fluid saturations and relative permeability in the Berea would require additional measurements and reservoir engineering expertise not available at KGS. If the topic is deemed sufficiently important by the consortium partners and funding is obtained, KGS would like to acquire data to better understand fluid behavior in the Berea reservoir. Potential data would include mercury injection/capillary pressure (MICP), and relative permeability measurements. KGS would also contract with a reservoir engineer to help interpret the data. In addition, actual reservoir data, from industry participants, (pressure, production volumes, and saturations) would improve this effort.

Though no specific tasks have been defined, it is anticipated that the measurements and analysis briefly discussed above could yield the following:

- An understanding of lithostratigraphic control on relative permeability and MICP properties.
- The relative permeability influence on hydrocarbon migration and distribution in the reservoir.
- A possible reservoir model with best practices for resource development in the Berea.

RESEARCH STAFF

The research will be conducted by a multi-disciplinary team of geologists and geochemists at the KGS, USGS, and the Ohio Geological Survey (Ohio Department of Natural Resources). The project will headed by co-principal investigators Steve Greb and Marty Parris at KGS. Investigator Greb brings expertise in clastic sedimentology and stratigraphy, while investigator Parris has experience in aqueous and organic geochemistry, and reservoir diagenesis. Cortland Eble (KGS) is an organic petrologist who will be responsible for analysis of organic-rich shales and thermal maturity measurements. Investigator Eble will work closely with Paul Hackley of the USGS in Reston, Va. Investigator Hackley is also an organic petrologist who will work on thermal maturity and attempt to geochemically match the oil with source rocks in the area. The Ohio Geological Survey will participate in the project, with their role determined by the level of funding obtained. Ron Riley will be the lead geologist for OGS. The Ohio Survey will provide digital logs, access to cores and well cuttings, and Berea porosity and permeability data from Ohio wells. With sufficient funding, OGS will provide spectral gamma ray scanning of cores, interpret additional stratigraphic data for Ohio wells, and integrate various analytical resources from the Ohio State University SEMCAL lab (www.earthsciences.osu.edu/semcal/).

Other KGS staff possibly involved in the project include Dave Harris, Tom Sparks, Brandon Nuttall, and Rick Bowersox.

LENGTH OF STUDY

The project will require approximately 18 months to complete. There will be interim deliverables at 6 and 12 months, with the final report to be completed at 18 months. Priorities for the interim deliverables will be set by project participants. KGS hopes to begin the study by June 2, 2014, and complete the work by December 1, 2015. A field trip will be offered for participants in the fall of 2014, after outcrop work is completed.

FUNDING AND BUDGET

Based on the previously described tasks, the estimated total project cost is $263,729, with KGS contributing one-half of the personnel cost (approximately $56k). Industry share of the project cost will be divided evenly by the number of companies participating. We are anticipating that 8-12 companies will participate at a cost of $20-25k per company. Since we will not have an exact cost until we know the number of participants, companies electing to participate in the project should indicate the maximum amount of funds they are willing to commit to fund the work. Companies will be contacted with a final number of companies and cost after the decision deadline. **We request that companies wanting to participate reply by April 11, 2014 (see response form in executive summary).** Project costs include personnel and laboratory analyses for shale, formation water, oil, and gas samples. Travel costs are for field work, sampling, and meetings.

Berea Consortium Budget			
	Industry Share	**KGS Share**	**Project Total**
Personnel	$37,664	$37,664	$75,327
Direct Costs			
Task 1	$8,500		$8,500
Task 2	$72,596		$72,596
Task 3	$8,902		$8,902
Reporting	$2,060		$2,060
Travel	$8,434		$8,434
UK F&A Cost	$69,078	$18,832	$87,910
Total	**$207,233**	**$56,496**	**$263,729**
KGS Cost Share		**21%**	

DATA CONFIDENTIALITY

KGS is part of the University of Kentucky, and as a public agency cannot perform confidential research. Data and interpretations must eventually be shared with the public. However, data and results from this project will not be released outside the consortium until formal KGS publications are completed. The publication of results may take up to a year after the end of the project. During this time consortium members will have exclusive use of the project results.

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Avila, J., 1983a, Area requested for tight formation designation in the Berea Sandstone, Pike County, Kentucky: Kentucky Geological Survey, Series 11, Open-file Report 83-0001, 100 p.

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Call	County	State	Recno	Operator	Farm Name	Well No.	Formation Cored
1546	Bath	KY		KGS_IMMR		D-4	SNBR-BDFD-OHIO
1544	Bath	KY		KGS_IMMR		D-2	SNBR-BDFD-OHIO
1545	Bath	KY		KGS_IMMR		D-3	SNBR-BDFD-OHIO
5671	Fleming	KY		KGS_IMMR		KEP-6	SNBR-BDFD-OHIO
5665	Fleming	KY		KGS_IMMR		KEP-4	SNBR-BREA-BDFD-OHIO
5673	Fleming	KY		KGS_IMMR		D-11	SNBR-BDFD-OHIO
812	Fleming	KY		KGS_IMMR		KEP-7	SNBR-BDFD-OHIO
811	Fleming	KY		KGS_IMMR		KEP-5	SNBR-BDFD-OHIO
1186	Johnson	KY	42373	Ashland Oil	Kelly-Watt-Bailey-Skaggs	KY-4	BREA-OHIO
821	Johnson	KY	43581	Ashland Oil	Wright-Ramey	1R	SNBR-BEREA
859	Johnson	KY	45797	Gillespie, G. M.	Bailey, Lowell	1	BEREA
5691	Lawrence	KY	11647	Ashland Expl	H. Neal	1	BEREA
5906	Lawrence	KY	101940	Columbia Nat Res	Simpson	20505	BEREA
270	Lawrence	KY	52302	Ky. West Va. Gas	Moore, Ruben	1087	BEREA
268	Lawrence	KY	37673	Ky. West Va. Gas	Moore, Milton	1122	SNBR-BEREA
5668	Letcher	KY	133365	Equitable Production	Equitable Production	566765	OHIO
6387	Lewis	KY		KGS-IMMR		KEP-3	SNBR-BREA-BDFD-OHIO
813	Lewis	KY		KGS-IMMR		KEP-8	SNBR-BREA-BDFD-OHIO
814	Lewis	KY		KGS-IMMR		KEP-9	SNBR-BREA-BDFD-OHIO
6386	Lewis	KY		KGS-IMMR	Charters	KEP-2	SNBR-BREA-BDFD-OHIO
5907	Martin	KY	66348	Columbia Nat Res	Pocahontas Land	20456	BREA-OHIO
1308	Martin	KY	87271	Columbia Nat Res	Pocahontas Dev Corp	21738	OHIO
1185	Martin	KY	65593	ERDA-Columbia Gas	Columbia Gas Trans	20336	BDFD-OHIO
1548	Montgomery	KY		KGS-IMMR		D-6	SNBR-BDFD-OHIO
1547	Montgomery	KY		KGS-IMMR		D-5	SNBR-BDFD-OHIO
5669	Perry	KY	134913	Equitable Production	Equitable Production	567319	OHIO
NEW	Pike	KY	137835	Equitable Production	Equitable Production	504353	OHIO
1257	Pike	KY	103897	Ashland Oil	Ford Motor Co.	69	OHIO
1258	Pike	KY	104995	Reuben L Graham	Ford Motor Co.	78	OHIO
1543	Rowan	KY		KGS-IMMR		D-1	SNBR-BDFD-OHIO
171	Rowan	KY	72660	KGS-USGS	Ellington, R. B	1	OHIO
3254	Adams	OH			G Thompson	HE-1	OHIO
2718	Adams	OH		Phillips Pet Co	J Knauff	OHAM-1	OHIO
2719	Adams	OH		Phillips Pet Co	Burlin Justice	OHAM-2	OHIO
3375	Lawrence	OH		Mitchell Energy		1	SNBR-BREA-BDFD-OHIO
3377	Lawrence	OH		Mitchell Energy		3	SNBR-BREA-BDFD-OHIO
3409	Scioto	OH		Aristech Chemical	Aristech Chemical	4	SNBR-BREA-BDFD-OHIO
2959	Scioto	OH		Continental Oil Co.	Dever Walter	1	BEREA
2813	Scioto	OH		Phillips Pet Co	R Moore	OHSO-1	SNBR-BREA-BDFD-OHIO
2814	Scioto	OH		Phillips Pet Co	C Ross	OHSO-2	SNBR-BREA-BDFD-OHIO
2816	Scioto	OH		Phillips Pet Co	D Metzger	OHSO-4	SNBR-BREA-BDFD-OHIO
2817	Scioto	OH		Phillips Pet Co	J Detwiller	OHSO-5	SNBR-BREA-BDFD-OHIO
2815	Scioto	OH		Phillips Pet Co	F Book	OHSO-3	OHIO
2818	Scioto	OH		Phillips Pet Co	H Hoffer	OHSO-6	BDFD-OHIO
3078	Scioto	OH		Rumpke	Rumpke Landfill	B-1	SNBR-BREA-BDFD-OHIO

Table 1. Pertinent Berea and related shale cores in Kentucky and Ohio.

Berea Study Area and Production Map

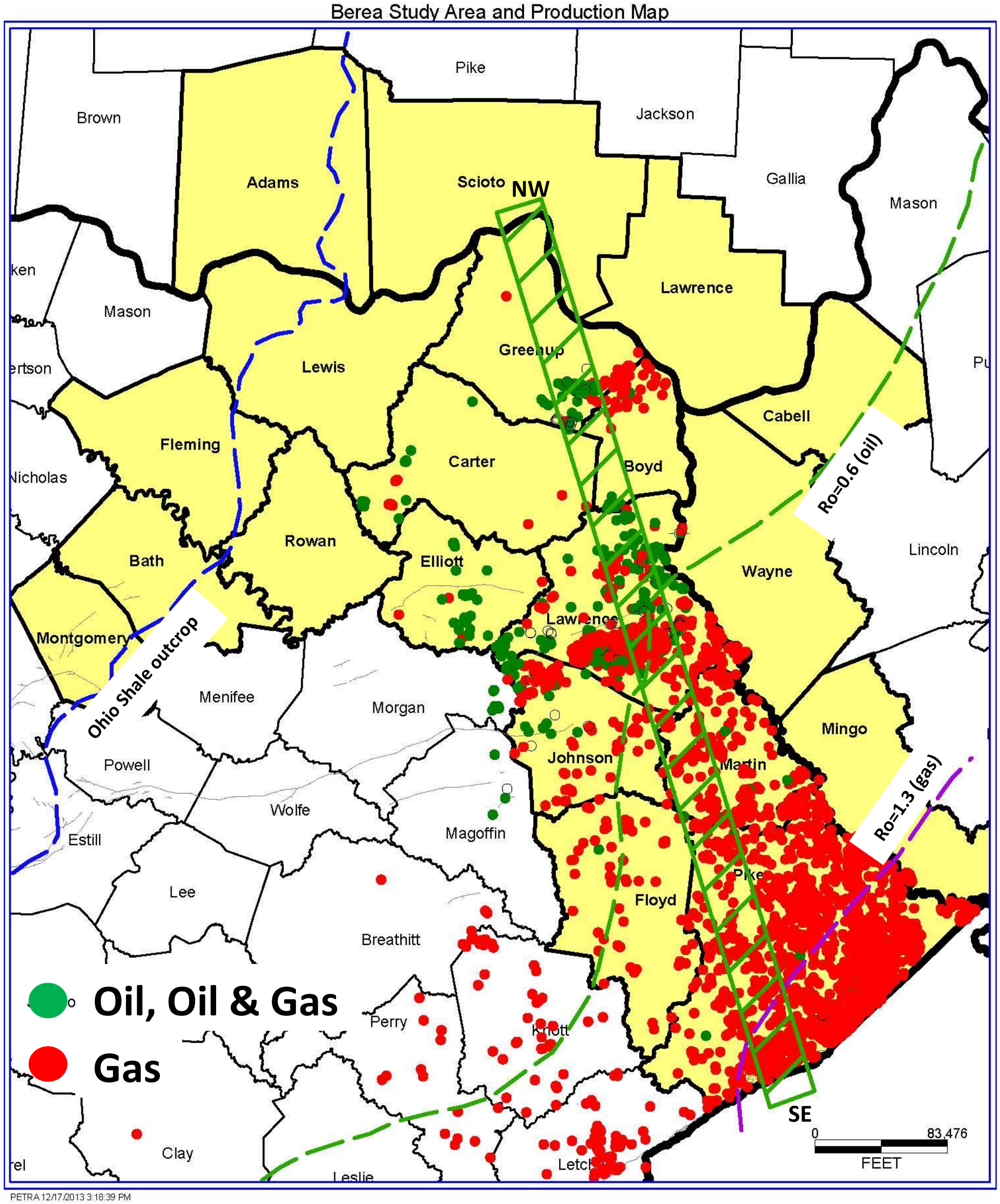

Fig. 1. Study area (yellow counties) and geographic distribution of Berea oil and gas completions in eastern Kentucky (2,778 wells). Oil production occurs predominantly in northeastern Kentucky, where maturity of the underlying Ohio Shale is lower, while gas production occurs primarily to the southeast. Green dashed line is the vitrinite reflectance isoline where Ro = 0.6% (western edge of oil window), and purple dashed line is Ro = 1.3% (western edge of gas window), from East and others (2012). Green hatched box is approximate location of thermal maturity sampling transect.

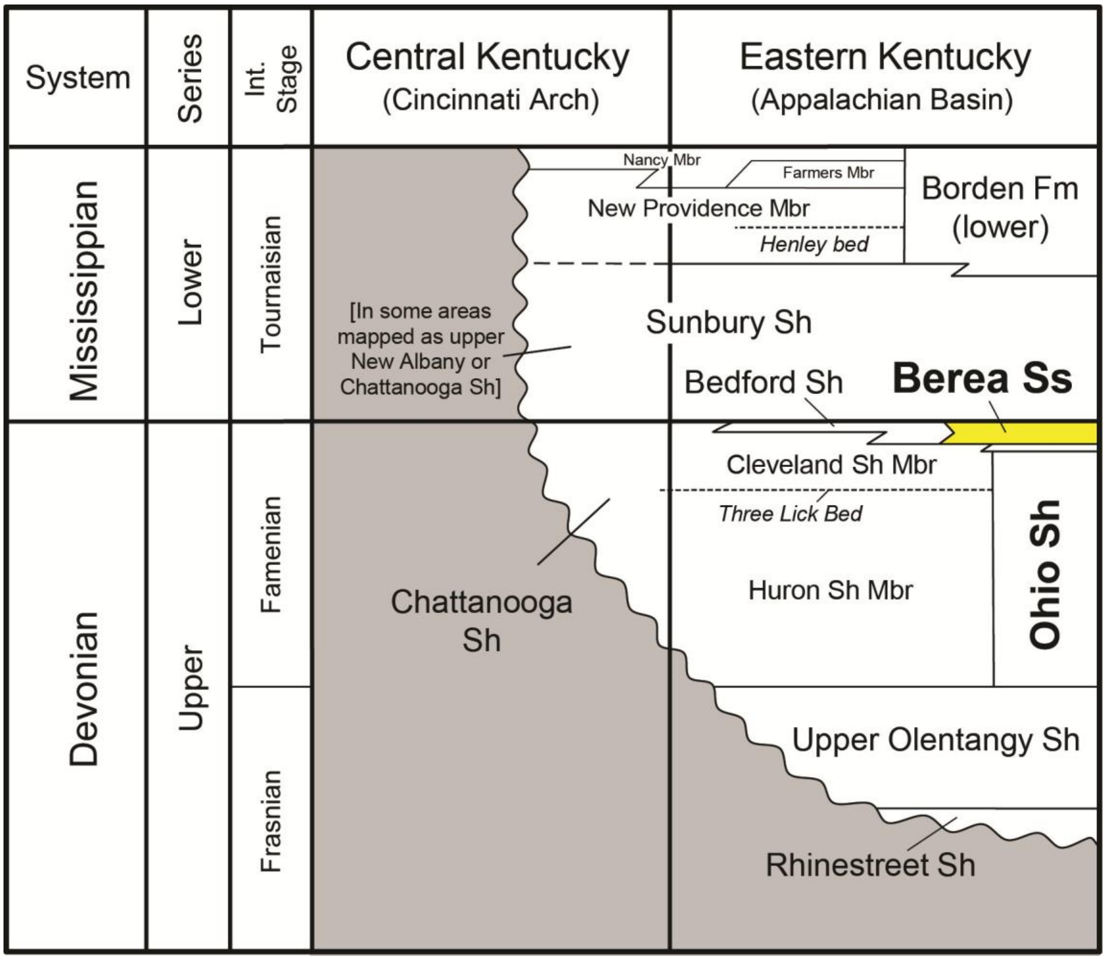

Figure 2. Stratigraphic correlation chart for Upper Devonian and Lower Mississippian units.

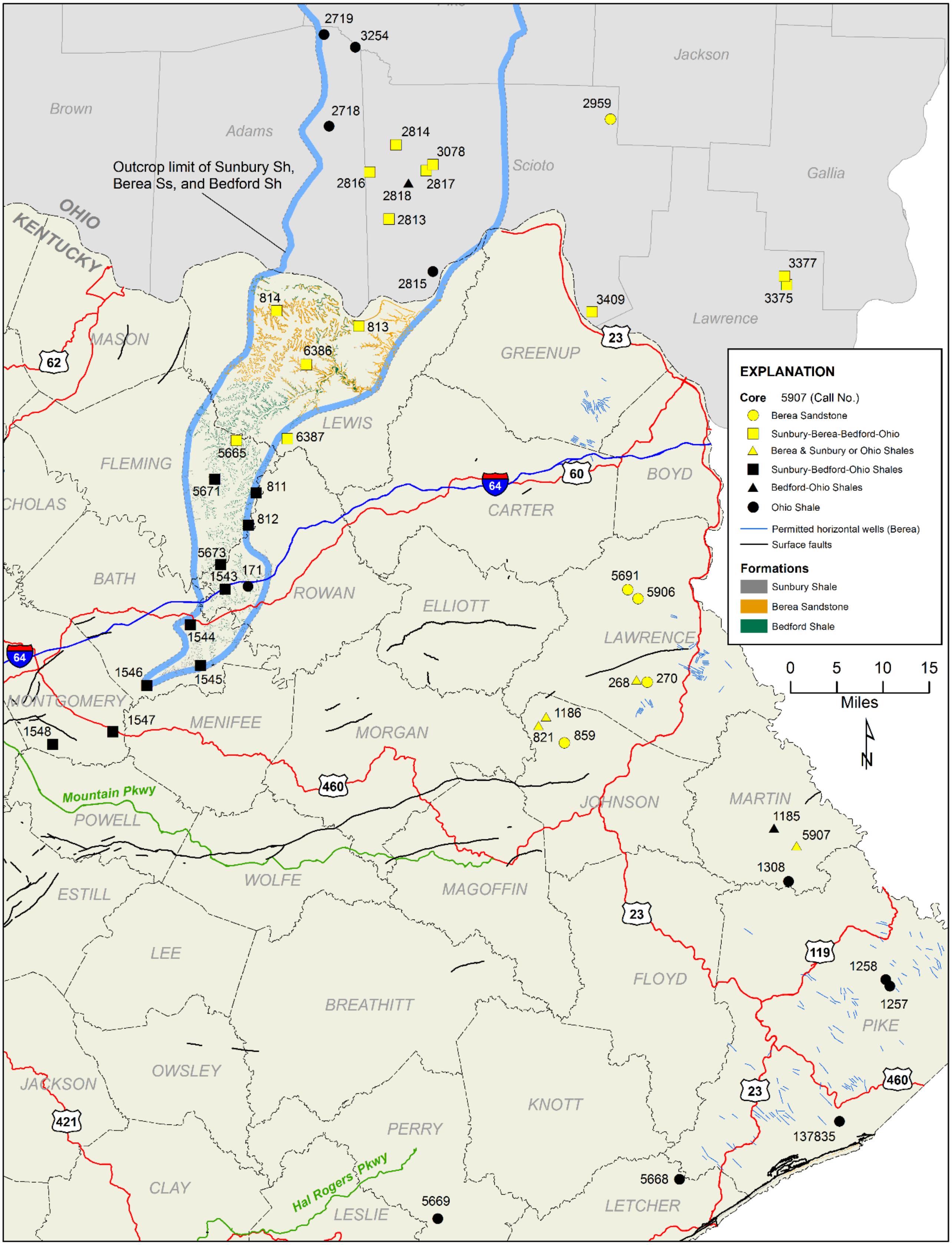

Fig. 3. Locations of cores to be included in the Berea project. Core locations are coded by the stratigraphic interval present. Locations of permitted horizontal wells in the Berea and Ohio Shale are shown by thin blue lines.