

**GEOLOGIC CHARACTERIZATION AND CARBON STORAGE
RESOURCE ESTIMATES FOR THE KNOX GROUP, ILLINOIS BASIN,
ILLINOIS, INDIANA, AND KENTUCKY**

Part 1. Regional Stratigraphic Correlations
Part 2. Knox Lithofacies and Core Descriptions, Western Kentucky
Part 3. Knox Carbon Storage Resource Estimates for the Illinois Basin

Topical Report

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An Evaluation of the Carbon Sequestration Potential of the Cambro-
Ordovician Strata of the Illinois and Michigan Basins

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Abstract

Research documented in this report includes (1) refinement and standardization of regional stratigraphy across the 3-state study area in Illinois, Indiana, and Kentucky, (2) detailed core description and sedimentological interpretation of Knox cores from five wells in western Kentucky, and (3) a detailed calculation of carbon storage volumetrics for the Knox using three different methodologies.

Seven regional cross sections document Knox formation distribution and thickness. Uniform stratigraphic nomenclature for all three states helps to resolve state-to-state differences that previously made it difficult to evaluate the Knox on a basin-wide scale. Correlations have also refined the interpretation of an important sandstone reservoir interval in southern Indiana and western Kentucky. This sandstone, a CO₂ injection zone in the KGS 1 Blan well, is correlated with the New Richmond Sandstone of Illinois. This sandstone is over 350 ft (107 m) thick in parts of southern Indiana. It has excellent porosity and permeability at sufficient depths, and provides an additional sequestration target in the Knox. The New Richmond sandstone interval has higher predictability than vuggy and fractured carbonates, and will be easier to model and monitor CO₂ movement after injection.

Cores from five wells in western Kentucky were described to allow interpretation of depositional facies and the control of depositional facies on reservoir properties. Knox lithofacies include stromatolite and thrombolite dolomite boundstones, skeletal/peloidal dolomite grainstone, dolomite mudstone, intraclast breccia/conglomerate, paleokarst breccia, and quartz sandstone. These lithofacies represent deposition in shallow subtidal to restricted intertidal/supratidal environments, and are remarkably similar across western Kentucky. Knox carbonates and sandstones were deposited on a broad restricted shelf with little facies variation prior to development of the present day Illinois Basin. Core analyses from three cores were classified by lithofacies to determine if primary depositional facies is correlated to reservoir quality. Quartz sandstones in the KGS 1 Blan well have the best reservoir properties of any lithofacies, averaging 8.8 percent porosity and 194 millidarcies permeability. Dolomite lithofacies vary in average porosity and permeability, but there is significant variability within a given lithofacies. Grainstones and breccias have the best dolomite reservoir properties, and dolomite mudstones have the lowest.

Geologic characterization of Cambrian-Ordovician Knox Group carbonates and sandstones has provided data necessary to calculate carbon dioxide (CO₂) storage resource estimates. Multiple deterministic-based approaches were used in conjunction with the probabilistic-based storage efficiency factors

published in the DOE methodology to estimate the carbon storage resource of the Knox Group. Results demonstrate how the range in uncertainty of storage resource estimates varies as a function of data availability and quality, and the underlying assumptions used in the different approaches. In the simplest approach, storage resource estimates were calculated from mapping the gross thickness of the formation and applying a single best estimate of the effective mean porosity of the formation. Results from this approach led to storage resource estimates ranging from 27 to 232 Gt at the P10 and P90 probability level, respectively. The second approach considered the depositional variation within the Knox Group by constructing a three-part subdivision based on the new analysis of clastic intervals and extensive picks of the lower Knox unit correlating to the Potosi Fm. Considering the variable thickness and effective porosity of each subunit resulted in very similar total storage resource estimates of 27 to 236 Gt. The storage estimates for each subunit were 13 to 144 Gt for the upper Knox unit, 1 to 11 Gt for the clastic unit, and 13 to 111 Gt for the lower Knox unit. The third approach attempted to account for the local-scale variability in reservoir quality as a function of both porosity and permeability by using core and log analyses to calculate explicitly the net effective porosity at multiple well locations, and interpolate those results throughout the basin domain. This approach resulted in significantly larger storage resource estimates of 448 to 728 Gt. The observed variability in results from the three different approaches is evaluated in the context of data and methodological constraints, leading to the conclusion that the storage resource estimates from the first two approaches are conservative, whereas the net porosity based approach may over-estimate the resource. Additionally, we calculated a hypothetical case of storage in cavernous porosity of the Lower Knox unit as 1 to 16 Gt based on idealized properties. This result indicates that the Knox Group may have high-quality reservoir intervals of either cavernous zones or clastic intervals that are of similar magnitude across the basin.

Executive Summary

This topical report documents work done by the Indiana and Kentucky Geological Surveys on regional characterization and carbon storage capacity calculations for the Knox Group in the Illinois Basin. The study area covers parts of Illinois, Indiana, and western Kentucky, where the Knox is at depths sufficient for supercritical phase carbon dioxide storage. Dolomite and sandstone intervals in the Knox have suitable reservoir properties for injection of CO₂, and provide potential carbon storage zones in areas where the Cambrian Mt. Simon Sandstone is absent, too deep, or lacks porosity.

Part 1, *Regional Stratigraphic Correlations*, documents regional Knox Group stratigraphy for the Illinois Basin in a series of well log cross sections. Existing Knox stratigraphic nomenclature has varied from state to state. This research has used a consistent stratigraphic framework for Illinois, Indiana and Kentucky to better evaluate the distribution of potential storage zones in the Knox. In particular, a thick sandstone-dominated interval in the lower Shakopee Dolomite has been correlated in Kentucky and Indiana. This zone had the best reservoir properties in the KGS 1 Blan well in Hancock County, Ky., and it thickens into southeastern Indiana. Injection tests with CO₂ in the Blan well indicate excellent injectivity. This sandstone interval appears to correlate with the New Richmond Sandstone of Illinois. The significance of this sandstone interval is that it is a mappable reservoir unit, reducing the risk of locating suitable porosity zones in the Knox. Knox dolomites contain vuggy, fracture, and sometimes cavernous porosity, but these intervals are laterally discontinuous, and remain difficult to predict. In addition, pore systems in a sandstone reservoir are more easily modeled to predict CO₂ behavior, and may allow more effective monitoring of CO₂ movement in the reservoir.

Part 2, *Knox Lithofacies and Core Descriptions, Western Kentucky*, documents the depositional facies, and porosity in cores from five cored wells in western Kentucky. Detailed core descriptions and core photographs of each lithofacies illustrate the thickness and distribution of Knox rock types. Core descriptions also include geophysical log data and core analysis data where available. Key interpretations from the core descriptions are that depositional facies in the Knox are very similar across western Kentucky. Knox dolomites consist of cyclic, shallow restricted marine subtidal to supratidal deposits. Microbial and algal boundstones (stromatolites and thrombolites) are a significant component of these rocks. Significant changes in Knox dolomite lithofacies do not occur across western Kentucky. Porosity occurs in both dolomites and sandstone, with higher average porosity and permeability in

sandstones. Core analysis data indicates dolomite reservoir quality varies significantly for a given lithofacies, and is controlled more by the dolomitization process than by primary depositional facies. Based on the cores examined, which ranged in depth from 1,700 ft (518 m) to over 12,000 ft (3,658 m) visible dolomite porosity decreases with depth. Porosity in Knox sandstones is more consistent than in dolomites, and suitable reservoir quality for CO₂ injection occurs to depths of at least 5,200 ft (1,585 m).

In Part 3, *Knox Carbon Storage Resource Estimates for the Illinois Basin*, multiple deterministic-based approaches were used in conjunction with the probabilistic-based storage efficiency factors published in the DOE methodology to estimate the carbon storage resource of the Knox Group. Results demonstrate how the range in uncertainty of storage resource estimates varies as a function of data availability and quality, and the underlying assumptions used in the different approaches. In the simplest approach, storage resource estimates were calculated from mapping the gross thickness of the formation and applying a single best estimate of the effective mean porosity of the formation. Results from this approach led to storage resource estimates ranging from 27 to 232 Gt at the P10 and P90 probability level, respectively. The second approach considered the depositional variation within the Knox Group by constructing a three-part subdivision based on the new analysis of clastic intervals and extensive picks of the lower Knox unit correlating to the Potosi Fm. Considering the variable thickness and effective porosity of each subunit resulted in very similar total storage resource estimates of 27 to 236 Gt. The storage estimates for each subunit were 13 to 144 Gt for the upper Knox unit, 1 to 11 Gt for the clastic unit, and 13 to 111 Gt for the lower Knox unit. The third approach attempted to account for the local-scale variability in reservoir quality as a function of both porosity and permeability by using core and log analyses to calculate explicitly the net effective porosity at multiple well locations, and interpolate those results throughout the basin domain. This approach resulted in significantly larger storage resource estimates of 448 to 728 Gt. The observed variability in results from the three different approaches is evaluated in the context of data and methodological constraints, leading to the conclusion that the storage resource estimates from the first two approaches are conservative, whereas the net porosity based approach may over-estimate the resource. Additionally, we calculated a hypothetical case of storage in cavernous porosity of the Lower Knox unit as 1 to 16 Gt based on idealized properties. This result indicates that the Knox Group may have high-quality reservoir intervals of either cavernous zones or clastic intervals that are of similar magnitude across the basin. Results are summarized in the table below.

Details of Knox Group Storage Resource Estimates	CO2 Storage Resource (billion metric tons)	
	P ₁₀ estimate	P ₉₀ estimate
Level 1-a: Single reservoir unit; assume effective porosity from core (6.4% mean); constant density (0.7 g/cc assumed); E= 0.64% (P10) and 5.5% (P90) for dolomite lithology	30	256
Level 1-b: same as above but using nphi mean porosity of 5.8% to correct for sampling bias of core dataset (core mostly from Arches province vs logs mostly from the reservoir domain).	27	232
Level 2-A: Upper Knox unit from two-part subdivision	14	122
Level 2-A: Lower Knox unit from two part subdivision	13	111
Level 2-B: Upper Knox unit from three-part subdivision	13	114
Level 2-B: Knox clastic unit from three-part subdivision	1	11
Level 2-B: Lower Knox unit from three-part subdivision	13	111
Level 3: Net porosity calculation; E = 16% (P10) and 26% (P90)	448	728
Idealized cavernous storage (30 meters of karst at upper Potosi; 15% effective porosity)	1	16

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Part 1. Regional Stratigraphic Correlations

David C. Harris, Kentucky Geological Survey

In order to provide a consistent stratigraphic framework for units within the Knox, basin-wide correlations were made using subsurface geophysical and well sample logs. Seven new cross sections document these correlations (Plates 1.1–1.7). Regional correlations were necessary to interpret a more precise stratigraphic interval for Knox cores in Kentucky, and allow comparison to equivalent intervals in Illinois and Indiana. In addition, the correlations included a significant reservoir sandstone encountered in the KGS 1 Blan well in Hancock County, Ky. This sandstone, initially identified as the Gunter Sandstone, had the best reservoir properties in the Blan well, and was the main target for Phase 2 CO₂ injection tests as part of this project (Bowersox and Hickman, 2012). Regional correlations have allowed the geographic extent and stratigraphic equivalents of this sandstone to be interpreted.

Historically subsurface stratigraphic correlation in the Cambro-Ordovician Knox Group across the Illinois Basin has been hindered by both geologic and nomenclature issues. Good quality modern logs through the entire Knox are scarce. More recent carbon sequestration demonstration wells and other waste disposal wells (ISGS ADM wells, Duke Edwardsport, Gibson, and East Bend wells; KGS Blan well) have helped to provide modern log data, but correlation within the Knox remains difficult. Thick intervals of massive dolomite with little shale content commonly lack distinct markers on gamma ray logs. Well-to-well variability on logs is also common, and may be a result of dolomitization introducing some radioactive elements to the Knox. Despite this, major stratigraphic units can be correlated across the basin.

Stratigraphic nomenclature used for the Knox in the Illinois Basin has been an inconsistent mixture of ranks and regional formation names. The Knox is considered a supergroup in Illinois and Indiana (Droste and Patton, 1985) and had long had group status in western Kentucky (Shaver, 1984). Knox formation names used in western Kentucky include both Appalachian Basin terms (Beekmantown Dolomite, Copper Ridge Dolomite) and Missouri terms (Cotter, Jefferson City, Roubidoux, Gasconade) (Shaver, 1984; Whitaker and others, 1992). Noger and Drahozal (2005) recommended raising the Knox Group to supergroup status in western Kentucky, and proposed an Ordovician Beekmantown Group and a Cambrian Copper Ridge Group. The proposed Beekmantown Group was composed of the Gunter Sandstone, Oneota Dolomite, and Shakopee Dolomite in ascending order. This was the first attempt to

bring Illinois and Indiana units into Kentucky. Hickman (2013) followed Noger and Drahovzal's classification, and extended the Kentucky nomenclature into Illinois and Indiana on regional cross sections.

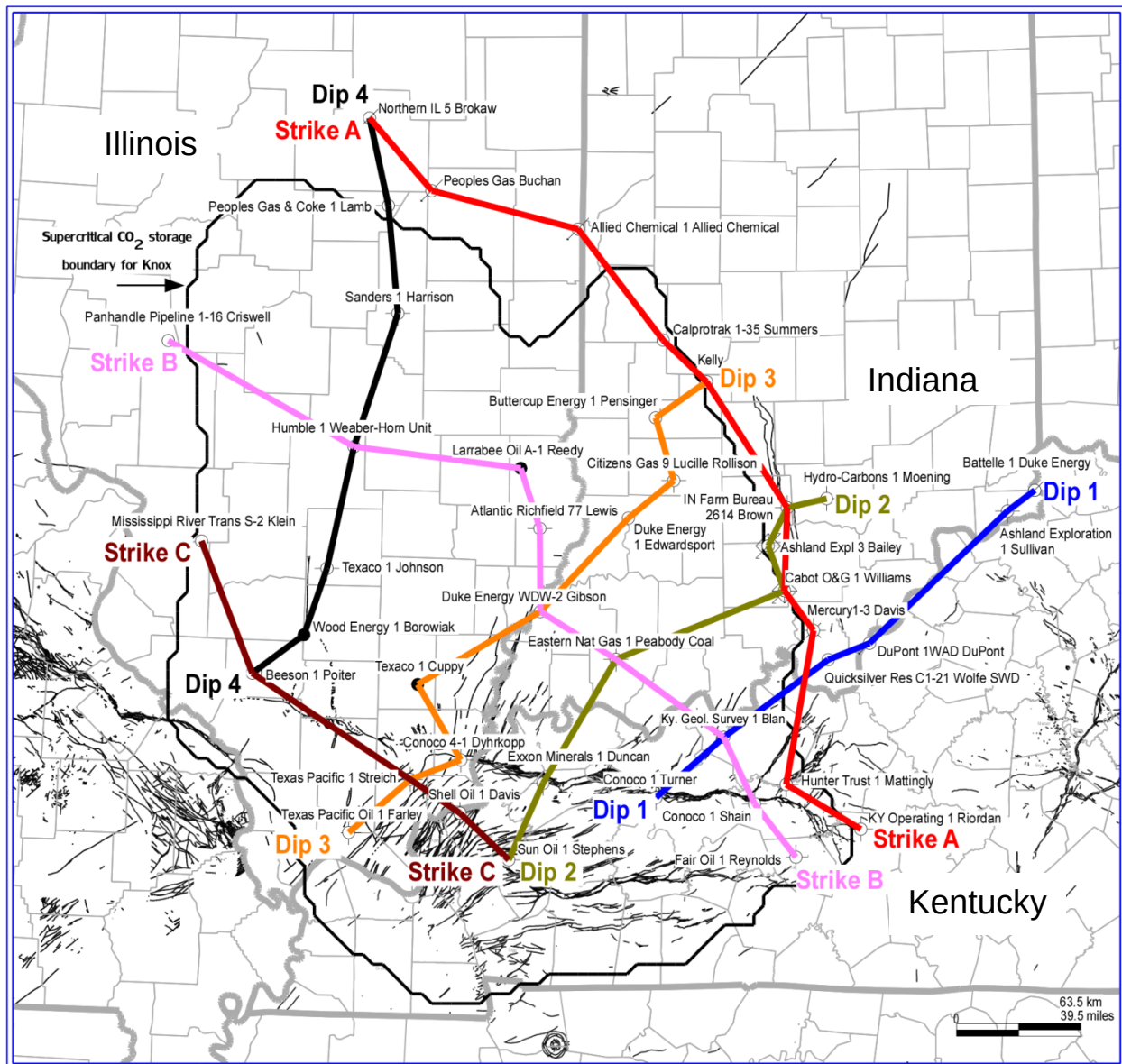


Figure 1.1. Map showing location of regional cross sections and wells used for Knox correlations. Heavy black line outlines area deep enough for supercritical CO₂ storage in the Knox. Light black lines are mapped surface faults.

Methods

For this project, a consistent stratigraphic framework across state lines was desired for characterization and CO₂ storage assessment. The cross sections included in this report are an attempt to achieve that goal. We are not proposing new nomenclature here, but rather attempting to correlate one set of stratigraphic units in all three states. Cross section wells were selected based on location and depth, and logs were hung using the post-Knox unconformity as the datum. Petra™ geologic interpretation software was used to construct the sections. Because of the similarity of Illinois and Indiana Knox formation picks, this nomenclature was chosen to extend into Kentucky. Recognition and correlation of porous sandstone units was difficult without photoelectric (Pe) logs. Sample descriptions and mud logs were checked to confirm the presence of quartz sandstone.

Sections are oriented in both strike and dip directions with respect to erosional truncation of the Knox at the post-Knox unconformity (Fig. 1.1). This is roughly northeast-southwest as shown by Knox thickness trends. A stratigraphic datum, the post-Knox unconformity, was used to hang the logs. Depths on the edges of the sections are depth below the datum surface. Well logs used in the sections include both scanned raster images of paper logs, and digitized log curves where available. For digitized logs, photoelectric (Pe) log curves are shaded red where values are below 2.5 to highlight the presence of quartz sandstone. The bulk density curve is shown rather than density porosity due to the presence of both dolomite and sandstone— a porosity curve for one matrix mineralogy would be invalid in different lithology. Wells and logs may extend deeper than shown on the sections. The focus of this work was the Knox, and thus not all wells are displayed to their total depth.

Knox stratigraphic units correlated include the Cambrian Potosi Dolomite and Eminence Dolomite in Illinois, and the combined interval in Indiana and Kentucky. The Ordovician section includes the Gunter Sandstone, Oneota Dolomite, New Richmond Sandstone, and the Shakopee Dolomite. Illinois correlations were based on sections previously published as part of this project (Askari-Khorasgani and others, 2013a and 2013b; Askari-Khorasgani and others, 2011). Indiana correlations were based on key wells published in Droste and Patton (1985).

Regional Dip Sections

Dip cross sections 1-4 (Plates 1.1–1.4) illustrate the erosional thinning of the Shakopee Dolomite at the post-Knox unconformity to the northeast. The most dramatic thinning is present on dip line 3, where the Shakopee ranges in thickness from 3,250 to 700 ft (991 -213 m) from southwest to northeast. The Potosi Dolomite depositionally thickens to the southwest.

These cross sections also show the correlation of a sandstone interval encountered in the KGS 1 Blan well in Hancock County, Ky. This interval consists of porous, medium to fine-grained sandstone interbedded with dolomite. It is about 150 ft (47 m) thick in the Blan well. Initial interpretation of this interval correlated this sandstone with the Gunter Sandstone in Illinois due to other Gunter formation picks in western Kentucky. Because of the excellent reservoir quality, considerable effort was made in this project to correlate this sandstone regionally. This unit is shaded in yellow on the cross sections. Dip section 1 was extended up onto the Cincinnati Arch to the northeast, where the Knox is too shallow for dense-phase CO₂ storage. This was done to include the Battelle 1 Duke Energy well in Boone County, Ky. and an older well in Switzerland County, Ind. These wells also encountered porous sandstone within the Knox, but very near the top of the Knox due to deeper erosion of the Shakopee Dolomite to the northeast. This Knox sandstone interval correlates with the Blan sandstone, and also occurs in wells in Harrison County, Ind, Meade Co., Ky. and Jefferson County, Ky. These Knox sandstones were documented by Droste and Patton (1985) who referred to them as Shakopee sandstones and mapped their distribution across much of southeastern Indiana (see Fig. 15 in Droste and Patton, 1985). Correlating the Blan sandstone with the Shakopee sandstones places it too high stratigraphically to be interpreted as the Gunter Sandstone. As discussed below, a more likely correlation is with the New Richmond Sandstone in Illinois.

On dip sections 3 and 4, the Shakopee/New Richmond sandstone pinches out to the southwest in deeper parts of the Illinois Basin. It is present across much of western Kentucky and southern Indiana on dip sections 1 and 2. The thickest occurrence is in the Indiana Farm Bureau 2614 Brown well (dip section 2), where most of the Shakopee section is sandstone (almost 400 ft (122 m)). The deeper Gunter Sandstone is possibly present in a few wells in western Kentucky, but is best developed in central Illinois on dip section 4. It also pinches out toward the deeper parts of the Illinois Basin.

Regional Strike Sections

Three regional strike sections (A, B, and C, Plates 1.5–1-7) run roughly perpendicular to the dip sections, and help to further illustrate the regional distribution and thickness of Knox units. The strike sections all show thickening of the Knox from central Illinois to Kentucky. Some of this northwestward thinning is due to erosion at the top of the Knox in Illinois, but most reflects depositional thickening to the south.

As on the dip sections, Shakopee, Oneota, and Potosi Dolomites are correlated across the study area. The Potosi is divided into the Eminence and Potosi in Illinois, based on tops provided by the Illinois State Geological Survey.

Strike sections A and B propose correlation of the Shakopee sandstones in southeastern Indiana and adjacent Kentucky with the New Richmond Sandstone in central and western Illinois. These correlations support a revised interpretation of the prominent sandstone interval in the KGS Blan well as an equivalent of the New Richmond Sandstone rather than the Gunter Sandstone. The Blan well is included on strike section B. The porous sandstone interval can be traced into the Duke Energy Gibson WDW-2 well where it is about 8,000 ft (2,438 m) deep. The sandstone has good reservoir properties at this depth, and serves as the injection zone in this well (Greb and others, 2012). In strike section B the sandstone thins across eastern Illinois, and thickens again in west central Illinois. In strike section A, the thick Shakopee sandstones in Indiana wells thin to the west, and are correlated with the New Richmond in the same stratigraphic position in Illinois.

A stratigraphic problem that remains to be resolved is the position of this sandstone with respect to the Shakopee and Oneota in Indiana and Kentucky. In Illinois, the New Richmond Sandstone occurs at the contact between the Shakopee and Oneota Dolomites (Askari-Khorasgani and others, 2013a and 2013b; Askari-Khorasgani and others, 2011; Willman and others, 1975). As shown on these sections, in Indiana and Kentucky the sandstone occurs within the Shakopee based on the traditional log picks for the base of Shakopee and top of Oneota Dolomites. This interpretation puts the sandstone entirely within the Shakopee, not at the Shakopee/Oneota boundary. One solution to this problem would be to raise the top of the Oneota Dolomite to the base of the sandstone to be consistent with Illinois usage. These cross sections show the current top of Oneota, at the base of the New Richmond in Illinois, and about 50-100 ft lower in Indiana and Kentucky.

Discussion

These cross section are an attempt at a consistent stratigraphic framework for Knox in the Illinois Basin. Stratigraphic correlations and nomenclature used in Illinois and Indiana have been carried into western Kentucky. These sections were used as the basis for carbon storage resource estimates in Chapter 3, and to interpret the stratigraphy of cores described in Chapter 2.

A key interpretation derived from this work is recognition of the significant distribution of the New Richmond and laterally equivalent sandstones in Indiana and western Kentucky. This interbedded quartz sandstone and dolomite interval has excellent porosity on logs, and permeability in the limited core data available. The sandstone-dominated injection zone in the KGS 1 Blan well in Hancock County, Ky. is reinterpreted as an equivalent to the New Richmond Sandstone, rather than the Gunter Sandstone. The stratigraphic position, thickness, and geographic distribution of this reservoir interval supports correlation with the New Richmond. The Gunter Sandstone is much thinner and limited to Illinois and a few scattered wells in western Kentucky. In addition, the medium to fine grain size and well-rounded, quartz-rich composition of the Blan sandstones are consistent with the New Richmond and Shakopee sandstones. This interval was identified in 67 wells in the three-state study area, and log data was used to map the gross thickness of the sandstone interval (Figure 1.2). The New Richmond Sandstone in Illinois is thin (less than 100 feet (30 m) and limited to the northern and western edges of the Illinois Basin, pinching out toward southern Illinois. The sandstone interval thickens to almost 400 feet (122 m) in south-central Indiana, and forms a northeast-southwest-oriented isopach thick extending into western Kentucky. The sandstone is present along the northern margin of the Rough Creek graben, but was not recognized farther to the south in Kentucky. The elongate area of thick sandstone represents a broad depocenter where quartz sands were transported across the Knox carbonate shelf from the northern source area. Sands may have been deposited in tidal channels or shallow marine bars. This interval represents a basin-wide influx of quartz sand across the Knox carbonate shelf, from a northern source area.

A substantial portion of the thick sandstone interval is located within the supercritical CO₂ storage area boundary for the Knox (Fig. 1.2). The thickest part of the sandstone interval lies on the eastern edge of the storage area boundary. CO₂ injection in this area could be problematic if CO₂ migrates updip to

shallower areas in the Knox. A significant area with gross sandstone thickness greater than 150 feet (46 m) lies deeper in the basin and would be suitable for carbon storage.

These sandstones should be considered a viable carbon storage target in the Knox for several reasons. First, Phase 2 injection testing in this project focused on the sandstone interval in the KGS 1 Blan well. Results of this work showed excellent injectivity (Bowersox and Hickman, 2012). The sandstones are interbedded with and overlain by tight dolomites in the Knox, in addition to tight Black River Limestone and Maquoketa Shale overlying the Knox. These impermeable interval provide excellent confinement for injected CO₂.

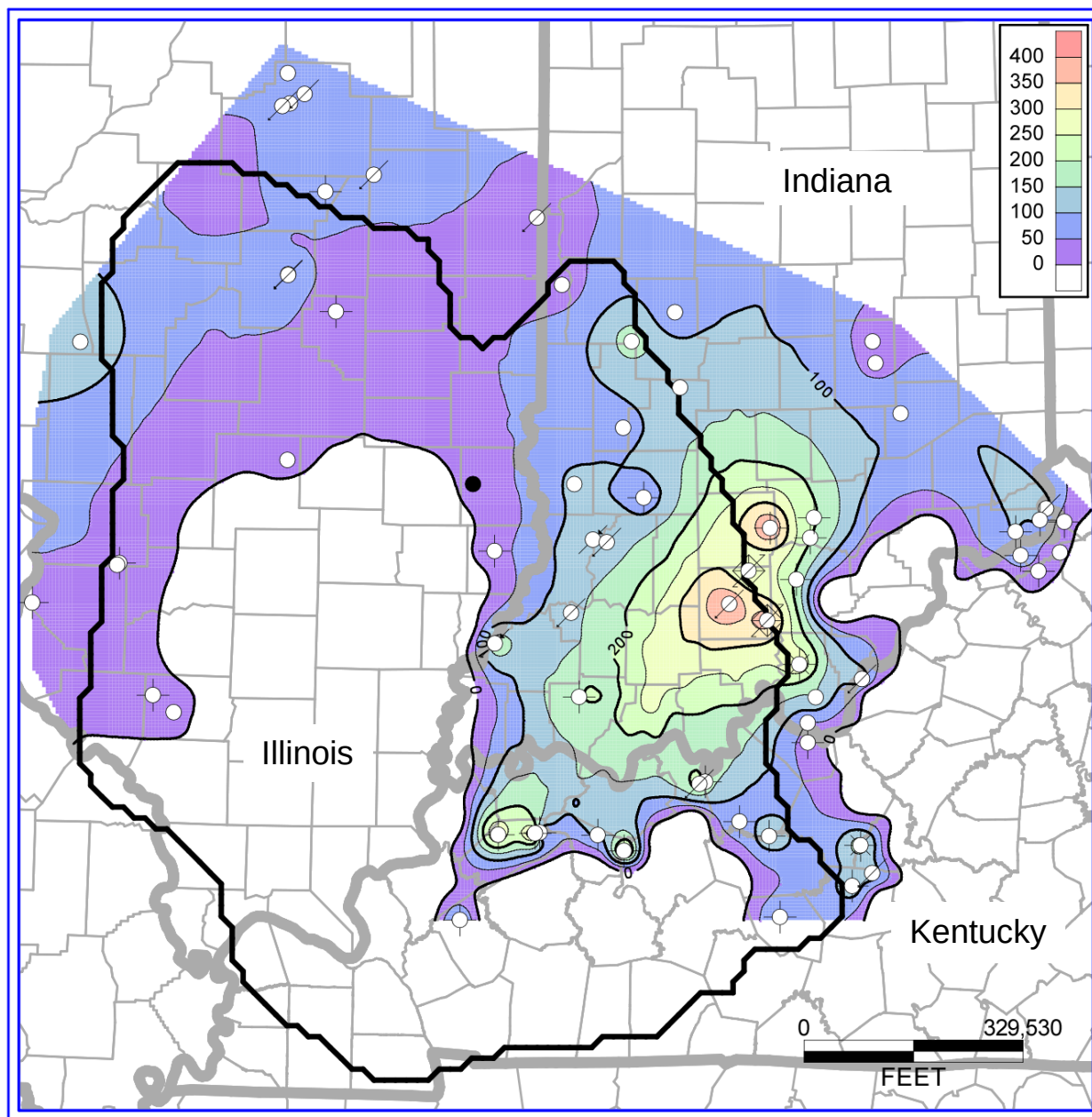


Figure 1.2. Isopach map of the New Richmond Sandstone and laterally-equivalent sandstones in the Illinois Basin. This porous sandstone pinches out in southern Illinois and southwestern Kentucky. A northeast-southwest trending band of thick sandstone is present in southern Indiana and adjacent Kentucky. Much of this sandstone occurs deep enough for dense phase CO₂ storage. Heavy black line outlines area deep enough for supercritical CO₂ storage in the Knox. Only wells with sandstone present are shown. Contour interval is 50 feet (15.2 m).

Sandstone reservoirs have several advantages over dolomite reservoirs with vuggy and fracture-dominated pore systems. The sandstone intervals are mappable, and reservoir quality is more predictable. Vuggy and cavernous porosity in Knox dolomites is fairly common, but its occurrence remains difficult to predict vertically within the Knox, and laterally across the basin. Sandstones may provide a lower risk reservoir target in certain areas of the basin. A sandstone reservoir will also be easier to model when trying to predict and monitor the movement of injected CO₂. Clastic pore systems are more homogenous than vuggy carbonates, and will behave in a more predictable way. Seismic imaging of an injected CO₂ plume will likely be more successful in thicker porous sandstones than vuggy carbonate zones.

Summary

Understanding of the thickness and distribution of Knox Group carbonates and sandstones has been improved with correlation of sub-units across the Illinois Basin using a consistent stratigraphic framework. These sections have extended Illinois and Indiana formation picks into western Kentucky. They also provide correlation of a key sandstone unit in Kentucky and Indiana with the New Richmond Sandstone of Illinois, and suggest a widespread influx of clastics occurred during lower Shakopee time. This sandstone has porosity, permeability and thickness suitable for carbon storage. Some stratigraphic details pertaining to the nature of the Shakopee/New Richmond/Oneota contact remain to be resolved in continued work.

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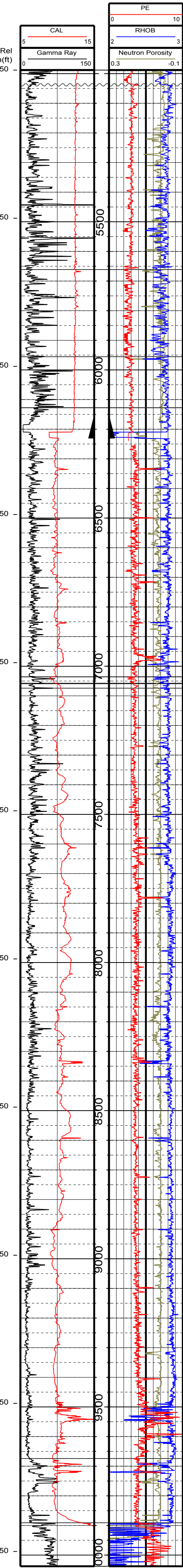
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Conoco 1 Turner, M
McLean Co., Ky.



Ky. Geol. Survey 1 Blan
Hancock Co., Ky.

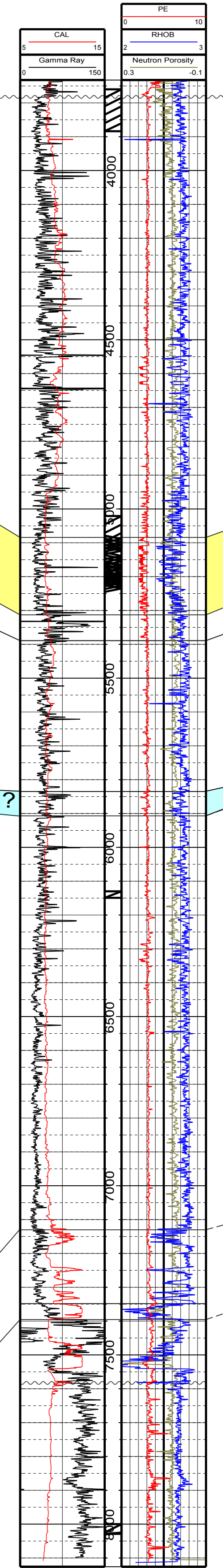
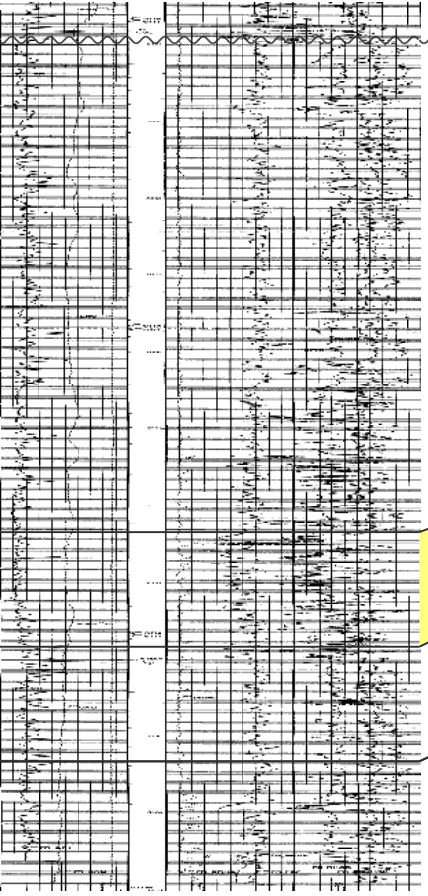


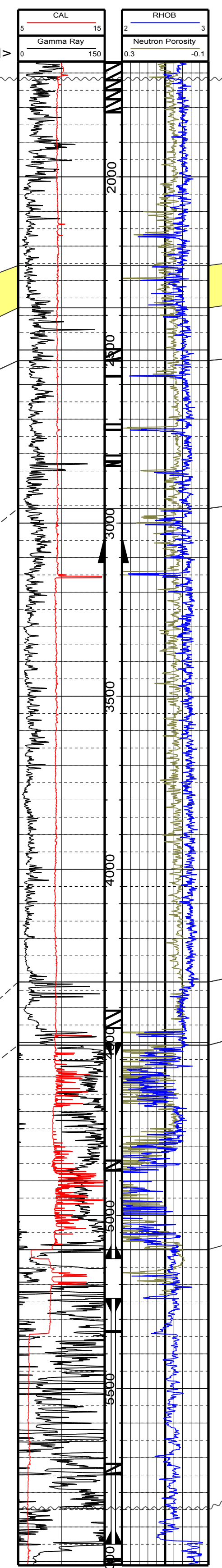
Plate 1.1
Knox Regional Section: Dip 1

Datum: post-Knox unconformity
Vertical Scale: 1 in = 250 ft

Quicksilver Res C1-21 Wolfe SWD
Harrison Co., In.

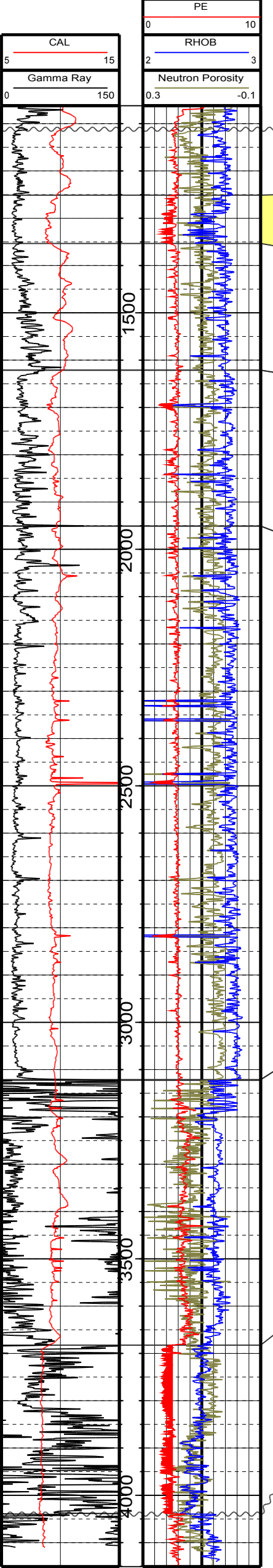


DuPont 1WAD DuPont
Jefferson Co., Ky.



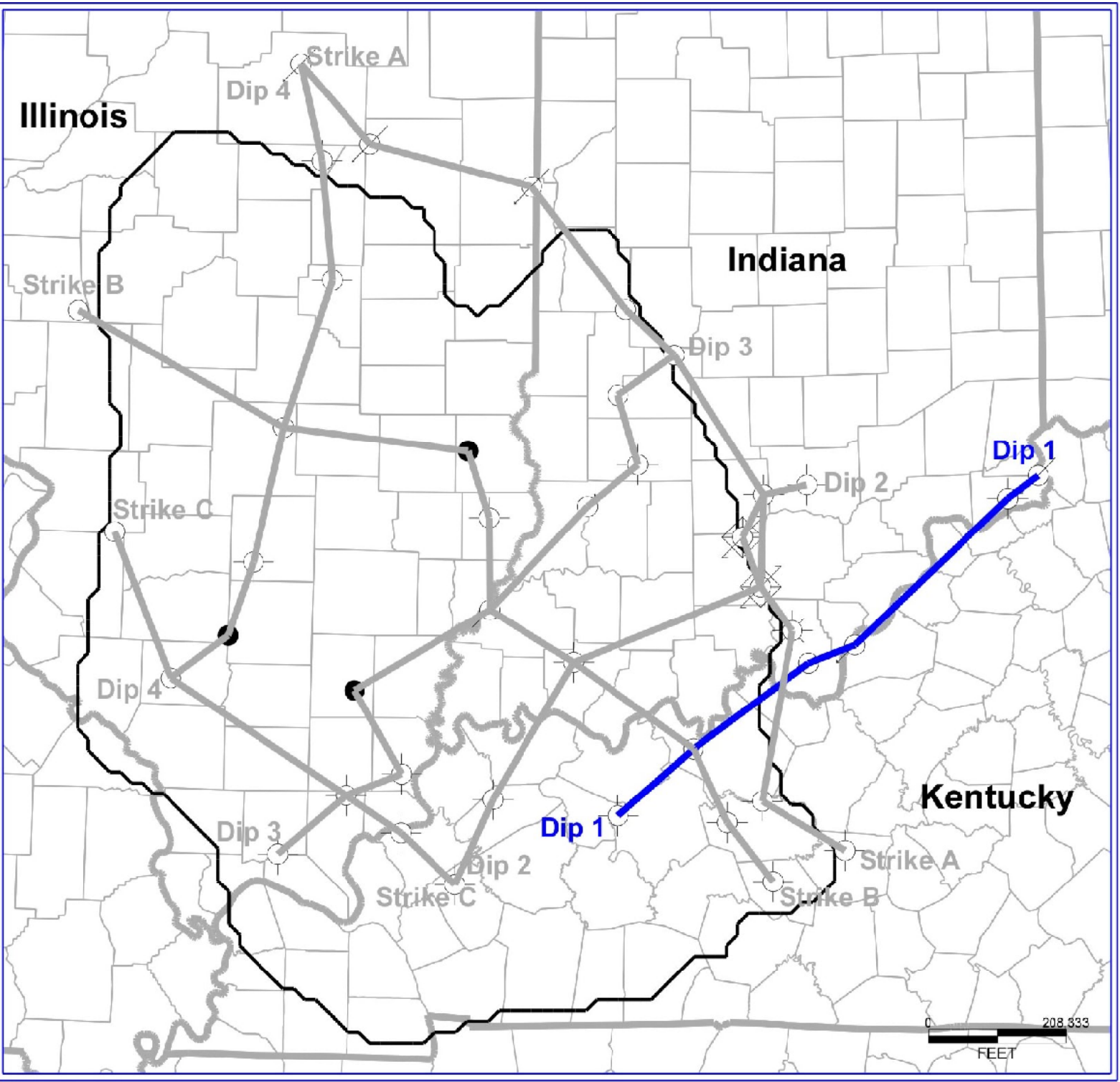
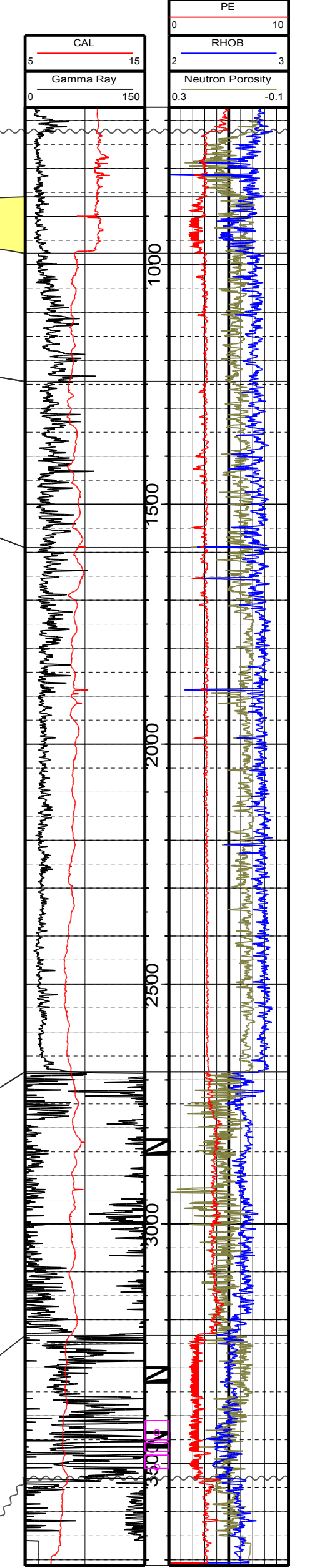
Ashland Exploration 1 Sullivan
Switzerland Co., In.

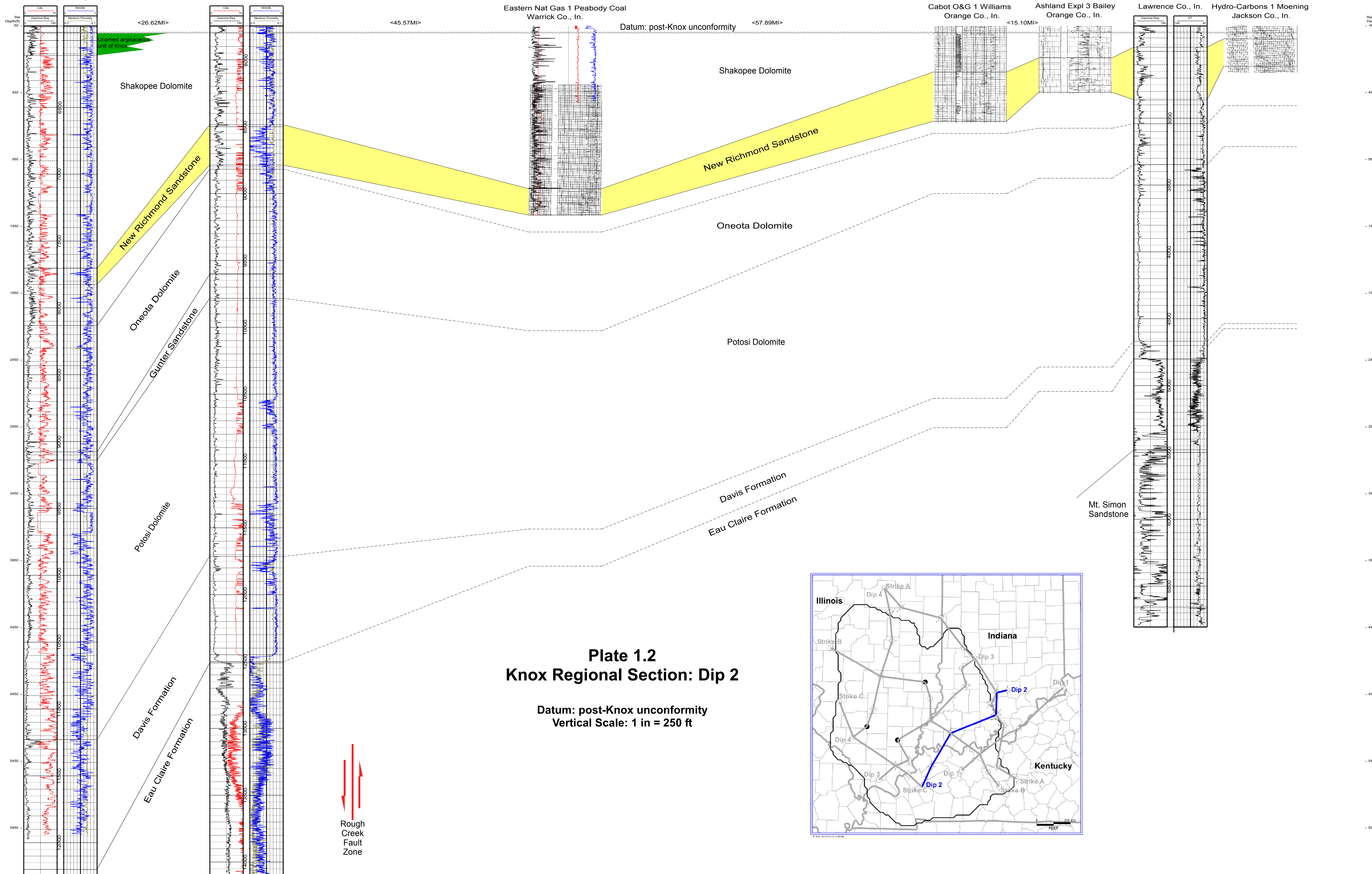
<10.85MI>



Battelle 1 Duke Energy
Boone Co., Ky.

<10.85MI>





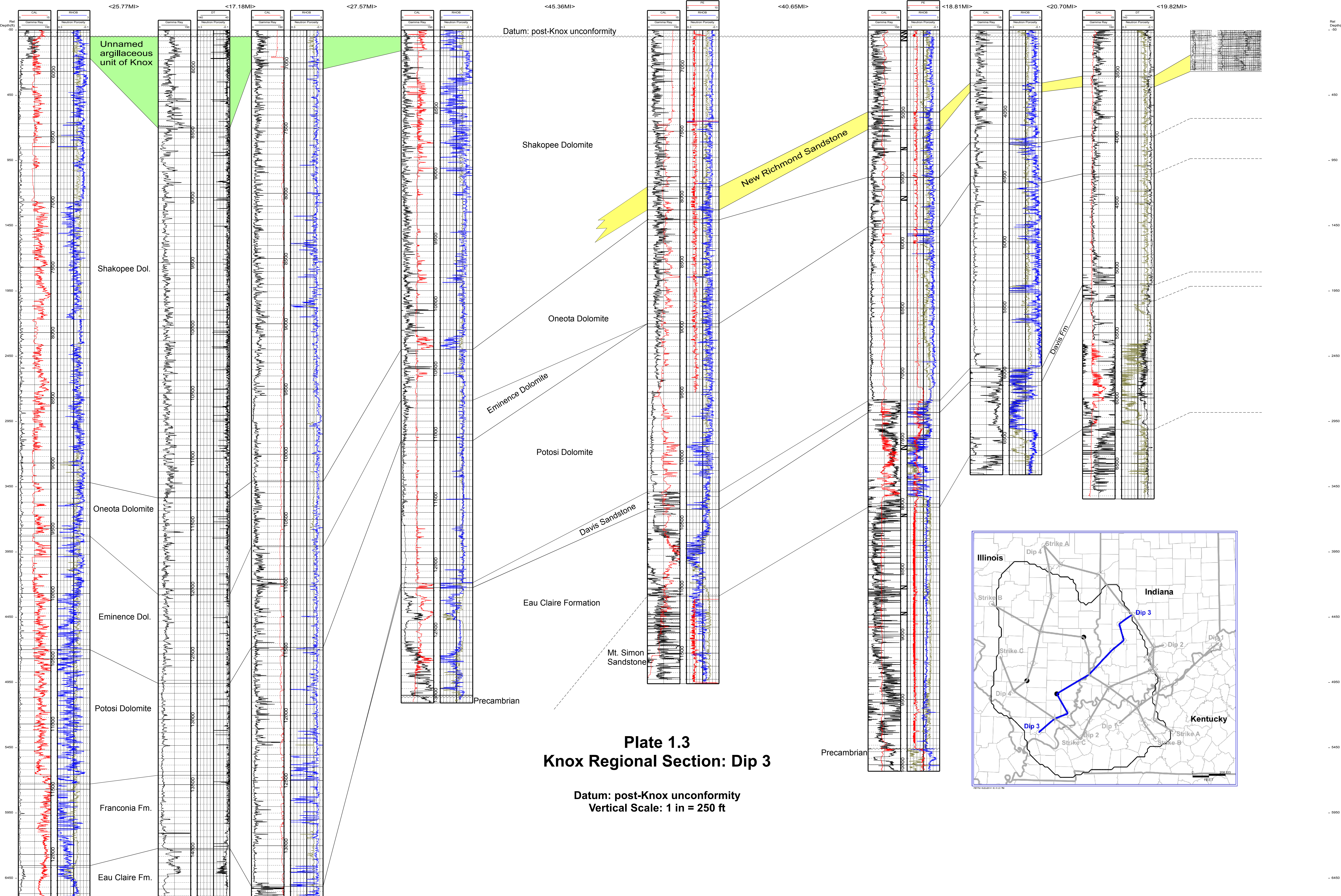


Plate 1.4 Dip 4

South

Beeson 1 Poiter
Perry Co., Il.

Wood Energy 1 Borowiak
Washington Co., Il.

Texaco, Inc. 1 Johnson, R.S.
Marion Co., Il.

Humble Oil 1 Weaber-Horn Unit
Fayette Co., Il.

Sanders, H C 1 Harrison
Moultrie Co., Il.

Peoples Gas & Coke 1 Lamb
DeWitt Co., Il.

Northern IL 5 Brokaw
McLean Co., Il.

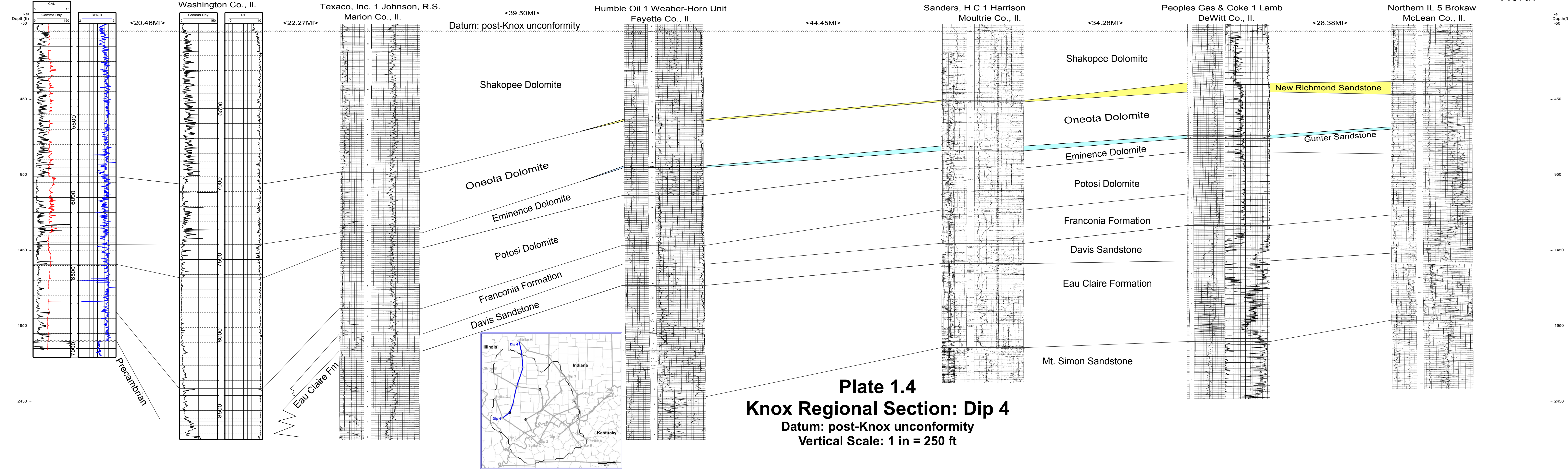


Plate 1.4 Dip 4

North

Plate 1.4
Knox Regional Section: Dip 4
Datum: post-Knox unconformity
Vertical Scale: 1 in = 250 ft

Plate 1.5 Strike A
NW

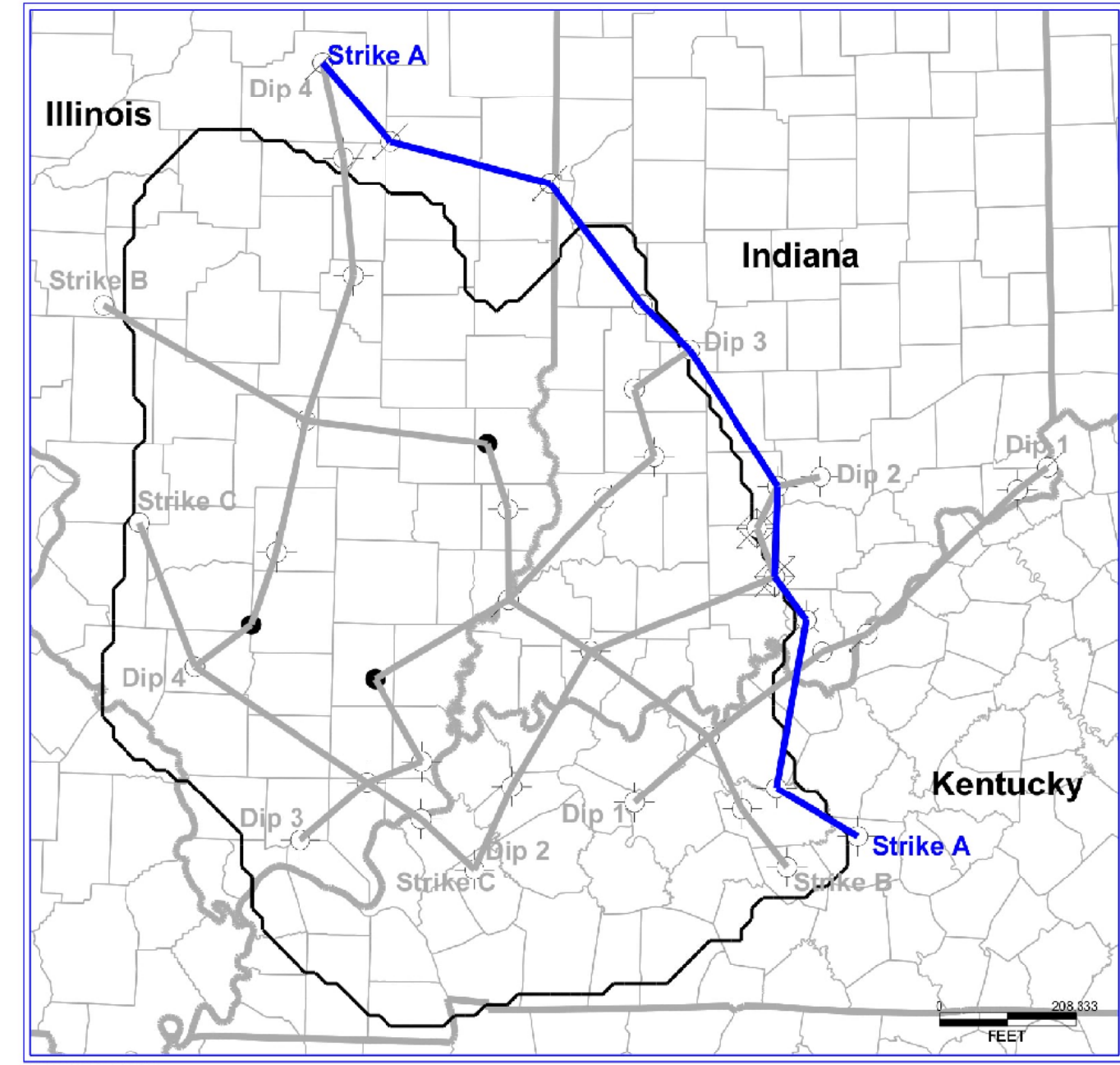
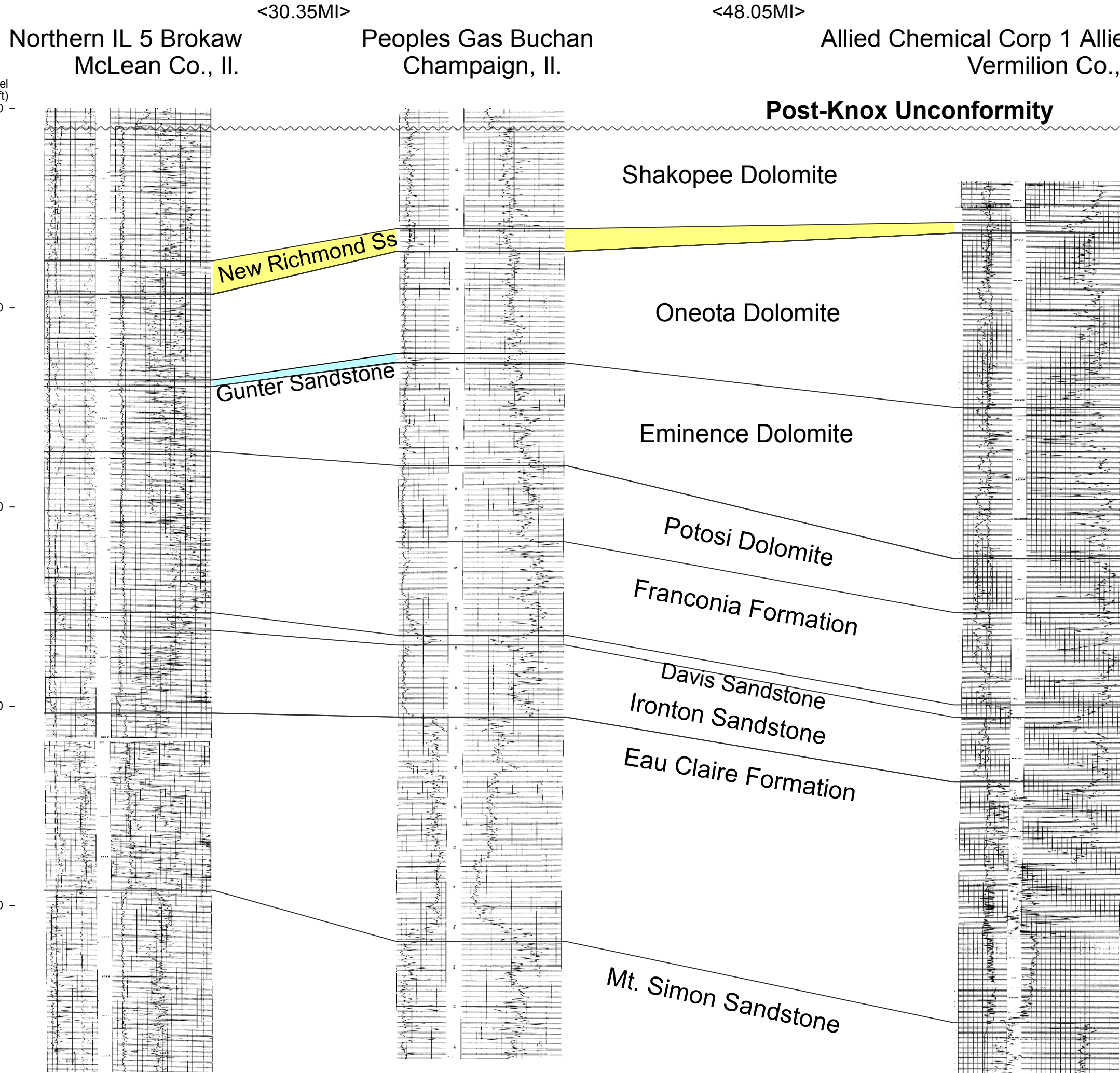


Plate 1.5
Knox Regional Section: Strike A
Datum: Post-Knox unconformity
Vertical Scale: 1 in = 250 ft

Plate 1.5 Strike A
SE

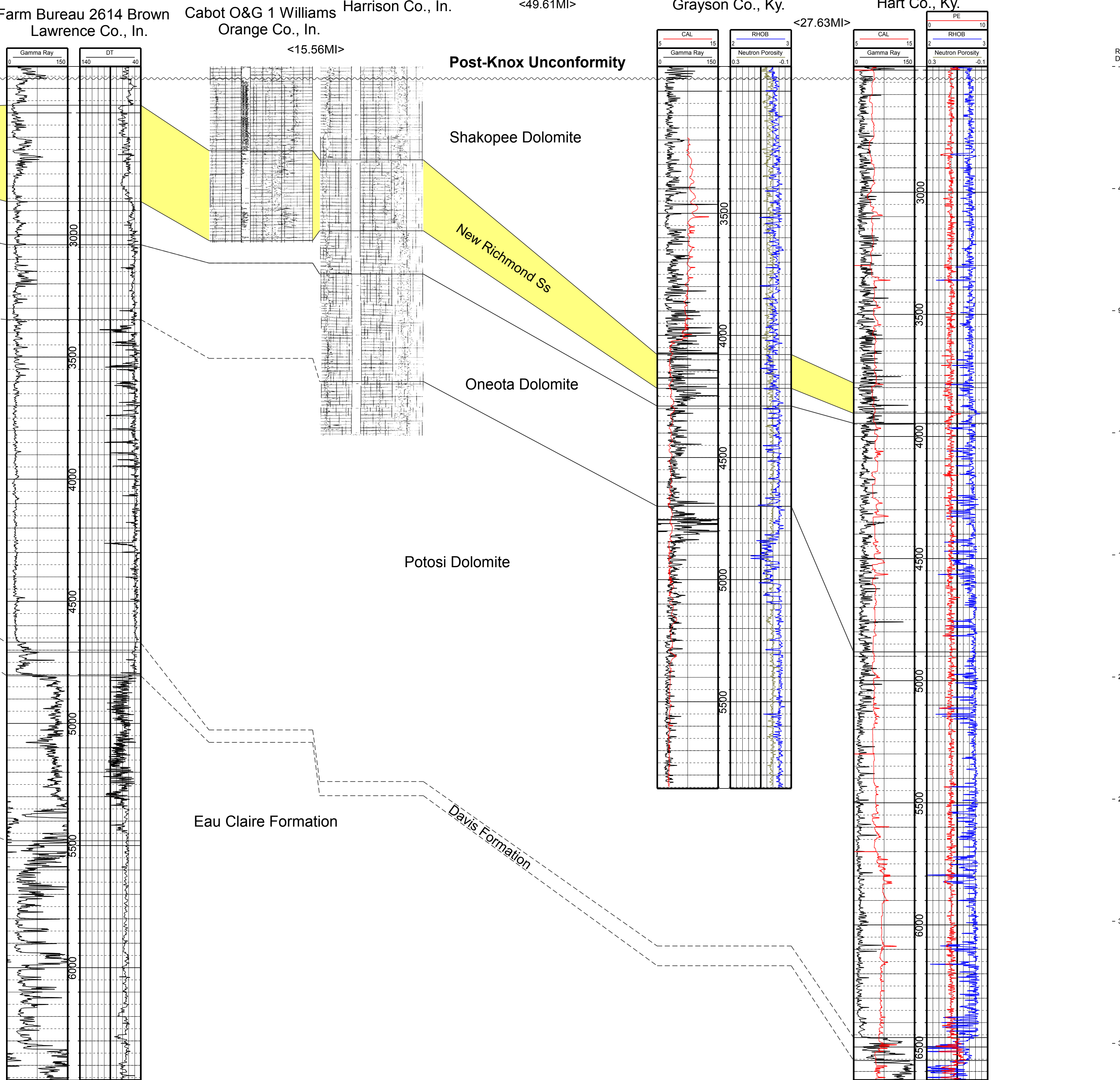


Plate 1.6 Strike B
NW

Plate 1.6 Strike B
SE Reynolds

Panhandle Pipeline 1-16 Criswell
Morgan Co., Il.

Humble Oil & Ref 1 Weaber-Horn Unit
Fayette Co., IL

Larrabee Oil A-1 Reedy, Abe Atlantic Richfield 77 Lewis, JB
Crawford Co., Il. Lawrence o., Il.

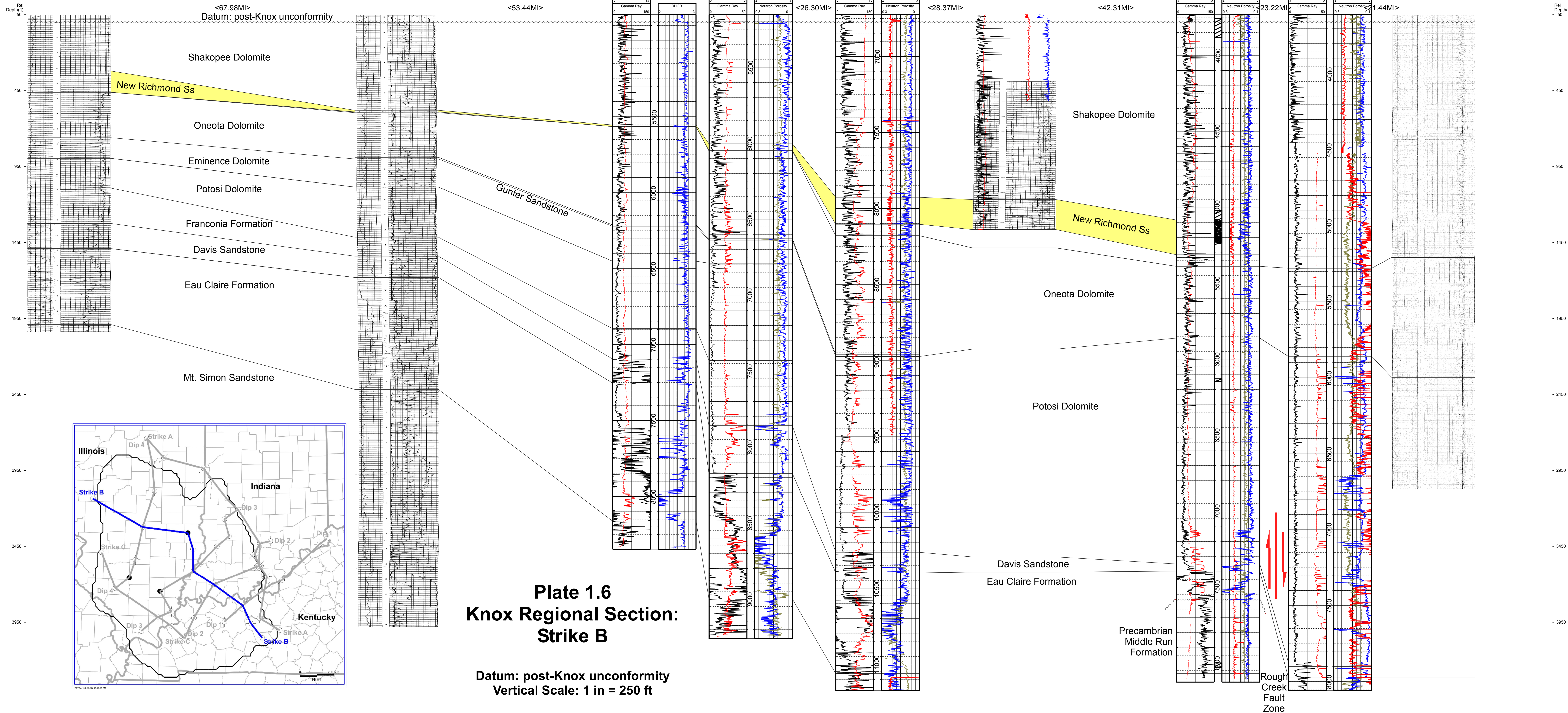
Duke Energy WDW-2 Duke-Gibson
Lewis, JB Gibson Co., In.

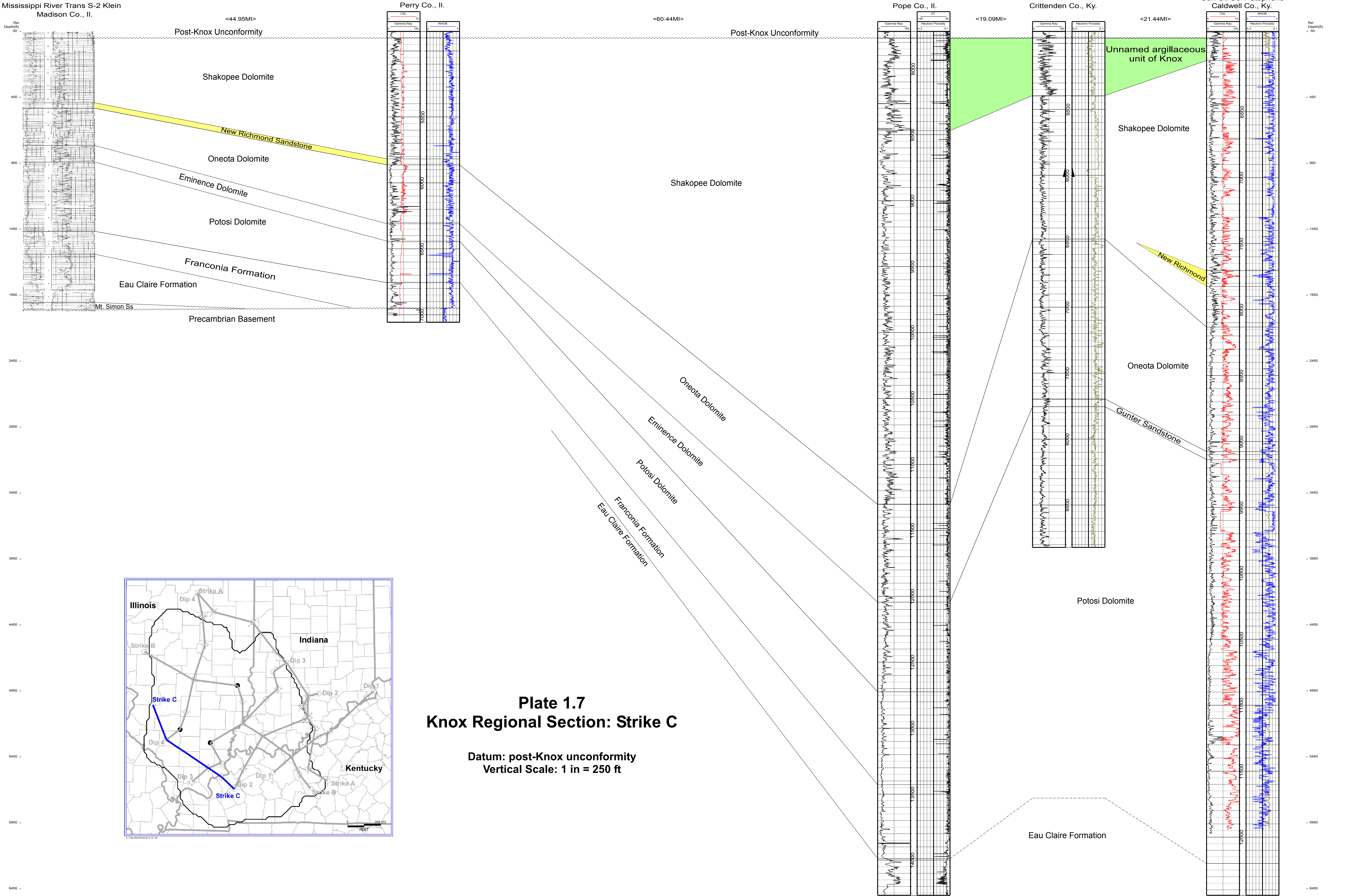
Eastern Nat Gas 1 Peabody Coal
Warrick Co., In.

Ky. Geol. Survey 1 Blau
Hancock Co., Ky.

Conoco 1 Shain
Grayson Co., Ky.

Fair Oil 1 Reynolds
Edmonson Co., Ky.





Part 2: Knox Lithofacies and Core Descriptions, Western Kentucky

David C. Harris

Knox carbonates have been cored extensively on the Cincinnati Arch in central Kentucky in the search for Mississippi Valley Type (MVT) lead-zinc-fluorite mineralization. These continuous cores are located east of the project study area, where the Knox is too shallow for dense phase CO₂ storage. Porosity and permeability of Knox carbonates on the Cincinnati Arch are very different than in deeper parts of the basin, and cannot be used as reliable analogs for reservoir properties. Detailed core work was limited to deeper parts of the Illinois Basin where cores are more limited, since the Knox is not a major target for oil or gas exploration.

Knox cores from five wells in western Kentucky were examined and described at the Kentucky Geological Survey Well Sample and Core Library in Lexington, Kentucky (Fig. 2-1, Fig.2-2, Table 2-1). The goals of this work were to document the lithology, depositional facies, porosity occurrence, and porosity types in the Knox. Most cores were described at a scale of 1 in. (2.2 cm.) = 2 ft (0.6 m.) of core. One core (Ada Belle 2A Hillman) that was in poor condition was described at a scale of 1 in. (2.2 cm.) = 10 ft (3 m.) Graphical core descriptions are included as Plates 2.1–2.5. Well log data and core analyses (where available) are included on the core descriptions.

Knox Lithofacies

Knox in western Kentucky consists primarily of dolomite (dolostone), with less abundant amounts of quartz sandstones and thin shales. Knox carbonates are pervasively dolomitized, and no limestone was observed in the Knox in cores studied. Despite the complete dolomitization, original depositional textures and sedimentary structures are preserved, and several distinct lithofacies can be recognized. All of the cores consist of sediments deposited in shallow subtidal, intertidal, and more limited supratidal environments. The cores show evidence of restricted marine conditions resulting from elevated salinity in a tropical and arid environment. Lithofacies recognized in the cores are summarized below.

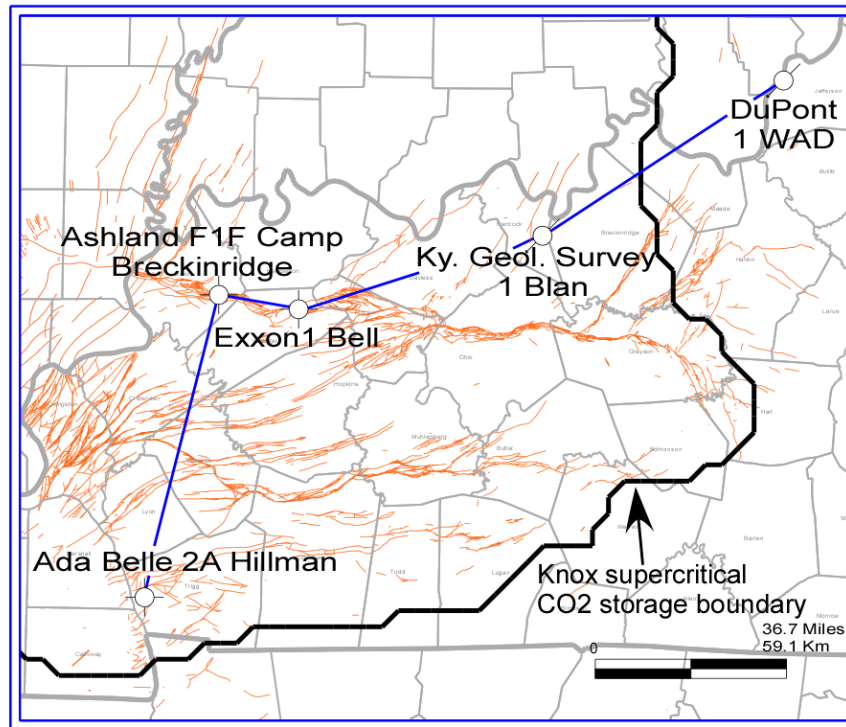


Figure 2-1. Location map for wells with Knox core. Red lines are mapped surface faults, and the heavy black line is the southern and eastern boundary where dense phase CO₂ storage is feasible in the Knox. The blue line indicates the location of the cross-section shown in Fig. 2-2.

Table 2-1. List of Western Kentucky wells with Knox core included in study.

Well Name	County	State	KGS Record	Stratigraphic Intervals	Depth Range (ft)	Core Footage	Well Logs	Core Analyses
E.I. Dupont 1WAD Dupont	Jefferson	KY	11169	Shakopee, Oneota	1710-2830	163	Yes	Yes
Ky. Geol. Survey 1 Blan	Hancock	KY	137114	Shakopee, New Richmond, Potosi	3760-6149	240	Yes	Yes
Ada Belle Oil 2A Hillman Land & Iron	Trigg	KY	17110	Shakopee	3500-3656	156	No	Yes
Exxon 1 Bell	Webster	KY	18323	Shakopee, New Richmond, Potosi	9469-12414	51	Yes	No
Ashland Oil F1F Camp Breckinridge	Union	KY	17212	Shakopee	8600-8625	25	No	No

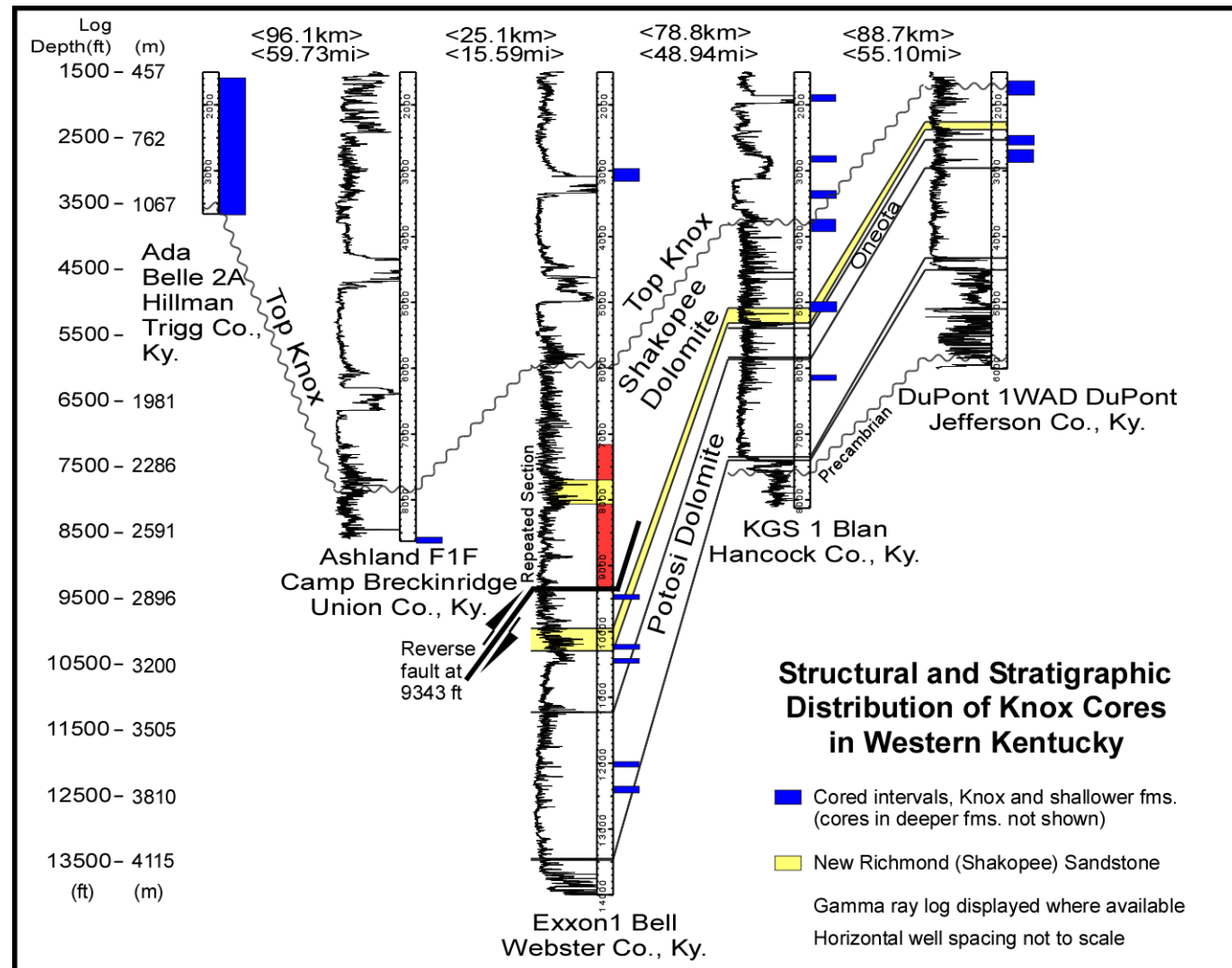


Figure 2-2. Structural cross section showing stratigraphic distribution of Knox and younger cores for the five wells included in the study. Well locations are shown in Fig. 2-1.

Stromatolite Boundstone

All of the cores examined with the exception of the Exxon 1 Bell contained intervals of laminated dolomite with features consistent with sediment trapping and deposition associated with blue-green algal and/or microbial mats in shallow subtidal to intertidal environments. These characteristics include irregular (crinkly) mm-scale horizontal laminations, and sets of low-angle dipping laminations (Figs. 2-3 and 2-4). Stromatolitic fabrics also include vertical laminated fabrics, such as columnar and digitate forms (Figs. 2-3c and 2-3d). The thickness and irregular geometry of these laminations distinguish them from current formed laminations, and suggest sediment binding by algal or microbial mats. Similar stromatolite boundstones have been documented in the Knox Group in the Black Warrior Basin (Fritz and others, 2012a) and in the Arbuckle Group in the midcontinent USA (Fritz and others, 2012b). Knox stromatolites in western Kentucky occur in the Shakopee, Oneota, and Potosi Dolomites. Stromatolite deposits show evidence of rare burrowing, and are commonly associated with intraclasts, resulting from erosion and local transport of algal mats. Stromatolite intervals commonly overlie thrombolite boundstones in cores, which are interpreted as deeper subtidal deposits. Based on analogy with modern stromatolites (Logan and others, 1974; Dill and others, 1986), this lithofacies is interpreted to represent deposition in intertidal to very shallow subtidal environments.

Thrombolite Boundstone

This fine-grained dolomite lithofacies is characterized by an irregular, clotted depositional texture defined by light and dark patches of dolomite (Figs. 2-5 and 2-6). Some thrombolite intervals have a vertical orientation to the clots, but most are random. Thrombolites are a non-laminated microbial structure (Aitken, 1967; Kennard and James, 1986), that are almost exclusively limited to Cambrian and Ordovician-age strata. These rocks are interpreted to be the result of calcification and sediment trapping by cyanobacteria colonies, and commonly form small meter-scale mounds or bioherms. Thrombolite intervals are common in the Knox, and were observed in all of the cored wells examined, in both the Shakopee and Potosi Dolomites. Thrombolite intervals occur up to 8 ft (2.4 m) thick in the KGS 1 Blan well, but are commonly 2-4 ft (0.6-1.2 m) thick. Thrombolite zones are commonly porous, with intercrystalline and some vuggy porosity. Primary vuggy porosity is occluded by anhydrite, celestite, or dolomite cements in some intervals (Figs. 2-5c, 2-5d, 2-6c).

In the cores described in this study, thrombolites commonly underlie and/or grade upward into laminated stromatolitic dolomite. In rare cases, stromatolite boundstones are sharply overlain by

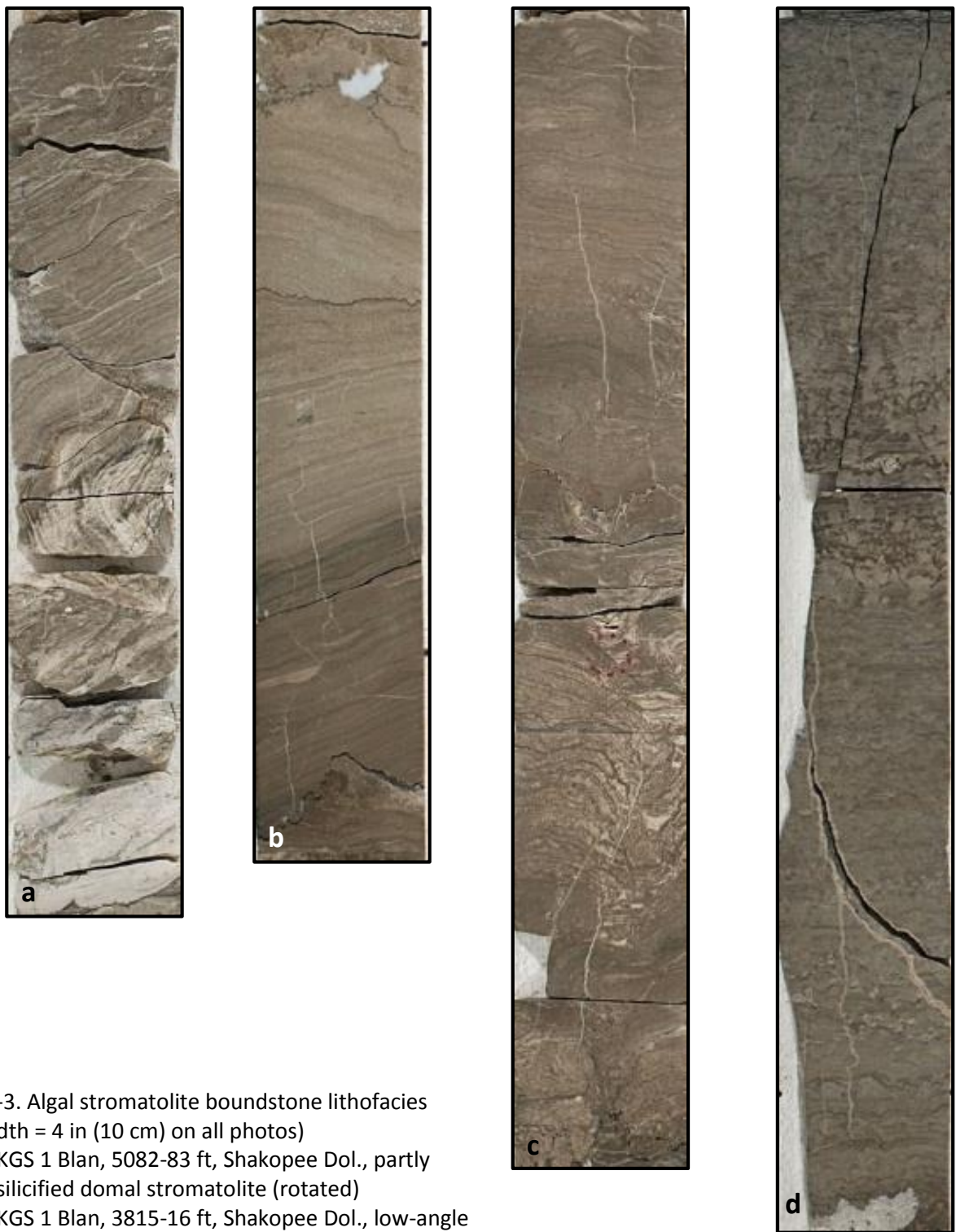


Figure 2-3. Algal stromatolite boundstone lithofacies
(core width = 4 in (10 cm) on all photos)

- a. KGS 1 Blan, 5082-83 ft, Shakopee Dol., partly silicified domal stromatolite (rotated)
- b. KGS 1 Blan, 3815-16 ft, Shakopee Dol., low-angle laminated stromatolite
- c. KGS 1 Blan, 3872-74 ft, Shakopee Dol., columnar stromatolite,
- d. KGS 1 Blan, 6139-41 ft, Potosi Dol., digitate stromatolites

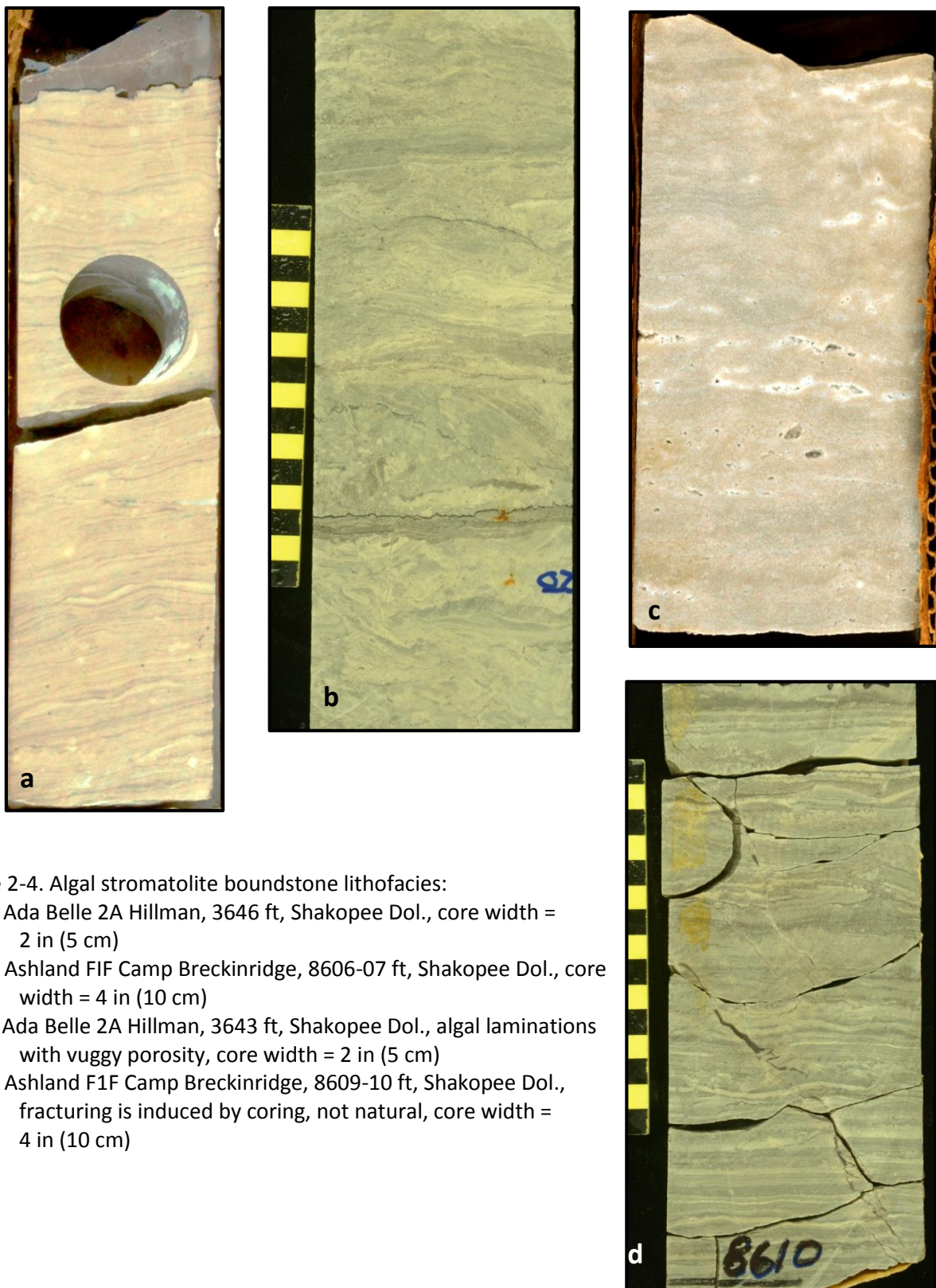


Figure 2-4. Algal stromatolite boundstone lithofacies:

- a. Ada Belle 2A Hillman, 3646 ft, Shakopee Dol., core width = 2 in (5 cm)
- b. Ashland F1F Camp Breckinridge, 8606-07 ft, Shakopee Dol., core width = 4 in (10 cm)
- c. Ada Belle 2A Hillman, 3643 ft, Shakopee Dol., algal laminations with vuggy porosity, core width = 2 in (5 cm)
- d. Ashland F1F Camp Breckinridge, 8609-10 ft, Shakopee Dol., fracturing is induced by coring, not natural, core width = 4 in (10 cm)

thrombolites (Fig. 2-5b). These examples are likely disconformable, and mark the top of an upward-shallowing depositional cycle, and subsequent transgression. Based on modern analogues in the Bahamas and Shark Bay, Western Australia, thrombolites have been interpreted as subtidal deposits (Feldmann and McKenzie, 1998; Jahnert and Collins, 2012). Fritz and others (2012a; 2102b) interpreted similar thrombolite facies in the Knox in Alabama, and in the Arbuckle Group as subtidal deposits. Knox thrombolite boundstones in western Kentucky are also interpreted as shallow subtidal deposits.

Skeletal-Peloidal-Ooid Grainstone/Packstone

Dolomite grainstones and packstones occur less commonly than the boundstone lithofacies in the cores examined. Grainstones are composed of a variety of grain types, but are lumped into a single lithofacies due to poor preservation of grains, and difficulty in identifying exact grain types due to dolomitization. Grainstone composition is best preserved in chert nodules, which pre-date dolomitization, and allows recognition of ooids, peloids, and skeletal grains. In dolomites, grainstones and packstones are identified by cross-bedding and low-angle current lamination, and relict grainy texture visible even when dolomitized. Grainstones can also contain fine- to medium-grained quartz sand grains, and dolomite intraclasts.

Grainstones are commonly ripple and less commonly trough cross-bedded (Fig. 2-7). Some grainstone/packstone intervals have low-angle cross-stratification that may be hummocky bedding resulting from storm deposition. This is not common, and hummocky cross-bedding is difficult to accurately identify in core. The grainstone/packstone lithofacies was deposited in higher energy environments, including tidal channels and shallow subtidal shoals or bars. Thinner grainstones may represent storm deposits. These rocks can contain both intercrystalline and moldic porosity.

Dolomite Mudstone

Fine-grained dolomite mudstones occur in all wells. These intervals are either massive, horizontally-laminated or bioturbated, and contain variable amounts of clays (Fig. 2-8). Laminations are defined by subtle grain-size differences, with some evidence of traction current scour and deposition. Laminations are thicker and more uniform than seen in the stromatolite boundstones. Thin shale drapes are sometimes associated with these intervals. Mudstones are commonly interbedded with thrombolite boundstones. Mudstones are interpreted as deeper and lower-energy subtidal deposits.



Figure 2-5. Core photographs of thrombolite boundstone lithfacies:

- a. Ada Belle Oil 2A Hillman, Shakopee Dol., 3579 ft, core width 2 in. (5 cm)
- b. Ada Belle Oil 2A Hillman, 3604 ft, Shakopee Dol., thrombolite overlying stromatolite, core width 2 in (5 cm)
- c. KGS 1 Blan, Shakopee Dol., 5057-59 ft core width 4 in (10 cm)
- d. KGS 1 Blan, Shakopee Dol., 3790-3796 ft, vuggy pores cemented by anhydrite/celestite, core width 4 in (10 cm)

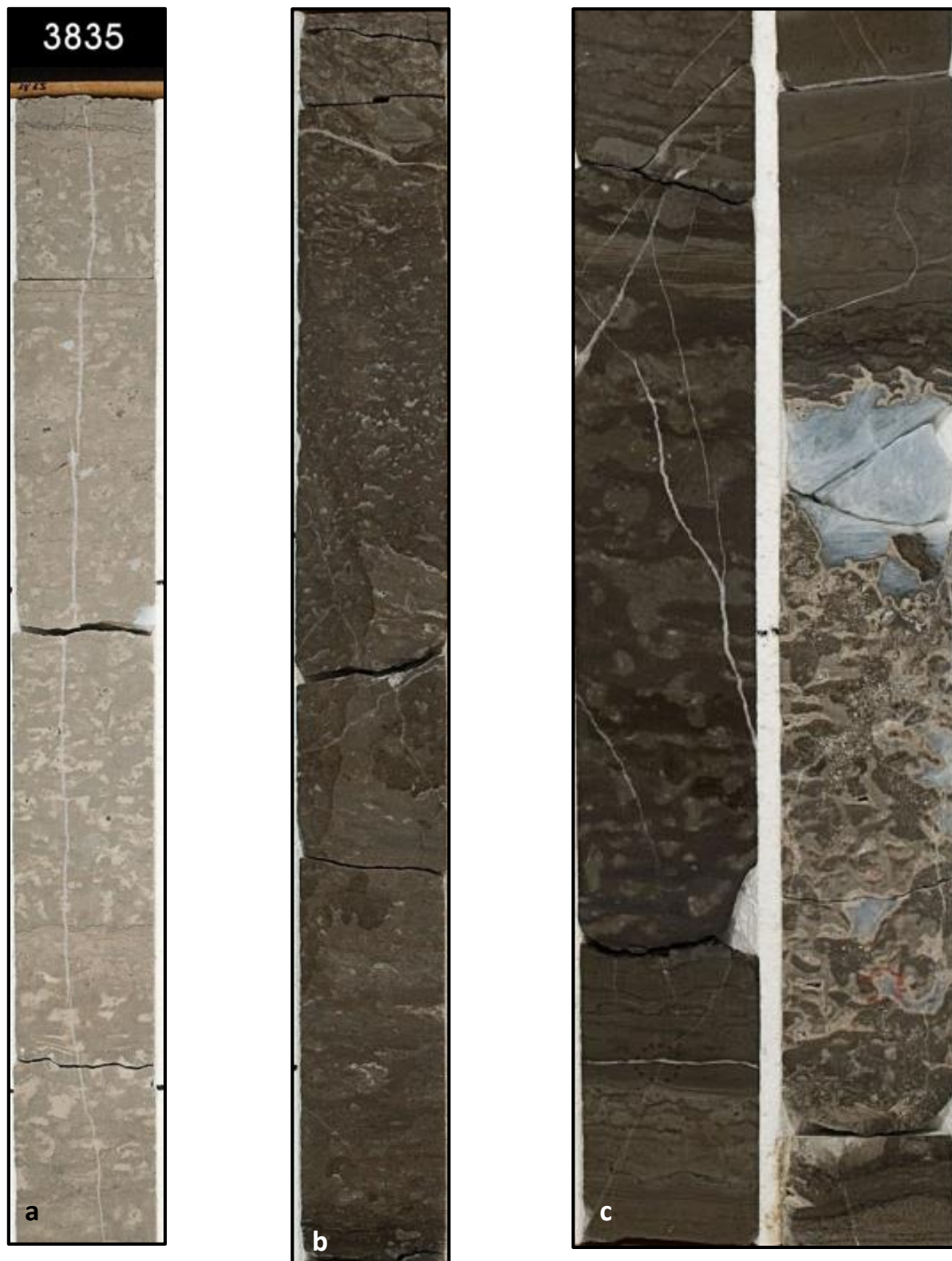


Figure 2-6. Thrombolite lithofacies: a. KGS 1 Blan, 3835-37 ft, Shakopee Dol., core width 4 in (10 cm)
 b. KGS 1 Blan, 6142-44 ft, Potosi Dol., core width 4 in (10 cm)
 c. KGS 1 Blan, 6131-33 (left) and 6134-36 (right), Potosi Dol., bluish-white mineral is celestite filling vuggy porosity, core width 4 in (10 cm)

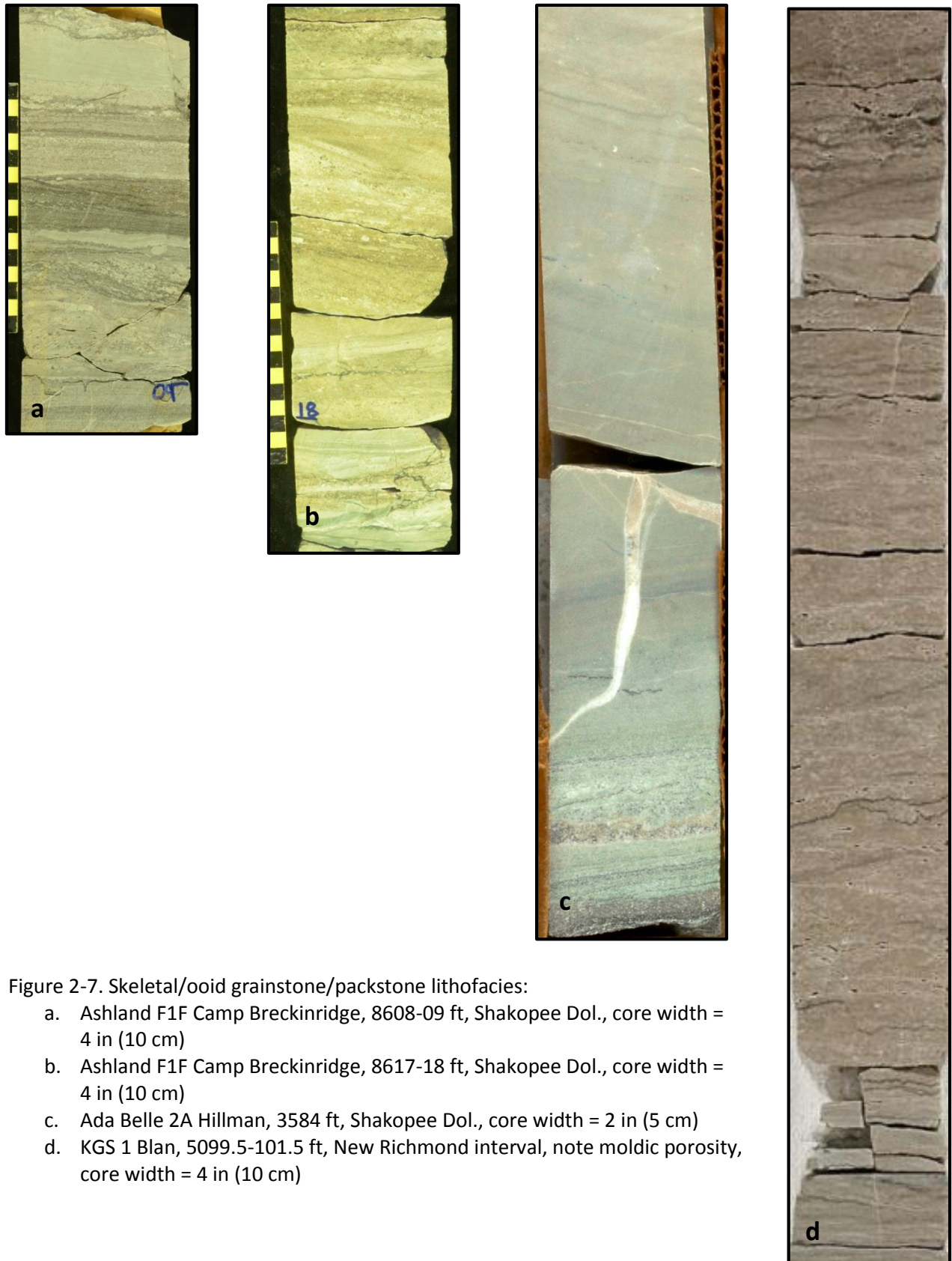


Figure 2-7. Skeletal/ooid grainstone/packstone lithofacies:

- a. Ashland F1F Camp Breckinridge, 8608-09 ft, Shakopee Dol., core width = 4 in (10 cm)
- b. Ashland F1F Camp Breckinridge, 8617-18 ft, Shakopee Dol., core width = 4 in (10 cm)
- c. Ada Belle 2A Hillman, 3584 ft, Shakopee Dol., core width = 2 in (5 cm)
- d. KGS 1 Blan, 5099.5-101.5 ft, New Richmond interval, note moldic porosity, core width = 4 in (10 cm)

They represent the deepest facies present in the cores, but water depths were still shallow enough to be impacted by storm and some wave energy.

Intraclast Breccia/Conglomerate

Dolomite intraclasts are a common grain type in the Knox, and can form intraclast conglomerates or sedimentary breccias (Fig. 2-9). Intraclasts range in size from sand, to pebbles and cobbles. Clasts are composed of typical Knox lithologies, usually laminated mudstones or stromatolites. These breccias are distinguished from other types of breccias (tectonic and solution collapse) by rounding of clasts and matrix sediment. Intraclast lags occur at the base of some grainstone intervals, overlying sharp, erosional contacts. They can also form in intertidal to supratidal environments, due to exposure and dessication. Intraclast breccias can have vuggy (Fig. 2-9c) and intercrystalline porosity, unless cemented by late dolomite.

Other breccia types occur in the Knox. Solution collapse breccias, and tectonic breccias form after deposition, and were not significant components of the core examined. One core, the Ada Belle Oil 2A Hillman Iron & Land, contains a breccia below the post-Knox unconformity that is almost 30 ft (10 m) thick. This breccia is interpreted as paleokarst, and is described separately below.

Paleokarst Breccia

Of the five cored wells examined, three were cored across the top of the Knox Group, a major erosional unconformity, and sequence boundary. Of the three cores that cut the unconformity surface, only one contains rocks that show evidence of underlying Knox karst development during exposure and erosion in the Middle Ordovician. Part of this interval is shown in Fig. 2-10. The core contains a chaotic mixture of angular clasts of several dolomite types, with a quartz sandy and argillaceous laminated matrix. This matrix is finely-laminated, with over steepened dips in some places. This matrix is interpreted to be internal sediment that filled space between breccia clasts in a karst zone at the top of the Knox. Collapse and filling of a cave system could explain the polymictic breccia and steeply dipping laminated internal sediments. This interval, from 3,513-3,542 ft (1,071-1,080 m) in the Ada Belle Oil 2A Hillman Land and Iron core (Trigg County, Ky.), is interpreted as paleokarst. Additional evidence for a karst origin is seen near the base of the zone, where clasts are coated with a rim of sparry dolomite cement, which is then

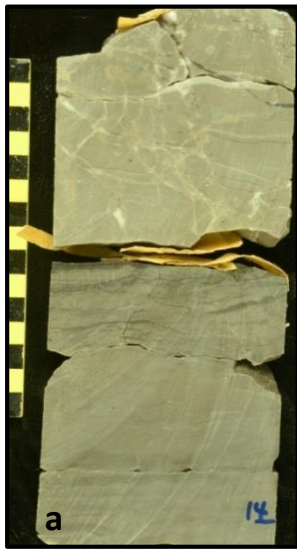


Figure 2-8. Dolomite mudstone lithofacies:

- a. Ashland F1F Camp Breckinridge, Shakopee Dol., 8613-14 ft, scale in cm, core width = 4 in.
- b. Ashland F1F Camp Breckinridge, Shakopee Dol., 8624 ft, scale in cm, core width = 4 in (10 cm)
- c. KGS 1 Blan, Shakopee Dol., 3847-50 ft, laminated argillaceous dolomite with thin shale, core width = 4 in, (10 cm)
- d. KGS 1 Blan, Shakopee Dol., 3862-65 ft, laminated to burrowed mudstone, argillaceous in part, core width = 4 in (10 cm)

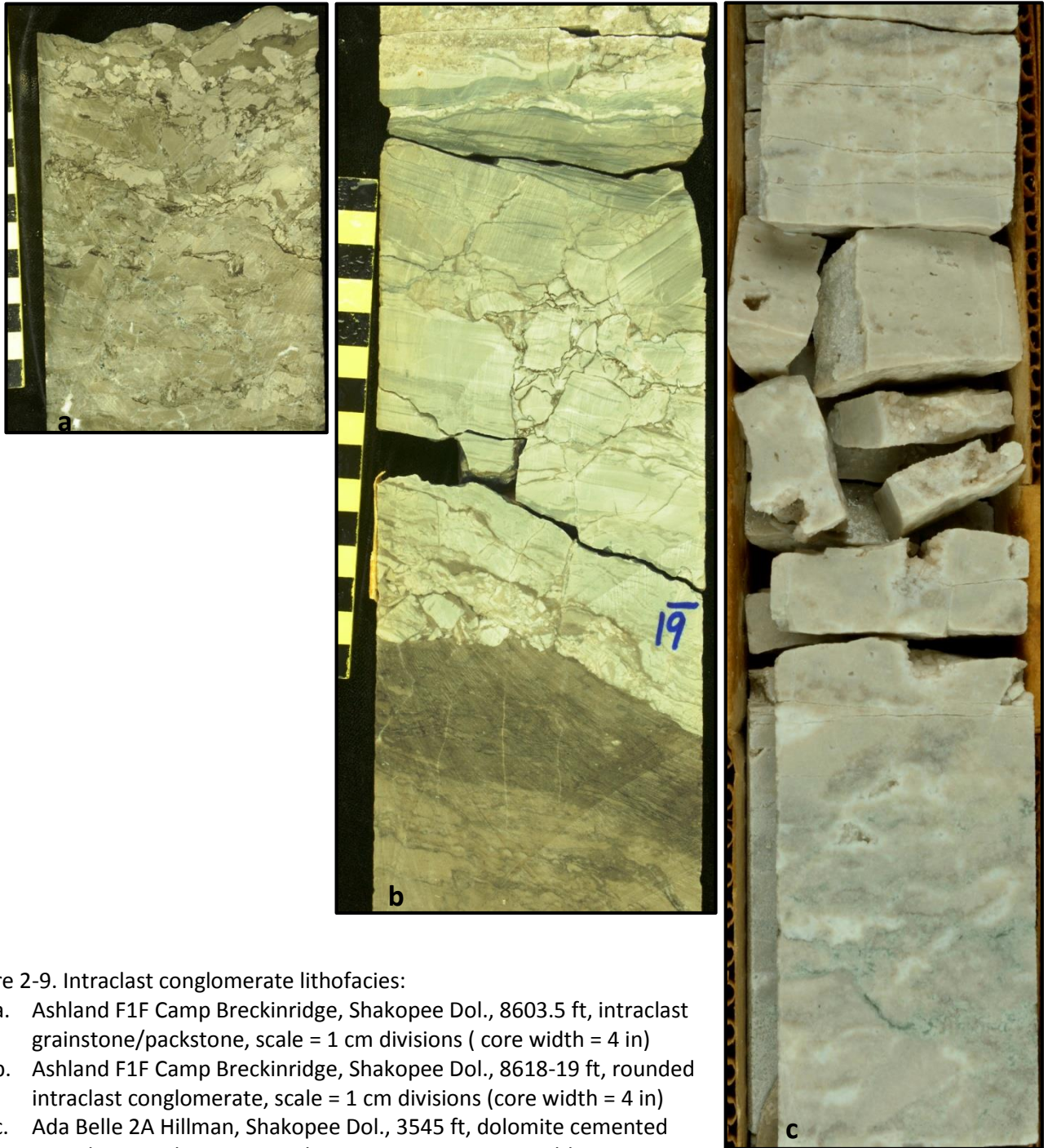


Figure 2-9. Intraclast conglomerate lithofacies:

- a. Ashland F1F Camp Breckinridge, Shakopee Dol., 8603.5 ft, intraclast grainstone/packstone, scale = 1 cm divisions (core width = 4 in)
- b. Ashland F1F Camp Breckinridge, Shakopee Dol., 8618-19 ft, rounded intraclast conglomerate, scale = 1 cm divisions (core width = 4 in)
- c. Ada Belle 2A Hillman, Shakopee Dol., 3545 ft, dolomite cemented intraclast conglomerate, with vuggy porosity, core width = 4 in (10 cm)

overlain by internal sediments. This indicates there was open void space in the breccia to allow early dolomite cements to form, while quartzose internal sediments were still being transported in the karst system. Karst processes create cavernous porosity through dissolution of limestone and dolomite. In this instance, karst solution voids were almost completely filled with internal sediments. Only minor vuggy porosity between breccia clasts was observed near the base of the interval. Dolomite clasts and matrix have minor intercrystalline porosity. Two core plugs were analyzed from the paleokarst matrix dolomite (see Fig. 2-10 for plug hole locations). Porosity was 3.1 percent at 3,520 ft (1072 m), and 3.99 percent at 3,526 ft (1,075 m). Permeability for both of these plugs was below detection levels.

The equivalent post-Knox unconformity is exposed in outcrop in the Valley and Ridge Province (Appalachian Basin) of southwest Virginia (Mussman and Read, 1986; Mussman and others, 1988). They document very similar features in Knox paleokarst cave-fill deposits (angular breccia clasts, quartzose laminated internal sediments). Paleokarst features in southwest Virginia can extend down to 65 m below the unconformity surface (Mussman and Read, 1986).

Paleokarst features were not observed below the unconformity in the E.I. Dupont 1WAD fee core in Jefferson County, Ky. or in the KGS 1 Blau core in Hancock County, Ky. Other shallower Knox cores examined by the author on the Cincinnati Arch lack paleokarst features below the unconformity, so the Trigg County example seems to be rather unique in Kentucky.

Quartz Sandstone

Intervals of sandy dolomite and thin quartz sandstones occur interbedded with dolomite in the upper Knox over much of western Kentucky and southern Indiana. Most of the western Kentucky cores contain beds of quartz sandy dolomite and thin quartz sandstone in the Shakopee or Oneota Dolomite. Sand grains are commonly medium to fine-grained, and well-rounded. These thin sands are typically isolated in thicker dolomite intervals.

Two wells have core from the New Richmond Sandstone interval (previously correlated as Gunter Sandstone), where quartz sandstones are thicker, and stacked into a gross interval over 200 ft (61 m) thick. Most of these sandstones have excellent reservoir properties, and could provide suitable injection zones for CO₂. The Exxon 1 Bell well has a 2 ft (0.6 m) core of dolomitic fine-grained sandstone to sandy dolomite that correlates with the New Richmond. This core at 10,231-33 ft (3,118-19 m) has no matrix porosity, but does contain one partly-cemented vug. It is difficult to interpret depositional environments

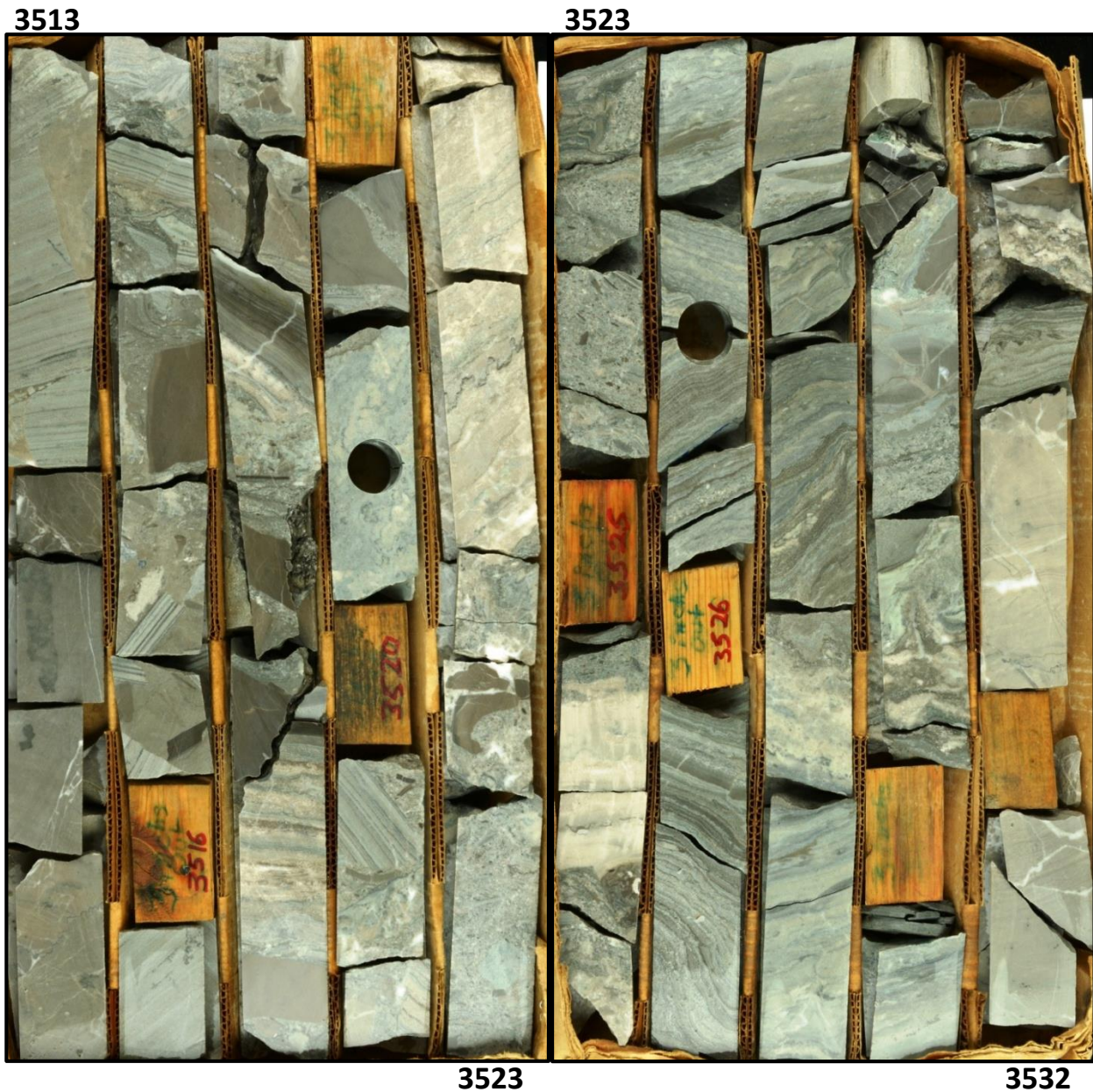


Figure 2-10. Interpreted paleokarst interval below post-Knox unconformity, Ada Belle 2A Hillman, 3,513-3,532 ft (1,071-1,080 m), chaotic mixture of clasts of several different lithologies in matrix of laminated, argillaceous dolomite with variable steep dips. Matrix is interpreted to be internal cave-fill sediments. Paleokarst continues down to 3,541 ft (1079 m). Holes in core are locations of plugs for measurement of porosity and permeability (3,520 ft (1,072 m) and 3,526 ft (1,075 m)). Core width = 2 in (10 cm).

Figure 2-11. Quartz sandstone lithofacies, all from KGS 1 Blan well, New Richmond interval, core width = 4 in (10 cm)

- a. Ripple cross-bedded sandstone with dolomite intraclasts (dark grains), med. grained, 5088-90 ft.
- b. Trough to low-angle cross-bedded sandstone, fine-to med. grained, 5114-16 ft.
- c. Bidirectional ripple cross-bedded quartz sandstone. Opposing dip on cross-bed sets indicates flow reversal, possibly from tidal currents. Sharp, erosional basal contact to dolomite with vuggy porosity, 5108-10 ft.



from an isolated two-foot core, but the presence of sandstone intraclasts and steeper dips suggests a higher energy tidal channel or bar environment.

Whole core of the upper part of the New Richmond sandstone interval was obtained during drilling of the KGS 1 Blan well in 2009, and 20 additional rotary sidewall cores of deeper sandstones were cut prior to Phase 2 injection work as part of this study in 2010. Porosity, permeability, and grain size data for the rotary sidewall cores is included with the whole core descriptions for the Blan well (Plate 2.2).

Quartz sandstones occur in beds up to 6 ft (3 m) thick in the cored interval in the Blan well. Thicker sandstones, up to 12.5 ft (3.8 m) are present below the cored interval as indicated on logs, including formation image logs. Sandstones are commonly cross-stratified, with both ripple and trough cross-bedding (Fig. 2-11). Some sandstones contain coarse sand-sized dolomite intraclasts, suggesting that erosion of carbonate sediments was occurring with sand transport and deposition. One sandstone interval contains ripple cross-bedding with opposing foreset dips (Fig. 2-11c). This “herringbone” cross-bedding is indicative of current reversal, common in tidal environments. Sandstones have some burrow traces, but are not heavily bioturbated in the cored interval.

Sandstones occur interbedded with dolomites containing variable amounts of quartz sand. A sandstone bed at 5,091 ft (1,551.7 m), sharply overlies an erosional contact with stromatolite boundstone below, and fines upward from a coarse-grained lag to medium-grained rippled sandstone. This bed has an abrupt upper contact with a thrombolite boundstone at 5,087 ft (1,550.5 m). These features suggest the sandstone was deposited in a shallow tidal channel.

Two deeper sandstone beds at 5,109.4 ft and 5,116.4 ft (1,557.3 and 1,559.5 m) are interbedded with subtidal grainstones and mudstones. The shallower sandstone has a sharp, possibly erosional base, fines upward from coarse to medium-grained, and is ripple cross-bedded in part. This 3 ft (1 m) unit is interpreted as a tidal channel deposit. The deeper sand is thicker (6 ft; 2 m), and coarsens upward slightly, with a dolomite intraclast lag at the top. It has low-angle to possible hummocky cross-bedding in the lower part, with ripple cross-bedding above. Burrowing increases toward the top of the unit. This sandstone may represent deposition on a subtidal bar or shoal, by storm or tidal currents.

Additional constraints on the depositional setting and origin of these quartz sandstones can be made by examining the vertical stacking and lateral continuity of clastic units. Figure 2-12 is a log cross section for the New Richmond sandstone interval in the Hancock and Breckinridge County area in western Kentucky. This sandstone interval was the best CO₂ injection zone in the KGS Blan test well (Bowersox et al). The KGS Blan well and Langford Oil Knight Brothers wells are about 1.8 miles (2.88 km) apart. The gross interval thins by 60 feet (18.3 m) from west to east. A photoelectric log run in the Blan well was used to identify sandstone (where P_e is < 2.5). A photoelectric log was not run in the older Knight Brothers well, but quartz sands are indicated by higher density porosity (confirmed by sample descriptions). Porous sandstone and tighter dolomite alternate in beds 1-12 ft (0.3-3.7 m) thick. The individual sandstone beds are difficult to correlate between wells on a scale of 1-2 miles (1.6 to 3.2 km), suggesting a depositional setting where sands were limited in their lateral extent, with carbonates adjacent. Sands may have been localized in deeper subtidal areas, between thrombolite mounds. This model would be similar to modern thrombolites and stromatolites growing in the Bahamas, where thrombolites are surrounded and encased in migrating carbonate sand dunes and bars (Feldmann and McKenzie, 1998)

Another example of the same sandstone interval is shown in Figure 2-13 for the northern Kentucky/southeast Indiana area on the Cincinnati Arch. The Knox in this area is too shallow for CO₂ storage, but the New Richmond (Shakopee) sandstone interval is well-developed. The gross interval is thinner than in Hancock/Breckinridge County, and the sands show a similar vertical stacking pattern. Individual sands are interbedded with dolomite, and are difficult to correlate. The lack of lateral continuity indicates the sandstones are not broad sheet-like marine shelf sands, but discontinuous bodies likely deposited in tidal channels, or subtidal shoals or bars, separated by carbonate facies (grainstones or thrombolites).

To summarize, quartz sandstones are interpreted as nearshore subtidal marine facies. Some sandstones have structures consistent with deposition by currents in tidal channels. Other intervals with low-angle cross-bedding may represent storm current deposits on shoals or bars. Sandstones are interbedded with subtidal dolomites. On a larger scale, the clastic-dominated New Richmond interval correlates over a broad area to other wells in Kentucky and southern Indiana (Figs. 2-2, 2-13). This interval represents a period when sand supply to the Knox shelf increased. The source area for quartz sand in the Knox was to

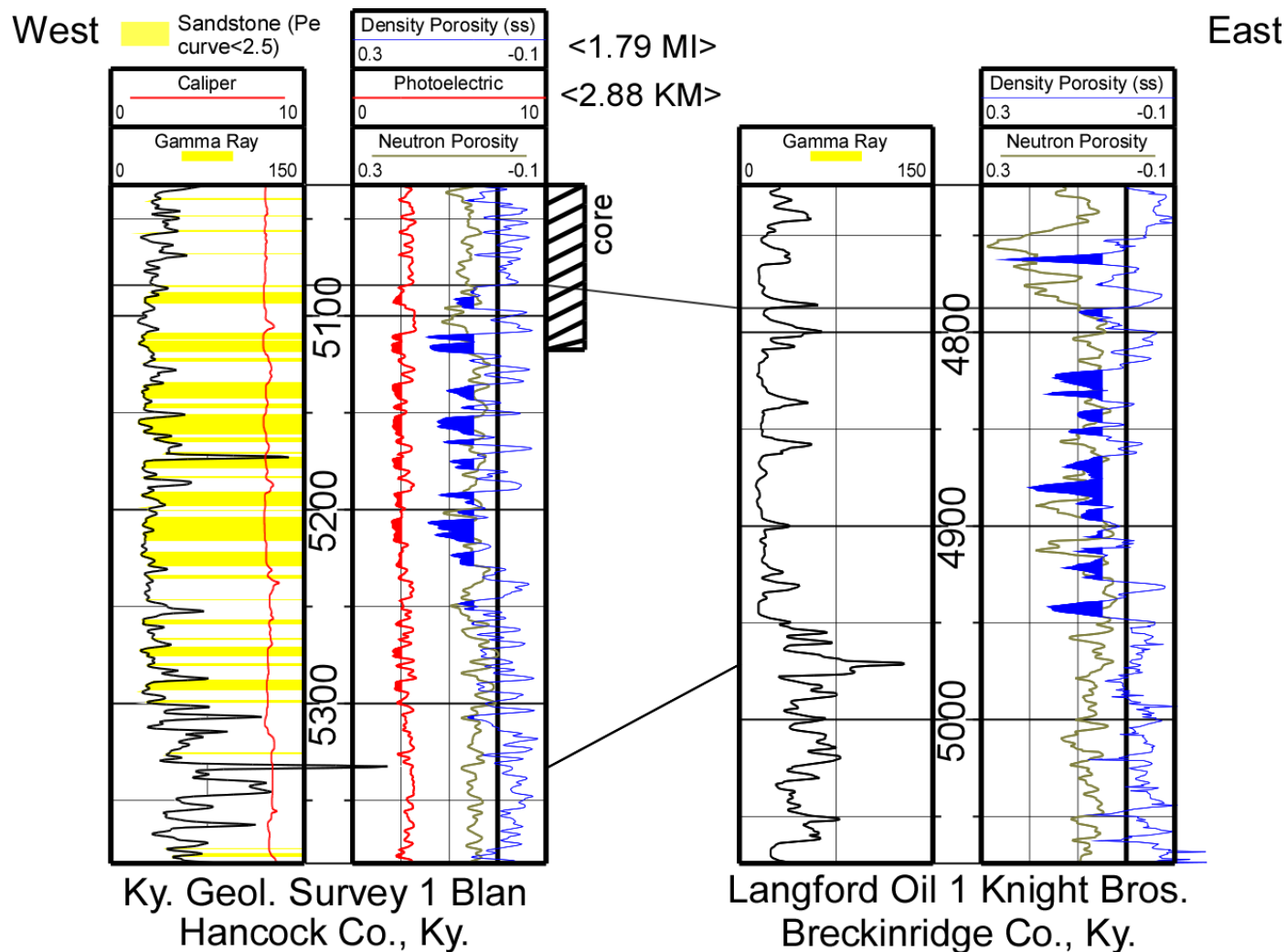


Figure 2-12. Well log cross section of the New Richmond (Shakopee) sandstone interval in the Hancock/Breckinridge County, Ky. area. Sandstone beds are shaded yellow on the KGS 1 Blan gamma ray log where the photoelectric log is < 2.5 (red curve). Density porosity logs (sandstone matrix) are shaded blue for porosity > 5%. Cross section illustrates the interbedded nature of the sandstones and dolomites, good reservoir quality of the sandstones, but the poor correlation of individual sandstone bed between the wells. Wells are 1.8 miles (2.88 km) apart. Photoelectric log not run in Knight Bros. well.

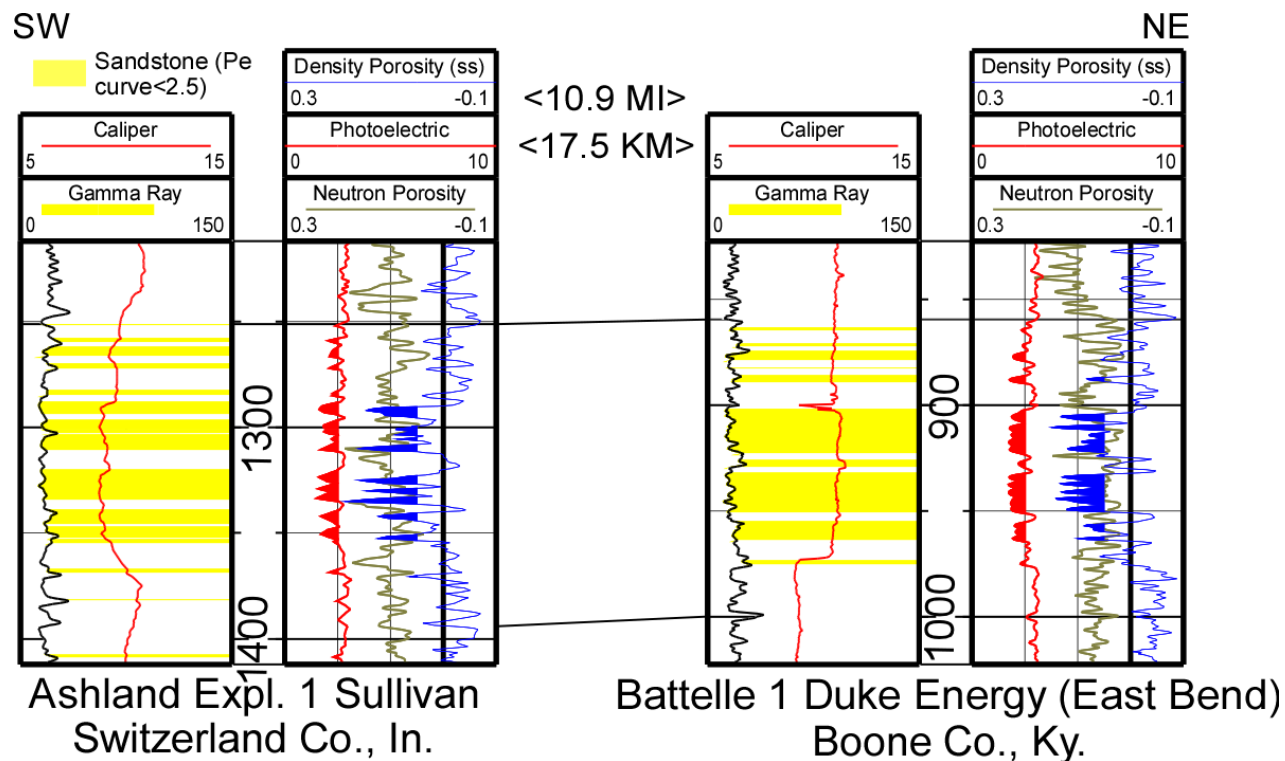


Figure 2-13. Well log cross section of the New Richmond (Shakopee) sandstone interval in the southeast Indiana and northern Kentucky area. This area is on the Cincinnati Arch, and is too shallow for carbon storage in the Knox. These wells are approximately 120 miles (193 km) northeast of the Hancock/Breckinridge County, Ky. wells in Fig. 12. The gross sandstone interval can be correlated across this distance, but individual sandstone beds are difficult to correlate between these wells, about 11 miles (17.5 km) apart.

the north and northwest, where an inner detrital belt existed during Knox carbonate deposition farther south (Derby and others, 2012). This inner detrital belt was composed of nearshore clastic deposits, adjacent to the exposed craton (Runkel and others, 2012). The cause of the increased clastic input is not known, but could include uplift in the source area, or changes in sand transport directions across the shelf. A major drop in sea level is not thought to have been a major control on sand supply, since carbonate sedimentation continued during quartz sand deposition

Depositional Cycles

The lithofacies described previously are frequently stacked vertically to form depositional cycles. In the Knox cores, cycles typically show an upward-shallowing sequence of lithofacies. Cycle boundaries are marked by thin shale partings, and by abrupt, sometimes erosive or stylolitic contacts between intertidal/supratidal laminites and subtidal mudstone or grainstones. Strombolites and mudstone/wackestones represent the deeper subtidal parts of cycles, with stromatolites and intraclast breccias forming the shallower intertidal/supratidal parts. Quartz sandstone core was limited to a few beds in one well, but they appear to be subtidal, and occupy the lower part of cycles.

Cycles are inferred to be generated by eustatic changes in sea level, and if preserved during exposure events, should be regionally correlative. No attempt was made to correlate cycles between wells in this study because the available cores sampled different stratigraphic intervals, and cycles are not readily identified on gamma ray logs in the Knox.

Cyclic peritidal deposition in the Knox and equivalent strata has been documented in numerous other areas (Fritz and others, 2012a; 2012b; Montanez and Read, 1992; Mussman and Read, 1986). This study provides important data to document remarkably similar lithofacies in western Kentucky in the Illinois Basin. The five cores examined are very similar in depositional facies and cyclicity, suggesting depositional environments and potential reservoir facies are present across much of the present-day Illinois Basin.

Knox Reservoir Quality

Three of the five cores examined have porosity and permeability data available, and these data are plotted on the core description sheets (Plates 2.2, 2.1, 2.5; KGS 1 Blan, Dupont 1WAD Fee, and Ada Belle

2A Hillman Iron and Land). To determine if depositional fabric controls reservoir quality, core analysis data were classified by lithofacies using the core descriptions. Porosity and permeability show a large amount of variability for each lithofacies (Fig. 2-14). This suggests that controls other than original depositional facies influence reservoir quality. Despite the scatter in the data, differences between lithofacies can be seen. Quartz sandstones have the best porosity and permeability of all the lithofacies. Sandstone data is primarily from the KGS 1 Blan well, and averages 8.8 percent porosity and 193.9 millidarcies permeability for 19 samples (Table 2). These samples are from the New Richmond interval (formerly interpreted as Gunter Sandstone).

Of the dolomite lithofacies, coarser-grained rocks such as grainstones and breccias have the best reservoir quality. Finer-grained mudstones and stromatolites have lower porosity and permeability. Larger-scale vuggy porosity is not represented in this data set, since it is based on 1-inch core plugs. Many of the high permeability intervals in Knox dolomites are characterized by large vuggy porosity, not sampled in these cores.

Table 2-2. Average porosity and permeability for lithofacies identified in the KGS 1 Blan, Ada Belle 2A Hillman, Dupont 1WAD Fee cores.

Lithofacies	Ave. Permeability (md)	Ave. Porosity (percent)	No. of samples
Breccia	4.3	5.4	11
Grainstone/packstone	14.1	4.2	15
Mudstone/wackestone	0.05	2.8	60
Stromatolite	0.59	3.2	16
Quartz Sandstone	193.9	8.8	19
Thrombolite	0.16	3.8	15

In addition to lithofacies, core data was plotted by burial depth to determine if depth is related to reservoir quality. These plots (Fig. 2-15) show no correlation with depth for porosity or permeability. However, core data for the two deepest wells (Ashland F1F Camp Breckinridge at 8,600 ft, and Exxon 1 Bell at 10-12,000 ft) are not available. These cores appear to have much lower porosity, which may be related to greater burial depth.

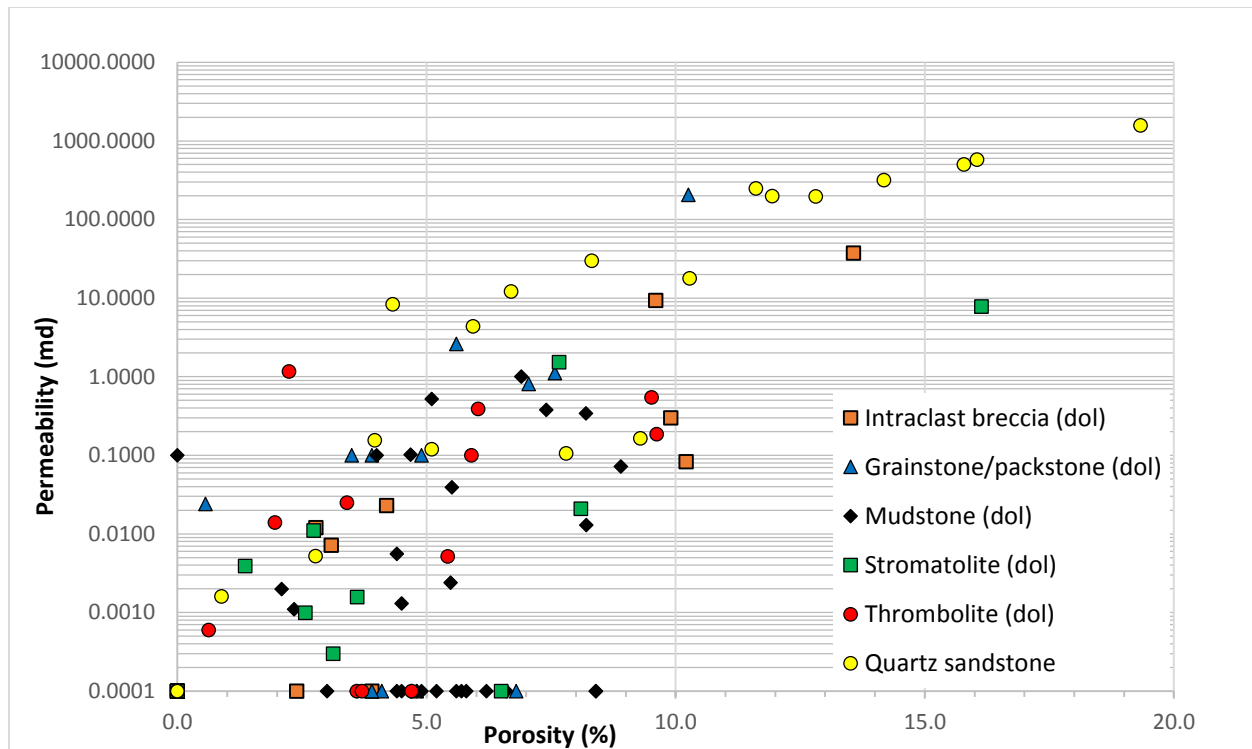


Figure 2-14. Plot of core porosity and permeability data for three Knox wells classified by lithofacies (n=136). Lithofacies includes five dolomite lithologies and quartz sandstone. There is considerable variability in reservoir quality for each lithofacies. Overall, quartz sandstones (mostly from the KGS 1 Blan well) show the best and most consistent reservoir properties. Of the 136 analyses plotted, 73 have permeability below instrument detection level, and were assigned a value of 0.0001 md, and fall on the x-axis.

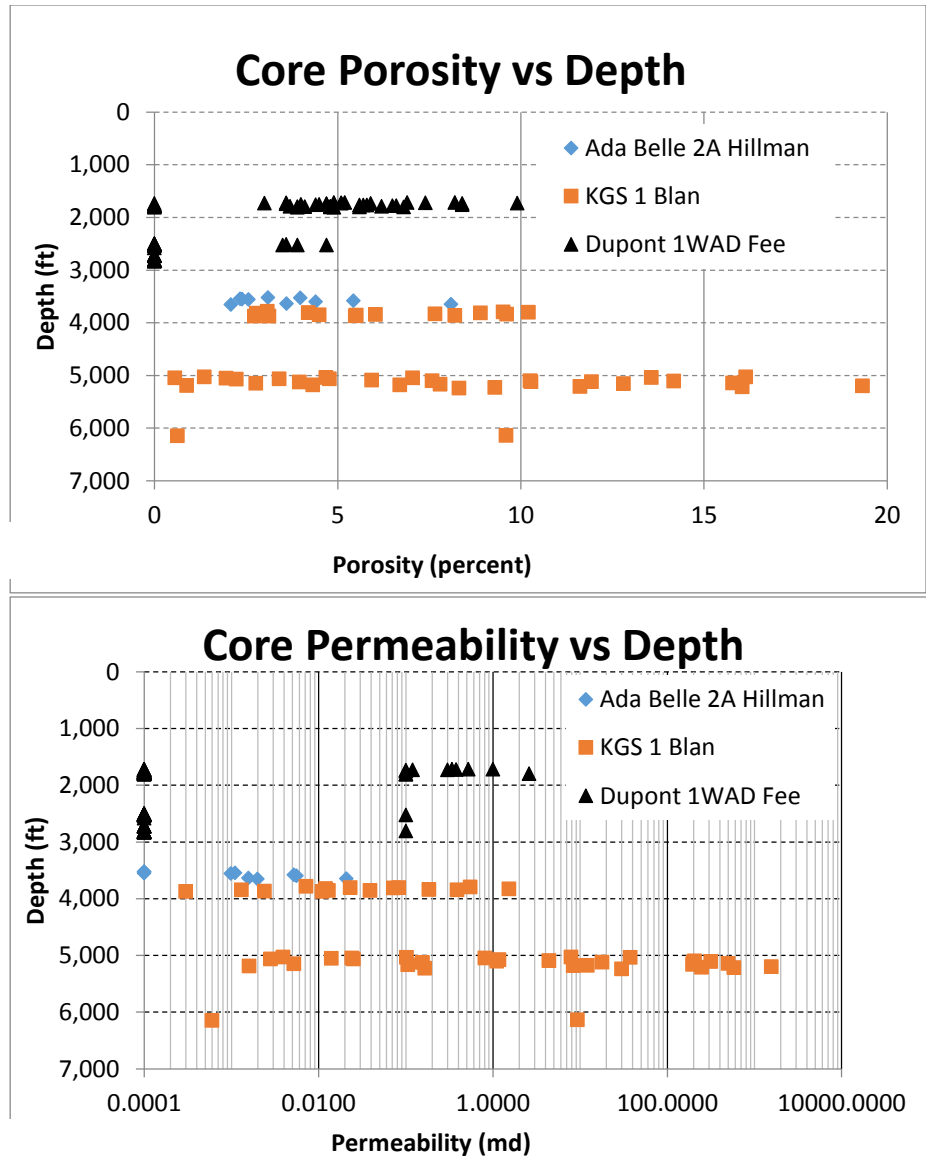


Fig. 2.15a

Fig. 2.15b

Figure 2-15a and b: Plots of Knox porosity and permeability versus depth for three cored wells. Porosity and permeability is not related to burial depth in these cores. Data is not available for the two deeper cores (8,000-12,000 ft).

Summary

Key interpretations from the core descriptions are that depositional facies in the Knox are very similar across western Kentucky. Knox dolomites consist of cyclic, shallow restricted marine subtidal to supratidal deposits. Microbial and algal boundstones (stromatolites and thrombolites) are a significant component of these rocks. Significant changes in Knox dolomite lithofacies do not occur across western Kentucky. Porosity occurs in both dolomites and sandstones, with higher average porosity and

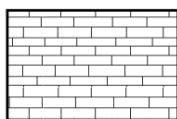
permeability in sandstones. Core analysis data indicates dolomite reservoir quality varies significantly for a given lithofacies, and is controlled more by the dolomitization process than by primary depositional facies. Based on the cores examined, which ranged in depth from 1,700 ft (518 m) to over 12,000 ft (3,658 m) visible dolomite porosity decreases with depth. Porosity in Knox sandstones is more consistent than in dolomites, and suitable reservoir quality for CO₂ injection occurs to depths of at least 5,200 ft (1,585 m), as seen in the KGS 1 Blan well.

Plates 2.1 – 2.5 Knox Core Descriptions

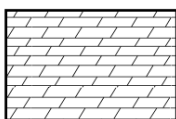
Knox core description sheets for the western Kentucky cores are included below as Plates 2.1 through 2.5. The legend for lithology patterns and graphics used in the descriptions is shown in Figure 2-16. Geophysical log data and core analysis data are plotted with the core descriptions where available.

Figure 2-16: Legend for Knox Core Descriptions Plates 2.1–2.5

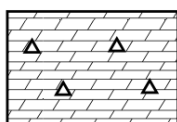
Lithology Patterns



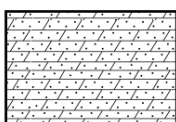
limestone



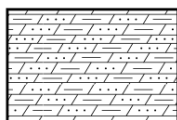
dolomite



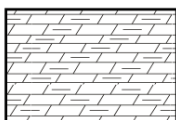
cherty dolomite



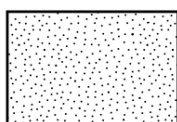
sandy dolomite



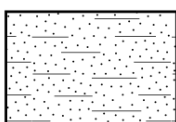
sandy argill. dolomite



argill. dolomite



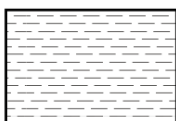
sandstone



argill. sandstone



siltstone



shale

Porosity Types

V	Vuggy porosity
MV	Micro-vuggy porosity (mm-scale)
IC	Intercrystalline dolomite porosity
M	Moldic porosity
IG	Intergranular porosity

Cycles

Upward-shallowing
depositional cycle



Grain Types



intraclasts



echinoderm



bryozoan



brachiopod



gastropod



stromatoporoid



coated grain

Other Features



chert



stromatolite



thrombolite



dessication (mud) cacks



open or partly-open fracture



healed fracture



vug



stylolite



bioturbation



ripple cross-bedding



trough cross-bedding

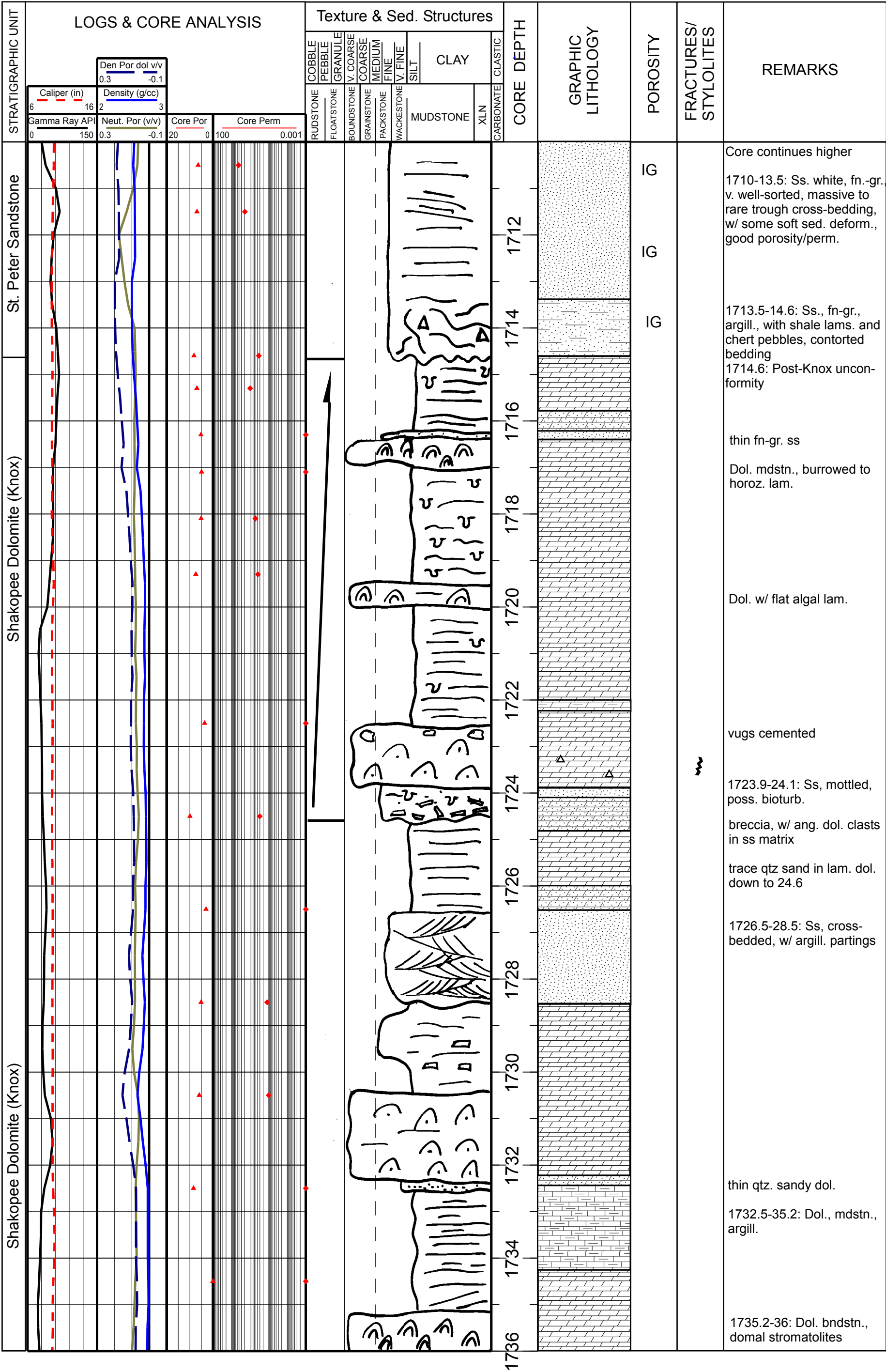
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WELL: E.I. Dupont No. 1WAD E.I. Dupont
PERMIT: 24576
COUNTY: Jefferson Co., Ky. ELEVATION: 452 ft
CARTER COORD.: 10-U-44

DEPTH: 1710–1736 ft
SHEET 1 OF 7
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft



Kentucky Geological Survey
UNIVERSITY OF KENTUCKY

CARTER COORD.: 10-U-44

VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT		LOGS & CORE ANALYSIS										Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/STYLOLITES	REMARKS													
Shakopee Dolomite (Knox)		Caliper (in)		Density (g/cc)		Gamma Ray API		Neut. Por (v/v)		Core Por		Core Perm		COBBLE		PEBBLE		GRANULE		V. COARSE		COARSE		MEDIUM		FINE		WACKSTONE		V. FINE		SILT		CLAY		CARBONATE		CLASTIC	
		6	16	2	3	0	150	0.3	-0.1	20	0	100	0.001	RUDSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE	MUDSTONE	XLN	MUDSTONE	XLN																
Shakopee Dolomite (Knox)																						1762		M			Core 3												
																						1738						Qtz. ss and dol. in core rubble											
																						1740		Interval not cored															
																						1742																	
																						1744																	
																						1746																	
																						1748																	
																						1750			Core 4														
																						1752		Sharp erosional contact overlain by cross-bedded qtz ss., fills mud cracks Dol., buff, horiz. lam., algal bndstn. at top, scattered cm-scale chert nodules															
																						1754			Qtz. ss, sh. w/ dol. intra-clast lag overlies sharp erosional contact.														
																						1756		Dol., mdstn., buff, argill. at base, w/ wispy styl.															
																						1758			IC?														
																						1760																	
																						1762																	

Kentucky Geological Survey
UNIVERSITY OF KENTUCKY

DEPTH: 1762-1788 ft
SHEET 3 OF 7
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	LOGS & CORE ANALYSIS										Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS																		
	Caliper (in)		Density (g/cc)		Gamma Ray API	Neut. Por (v/v)	Core Por	Core Perm	COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY	CARBONATE	CLASTIC																							
	6	16	2	3																																							
	Den Por dol v/v		MUDSTONE	XLN	RUDSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE	MUDSTONE	XLN	CARBONATE	CLASTIC																													
	0.3	-0.1																																									
	Gamma Ray API	Neut. Por (v/v)	Core Por	Core Perm	0	150	0.3	-0.1	20	0	100	0.001																															
Shakopee Dolomite (Knox)																						Shakopee Dolomite (Knox)																					
Log plots showing Caliper (in), Density (g/cc), Gamma Ray API, Neut. Por (v/v), Core Por, and Core Perm.																						Texture and sedimentary structure logs showing various sedimentary features like mudstone, floatstone, boundstone, grainstone, packstone, wackstone, silt, clay, and carbonates/clastics.																					
1788																						1788																					
1786																						1786																					
1784																						1784																					
1782																						1782																					
1780																						1780																					
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1770																						1770																					
1768																						1768																					
1766																						1766																					
1764																						1764																					
1762.6-64: Dol., thrombolite, sharp up. contact w/ argil. dol. mudstn.																						1762.6-64: Dol., thrombolite, sharp up. contact w/ argil. dol. mudstn.																					
Dol. buff, thin parallel lam., grades up to thrombolite																						Dol. buff, thin parallel lam., grades up to thrombolite																					
Ss, fn-md. gr., argill., sharp lower contact																						Ss, fn-md. gr., argill., sharp lower contact																					
Dol., intraclast cgl., coarse to pebble-size clasts, in micrite matrix, w/ poss. thin thrombolite., scattered qtz. sand in upper foot, poss. infill from overlying bed																						Dol., intraclast cgl., coarse to pebble-size clasts, in micrite matrix, w/ poss. thin thrombolite., scattered qtz. sand in upper foot, poss. infill from overlying bed																					
Steeper dip																						Steeper dip																					
Dol., buff, burrow-mottled																						Dol., buff, burrow-mottled																					
1775-76: core rubble, dol. w/ qtz. ss.																						1775-76: core rubble, dol. w/ qtz. ss.																					
1776-78: Dol., irreg. lam. to clotted, thrombolite																						1776-78: Dol., irreg. lam. to clotted, thrombolite																					
1778-80.6: Dol.thrombolite bndstn., clotted texture w/ internal sed.																						1778-80.6: Dol.thrombolite bndstn., clotted texture w/ internal sed.																					
Erosional contact overlain by ss.																						Erosional contact overlain by ss.																					
Sharp erosional contact overlain by ss. and sandy dol. Ss. partly silicified.																						Sharp erosional contact overlain by ss. and sandy dol. Ss. partly silicified.																					
Dol., buff, parallel lam., hor. to low angle, poss. tidal current lam.																						Dol., buff, parallel lam., hor. to low angle, poss. tidal current lam.																					
Shale parting along stylolite, erosional contact.																						Shale parting along stylolite, erosional contact.																					
Dol.-cmdtd. vugs, partly open, poss. anhyd. replacement																						Dol.-cmdtd. vugs, partly open, poss. anhyd. replacement																					

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DEPTH: 1788-2500 ft
SHEET 4 OF 7
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	LOGS & CORE ANALYSIS										Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS	
	Caliper (in)		Density (g/cc)		Gamma Ray API	Neut. Por (v/v)	Core Por	Core Perm	COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY	CLASTIC							
	6	16	2	3																						
MUDSTONE		XLN	CARBONATE																							
Shakopee Dolomite (Knox)																					V			Dol. med. brown, lam. w/ cm. scale vugs filled w/ int. sed., poss. thrombolite., no por.		
																										Dol. lt. buff, thin parallel lam., tidal?
																										Ss and sandy dol. over shale parting
																										Dol. coarse grnstrn. w/ mottled text.,pyrite along bedding planes and fracs.
																							Dol. cmted. vugs, elongate w/ bedding			
																							Dol v. fn. grnstrn., lam. w/ small-scale cross-bedding			
																							1805.5-05.8: Dol. breccia, exposure horizon w/ chert between clasts, porous, w/ vuggy and intercrys. por.			
																							Shaly laminations			
																							Base Core 5			
Shakopee Dolomite (Knox)																					V			Top Core 6		
																										Dol. cm. thick lam., white chalky micro-por. chert parallel to bedding

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WELL: E.I. Dupont No. 1WAD E.I. Dupont DEPTH: 2500–2526 ft
 PERMIT: 24576 SHEET 5 OF 7
 COUNTY: Jefferson Co., Ky. ELEVATION: 452 ft DESCRIBED BY: D. C. Harris
 CARTER COORD.: 10-U-44 VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT		LOGS & CORE ANALYSIS										Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS	
												COBBLE					CLAY										CLASTIC
												PEBBLE		GRANULE			MUDSTONE		XLN								
												RODSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE	SILT									
		Caliper (in)	Density (g/cc)	Gamma Ray API	Neut. Por (v/v)	Core Por	Core Perm	RODSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE	MUDSTONE	XLN	CARBONATE											
		6 16	2 3	0 150	0.3 -0.1	20 0	100 0.001																				
Shakopee Dolomite (Knox)																						2502				cm-scale vugs cmtd. by saddle dol.	
																						2504					
																						2506					Dol., med. brown, sl. argill., nod. to burrow-mottled, tight.
																						2508					
																						2510					3-inch sandy dol. at base, sharp lower contact
																						2512					
																						2514					2514-14.5: Dol., med. brown, current lam., sl. argill. 2514.5-15: core missing
																						2516					6-inch cross-bedded ss., dol. and argil.
																						2518					vert. burrows or dessication cracks sharp contact
																						2520					Dol., algal bndstn., irreg. lam. w/ interbedded burrowed dol.
Shakopee Dolomite (Knox)																						2522		Dol., thin lam., grnsth.-pksth., ripple and low-angle cross bedded			
																						2524					
																						2526		Dol., thin-lam. to low-angle ripple lam., sharp upper contact			

WELL: E.I. Dupont No. 1WAD E.I. Dupont
PERMIT: 24576
COUNTY: Jefferson Co., Ky. ELEVATION: 452 ft
CARTER COORD.: 10-U-44

DEPTH: 2526–2726.8 ft
SHEET 6 OF 7
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	LOGS & CORE ANALYSIS								Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS												
									COBBLE					PEBBLE										GRANULE					CLAY						
	Caliper (in)					Density (g/cc)					Den Por dol v/v					MUDSTONE								CLASTIC											
	Gamma Ray API					Neut. Por (v/v)					Core Por					Core Perm								XLN					CARBONATE						
	0 150					0.3 -0.1					20 0					100 0.001																			
Shakopee Dolomite (Knox)																			2526					2526-29: Dol., med-brown, flat pebble cgl., pebble to cobble-size, micrite matrix, poss. mudcracks on bedding plane at 2527											
																			2528																
Shakopee Dolomite (Knox)																			2530					2529-31: Dol. med-brown, argill., w/ wispy styl., horoz. lam. w/ burrows, few dol.-cntd. vugs- no open vugs											
																			2532																
Oneota Dolomite (Knox)																			2532					Core 7											
																			2576																
Oneota Dolomite (Knox)																			2578					Dol., buff, mudstn., cherty, w/ rare dol. lined vugs											
																			2578																
Oneota Dolomite (Knox)																			2716					Core 8											
																			2718																
Oneota Dolomite (Knox)																			2720					stylolite wrapped around chert nodule, w/ iron stain											
																			2722																
Oneota Dolomite (Knox)																			2724					2717.5-26.8: Dol., buff, mudstn. to wkstn., horiz. lam., w/ abund. burrows											
																			2726																
Oneota Dolomite (Knox)																			2728					Scattered chert nodules											
																			2728																
Oneota Dolomite (Knox)																			2728					from 2722 to 26.8 has scattered open vugs lined with saddle dol cement., dol. matrix is tight.											
																			2728																
Oneota Dolomite (Knox)																			2728					vugs round to elongate along bedding.											
																			2728																
Oneota Dolomite (Knox)																			2728					Bottom core 8											
																			2728																

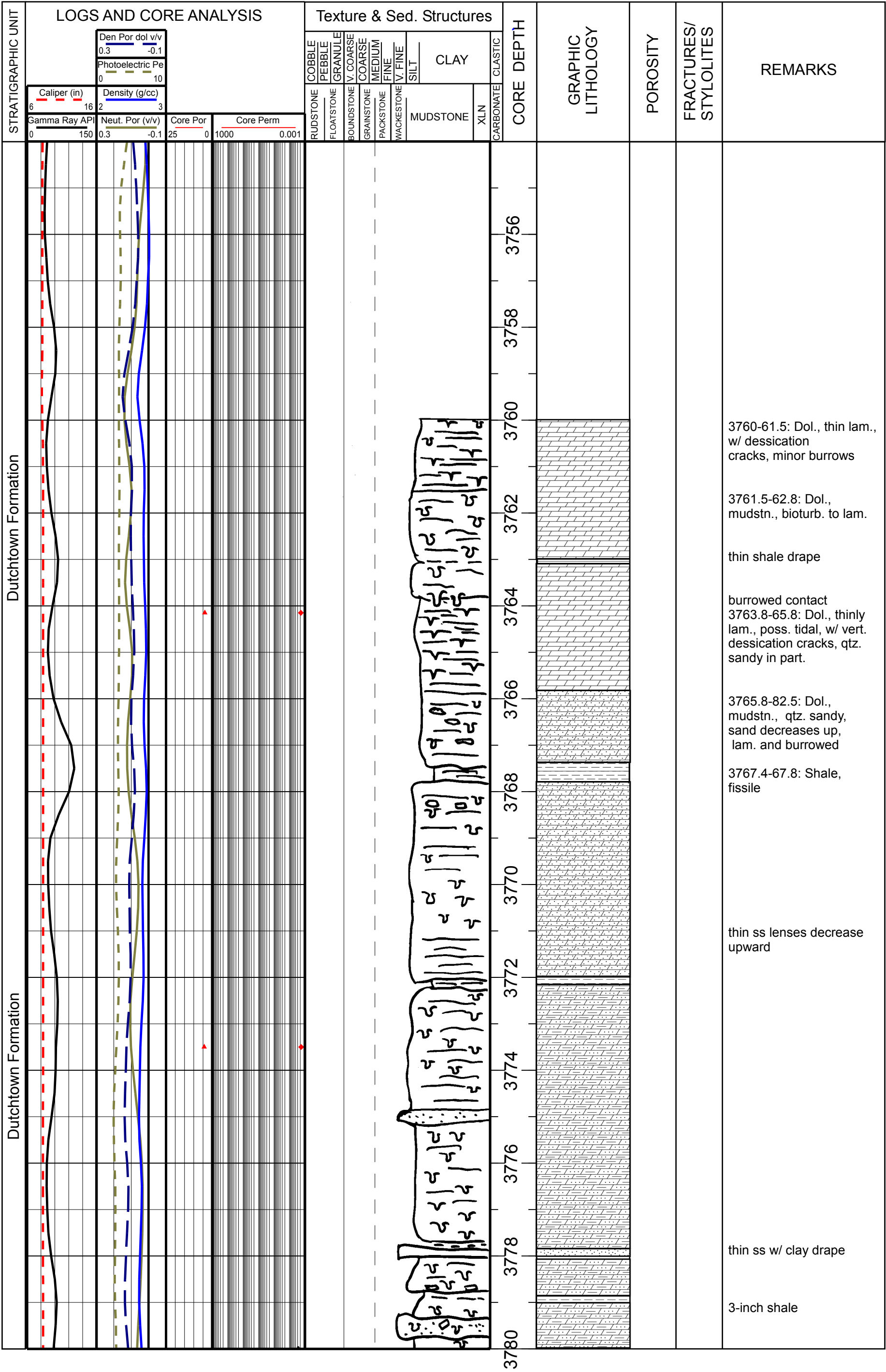
DEPTH: 2804-2830 ft
SHEET 7 OF 7
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

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[illegible]

WELL: Kentucky Geological Survey No. 1 Blan, M.
PERMIT: 104925
COUNTY: Hancock, Ky. ELEVATION: 620 ft
CARTER COORD.: 12-P-34

DEPTH: 3760–3780 ft
SHEET 1 OF 11
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft



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DEPTH: 3780-3806 ft
SHEET 2 OF 11
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

[illegible]

Plate 2.2.2

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WELL: Kentucky Geological Survey No. 1 Blan, M. DEPTH: 3806–3832 ft
 PERMIT: 104925 SHEET 3 OF 11
 COUNTY: Hancock, Ky. ELEVATION: 620 ft DESCRIBED BY: D. C. Harris
 CARTER COORD.: 12-P-34 VERTICAL SCALE: 1 in = 2 ft

[illegible]

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WELL: Kentucky Geological Survey No. 1 Blan, M.
 PERMIT: 104925
 COUNTY: Hancock, Ky. ELEVATION: 620 ft
 CARTER COORD.: 12-P-34

DEPTH: 3832-3858 ft
SHEET 4 OF 11
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	LOGS AND CORE ANALYSIS										Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS																																			
	Caliper (in)		Density (g/cc)		Gamma Ray API	Neut. Por (v/v)	Core Por	Core Perm	COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY	CLASTIC																																									
	6	16	2	3																																																								
	0	150	0.3	-0.1	25	0	1000	0.001	RUDSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKESTONE	MUDSTONE	XLN	CARBONATE																																											
Shakopee Dolomite (Knox)																																																			Core depths 1 ft deeper than log depth									
											Shakopee Dolomite (Knox)										Shakopee Dolomite (Knox)																																							

Kentucky Geological Survey
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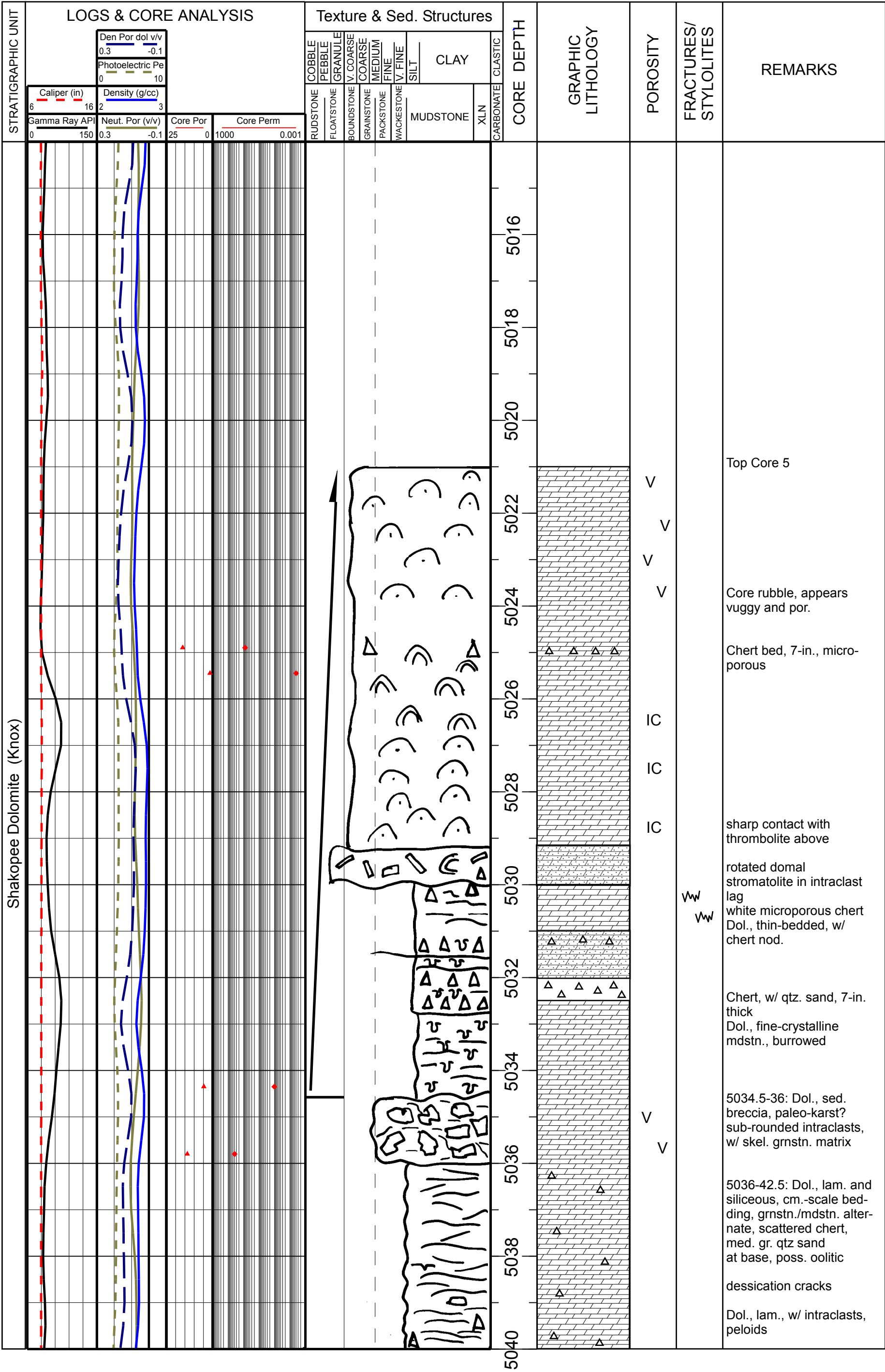
DEPTH: 3858-3884 ft
SHEET 5 OF 11
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	LOGS AND CORE ANALYSIS							Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLITES	REMARKS			
	Caliper (in)		Density (g/cc)		Gamma Ray API	Neut. Por (v/v)	Core Por	Core Perm	COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT						CLAY	CLASTIC	
	6	16	2	3																					
	0	150	0.3	-0.1	25	0	1000	0.001	RUDSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE	MUDSTONE	XLN	CARBONATE								
Shakopee Dolomite (Knox)																		3858							
																		3860							
																		3862							
																		3864							
																		3866							
																		3868							
																		3870							
																		3872							
																		3874							
																		3876							
Shakopee Dolomite (Knox)																		3878							
																		3880							
																		3882							
																		3884							

WELL: Kentucky Geological Survey No. 1 Blan, M.
PERMIT: 104925
COUNTY: Hancock, Ky. ELEVATION: 620 ft
CARTER COORD.: 12-P-34

DEPTH: 5021–5040 ft
SHEET 6 OF 11
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

Plate 2.2.6



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WELL: Kentucky Geological Survey No. 1 Blan, M.
 PERMIT: 104925
 COUNTY: Hancock, Ky. ELEVATION: 620 ft
 CARTER COORD.: 12-P-34

DEPTH: 5040–5066 ft
 SHEET 7 OF 11
 DESCRIBED BY: D. C. Harris
 VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	LOGS & CORE ANALYSIS										Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS
	Caliper (in)		Density (g/cc)		Gamma Ray API	Neut. Por (v/v)	Core Por	Core Perm	COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY	CLASTIC						
	6	16	2	3																					
	0	150	0.3	-0.1	25	0	1000	0.001	RUDSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE	MUDSTONE	XLN	CARBONATE								
Shakopee Dolomite (Knox)																					5042		V		5042.5-50: Dol., chert common, thin-bed., sed. breccia in pt. w/ dol. clasts, chalky microporous chert, abund. fenestral vuggy por., lam., w/ poss. dessication cracks Dol., cherty, breccia intervals, some silicified. Chert is chalky, microporous Dol., rounded intraclast breccia, w/ dol. spar cmt. sharp erosional upper contact to qtz. sandy dol. Sh., thin parting capping intraclast pel. pkstn./grnstrn.
																					5052		V		
																					5058		V	VW	
																					5062		V	VW	
																					5064				
																					5068				
																					5072				
																					5076				
																					5080				
																					5084				

Plate 2.2.7

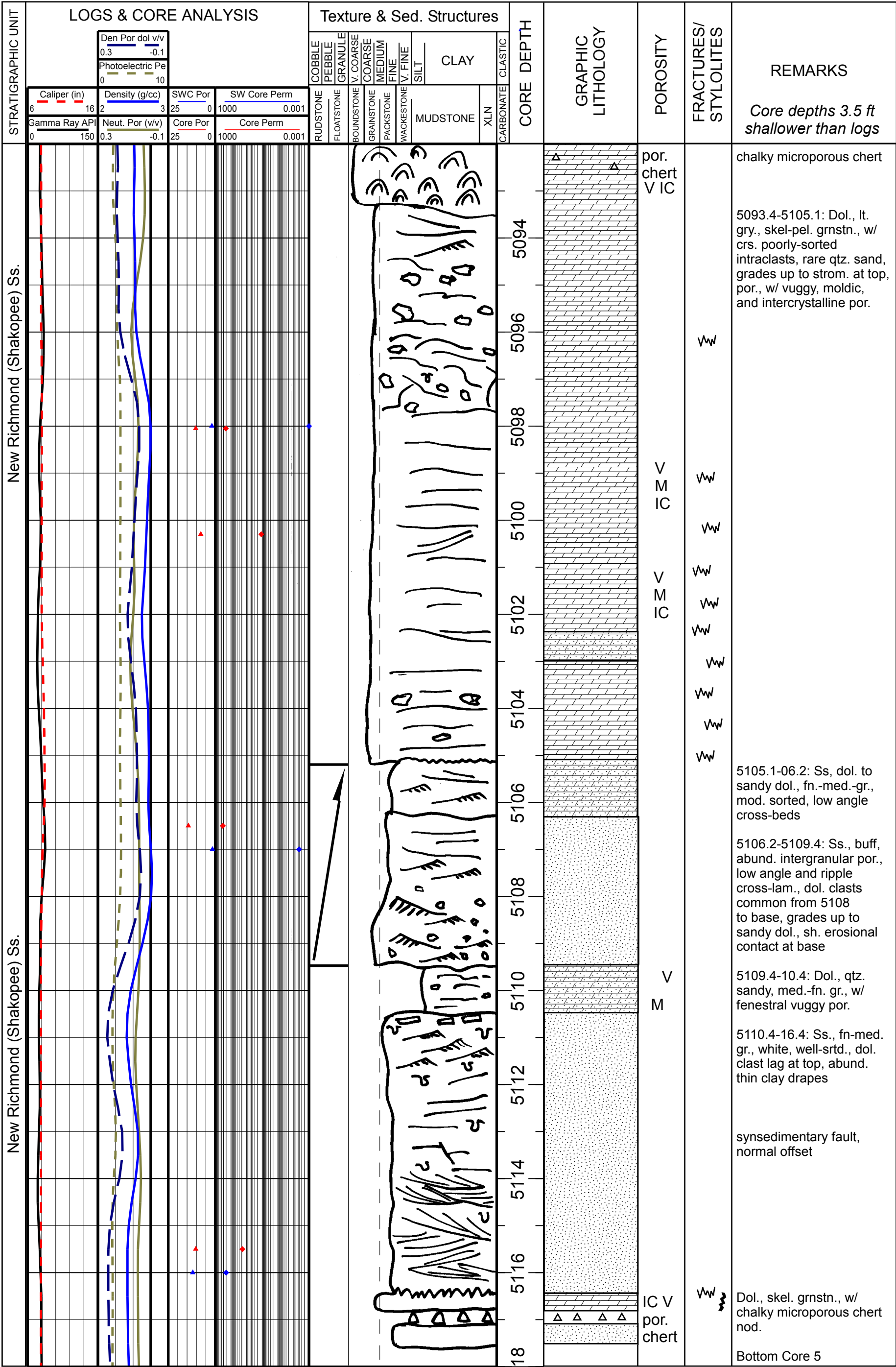
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WELL: Kentucky Geological Survey No. 1 Blan, M.
 PERMIT: 104925
 COUNTY: Hancock, Ky. ELEVATION: 620 ft
 CARTER COORD.: 12-P-34

DEPTH: 5066-5092 ft
 SHEET 8 OF 11
 DESCRIBED BY: D. C. Harris
 VERTICAL SCALE: 1 in = 2 ft

[illegible]

WELL: Kentucky Geological Survey No. 1 Blan, M. DEPTH: 5092–5117.5 ft
PERMIT: 104925 SHEET 9 OF 11
COUNTY: Hancock, Ky. ELEVATION: 620 ft DESCRIBED BY: D. C. Harris
CARTER COORD.: 12-P-34 VERTICAL SCALE: 1 in = 2 ft



WELL: Kentucky Geological Survey No. 1 Blan, M.
PERMIT: 104925
COUNTY: Hancock, Ky. ELEVATION: 620 ft
CARTER COORD.: 12-P-34

DEPTH: 5124-5235 ft (sidewall cores)
SHEET 10 OF 11
DESCRIBED BY: Core Labs
VERTICAL SCALE: 1 in = 10 ft

STRATIGRAPHIC UNIT	LOGS & SIDEWALL CORE ANALYSIS						Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS				
	Caliper (in)		Density (g/cc)		SWC Por	SW Core Perm	COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY						CLASTIC			
	Gamma Ray API		Neut. Por (v/v)																				MUDSTONE	XLN	CARBONATE
	0 150		0.3 -0.1																						
New Richmond (Shakopee) Ss.																									

Rotary Sidewall Cores

5124: Sandstone, med. gr., sl. calcareous, shaly streaks

5139: Sandstone, med. gr.

5147: Sandstone, fine-med. gr., sl. dolomitic

5155: Sandstone, med. gr.

5165: Sandstone, v. fn.-gr., oolitic

5168: Dolomite, crystalline perm.=0.0003 md.

5175: Sandstone, fine-med. gr.

5178: Sandstone, fine-med. gr., sl. dolomitic

5187: Sandstone, fine-med. gr., sl. dolomitic, w/ shaly streaks

5195: Sandstone, med. gr., vuggy porosity, perm=1570 md.

5201: Sandstone, fn. gr., chalky, oolitic, no perm. data

5207: Sandstone, fn.-med. gr.

5213: Sandstone, med. gr.

5219: Sandstone, v. fn.- fn gr., dolomitic, perm. below detection limit

5227: Sandstone, v. fn. gr., foss., sl. dolomitic

5235: Sandstone, fn.-med. gr.



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[illegible]

WELL: Exxon No. 1 Bell, Jimmy
PERMIT: 29845
COUNTY: Webster Co., Ky. ELEVATION: 395 ft
CARTER COORD.: 23-N-24

DEPTH: 9468.7–9479 ft
SHEET 1 OF 3
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	GEOPHYSICAL LOGS				Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS					
					COBBLE		PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT						CLAY	CLASTIC			
	RUDSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKESTONE																MUDSTONE	XLN	CARBONATE
	Caliper (in) 6 16		Gamma Ray (API) 0 150		Density (g/cc) 2 3																			
Shakopee Dolomite (Knox)															9468					Core is approx 125 below main Rough Creek fault cut at 9343 ft.				
															9468					9468.7-79: Dol., dk. gry., skel. wkstn./pkstn., tectonic breccia in pt., steep dip, 45-60 deg., abund. fracs. healed by dol., no porosity				
															9470					9471-71.7: Dol., mottled, poss. thrombolite				
															9472					breccia				
															9474					thin grnstn.				
															9476					fault breccia; truncates stylolites				
															9478					fractures healed w/ dol. cmt.				
															9480					9477.8-79: core rubble				

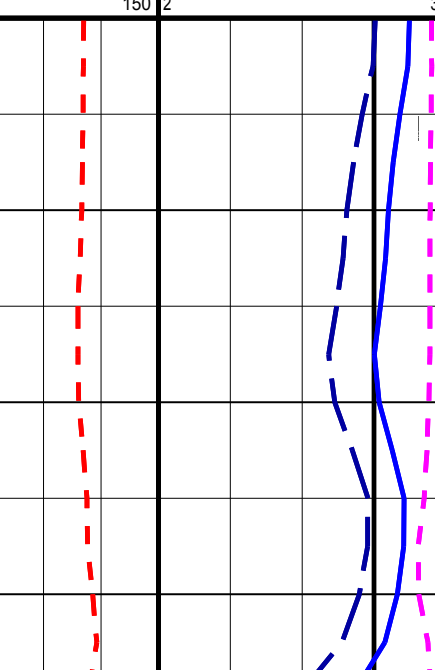
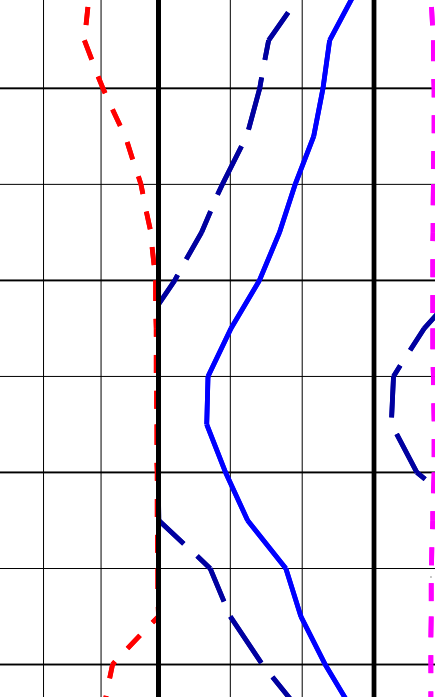
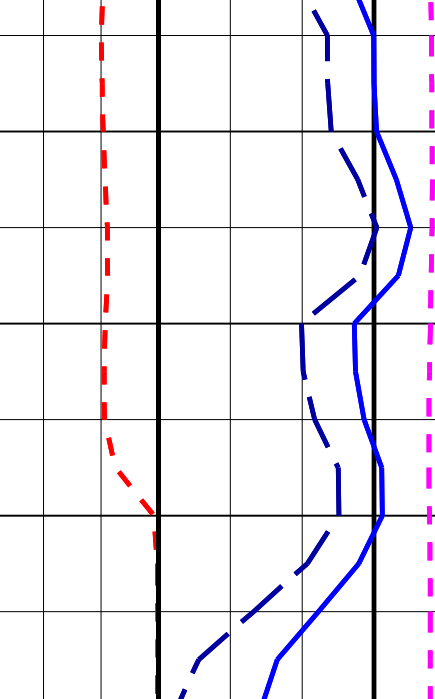
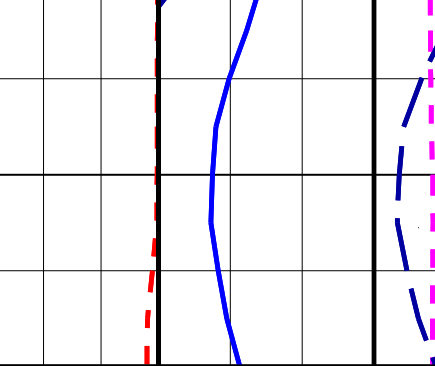
WELL: Exxon No. 1 Bell, Jimmy
PERMIT: 29845
COUNTY: Webster Co., Ky. ELEVATION: 395 ft
CARTER COORD.: 23-N-24

DEPTH: 10,231–12,388 ft
SHEET 2 OF 3
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

STRATIGRAPHIC UNIT	GEOPHYSICAL LOGS				Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS								
	Caliper (in)		Sonic (ms/ft)		COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY						CLASTIC							
	Density Porosity (dol matrix, v/v)		RUDSTONE	FLOATSTONE																	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE	MUDSTONE	XLN	
	Density (g/cc)																										CARBONATE
	Gamma Ray (API)																										
	6	16	140	40																							
	0	150	2	3																							
New Richmond Ss. (Knox)															10230		V	vw	10231-33: Ss, dolomitic, fn. gr., poorly-sorted, w/ chert and ss intraclasts, chert bands replace ss, cmtd. by dol., 45 deg. dip at base. One partly-cmtd. vug.								
															10232												
															10233												
															10234												
Shakopee/Oneota Dol. contact (Knox)															10444		w	2 ft of core missing	10443-447: Dol., dk. gry., w/ abund. dol.-healed fractures. Some fracs. breccia-filled. No vis. porosity.								
															10446												
															10448												
															10449												
Potosi Dol. (Copper Ridge) (Knox)															12012		M	vw	12011-15: Dol. lt. gry., mottled, grnstr., poss. oolitic, grains poorly preserved. Dol. is coarsely-crystalline. Moldic porosity w/ small vugs. Dip of styl. suggests cross-bedding. Anhydrite vug near base.								
															12014												
															12016												
															12018												
Potosi Dol. (Copper Ridge) (Knox)															12384		M	vw	12384-88: Dol., bndstn., thrombolite w/ clotted texture, anhydrite cmt. No porosity.								
															12386												
															12388												
															12390												

DEPTH: 12,388–12,414 ft
SHEET 3 OF 3
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 2 ft

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STRATIGRAPHIC UNIT	GEOPHYSICAL LOGS				Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/ STYLOLITES	REMARKS			
	Caliper (in)	Gamma Ray (API)	Density Porosity (dol matrix, v/v)		COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY						CLASTIC		
			Density	Porosity																	MUDSTONE	XLN
			0.3	-0.1																		
			6	16																		
0	150	2	3	RUDDSTONE	FLOATSTONE	BOUNDSTONE	GRAINSTONE	PACKSTONE	WACKSTONE					CARBONATE								
Potosi (Copper Ridge) Dolomite (Knox)																						
Potosi (Copper Ridge) Dolomite (Knox)																						

WELL: Ashland Oil No. F1F Camp Breckinridge Tr. 3 DEPTH: 8600–8624.5 ft
PERMIT: 16705 SHEET 1 OF 1
COUNTY: Union, Ky. ELEVATION: 481 ft DESCRIBED BY: D. C. Harris
CARTER COORD.: 15-N-21 VERTICAL SCALE: 1 in = 2 ft



Shakopee Dolomite (Knox)										Shakopee Dolomite (Knox)										STRATIGRAPHIC UNIT
																				CORED INTERVAL NOT LOGGED
																				Texture & Sed. Structures RUDSTONE COBBLE PEBBLE GRANULE BOUNDSTONE V. COARSE GRAINSTONE COARSE PACKSTONE MEDIUM WACKSTONE FINE V. FINE SILT MUDSTONE CLAY CARBONATE CLASTIC

DEPTH: 3500-3530 ft
SHEET 1 OF 2
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 10 ft

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STRATIGRAPHIC UNIT					
SHAHOPEE DOLOMITE SHAKOPEE DOLOMITE (KNOX)	EVERTON DOLOMITE				
	Note: core slabbed, but in poor condition. Core not marked with depth or up direction. Many boxes contain less core than depth interval on box. Intervals may be jumbled.				
Corehole not logged Core Por 200 Core Perm 1000.001					
RUDSTONE COBBLE PEBBLE GRANULE V. COARSE GRAINSTONE PACKSTONE WACKESTONE V. FINE SILT CLAY MUDSTONE XLN CARBONATE CLASTIC					
CORE DEPTH					
GRAPHIC LITHOLOGY					
POROSITY					
FRACTURES/STYLOLITES					
REMARKS					

Plate 2.5.1

WELL: Ada Belle Oil No. 2A Hillman Land and Iron
PERMIT: N/A
COUNTY: Trigg, Ky.
CARTER COORD.: 16-D-18

DEPTH:3530–3656 ft
SHEET 2 OF 2
DESCRIBED BY: D. C. Harris
VERTICAL SCALE: 1 in = 10 ft

STRATIGRAPHIC UNIT	Note: core slabbed, but in poor condition. Core not marked with depth or up direction. Many boxes contain less core than depth interval on box. Intervals may be jumbled.										Texture & Sed. Structures										CORE DEPTH	GRAPHIC LITHOLOGY	POROSITY	FRACTURES/STYLOLITES	REMARKS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
											COBBLE	PEBBLE	GRANULE	V. COARSE	COARSE	MEDIUM	FINE	V. FINE	SILT	CLAY						CLASTIC																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
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Part 3: Knox Carbon Storage Resource Estimates for the Illinois Basin

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One of the primary goals of the Cambro-Ordovician Project is to integrate the various aspects of geological characterization into best estimates of the carbon storage resource in deep saline formations at basin scale. In part 3 of the topical report we document the analysis of the thick Knox Group interval to produce a series of storage resource estimates (SRE) following the hierarchical approach of increasing complexity that was outlined previously in our earlier work (Ellett et al., 2013; Barnes and Ellett, 2014). This approach allows us to compare and contrast results evolving from simple geological models to more complex and conceptual representations of the potential reservoir units. A central objective of this approach is to provide a method that might enable us to demonstrate reduction of uncertainty in regional-scale SRE calculations—a primary goal of the US DOE Carbon Storage R&D program. The progression of specific methods used to calculate SRE of the Knox Group interval was as follows:

- 1) Standard US DOE methodology (Goodman et al., 2011) based on mapping the gross unit thickness and using a single estimate of the effective mean porosity for the Knox Group interval.
- 2) Subdivision of the Knox Group into three distinct units: upper Knox dolomites, lower Knox dolomites and Knox clastic intervals.
- 3) Explicit net porosity calculations based on well logs and porosity-permeability relations from core analyses.

In addition to those three methods, we explored how conceptual or idealized properties of the Knox Group might impact our regional-scale SRE. Of particular focus was an attempt to characterize dominant pore types for the reservoir-type facies within the Knox Group and apply such a characterization to SRE calculations.

3.1 Simple SRE calculation following the standard US DOE methodology

The standard DOE methodology for SRE calculations uses the volumetric equations and storage efficiency factors published in Goodman et al. (2011). In this approach, a formation-level average porosity value and other parameters are applied to the total bulk rock pore volume of the reservoir to calculate storage resource at the 10th and 90th percentile probability range. Figure 3.1-1 shows the Knox interval thickness map over the potential CO₂ reservoir domain where the depth of the reservoir interval is greater than 800 meters. Figure 3.1-2 shows the distribution of porosity values from conventional core plug analyses of Knox Group units (n = 958). Assuming that the effective porosity value equals the mean core porosity of 6.4%, a constant CO₂ density of 0.70 g/cc, and efficiency factors for dolomite lithology results in a storage resource estimate of 32 to 271 gigatonnes for P₁₀ and P₉₀, respectively. Note that this estimate for the Knox Group is nearly twice as large as the resource estimate of the Mount Simon Sandstone in the Illinois Basin region (Atlas IV, NETL, 2012).

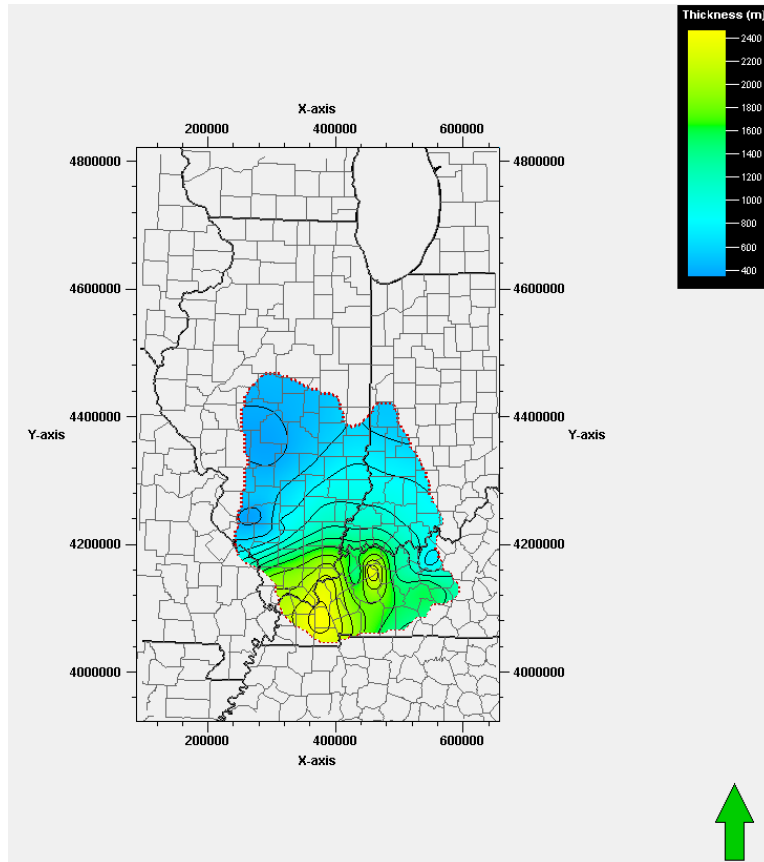


Figure 3.1-1. Gross thickness of the Knox Group interval where it occurs as a potential CO₂ storage reservoir in the Illinois Basin. Thickness ranges from about 300 meters in the central Illinois to nearly 2,500 meters in western Kentucky.

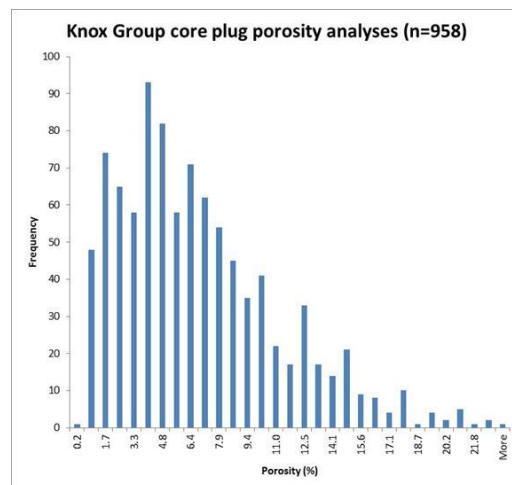


Figure 3.1-2. Porosity distribution of the Knox Group interval from all available core plug analyses (n = 958).

Despite assembling a database of nearly 1,000 analyses to characterize the porosity distribution of the Knox Group interval, concern was raised regarding sample bias since the core well locations occurred primarily in the Arches province along the perimeter of the Illinois Basin where the depth is often shallower than the potential reservoir domain (see map in figure 3.1-3a). To evaluate this potential bias, geophysical logs were analyzed for about 40 wells that lie within the potential reservoir boundary (fig 3.1-3b). Lithologic matrix corrections were applied to density, neutron and sonic logs and it was determined that neutron logs provided the most reasonable calculation of formation porosity. Figure 3.1-4 shows that the Knox Group interval porosity distribution from neutron logs at 35 wells across the basin closely matches the core-based distribution (figure 3.1-2) but with a slightly lower mean value of 5.8%.

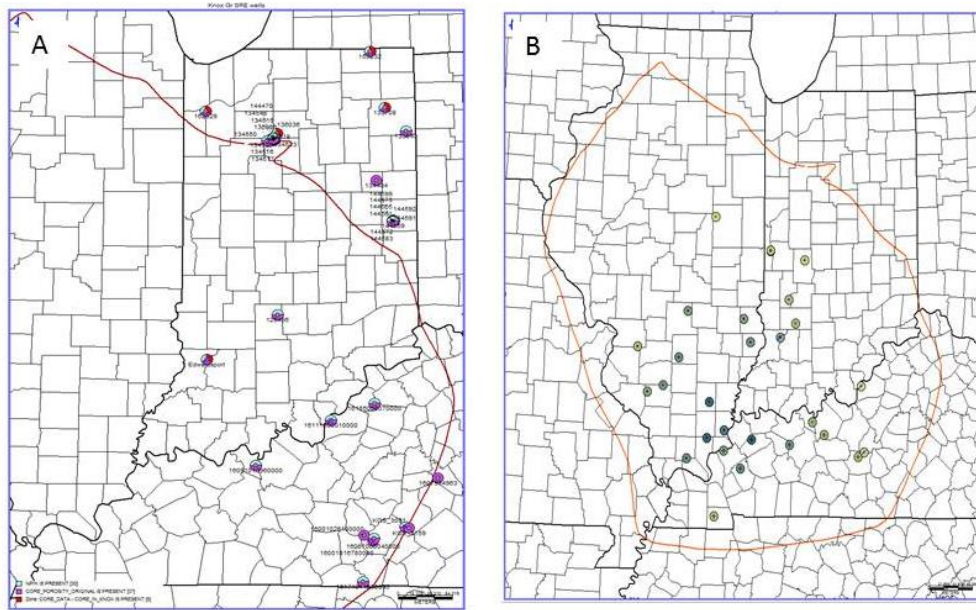


Figure 3.1-3. A) well locations of Knox Group sample core analyses. B) well locations with quality neutron porosity logs.

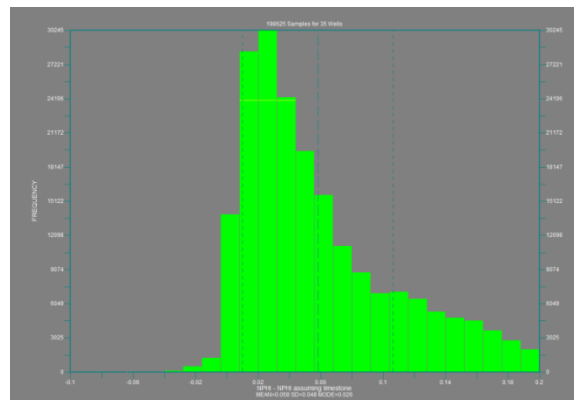


Figure 3.1-4. Porosity distribution of the Knox Group interval from neutron logs at 35 wells centered on the potential reservoir domain.

Assuming that the Knox Group effective porosity value is better represented by the mean neutron log porosity of 5.8% resulted in a slightly lower storage resource estimate of 29 to 246 gigatonnes for P_{10} and P_{90} , respectively.

3.2 Subdivision of the Knox Group interval

In our earlier characterization work on the clastic St Peter Sandstone in both the Illinois and Michigan Basins we found that despite the various depositional and diagenetic controls on porosity development, a general decline in porosity was observed with burial depth (Barnes and Ellett, 2014). This generalized porosity-depth relationship is often observed in siliciclastics as a result of greater compaction and cementation occluding pore space. Those results were used to generate a second-level SRE based on spatially varying porosity that was considered to be more accurate than the initial SRE. The initial SRE likely overestimated the resource by virtue of applying a relatively high effective mean porosity value (sample bias to shallow depths) throughout the entire potential reservoir domain.

Evaluating diagenetic controls on porosity development in the Knox Group dolomites has proven to be more challenging than in the St Peter Sandstone. Prior work on the Upper Knox in the Appalachian Basin by Montanez (1994) found multiple stages of dissolution and five generations of regionally correlated dolomite cements with late diagenetic dolomites showing significantly enhanced porosity and permeability. More recent work on the Lower Knox in the Illinois Basin by ISGS project partners also shows multiple generations of late-stage dolomite cements as well as chalcedony and mega-quartz lined vugs that may suggest significant porosity enhancement (vuggy- to cavernous-type porosity) related to the regional Knox unconformity and paleokarstification processes (Freiburg and Leetaru, 2012). Work on the Blan Well study by KGS project partners suggested that porosity in the Knox Group did exhibit a compaction-based trend at that location, but the depth-dependent reduction in porosity was fairly minor at 1.19% per 1,000 ft of depth (Bowersox and Hickman, 2012). In our regional-scale analysis of well logs and core data we did not find evidence of a consistent, depth-dependent porosity trend that might be accurately generalized for SRE calculations. Thus to improve our characterization of SRE of the Knox Group interval, our second-level approach was based on the subdivision of the thick Knox interval into two, and later three distinct subunits, each with their own thickness and porosity distributions.

Figure 3.2-1 shows the subdivision of an upper unit comprised primarily of the Prairie Du Chien Group/Shakopee, Oneota, Beekmantown dolomites (and Everton dolomite where present) and a lower unit that correlates with the Potosi and Copper Ridge Dolomite Formations. Porosity distributions based on core analyses show mean values of 6.5% for the upper Knox unit and 5.2% for the lower Knox unit. Despite the significant differences in spatial distribution shown in figure 3.2-1, we found that the resulting storage resource estimate was fairly evenly divided between the two units—15 to 131 gigatonnes for the Upper Knox unit and 13 to 115 gigatonnes for the Lower Knox unit.

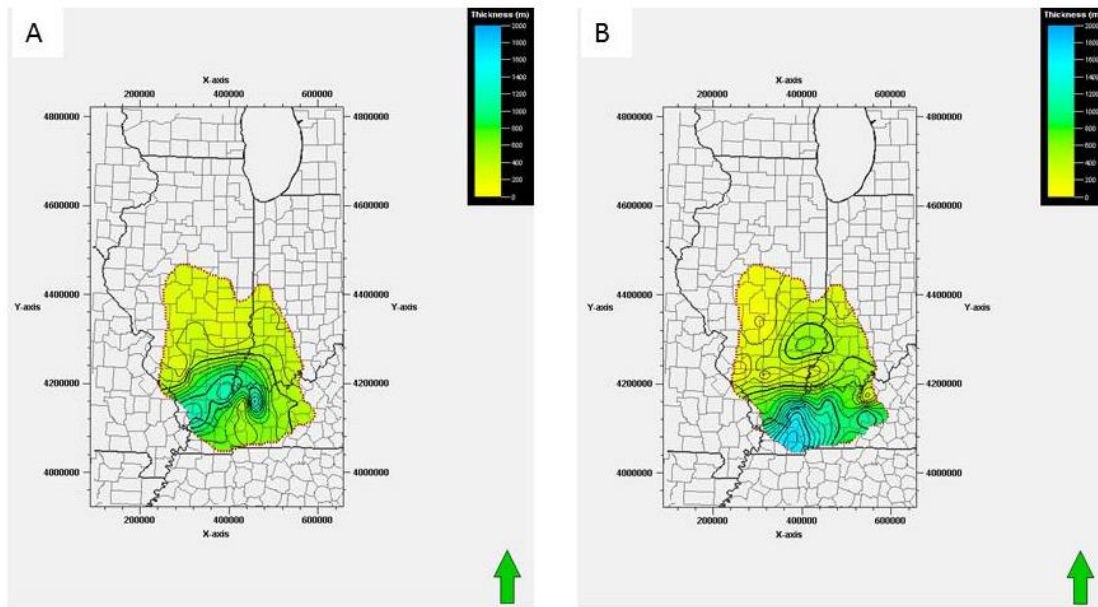


Figure 3.2-1. Thickness of the upper (a) and lower (b) units within the Knox Group interval in the two-part subdivision.

Clastic intervals comprise a relatively small proportion of the Knox Group, but work by KGS and ISGS partners indicated that at least two such formations could be considered viable storage reservoir targets at the regional scale—the New Richmond Sandstone and the Gunter Sandstone. Defining stratigraphic correlations of these units across the entire potential reservoir domain was covered in Part 1 of this report. For the purpose of calculating SRE for the clastic subunits of the Knox Group, a net sand mapping approach was followed. Figure 3.2-2 shows the net sand thickness across the potential reservoir domain. Note the order of magnitude reduction in range of thickness compared to the upper and lower dolomite units shown in figure 3.2-1. Well logs from the identified sandy intervals consistently exhibit higher porosity than the surrounding dolomites and the available core analyses from the KGS Blan Well were used to estimate the unit-level mean porosity as 8.8%. Applying the efficiency factors for clastic lithology and assuming the same constant CO₂ density as earlier resulted in SRE of 1 to 12 gigatonnes for the combined Knox clastic intervals. These units lie within the Upper Knox of the earlier two-part subdivision, thus subtracting out their gross thickness contribution resulted in a small reduction in SRE of the Upper Knox unit to 14 to 122 gigatonnes.

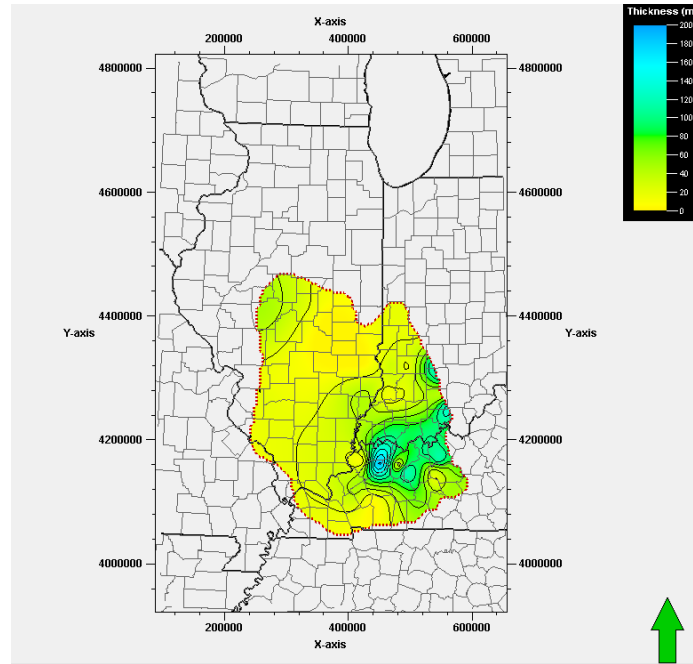


Figure 3.2-2. Gross thickness of the total sandy intervals (New Richmond Ss and/or Gunter Ss) within the Knox Group used for the three-part subdivision SRE calculation. Note the order of magnitude difference in range versus the maps in Figure 3.2-1.

3.3 Reservoir characterization by explicit net porosity calculations

A third-level SRE was completed by way of net porosity calculations. Figure 3.3-1 shows the relatively weak correlation between porosity and permeability in all Knox Group core samples within our project data base. Assuming a 5 millidarcy threshold for reservoir-type facies resulted in a porosity cutoff value of approximately 10% based on the best fit exponential equation shown in figure 3.3-1.

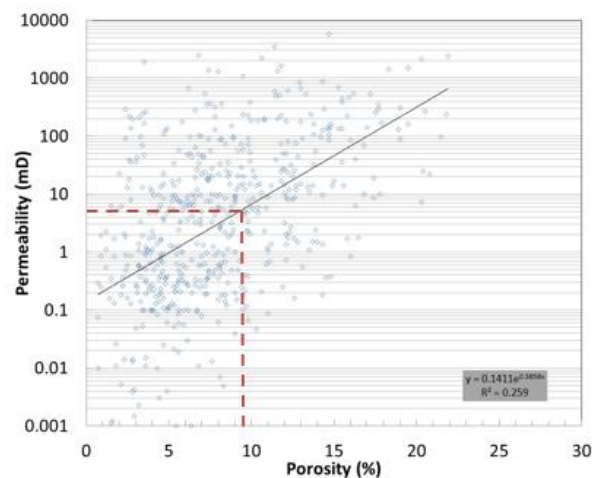


Figure 3.3-1. Weak correlation between porosity and permeability from all available Knox Group core analyses.

We applied the 10% porosity cutoff value to both neutron and density-based porosity logs from our data base of 35 deep wells that span the reservoir domain (see figure 3.1-3b). This approach explicitly eliminates the portions of the formation that are not considered to be suitable reservoir-type facies, thus allowing for the application of higher efficiency factors to the resultant net-porosity volume (Goodman et al., 2011). Figure 3.3-2 shows the thickness of net porosity meters derived from interpolation of the neutron-based data. We found significant discrepancies in net-to-gross values between the neutron and density-based porosity calculations where logs were co-located ($n = 20$) and again we selected the neutron-based results as more accurate given their superior correlation with core-derived porosity.

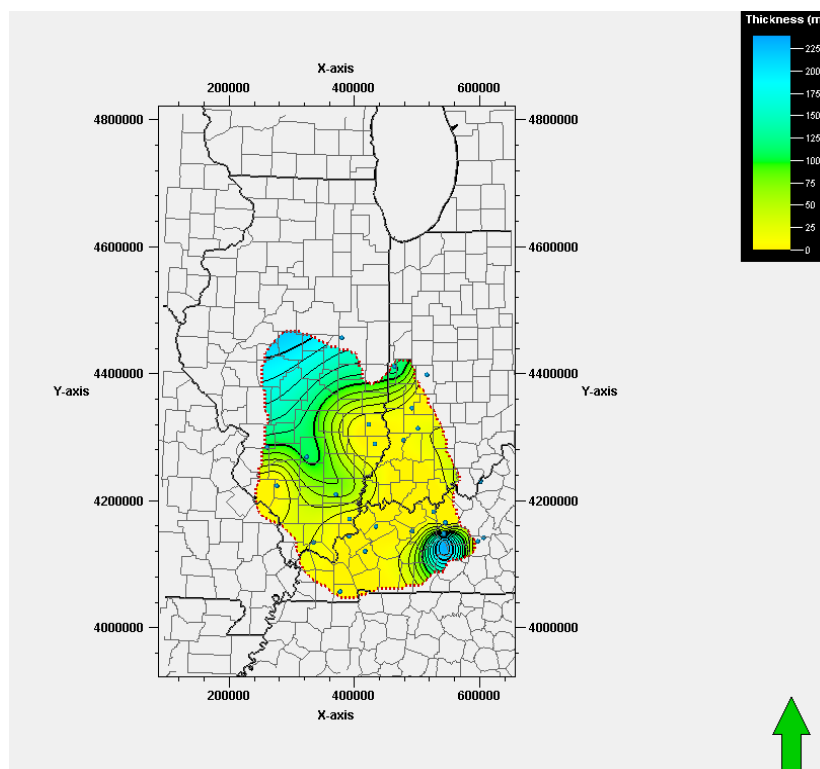


Figure 3.3-2. Thickness of net porosity meters of the Knox Group.

Applying the commensurate higher efficiency factors from Goodman et al. (2011) for dolomite lithology ($P_{10} = 16\%$, $P_{90} = 26\%$) led to SRE of 634 to 1,030 gigatonnes. This significant increase in SRE relative to SRE from earlier methods is consistent with results found in our prior studies of other formations (Ellett et al., 2013; Barnes and Ellett, 2014) and is believed to arise from a combination of 1) inadequate data sampling due to sparse (or poor quality) well logs relative to the inherent heterogeneity of the formation, and 2) methodological limitations inherent in Goodman et al. (2011). In the case of our Knox Group analysis, net porosity thickness shown in figure 3.3-2 does not correlate well with thickness of subunits (e.g., fig 3.2-2) or burial depth, thus it is difficult to determine whether geological processes might be responsible for this distribution of net porosity, or if it is simply an artifact of the limited available data.

3.4. Pore-type characterization approach to storage resource estimation

3.4.1 Concept/Objective

The objective of this approach is to establish dominant pore types from petrographic and MICP analysis of core from the Knox Group interval and correlate to geophysical log response to assign reservoir and seal-type facies with separate porosity distributions for net porosity calculations and interpolation to SRE.

3.4.2 Justification/Background

Four wells in Indiana have complete recovery of core from the Knox Group interval. Analysis of these core samples revealed a promising correlation between visible porosity (primarily observed as vuggy-type pores) and well-log response. Note, however, that all four of these wells are located in the Arches province in northern Indiana rather than within the deeper Illinois Basin region. Within the potential reservoir storage domain is the Edwardsport IGCC#1 well (ID# 164778) which has three cored intervals from the Knox Group. The current study is based on the analysis of 30 total core samples selected from the Edwardsport well and three of the Arches wells (figure 3.4-1).

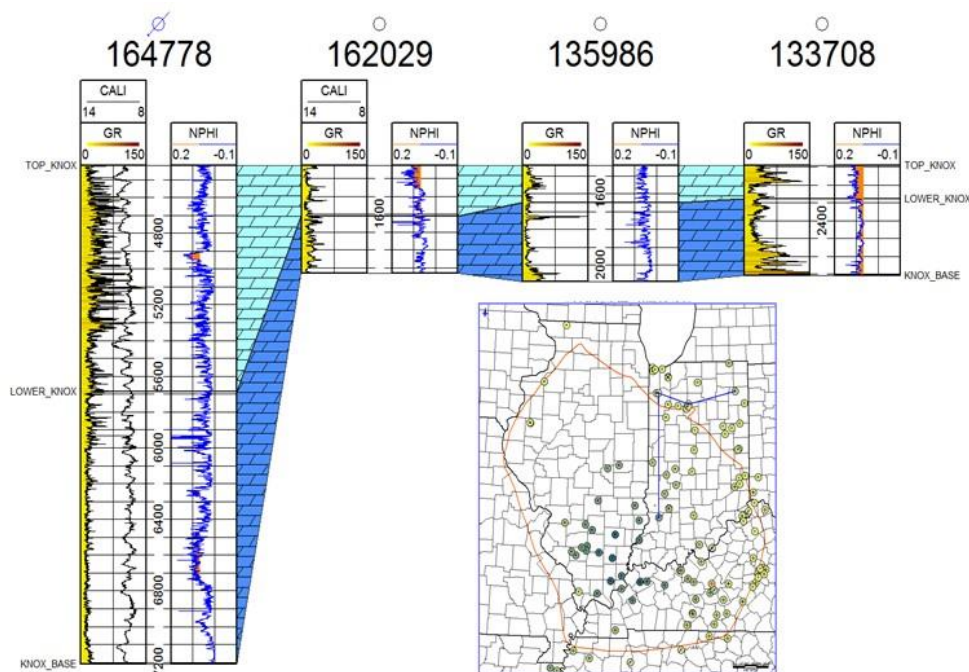


Figure 3.4-1. Basin-to-Arch (SW-NE) cross section in Indiana from four wells containing Knox Group interval core.

3.4.3 Methods

A total of 30 core samples were selected for petrographic study and MICP analysis. Each sample was specifically selected as being representative of the surrounding core interval of interest. In accordance with the visual porosity identification and log signature correlation mentioned above:

- One-half of the samples were selected as likely representing potential CO₂ reservoir facies
- Approximately one-quarter were estimated to represent seal-type facies
- Approximately one-quarter were considered unknown
- 70% of the samples that were considered as representing either reservoir or seal-type facies had a characteristic log signature that was commensurate with this designation.

The designation of specific pore types and pore distribution characteristics follows the general classification system of Lucia as modified by Lonoy (2006).

3.4.4 Results

Results of the petrographic study are presented in Table 3.4-1, indicating the dominance of three pore types within the Knox Group—vuggy pores, intercrystalline macropores (> 60 µm) and intercrystalline mesopores (20-60 µm). Of the 30 thin-section samples analyzed, 62% of photomicrographs had vuggy porosity, 42% had intercrystalline macroporosity, and 29% had intercrystalline mesoporosity. Significantly less frequent were observations of fracture porosity and interparticle porosity. One-half of the eight samples that were originally estimated as representing seal-type facies had no observable porosity in thin section.

Although vuggy porosity dominated the classification, we did not find evidence of this pore type occurring more frequently near key stratigraphic horizons associated with regional unconformities—the top of the Knox Group (Sauk sequence boundary) or at the top of the Potosi Dolomite (Cambrian-Ordovician boundary).

Numerous samples indicated that a minor degree of depositional fabric had been preserved against a strong overprint of dolomite crystallization, however, the results from our sample set were considered too ambiguous to define a clear depositional control on porosity development that might be applied robustly and accurately to regional-scale SRE calculations. Core samples from the KGS Blan well provided clearer evidence of vuggy porosity development associated with stromatolites, but regionalization of such results will require further work and likely access to additional core samples.

80% of the samples showed some degree of interconnectedness although this was often moderate or occasional. Connectivity was more pervasive in samples with intercrystalline pore type than vuggy pore type due to the more uniform versus patchy distribution, respectively. However, it should be noted that evaluating vuggy pore connectivity from 2-D thin sections is likely to underestimate results versus 3-D imaging such as the multiple CT-scans presented by Freiburg and Leetaru (2012).

Well ID	Depth (ft.)	Quadrant of photo micrograph	Pore Types	Distribution/Frequency of Pore types	Connected/Not Connected	General Comments
162029	1369	Q1	vuggy; fractures	uniform distribution of vugs; fractures patchy	fractures connecting vugs; large vugs connected	vuggy porosity connect via fractures; large porosity present
		Q4	vuggy; fractures	uniform distribution of vugs; fractures patchy	fractures connecting vugs; vugs connected adjacent to one another	vuggy porosity connected via fractures and adjacent vugs
162029	1382	Q1	Vuggy	patchy	Occasional connectivity mostly filled by quartz	pervasive quartz lining vugs; silicified fossil fragments
		Q4	Vuggy; intercrystalline micropores	patchy	Occasional connectivity mostly filled by quartz	pervasive quartz lining vugs; silicified fossil fragments
162029	1454	Q1	intercrystalline macropores; fractures	uniform distribution of intercrystalline macropores; only one fracture	connected between adjacent pores and through fractures	oil present in fractures and intercrystalline pores
		Q4	intercrystalline macropores	uniform distribution of intercrystalline macropores	connected between adjacent pores and through fractures	some ooids preserved in dolomite; grains clearly still visible; oil present in fractures and intercrystalline pores
162029	1646	Q1	fracture; minor intercrystalline macropores	fractures; sparse	not connected	oil present in fractures
		Q4	none	none	none	completely crystalline; no porosity observed
162029	1898	Q1	vuggy; intercrystalline macropores-mesopores	patchy vugs; relatively uniform intercrystalline macro-mesopores	adjacent pores connected; more pervasive interconnectivity where vugs and intercrystalline pores overlap	
		Q4	vuggy	patchy to sparse vugs	not interconnected unless directly adjacent to other vugs	not as interconnected as the other quadrant
135986	1451	Q1	intercrystalline macropores-mesopores; vuggy; fracture	uniform intercrystalline macropores-mesopores; sparse vugs	intercrystalline macro-mesopores well connected; vugs not well connected unless adjacent to intercrystalline pores; only one fracture observed	intercrystalline macropores pervasive throughout slide well connected
		Q4	intercrystalline macro-meso pores; vuggy	uniform intercrystalline macropores-mesopores; sparse vugs	intercrystalline macro-mesopores well connected; vugs not well connected unless adjacent to intercrystalline pores	intercrystalline macropores pervasive throughout slide well connected
135986	1513	Q1	vuggy; intercrystalline macropores	patchy vugs; relatively uniform intercrystalline macropores	intercrystalline macropores well connected throughout; vugs well connected to the intercrystalline macropores	most of the larger vugs filled with clays/muds; possible rip-up clasts
		Q4	vuggy/moldic macropores; intercrystalline macropores	sparse moldic porosity; patchy intercrystalline macropores	intercrystalline macropores well connected; moldic pores not well connected	larger vugs/molds filled with clays/muds; moldic porosity could have replaced fossils?
135986	1765.5	Q1	vuggy/moldic; intercrystalline macropores-mesopores	patchy intercrystalline macro-mesopores; sparse vugs/moldic pores	intercrystalline macropores well connected; moldic/vuggy pores not well connected	mud and calcite present in large molds/vugs
		Q4	none	none	none	quadrant is all crystalline
135986	1995	Q1	vuggy	patchy vugs	poorly connected	
		Q4	vuggy	patchy vugs	poorly connected	
135986	2042	Q1	fracture; interparticle micropores	patchy to sparse	poorly connected	depositional fabric with minimal porosity; oil present
		Q4	sparse vugs/molds	vuggy pores sparse	vugs not connected	oil present
133708	2115	Q1	intercrystalline macro-mesopores	uniform intercrystalline macro-mesopores	interconnected	highly dolomitized; some evidence of original grains could be ooids
133708	2115.5	Q1	intercrystalline macro-mesopores	uniform intercrystalline macro-mesopores	interconnected	highly dolomitized; oil present in some pore space
133708	2289.5	Q3	vuggy	patchy vugs	poorly connected	

Well ID	Depth (ft.)	Quadrant of photo micrograph	Pore Types	Distribution/Frequency of Pore types	Connected/Not Connected	General Comments
		Q2	sparse intercrystalline macro-mesopores; stylolite	patchy intercrystalline macro-mesopores	not connected	clay-filled stylolite or oil; very minimal porosity
133708	2308	Q2	vuggy	patchy vuggy pores	vugs connected near adjacent vugs	
		Q3	vuggy	uniform vuggy pores	vugs connect to adjacent vugs	vugs more elongate and uniform in distribution compared to Q2 image
133708	2456.5	Q1	vuggy	patchy vuggy pores	minor connection; vugs mostly filled	large vugs but mostly filled with anhydrite or calcite
		Q2	vuggy	sparse vuggy pores	minor connection; vugs mostly filled	large vugs but mostly filled with anhydrite or calcite
133708	2611	Q1	intercrystalline meso-macropores	patchy intercrystalline macro-meso pores	poorly connected	clay drapes prevalent
		Q2	vuggy; fracture; intercrystalline meso-macropores	sparse vugs; single fracture; patchy	moderately connected	clay drapes prevalent
133708	2648	CENTER	intercrystalline macro-meso-micropores	uniform distribution	interconnected throughout	thin depositional layering preserved; oil present in some pore spaces
133708	2687.5	Q1	intercrystalline macro-meso-micropores; fractures	uniform distribution of intercrystalline pores; few fractures	interconnected throughout	depositional fabric preserved; oil present in fractures and in small amounts of pore space
		Q4	intercrystalline macro-meso-micropores; fractures; vuggy	uniform distribution of intercrystalline pores; few fractures; sparse vugs	interconnected throughout	oil present in fractures and in small amounts of pore space
164778	4431.4	Q1	vuggy; intercrystalline macropores	patchy vuggy and intercrystalline macro pores	connected between adjacent pores	brecciated texture in half of image
		Q3	vuggy; intercrystalline macro-meso pores	sparse intercrystalline macro-meso pores and vuggy pores	vugs not connected; intercrystalline macro-meso pores connected adjacent to one another	
164778	4447.1	CENTER	sparse interparticle	very sparse pores	not connected	Shakopee sand unit; interparticle space is filled
164778	4447.5	CENTER	none	none	none	thin sandy lens in complete crystalline matrix
164778	5271.1	Q2	vuggy	patchy	vugs connected adjacent to other vugs	large open vugs
		Q4	vuggy	patchy	vugs connected adjacent to other vugs	large open vugs
164778	5284.7	Q1	vuggy	uniform large vugs; patchy fractures	connected vugs, fractures and large vugs	cherty matrix and spherical clasts
		Q4	vuggy; fractures	uniform large porosity; sparse fractures	connected vugs; interconnected fractures and large porosity	cherty matrix and clasts appear dissolved by vuggy pore
164778	5286.3	Q1	none	none	none	contact between dolomitized micrite and cherty interval
		Q4	none	none	none	contact between dolomitized micrite and cherty interval
164778	5287.1	Q1	moldic; vuggy	intermediate	connected	siliceous interval
		Q4	moldic; vuggy	intermediate	connected with clay filling some voids	siliceous interval
164778	5654.8	CENTER	fracture; minor intercrystalline mesoporsity	very sparse pores	not connected	oil or clay filled fractures; almost no porosity
164778	5659.4	Q2	fracture; intercrystalline macro-mesopores	sparse intercrystalline meso-macropores	occasional connectivity	minor grains preserved in crystalline matrix
		Q4	intercrystalline macro-mesopores	sparse intercrystalline meso-macropores	occasional connectivity	minor grains preserved in crystalline matrix
164778	5665.5	CENTER	none	none	none	no porosity observed
164778	5671.8	Q1	none	none	none	no porosity observed

Table 3.4-1. Results from petrographic analysis of Knox Group samples from four wells in Indiana.

Results from the MICP analyses provide better insight into the complex relation between porosity and permeability in these highly heterogeneous pore systems. Interestingly, the generalized porosity-permeability relation from MICP samples (i.e. exponential equation from log-linear regression) agrees closely with the relation derived previously from all available conventional core analyses (n=560 from 39 wells). Figure 3.4-2 shows that although the generalized porosity-permeability correlations are relatively weak, in both data sets a hypothesized reservoir-grade permeability cutoff value of 5 millidarcy equates to a porosity value of approximately 10%. Both data sets also support the notion that a 10% porosity cutoff is perhaps a conservative threshold for net porosity calculations since relatively few conventional samples, and no MICP samples, lie within the quadrant of >10% porosity and < 5 mD permeability.

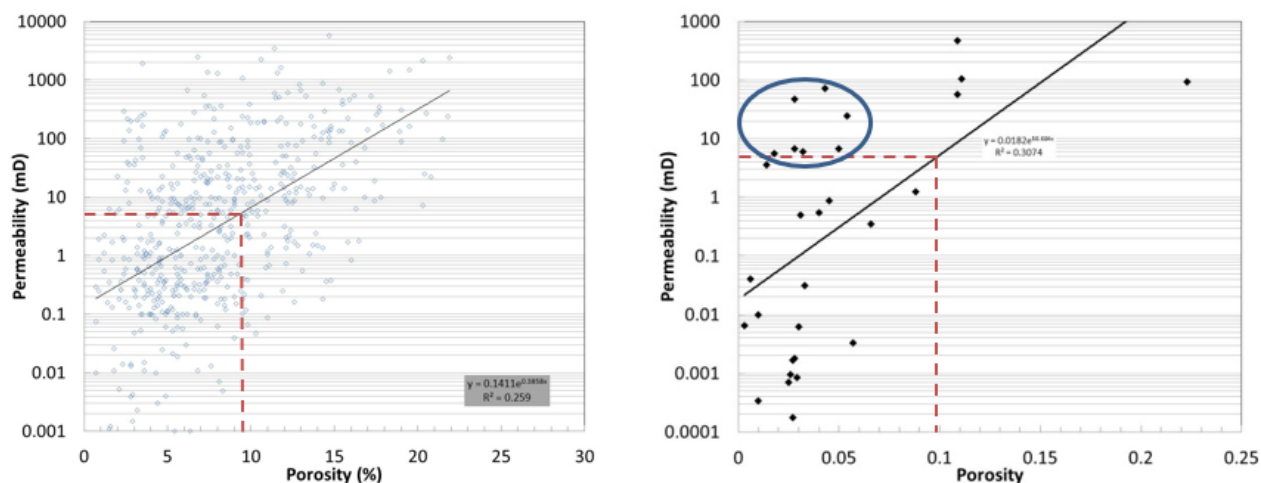


Figure 3.4-2. Weak correlation of porosity and permeability in Knox Group samples from (A) all available conventional analyses throughout the region (n = 560) and (B) MICP analyses (n = 30).

MICP results shown in figure 3.4-2b also helped to reveal an interesting characteristic of these dolomites through a cluster of approximately 1/4 of the samples that had low porosity (1.8 to 5.4%) but relatively high permeability (>5 mD). All of those samples had a dominant pore type of vuggy and low MICP threshold pressures of < 4 psi. These results suggest that intervals of the Knox Group that are dominated by vuggy-type porosity may provide suitable reservoir storage for CO₂ despite their relatively low porosity. These results also lend further support to the earlier notion that a 10% porosity cutoff value is likely to provide very conservative estimates of net porosity for SRE calculations. Figures 3.4-3 and 3.4-4 below provide representative examples from this cluster of sample types.

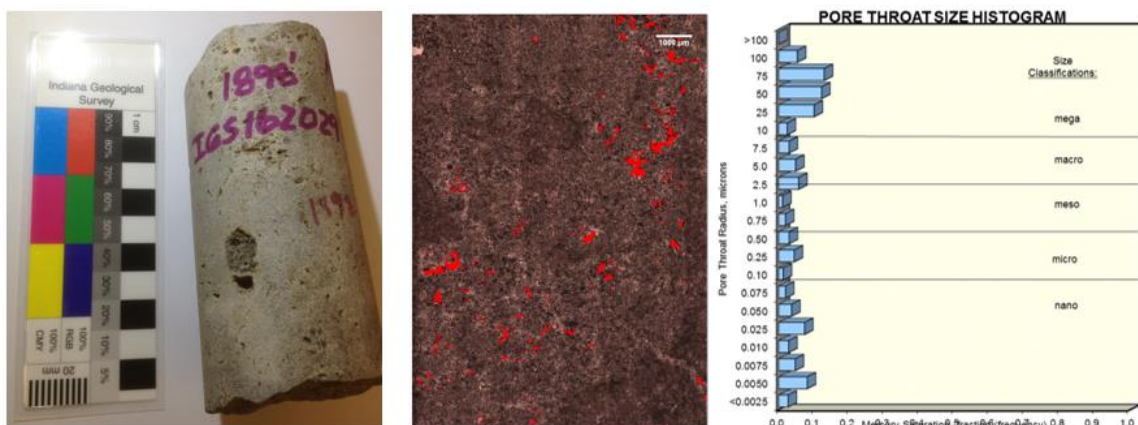


Figure 3.4-3. Example of Knox Group dolomite dominated by vuggy pore type with only low-to-moderate porosity (4.3% for MICP sample) but reservoir-grade permeability (73 mD). Sample is from well 162029 at 1,898 ft depth.

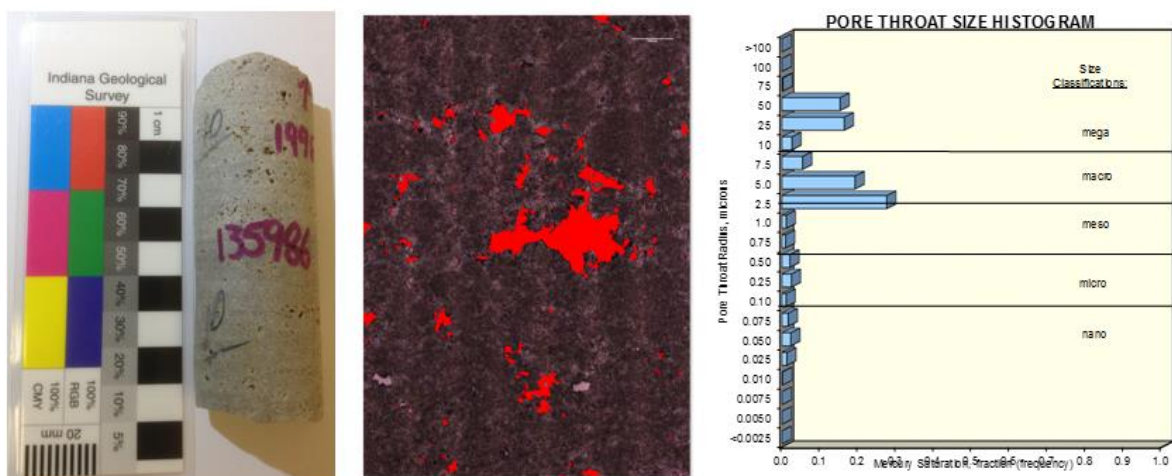


Figure 3.4-4. Similar to 3.4-3—example of Knox Group dolomite dominated by vuggy pore type with only low-to-moderate porosity (5.4% for MICP sample) but reservoir-grade permeability (25 mD). Sample is from well 135986 at 1,995 ft depth.

In addition to identifying pore types and characteristics, thin section photomicrographs were processed using the public domain ImageJ software to quantify porosity within different quadrants of the photomicrograph (see red areas in figures 3.4-3b and 3.4-4b). Porosity was also measured from conventional core plug analyses where available (Edwardsport well) and all wells had available neutron logs for porosity calculation. We found the correlation between MICP-based porosity and other methods to be only weakly correlated. This result is attributed to the inherent variability of the specific sample material analyzed across methods, variable scale of investigation, and the highly heterogeneous nature of the samples. A summary of these results is given in Table 3.4-2 in which reservoir-type facies are color coded blue and seal-type facies are color coded red. Intermediate facies are coded white.

		MICP analysis				Thin Section analysis				Well logs	Conventional core analysis	
Sample ID	depth (ft)	Swanson Permeability (mD)	Porosity (%)	Threshold pressure (psi)	median pore throat radius (um)	Pore types	Quadrant1 Porosity (%)	Quadrant2 Porosity (%)	TS Mean Porosity (%)	NPHI/DPHI Porosity (%)	Porosity (%)	Permeability (mD)
2m-162029	1369	47.4	2.8%	1.1	12.4	vuggy; fracture	17.7	3.7	10.7	12.0%	N/A	N/A
1m	1382	5.58	1.8%	1.2	0.39	vuggy	3.9	0.1	2.0	12.0%	N/A	N/A
3m	1454	0.00328	5.7%	286.6	0.0361	intercrystalline macropores	7.3	7.9	7.6	8.0%	N/A	N/A
4m	1646	3.59	1.4%	1.2	0.0289	sparse fracture	0	0	0.0	10.0%	N/A	N/A
5m	1898	72.7	4.3%	1.2	2.87	vuggy; intercrystalline	2.2	2.6	2.4	8.0%	N/A	N/A
6m-135986	1451	0.0312	3.3%	37.9	0.218	all	1.7	2.4	2.1	6.0%	N/A	N/A
7m	1513	56.9	10.9%	1.2	1.29	vuggy; intercrystalline	3.2	4.4	3.8	8.0%	N/A	N/A
8m	1765.5	6.72	5.0%	3.8	0.793	vuggy	2.4	0	1.2	8.0%	N/A	N/A
9m	1995	24.6	5.4%	2.3	3.23	vuggy	5.7	3.9	4.8	3.0%	N/A	N/A
10m	2042	0.5	3.1%	5.1	0.0574	sparse	0.1	0.3	0.2	5.0%	N/A	N/A
11m-133708	2115	0.00614	3.0%	366.5	0.0927	intercrystalline macro-mesopores	2.9		2.9	10.0%	N/A	N/A
12m	2115.5	0.0018	2.8%	364	0.0519	intercrystalline macro-mesopores	1.4		1.4	10.0%	N/A	N/A
13m	2289.5	6.71	2.8%	1.9	0.329	vuggy; intercrystalline	1.6	0.1	0.85	10.0%	N/A	N/A
14m	2308	0.866	4.5%	4.4	1.01	vuggy	3.3	1.7	2.5	7.5%	N/A	N/A
15m	2456.5	470	10.9%	1.2	19.9	vuggy	1.8	1.2	1.5	8.0%	N/A	N/A
16m	2611	0.000949	2.6%	598.6	0.0385	all	0.1	0.5	0.3	7.5%	N/A	N/A
17m	2648	93.8	22.3%	8.2	4.1	intercrystalline macro-mesopores; interparticle	0.4		0.4	13.0%	N/A	N/A
18m	2687.4	0.351	6.6%	38.3	0.477	all	0.5	0.4	0.45	9.0%	N/A	N/A
19m-164778	4414.4	104	11.1%	1.8	8.7	St Peter Ss	8.1	14.6	11.4	7.0%	15.2%	205.00
20m	4431.4	0.00991	1.0%	43.3	0.12	vuggy; intercrystalline	4.8	0.1	2.4	2.0%	12.7%	12.00
21m	4447.1	0.000847	2.9%	283.5	0.0333	sparse	0.4		0.4	1.5%	N/A	N/A
22m	4447.5	0.000175	2.7%	285	0.0136	none	0.0		0.0	2.0%	<0.03	<0.10
23m	5271.1	5.96	3.2%	3.2	2.35	vuggy	11.0	19.1	15.1	6.0%	11.8%	17.00
24m	5284.7	0.544	4.0%	12.2	0.309	vuggy	7.2	39.1	23.1	5.5%	8.9%	2.40
25m	5286.3	0.000336	1.0%	1362.1	0.0432	none	0.1	0.6	0.3	3.5%	3.0%	<0.10
26m	5287.1	1.23	8.8%	10	0.627	moldic; vuggy	3.8	5.8	4.8	3.5%	12.4%	1.20
27m	5654.8	0.000692	2.5%	1429	0.0297	fracture; intercrystalline	0.0		0.0	2.5%	3.3%	<0.10
28m	5659.4	0.00168	2.7%	319.7	0.0489	fracture; intercrystalline	0.1	0.0	0.1	1.0%	6.2%	<0.10
29m	5665.5	0.00651	0.3%	18.2	0.0443	none	0		0.0	1.0%	<0.03	<0.10
30m	5671.8	0.0402	0.6%	24.5	1.34	none	0		0.0	0.5%	<0.03	0.31

Table 3.4-2. Summary of pore-type characterization results from Knox Group samples in Indiana showing reservoir (blue) and seal (red) type facies designations. Ninety percent of reservoir-type facies have the dominate pore type of vuggy.

Perhaps the greatest challenge in applying a pore-type approach for SRE calculations in the Knox Group dolomites lies in the fact that most samples contain more than one pore type and correlations to attempt assignment of a dominant pore-type classification/porosity distribution to specific stratigraphic units proved elusive. Despite the various challenges, our analysis provided some important insight on the reservoir potential of the Knox Group dolomites. Key observations were:

- 1) The majority of the Knox Group dolomite interval is dominated by seal-type facies with microdarcy level permeability and very minor intercrystalline and/or fracture porosity amounting to less than 5% total porosity.
- 2) The presence of vuggy-type porosity is the dominant factor in development of reservoir-type facies.
- 3) Future work on Knox Group reservoir characterization should aim to clarify regional-scale depositional and diagenetic controls on vuggy-type porosity development as a promising approach to predicting the occurrence of reservoir-type facies and improving SRE calculations.

3.5 Hypothesizing the potential storage resource of cavernous porosity from paleokarstification

Throughout the Illinois Basin, the Knox Group dolomites have served as a reservoir for several UIC Class I injection wells, numerous Class II wells, as well as gas storage wells. It has long been known that portions of the Lower Knox Group in particular (Potosi Dol.) contain cavernous porosity that is presumably associated with paleokarstification processes. ISGS project partners recently documented multiple occurrences of lost circulation and bit drops when drilling through the Potosi Dol. and they speculated that cavernous porosity is likely an extensive feature of the Potosi Dol. across the Illinois Basin as a result of a paleokarst from a regional unconformity (Freiburg and Leetaru, 2012).

To evaluate the potential storage resource of cavernous-type porosity in the Lower Knox we used reasonable estimates of the potential thickness (100 m) and effective porosity (15%) of such a feature, and applied this to our volume of Lower Knox unit. SRE for this idealized case was 1 to 18 Gt, suggesting that cavernous-type intervals of the Knox Group might provide a reservoir of similar storage resource as the clastic units.

3.6 Final SRE results: refinement of the net area of the Knox Group reservoir

Permitting of CO₂ injection into saline formations by the EPA UIC program requires that storage is only considered for the portion of the formation in which total dissolved solids of native brines exceed 10,000 ppm. Furthermore, to ensure that CO₂ remains in a dense supercritical phase, the standard approach to defining the net area of a potential saline formation storage reservoir is to remove any area of the storage formation that has a reservoir/seal contact boundary lying above 800 meters depth. During the technical review of our results, we found that a portion of the Knox Group reservoir in the state of Illinois did not meet these requirements. As a result, we redefined the reservoir boundary accordingly as shown in figure 3.6-1. The volumetric equations mentioned earlier were re-calculated for this reduced reservoir domain and the final SRE results are given in table 3.6-1 below.

Note that the recent work of Ellett et al. (2013) indicates that the application of efficiency factors published in the DOE methodology (Goodman et al., 2011) to a reservoir volume that has been spatially constrained based on water quality (10,000 ppm requirement) and CO₂ phase criteria (>800 m depth for suitable P and T conditions) will effectively underestimate the resource. As a result it should be noted that the storage resource estimates given in table 3.6-1 are considered to be conservative estimates for the Knox Group reservoir. A manuscript is currently in preparation to address such methodological issues and the assessment of uncertainty in SRE calculations (Ellett et al., in prep). At this time it is our recommendation that reporting of a single best estimate of storage resource for the Knox Group, such as in the forthcoming Atlas V by NETL, should use the three-part subdivision highlighted in Table 3.6-1.

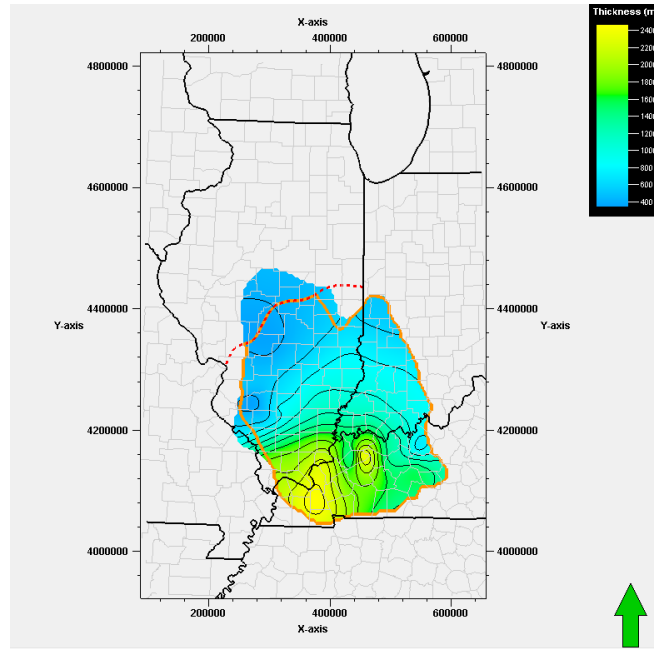


Figure 3.6-1. Map showing the portion of the Knox Group reservoir (figure 3.1-1) in Illinois that was explicitly removed from the final SRE calculations based on the 10,000 ppm criteria (dashed red line) or the seal contact defined at top of St Peter Ss. Only the area inside the orange outline was used for the final volumetric calculations.

Details of Knox Group Storage Resource Estimates	CO2 Storage Resource (billion metric tons)	
	P ₁₀ estimate	P ₉₀ estimate
Level 1-a: Single reservoir unit; assume effective porosity from core (6.4% mean); constant density (0.7 g/cc assumed); E= 0.64% (P10) and 5.5% (P90) for dolomite lithology	30	256
Level 1-b: same as above but using nphi mean porosity of 5.8% to correct for sampling bias of core dataset (core mostly from Arches province vs logs mostly from the reservoir domain).	27	232
Level 2-A: Upper Knox unit from two-part subdivision	14	122
Level 2-A: Lower Knox unit from two part subdivision	13	111
Level 2-B: Upper Knox unit from three-part subdivision	13	114
Level 2-B: Knox clastic unit from three-part subdivision	1	11
Level 2-B: Lower Knox unit from three-part subdivision	13	111
Level 3: Net porosity calculation; E = 16% (P10) and 26% (P90)	448	728
Idealized cavernous storage (30 meters of karst at upper Potosi; 15% effective porosity)	1	16

Table 3.6-1. Summary of final storage resource estimates for the Knox Group in the Illinois Basin

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