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STRATIGRAPHIC VARIABILITY AND PETROPHYSICAL CHARACTERISTICS OF THE PENNSYLVANIAN PRUE SANDSTONE AND OSWEGO LIMESTONE, CENTRAL LINCOLN COUNTY, OKLAHOMA

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STRATIGRAPHIC VARIABILITY AND PETROPHYSICAL CHARACTERISTICS OF THE PENNSYLVANIAN PRUE SANDSTONE AND OSWEGO LIMESTONE, CENTRAL LINCOLN COUNTY, OKLAHOMA

A THESIS APPROVED FOR THE

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ABSTRACT

The Prue Sandstone in Lincoln County, Oklahoma is interpreted to have been deposited in a tidally influenced deltaic environment. The Prue Sandstone consists of three main subenvironments: incised valley fills, distributary channels, and fluvial flood plains. Distributary channels are characterized by light gray, medium to fine grain micaceous sandstones with localized flaser and wavy laminations. Fluvial flood plains exhibit planar laminations to wavy laminations of fine-grained gray sandstone and dark mudstone. Coal in the upper Prue Sandstone is associated with fluvial flood plains. Coal is discontinuous in the study area and separated by sandstones and shales. The Oswego Limestone represents a shallow-marine to marine environment that was situated along a southwest-northeast trending shoreline. The Excello Shale separates the Oswego Limestone and the Prue Sandstone and is thin and continuous across the study area. While both the Oswego Limestone and the Prue Sandstone are known hydrocarbon reservoirs in Lincoln County, Oklahoma, their stratigraphy, sedimentology, and reservoir characteristics have not been extensively studied. Therefore, this study explores the Prue Sandstone and Oswego Limestone structure, lithology, total porosity, effective porosity, water saturation, and bulk volume hydrocarbon through well-log analysis and 3-D geostatistical modeling.

In the 224-mi^2 (580 km^2) study area, >400 wells were used for stratigraphic correlations. Of the 400 wells used for correlations, 198 wells were digitized to provide a combination of gamma-ray, neutron-porosity, bulk-density, and resistivity logs. Two wells close to the study area provide core from selected intervals. Subsurface correlation and mapping and petrophysical analyses of the Prue Sandstone and Oswego Limestone were based on well-log data. The Oswego Limestone and Prue Sandstone thickness vary from ~2–45 ft (~0.61–13.71 km) and

~50–150 ft (~15.24–45.72m), respectively. Petrophysical analysis of the sandstones within the Prue Sandstone indicate effective porosity values from 1–29% and S_w values from 21–100%. The Oswego Limestone total porosity varies from 0–26% and S_w values range from 20–100%. Three-dimensional reservoir models of the Oswego Limestone and Prue Sandstone illustrate the high reservoir heterogeneity across the study area that is controlled by the stratigraphic variability of lithologies and their depositional trends.

INTRODUCTION

The Oswego Limestone and the Prue Sandstone are hydrocarbon reservoirs in Lincoln County, Oklahoma. Studies specific to the Prue Sandstone in Oklahoma have been completed in Creek and Nowata counties to the northeast, Noble County to the northwest, Oklahoma County to the southwest and in west-central Lincoln County (Candler, 1971; Ropp, 1991; Broker 2001, Huhnke, 2004; Ahmadian, 2019). Several regional studies of the subsurface geology of Oklahoma and the midcontinent describe the Oswego Limestone and the Prue Sandstone as reservoirs in the vicinity of Lincoln County (Blumenthal, 1956; Cole, 1958; Ferguson, 1964; Krumme 1981). Krumme (1981) specifically addresses the limestones of the Marmaton Group, including the Oswego Limestone and describes the distribution and stratigraphy of the Prue Sandstone in multiple counties of central and eastern Oklahoma. A more recent study by Broker (2001) of the Prue Sandstone in southeastern portion of the Anadarko Basin utilizes geologic modeling and interprets the reservoirs as incised valley fill sandstones with lesser production from delta-front sandstones. The most extensive previous study on the Prue Sandstone in Lincoln County was completed by Ropp (1991) and evaluates reservoir properties of the sandstone.

While the Prue Sandstone and the Oswego Limestone are known subsurface reservoirs for hydrocarbons, the stratigraphy, sedimentology, and related reservoir characteristics are poorly understood within the study area and limited documented studies have been performed utilizing 3-D geostatistical modeling methods, petrophysical analysis, with well and core data. This research focuses on the stratigraphic and petrophysical characteristics of the Pennsylvanian Oswego Limestone and the Prue Sandstone in a 224-mi^2 (~580 km^2) area of central Lincoln County, Oklahoma (townships 13, 14, 15 N, ranges 3, 4, 5 E). The study area is located southeast of the Nemaha Uplift on the Cherokee Platform (Figure 1). Therefore, for both the Oswego

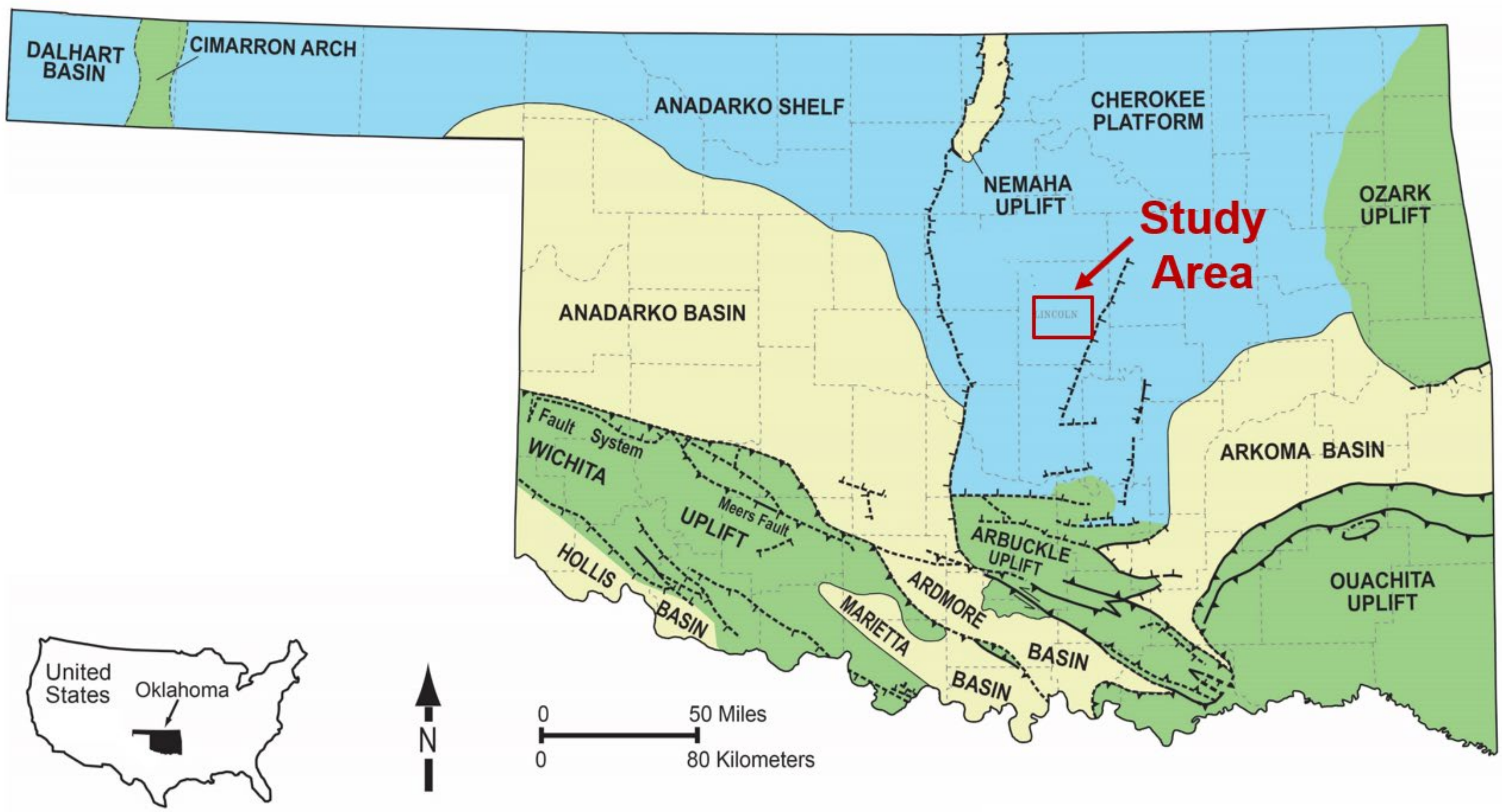

Figure 1: Regional map of major geologic provinces of Oklahoma with study area outlined. The study area is in central Lincoln County, Oklahoma on the Cherokee Platform (modified after Campbell et al., 1988; Northcutt and Campbell, 1995; Johnson and Luza, 2008).

Limestone and the Prue Sandstone, this study explores the stratigraphy and thickness trends, lithological variability, and the spatial variability total porosity, effective porosity, and fluid saturations through well-log petrophysical analyses and 3-D geostatistical modeling in order to determine 1) what are the sedimentological characteristics and pore types?, 2) what are the main lithologies and values of porosity, water saturation and bulk volume hydrocarbon?, 3) what is the stratigraphic and structural variability?, 4) what is the spatial variability of lithology and petrophysical properties and what do they suggest regarding depositional environment and reservoir potential?, 5) how does bulk volume hydrocarbon relate to depositional trends?.

GEOLOGIC SETTING

The Prue Sandstone (surface name Lagonda Sandstone) in central Oklahoma was deposited during the middle Pennsylvanian (Desmoinesian) and has previously been described as deposited in settings from shallow water to fluvial-deltaic in nature (Cole, 1958, Wanless et al, 1963, Ferguson, 1964, Campbell et al, 1997) (Figure 2). Regression during the late Mississippian exposed the Cherokee Platform while the seas remained in the Anadarko and McAlester basins (Figure 3; Krumme, 1981). During the Pennsylvanian, a relative rise in sea level covered portions of the Cherokee Platform to the south of the study area (Krumme, 1981). The intervals of shale, limestone, and sandstone in the middle Pennsylvanian have been described as cyclothyms (Blumenthal, 1956, Wanless et al, 1963, Heckel, 1983). Cyclothems consisting of, in descending order, of shale, limestone and sandstone show periods of changes in sea level, though discontinuous sedimentation may make them difficult to determine (Wanless et al, 1963). The Krebs and Cabaniss groups (previously grouped as the Cherokee Group) sit unconformably

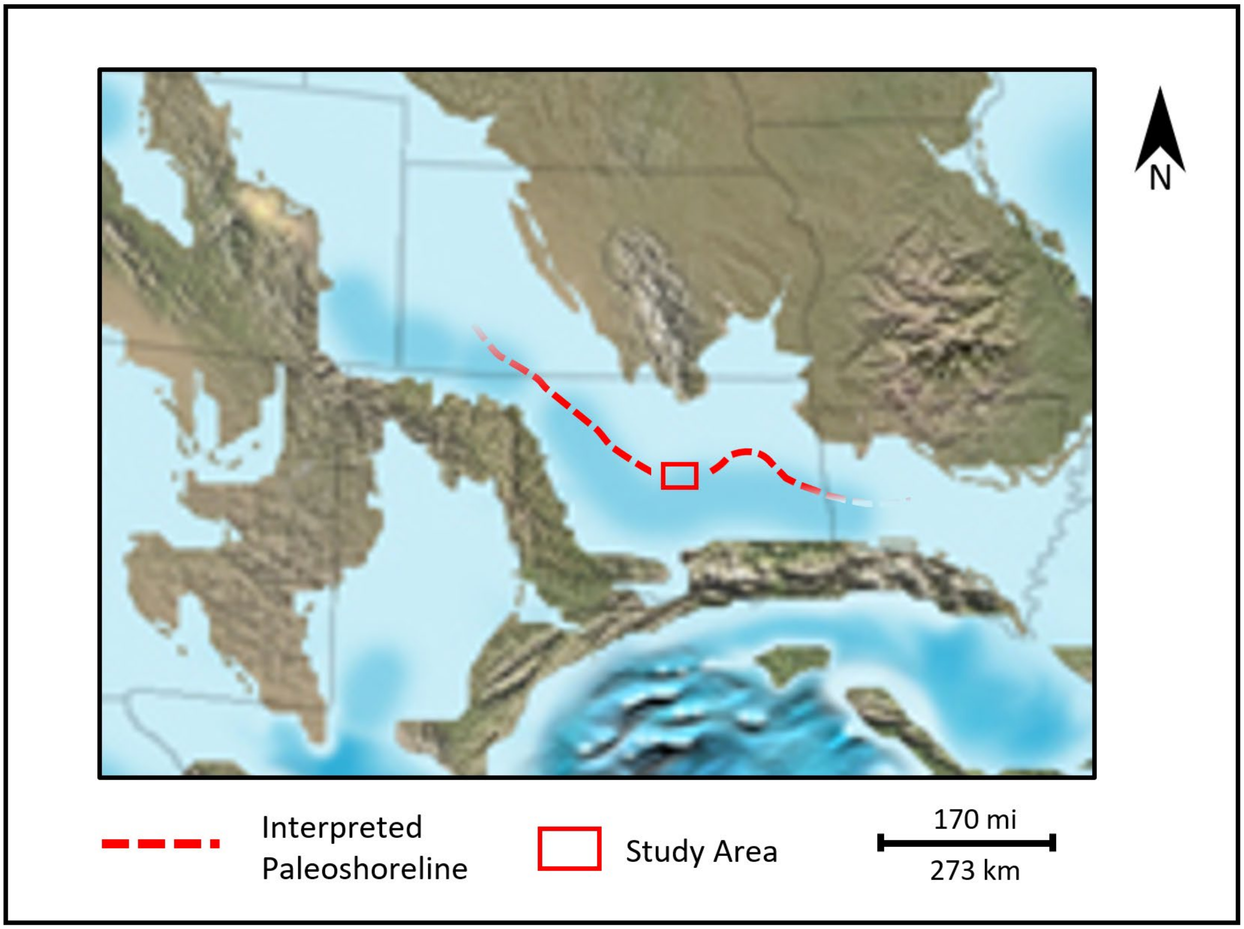

Figure 2: Paleogeographic map the central United States, including Oklahoma, during the Middle Pennsylvanian. An interpreted paleo-shoreline (red-dashed line) for the Oswego Limestone and Prue Sandstone is shown (Modified from Blakey, 2013).

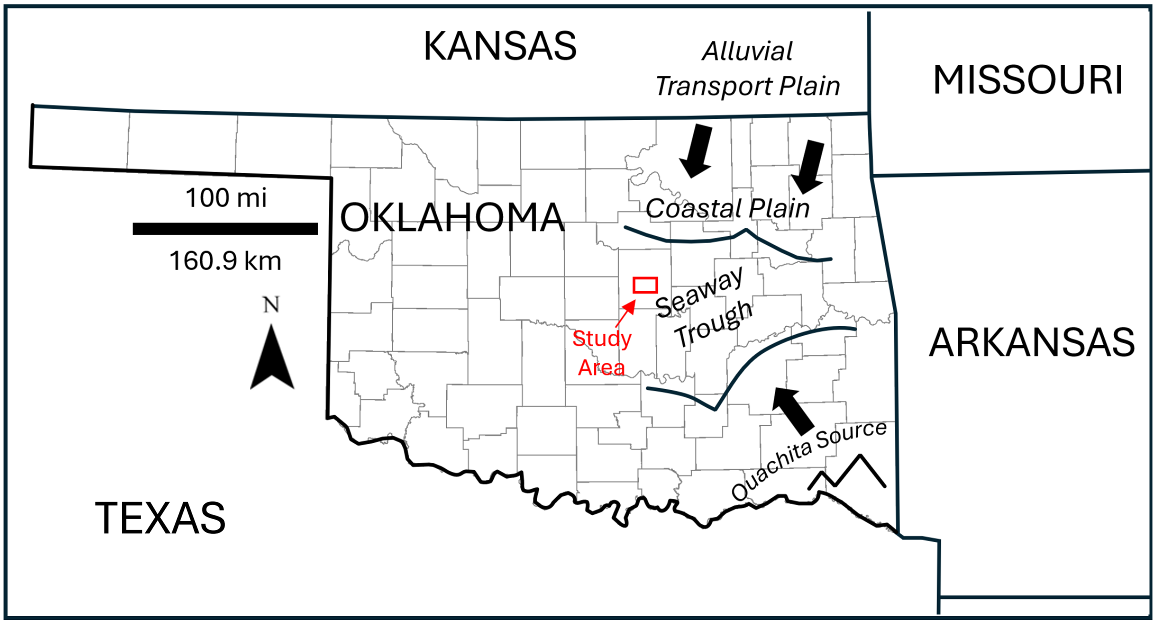

Figure 3: Paleogeographic map the central United States, including Oklahoma, during the Middle Pennsylvanian. Interpreted environments of depositions are outlined including coastal plains and the directions of sediment transport from the north-northeast (Modified from Krumme, 1981).

above the Mississippian strata (Berg, 1973; Ropp, 1991) and represent periods of transgression with regressions leading to the deposition of sandstones bounded by limestones and shales (Howe, 1956, Stirling 1998). The Prue Sandstone interval is the youngest of four sandstone intervals within the Cherokee Group. The Prue Sandstone was deposited during middle Pennsylvanian and is described as a gray to tan, very-fine to medium-grained sandstone, with shaley sandstones and coal (Blumenthal, 1956; Cole, 1958; Ropp, 1991). Coal in the Prue Sandstone interval is less common in central Oklahoma than in stratigraphically equivalent deposits to the northeast in Kansas and Illinois (Wanless et al, 1963). The Iron Post Coal at the top of the Prue Sandstone is not laterally continuous across the study area but is present in some locations (Wanless et al, 1963). Pennsylvanian sandstones and shales in Lincoln County are laterally variable (Cole, 1958, Candler, 1976). The sandstones within the Prue Sandstone are described as deposited within deltaic complexes as fluvial and distributary channels sands or as lobate bodies on the margins amid muds and swamps (Brenner, 1989).

The Prue Sandstone interval is bound above in the northwestern portion of the study area by the Oswego Limestone and associated shales to the southeast; an important subsurface marker and hydrocarbon reservoir in places (Cole, 1958). The Oswego Limestone is described as a crystalline tan to gray limestone with portions being dolomitic (Cole, 1958). In the central and southern parts of the study area, the Prue Sandstone is separated from the Oswego Limestone by the Excello Shale and in some locations the Breezy Hill Limestone (Ropp, 1991, Brenner 1989). Previous studies combine the Oswego Limestone and the Breezy Hill Limestone as the Oswego Limestone, but a distinction is made between the Oswego Limestone, Excello Shale, and the Breezy Hill Limestone for this study (Krumme 1981). The Excello Shale is 1.29—8.40 ft (0.39-2.56 m) (described in outcrop to the east of Lincoln County as black shale with thin laminations and abundant phosphate nodules (Ece, 1989). When present, the Excello Shale is notable in well logs within the study area due to its high gamma-ray signature (Figure 4). The Prue Sandstone overlies the Verdigris Limestone (Figure 5), a gray to brown fossiliferous crystalline limestone. The Verdigris Limestone exhibits lower gamma-ray and slightly higher deep resistivity signatures than the overlying Prue interval (Blumenthal, 1956).

METHODS

Sedimentological Analysis

Analysis of two cored wells located near the study was performed to better understand the lithologies, facies, and environment of deposition of the Prue Sandstone. The Sun Expl & Prod Co 3-6 Creiss Waterflood U well contains 109 ft (33.2 m) of core through the entire interval of the Prue Sandstone and is located approximately 4 mi (6.4 km) east of the study area (Figure 6). The Gulf Oil Corp 1 Hamm WF is 0.5 mi (0.8 km) south of the study area, covers 17 ft (~5.2 m) of the Prue Sandstone and was previously described by Ropp (1991) and interpreted as an incised channel fill deposit. Each core was described in terms of lithologies and facies through observations of composition, sedimentary structures, grain size, color, and diagenetic textures. Thin sections were acquired, 7 from Sun Expl & Prod Co 3-6 Creiss Waterflood U (TS 1–7) and 3 from Gulf Oil Corp 1 Hamm WF (TS 8–10) and prepared with blue resin to evaluate porosity. Calcite stain was used to identify calcite present. Each thin section was described using a petrographic microscope under both plain and cross polarized light and evaluated for minerals present, grain size and shape, and for porosity and pore types of the Prue Sandstone.

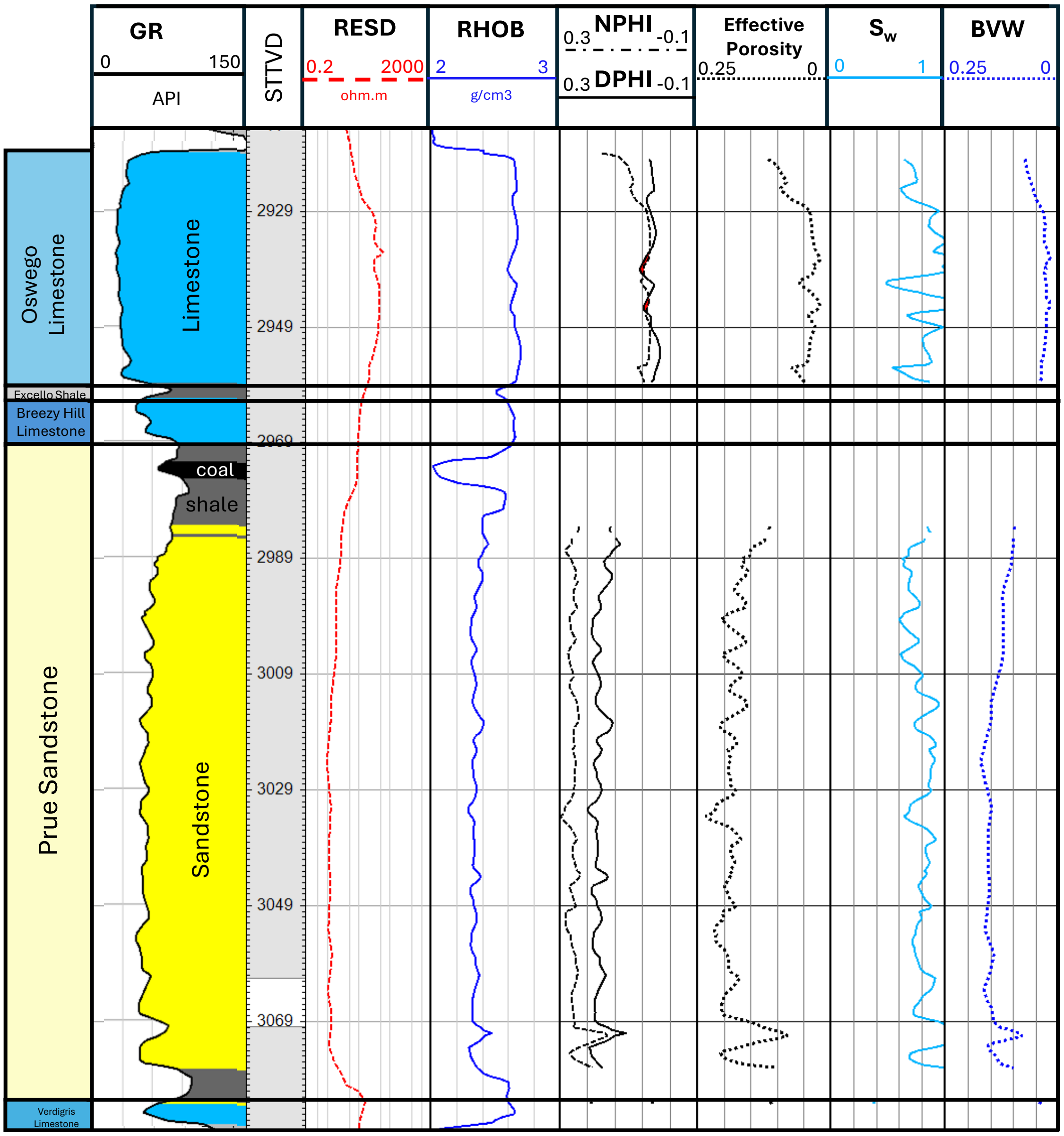

Figure 4: Type log (Petroleum Resources 1 Miller) showing porosity, water saturation and bulk volume water) for both the Oswego Limestone and the Prue Sandstone Interval. Petrophysical calculations were limited to reservoir lithologies and were used to estimate bulk hydrocarbon volume and visualize gas saturation sandstone signatures for subsurface mapping.

System	Series	Group	Subsurface Name
Pennsylvanian	Desmoinesian	Marmaton	Little Osage Shale
			Oswego Limestone
		Cabaniss	Excello shale
			Breezy Hill limestone
			Prue Sandstone
			Verdigris Limestone
			Oakley Shale
			Skinner Sandstone
		Krebs	Pink Limestone
			Red Fork Sandstone
			Inola Limestone
			Bartlesville Sandstone
			Brown Limestone
Mississippian	Meramecian Osagean		Mayes Limestone

Figure 5: General stratigraphic column containing Prue Sandstone and Oswego Limestone and bounding formations. (Modified from Ropp 1991)

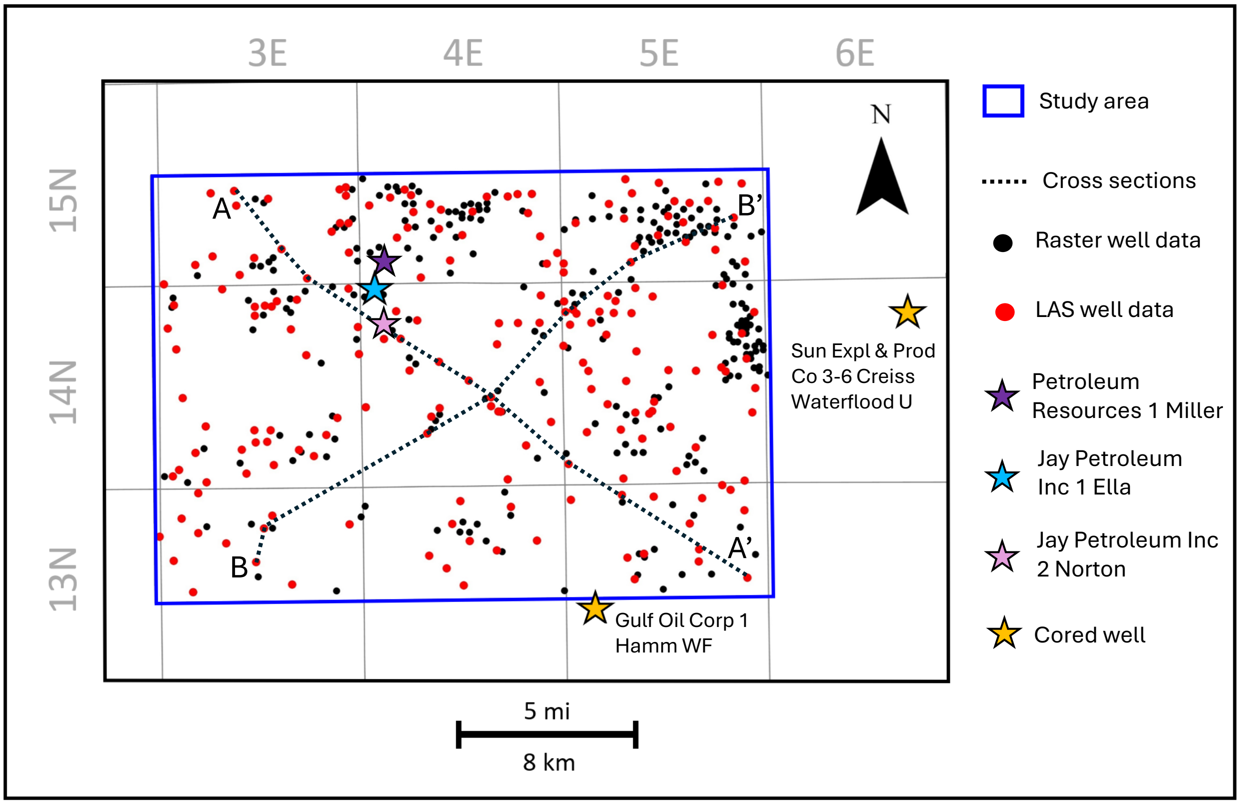

Figure 6: Map of study area showing available raster well data, LAS well data, cored wells, cross sections, and type wells used. The study area and model outline are shown in blue.

Petrophysical Log Analysis

Petrophysical log analysis was completed to determine the values of porosity, water saturation, bulk volume water and bulk volume hydrocarbon in both the Prue Sandstone and Oswego Limestone. Prior to petrophysical and well-log analysis, raster logs were digitized to create a dataset of >175 wells with a combination of gamma-ray (GR), bulk-density (RHOB), neutron-porosity (NPHI), and deep-resistivity (RESD) logs (Figure 4, Appendix A).

Lithology logs were created in each well using GR and RHOB logs to allow for lithology determination in each available well in the absence of core data. Sandstone was classified based on GR values of ≤80 API (Appendix B) Rock with a GR values >80 API was classified as a shale. Coal occurs in the upper portion of the Prue Sandstone and was classified based on RHOB values of <2.1 g/cm^3.

The Oswego Limestone above the Prue Sandstone is also a hydrocarbon reservoir in portions of the study area. Limestone was classified based on a combination of GR values of <50 API and RHOB values >2.6 g/cm^3. Shales in the Oswego Limestone were classified based on a GR of ≥50 API (Appendix C).

Matrix adjustments

Prior to calculating both total and effective porosity (PHIE) values and water saturation, adjustments were made to ensure the correct matrix by zone for both neutron porosity logs (NPHI) and density porosity logs (DPHI). The NPHI logs available were on a limestone matrix and were converted to a sandstone matrix for the Prue Sandstone. NPHI well logs for sandstone packages within the Prue Sandstone were adjusted using an estimation derived from petrophysical cross plots of apparent limestone porosity vs bulk density (Schlumberger Log Interpretation Charts, 1997; Appendix D). DPHI was calculated in the Oswego Limestone using a matrix density (ρ_{ma}) of 2.71 g/cm^3, RHOB from LAS well logs and a fluid density (ρ_f) of 1.0 g/cm^3, in the absence of laboratory readings (equation 1). For the Prue Sandstone interval, DPHI was calculated using a matrix density (ρ_{ma}) of 2.65 g/cm^3, RHOB from LAS well logs and a fluid (ρ_f) of 1 g/cm^3 in the absence of laboratory readings was used (equation 1, Asquith and Krygowski, 2004).

equation 1:

$$DPHI = \frac{\rho_{ma} - RHOB}{\rho_{ma} - \rho_f}$$

Porosity

Total porosity was calculated for the Oswego Limestone and the Prue Sandstone intervals. For the Oswego Limestone, total porosity (PHIT) was calculated using the NPHI and DPHI on a limestone matrix of 2.71 g/cm^3 (equation 2). In the Prue Sandstone, the PHIT was calculated using NPHI and DPHI on a sandstone matrix of 2.65 g/cm^3 (equation 2). To correct shale content within the reservoir, shale volume for the Prue Sandstone was calculated using the GR index or shale-volume (Vsh) equation (equation 3, Asquith and Krygowski, 2004). A GR reading representing clean sandstone, GR_{clean} = 40 API, was used and a GR reading of shale, GR_{shale} = 120 API, was used. PHIE for the Prue Sandstone was calculated using the PHIT in combination with the calculated shale volume (equation 4). PHIE was not calculated for the Oswego Limestone because the shale in the Oswego Limestone is not interbedded with the reservoir lithology of limestone. Porosity values outside of the reservoir lithologies of sandstone and limestone were removed.

equation 2:

$$PHIT = \sqrt{\frac{NPHI^2 - DPHI^2}{2}}$$

equation 3:

$$V_{Sh} = \frac{GR - GR_{clean}}{GR_{shale} - GR_{clean}}$$

equation 4:

$$PHIE = PHIT \times (1 - V_{Sh})$$

Water Saturation

Water saturation (S_w) was calculated for the reservoir lithologies of the Prue Sandstone and Oswego Limestone using the basic Archie Equation (Archie, 1942). The formation water resistivity of R_w = 0.035 was used for both the Prue Sandstone and the Oswego Limestone (Spalvieri, 2023). Deep resistivity values were from deep-resistivity logs (RESD).

For the Oswego Limestone, S_w was calculated using a cementation constant of *a*=1, cementation exponent of *m*=2, and saturation factor of *n*=2 (Archie, 1942; equation 5). The constants used were based on assumptions of a clean limestone (Asquith and Krygowski, 2004; Archie, 1942).

For the Prue Sandstone, S_w was calculated using a cementation constant of *a*=0.81, cementation exponent of *m*=2, and saturation factor of *n*=2 (Archie, 1942; equation 5). The constants used were based on assumptions of a clean, consolidated sandstone (Asquith and Krygowski, 2004; Archie, 1942).

The separate S_w calculations for the Prue Sandstone and the Oswego Limestone were combined into a single S_w log for reservoir lithologies of sandstone and limestone.

equation 5:

$$S_w^n = \frac{a \times R_w}{PHIE^m \times RESD}$$

Bulk Volume Water

Bulk volume water (BVW) was calculated using total porosity and S_w using a limestone matrix in the Oswego Limestone (equation 6a, Asquith and Krygowski, 2004). In the Prue Sandstone, PHIE and S_w using a sandstone matrix was used (equation 6b, Asquith and Krygowski, 2004). BVW allows for S_w to be analyzed relative to the available pore space within the reservoir.

equation 6a:

$$BVW = PHIT \times S_w$$

equation 6b:

$$BVW = PHIE \times S_w$$

Gas Saturation Signature

For the Prue Sandstone, PHIE and BVW were plotted side by side on a log track on fractional, reversed scale (0-1) to visually identify separation between the two curves. A positive separation was flagged (labeled) as the signature for gas saturation (presence of gas) within the sandstone. Both discrete (i.e., discrete logs classified as gas present or not) and continuous (i.e., logs values correspond to variations in gas saturation) BVH logs were generated using the PHIE and BVW logs.

Bulk Volume Hydrocarbons

BVW was also used to estimate Bulk Volume Hydrocarbon (BVH) by subtracting PHIT for the Oswego Limestone and BVW (equation 7a). For the Prue Sandstone, PHIE was subtracted from BVW (equation 6b, equation 7b). Because BVW is S_w relative to porosity, the difference between the two shows that not all available pore space is being occupied by water, with the remainder of available pore space being occupied by hydrocarbons.

equation 7a:

$$BVH = PHIT - BVW$$

equation 7b:

$$BVH = PHIE - BVW$$

Subsurface Mapping

Subsurface mapping of the Prue Sandstone, Oswego Limestone, and bounding formations was completed through interpretation of formation tops using raster log images and digital logs in >400 wells (Figure 6).

In addition to the top and base of the Prue Sandstone and Oswego Limestone, additional formations were mapped to provide regional stratigraphic and structural context. These formations include the top and base of the Excello Shale, Breezy Hill Limestone and, where present, the Verdigris Limestone. Isopach maps were generated for the Oswego Limestone, Excello Shale, Breezy Hill Limestone and Prue Sandstone from point sets represent the difference between the respective upper and lower formation tops, then gridded using convergent interpolation. Structural maps were generated by adding the isopach created of the base surface of a formation to generate the top surface. By creating structural maps based on the addition of the isopach surfaces, the integrity of thinner intervals such as the Excello Shale and Oswego Limestone was preserved. Generating structural maps using convergent interpolation alone allowed for the top and base structural maps of the thinner intervals to cross in areas without significant well control (Figure 7).

To complete discrete mapping of gas saturation in the study area, PHIE and BVH were plotted side by side on a fractional, reverse scaled log track. The separation between the PHIE and BVH curves was color-filled with green and the distance between the BVH curve and the right-hand track of the log was color-filled blue. Once formatted, each well in the study was analyzed to check for separation between the curves that increased towards the top of a sandstone package. Each well observed to contain the log signature was labeled for gas saturation. The location of these wells was then used to observe their special distribution across the study area.

3-D Reservoir Modeling

To aid achieving the goal of understanding the spatial variability of lithology and the petrophysical properties determined through petrophysical log analysis, an accurate 3-D model is critical to evaluate between available well data. Commercial software was used to create the three-dimensional structural and stratigraphic framework (3D grid) for the study area that encompasses and represents 5 stratigraphic zones. These zones in stratigraphic order from base

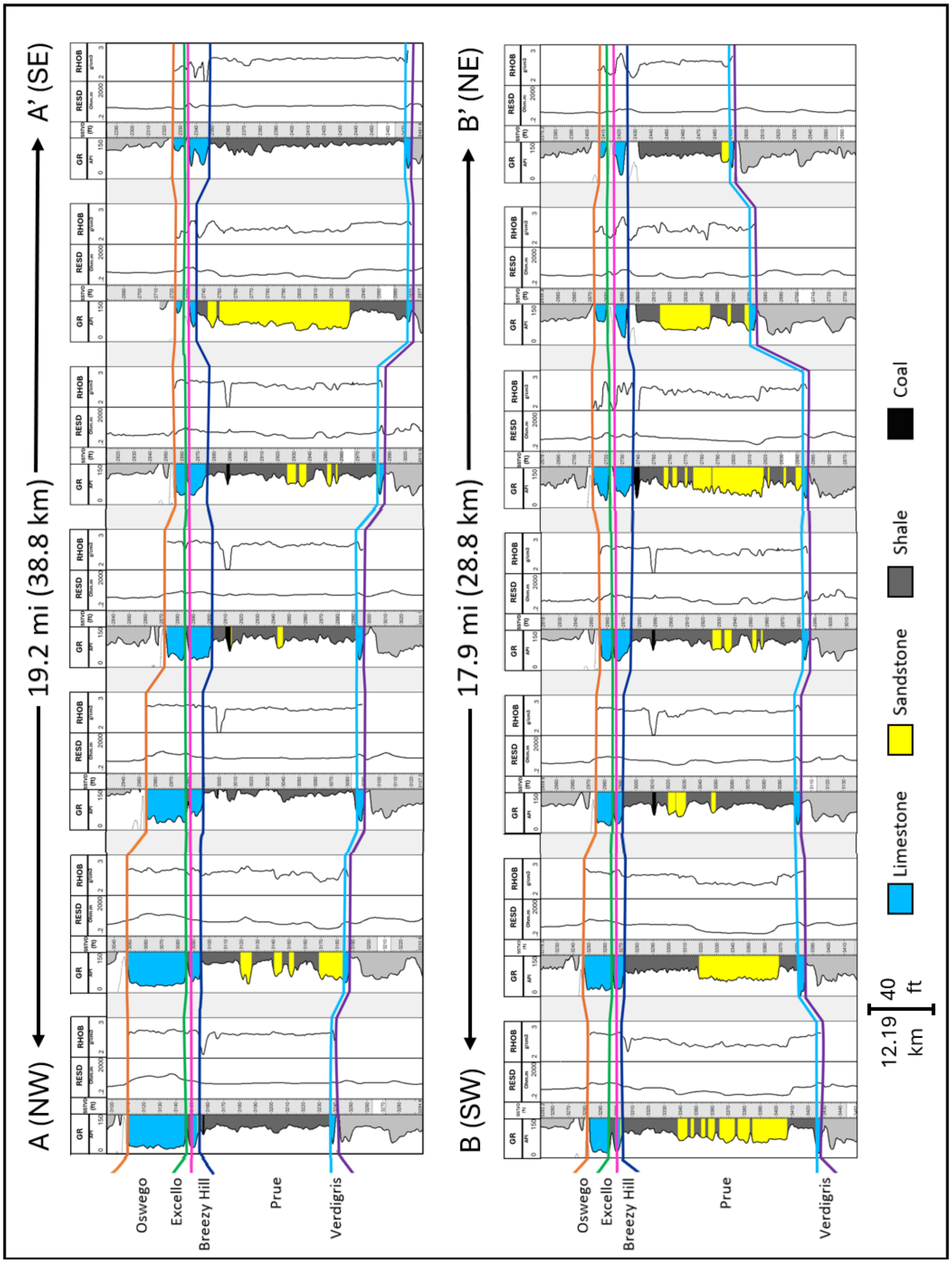

Figure 7: Northwest-southeast (A-A') and southwest-northeast (B-B') cross sections across study area from showing mapped intervals. Sandstone is present in the Prue Sandstone as both large, consolidated packages and as isolated, thin packages. Shales are heterogenous in the interval. Coals are not laterally continuous and are located at the top of the interval. Cross sections are flattened on Excello Shale, and wells are uniformly spaced. See Figure 3 for cross section locations.

to top include the Verdigris Limestone, Prue Sandstone, Breezy Hill Limestone, Excello Shale, and Oswego Limestone.

Each zone was defined by using the structure and isopach maps. Following the generation of horizons used in the structural model, an aerial cell size of 200 ft x 200 ft (~61 x ~61 m) was used. Proportional layering was used with an approximate cell thickness in the Prue Sandstone and Oswego Limestone of 2 ft (0.61 m). To limit the minimum thickness of layers, especially in areas where stratigraphic truncation occurs, the minimum cell thickness was set to 0.25 ft (0.076 m). The number of cells in the structural model (3D grid) is 12,941,760.

Lithology Modeling

After the creation of the three-dimensional structural and stratigraphic framework, lithology logs were upscaled to the 3-D model grid by assigning a single lithology class to a cell based on the most abundant lithology within a cell. The target fractions of each lithology were obtained from the upscaled lithology logs. Lithology was manually assigned for the Excello Shale and Breezy Hill Limestone. Sequential-indicator simulation (SIS) was used to model lithologies in the Prue Sandstone zone consisting of sandstone, shale, and coal. SIS was also used in the Oswego Limestone zone to model lithologies of either limestone or shale. The model constraints include: 1) the stratigraphic and structural framework (3-D grid), 2) upscaled lithology logs, 3) variogram parameters by zone, 4) lithology percentages by zone, and 5) a vertical lithology proportion curve. Horizontal variogram ranges were assigned based on the expected scales of geologic features. Vertical variogram ranges were assigned based on vertical lithology variograms generated from the lithology logs. Azimuth directions were assigned for horizontal variograms based on trends from interpreted isopach and structure maps (Appendix E) In order to follow the southwest-northeast trend line dividing limestone prominence to the northwest and shale to the southeast, 40 and 310 degrees were used for the major and minor azimuth directions respectively. A major azimuth of 335 degrees and a minor azimuth of 245 degrees was used for the Prue Sandstone to follow the length of the elongate sandstone bodies present.

Petrophysical Property Modeling

A 3-D porosity model was generated to evaluate the distribution of effective porosity (PHIE) in the Prue Sandstone and total porosity (PHIT) in the Oswego Limestone within the study area. PHIT and PHIE logs were biased to the lithology logs and upscaled using an arithmetic mean. The effective and total porosity model was generated using sequential-Gaussian simulation (SGS) and was constrained to 1) 3-D lithology model, 2) upscaled PHIT and PHIE logs (biased to lithology), 3) porosity histograms by zone and lithology, and 4) variogram parameters by zone and lithology. Horizontal porosity variogram ranges were based on values used for lithology modeling but were reduced to account for internal porosity heterogeneity within reservoir lithologies (Appendix F). Porosity and S_w were only modeled in limestone for the Oswego Limestone and sandstone within the Prue Sandstone.

A 3D S_w model was developed to assess the spatial distribution of S_w. Shale and coal were assigned a constant S_w value of 1. The 3D S_w model was generated using sequential-Gaussian simulation (SGS), constrained to: (1) the 3D lithology model, (2) upscaled S_w logs biased to the lithology logs using an arithmetic mean, (3) S_w histograms for sandstone per zone, and (4) horizontal and vertical variogram parameters (Appendix G) per zone. In addition to the application of a normal score transform, the major and minor horizontal variogram ranges were set to 5000 and 3000 ft (~1524 and ~914.4 m) respectively, while the vertical variogram parameters were estimated to be approximately 10 ft (~3.05 m) (Appendix G).

Bulk Volume Water Modeling

To preserve the constraints of both the S_w model and the porosity model, a BVW model was generated by multiplying the S_w model with the porosity model.

Bulk Volume Hydrocarbon Analysis

BVH logs were classified as present when the difference between the PHIE (or total porosity in the Oswego Limestone) and BVW was larger than zero. BVH was created as a discreet model through subtracting the previously created PHIE model and BVW model; where the value was larger than 0, a value of 1 was assigned and where less than 0, a value of 0 was assigned allowing for the special distribution to be evaluated. When modeling BVH as a continuous property, the previously modeled PHIE model and BVW model were subtracted, allowing for the magnitude of the difference between PHIE and BVW to be observed. By utilizing the previously modeled PHIE and S_w models, BVH is constrained to: (1) the 3D lithology model, (2) upscaled PHIE and BVW logs, (3) PHIE and S_w histograms per zone, and (4) horizontal and vertical PHIE and S_w per zone (Appendix F and G).

RESULTS

Prue Sandstone Lithologies, Framework Grains, and Porosity

Sun Expl & Prod Co 3-6 Creiss Waterflood U

The Prue Sandstone interval (109 ft; ~33.22 m) in the Sun Expl & Prod Co 3-6 Creiss Waterflood U core consisted of interbedded sandstone, siltstone, and shale (Figure 8, Appendix H). The lower portion of the Prue Sandstone consists of dark, organic-rich shale overlain by

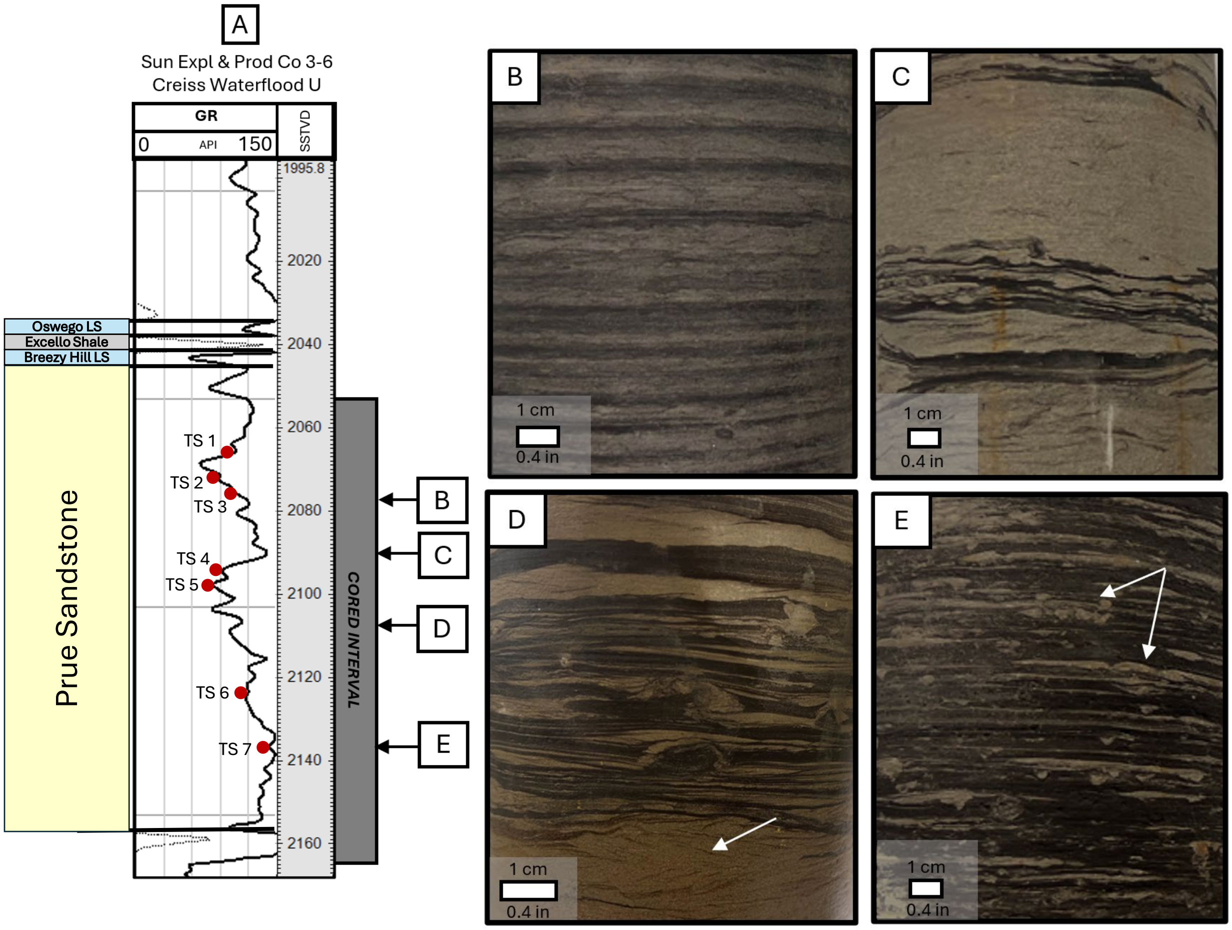

Figure 8: A) Gamma ray log of Sun Expl & Prod Co 3-6 Creiss Waterflood U cored through the Prue Sandstone. The location of 7 thin sections from the core are shown on the gamma ray log (TS1-TS7). Four images of the core and their locations on the well log are shown. B) Planar and wavy laminations of sandstone and mudstone (white arrows). C) Sandstones are very-fine to fine-grained, light gray to tan, and micaceous. D) Herring-bone cross-bedding (white arrow). E) Burrows and disturbed bedding in the Sun Expl & Prod Co 3-6 Creiss Waterflood well within layers of interbedded sandstone and shale (white arrows).

interbedded mudstone and siltstone with filled burrows that disrupt the planar lamina (Figure 8E). Sandstone intervals in the core consist of very fine to fine-grained, light gray to tan sandstone with wavy lamina of shale as well as burrows and contorted lamina. Herringbone cross-bedding is within these interbedded portions of sandstone and shale (Figure 8D). The thin sections show subrounded-subangular, moderately sorted quartz sandstone containing minor amounts of feldspar and muscovite. Organic material exists both as clasts within the matrix and as lamina within the rock. Pore types include intergranular, channel, and fracture porosity with values ranging from ~1-15% (Figure 9A).

Gulf Oil Corp 1 Hamm WF

The Gulf Oil Corp 1 Hamm WF well was previously described by Ropp in 1991. The cored interval consists of 17 ft (~5.2 m) of Prue Sandstone (Appendix I). The cored interval includes siltstone and fine-grained tan to buff sandstone interbedded with dark shale. Both flaser and wavy laminations are present with burrows. Thicker (x-x ft; x-x m) intervals of clean sandstone lack significant sedimentary structures. Thin sections from the Gulf Oil Corp 1 Hamm WF core exhibit well-sorted, subrounded-subangular quartz framework grains with minor amounts of muscovite and feldspar. Porosity ranges from ~7-20%. Organic clasts are present within the thin sections but are not laminated as in the Sun Expl & Prod Co 3-6 Creiss Waterflood U thin sections (Figure 9B). Based on observations from core and thin-section analysis, sandstone is the main reservoir lithology within the Prue Sandstone interval.

Petrophysical Properties

The Oswego Limestone is primarily limestone (84.3%) and shale (15.7%) based on estimated lithologies from well data. Total porosity in the limestones ranges from 0–26% with an

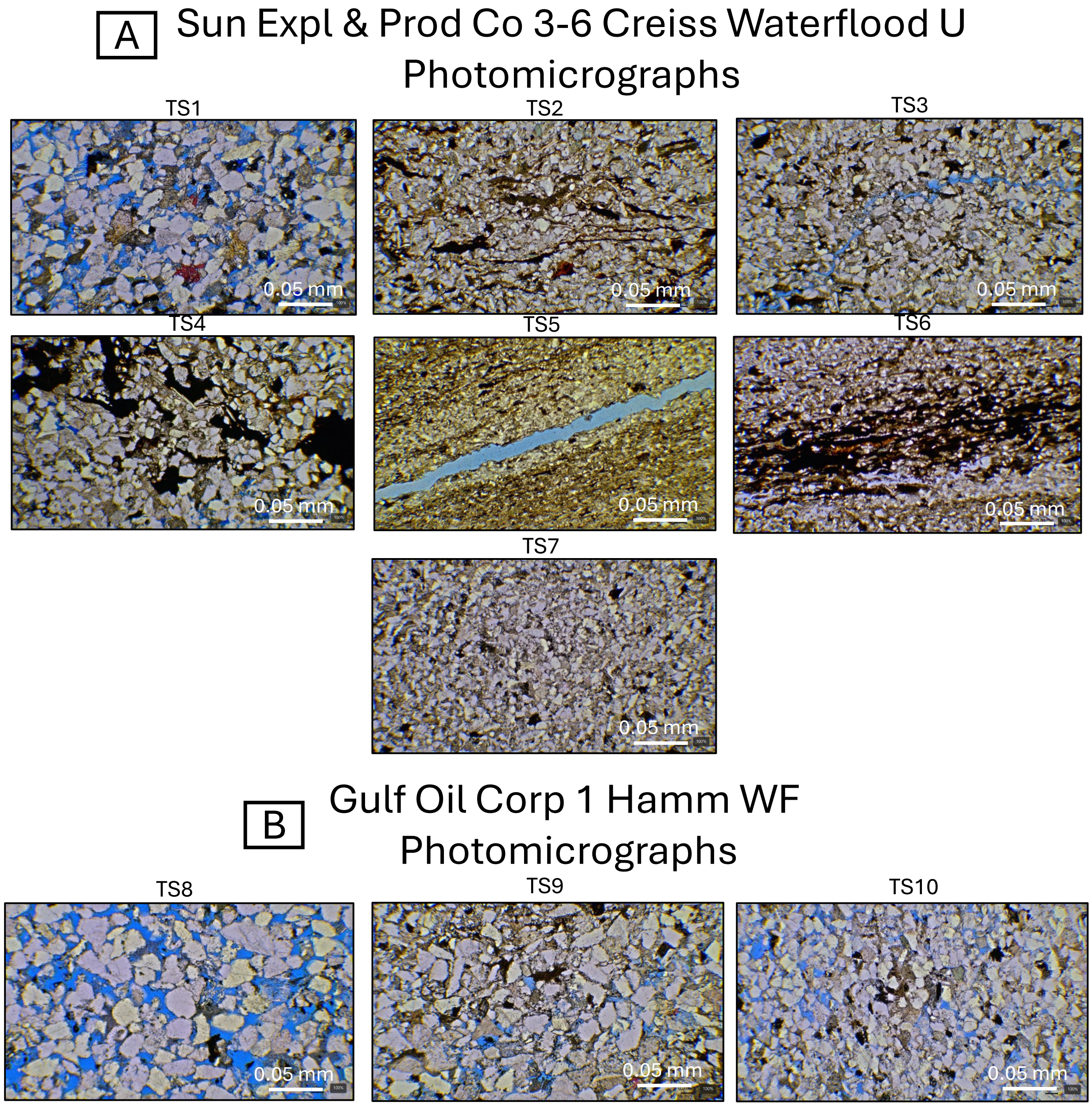

Figure 9: A) 7 thin sections taken from the CRIESS WF core were taken (TS1-TS7). All the thin sections are observed to contain some amount of organic matter. TS1) Subrounded-subangular, moderately well-sorted quartz sandstone with intergranular porosity estimated at approximately ~%. Small amounts of calcite are seen but are not consistent throughout the TS1 thin section. TS2) Fine-grained subrounded-rounded quartz interbedded with non-laminar mud and organic material. Minor amounts of calcite grains are present. Minimal intergranular porosity is seen, ~>1%. TS3) Well-cemented subrounded-rounded quartz sandstone with organic clasts present. Channel porosity is observed, ~%. TS4) Large clasts of organic material present. Thin sections were taken B) 3 thin sections were taken from the HAMM-1 core (TS8-TS10).

average porosity of 6%. (Appendix K). S_w in limestone ranges from 20–100% with an average of 80% (Appendix L). S_w calculated in limestones indicates only 4.9% of limestones to contain water saturations less than 40%. BVW in limestones ranges from 2–10%, with the 37.8% of values falling between 3-4%. BVH in limestones ranges from with an average of 0–20%, with the highest values for BVH being located central to the study area in limestones-oriented northeast to southwest.

The Prue Sandstone is primarily sandstone (28.8%), shale (69.7 %), and coal (1.3%) based on estimated lithologies from well data. Limestone is negligible in the Prue Sandstone (Appendix M). Shale volume of sandstones in the Prue ranges from 0–50%. The log-calculated total porosity ranges from 1-24%. The log-calculated PHIE in the sandstones ranged from 7–15%, showing a reduction from the total porosity calculated (Appendix N). S_w in sandstones within the Prue Sandstone ranges from 21–100% with an average S_w of 84%. S_w was not calculated for shale and coal. Bulk volume water in sandstones ranges from 4–22%. BVH in sandstones ranges from 0–21%.

Stratigraphic Framework and Subsurface Maps

The stratigraphic framework was constructed through structure and isopach mapping of the Oswego Limestone, Excello Shale, Breezy Hill Limestone, Prue Sandstone, and Verdigris Limestone (Figure 10). Structural mapping of the Oswego Limestone resulted in values ranging from -2196– -3491 ft (-669.34– -1064.06 m) with isopach map show thickness values ranging from 2.4–45.7 ft (0.7–13.9 m) (Figure 11). All structural surfaces dip to the west-southwest. Faults are pre-depositional and while some smaller faults may extend upward into the Prue

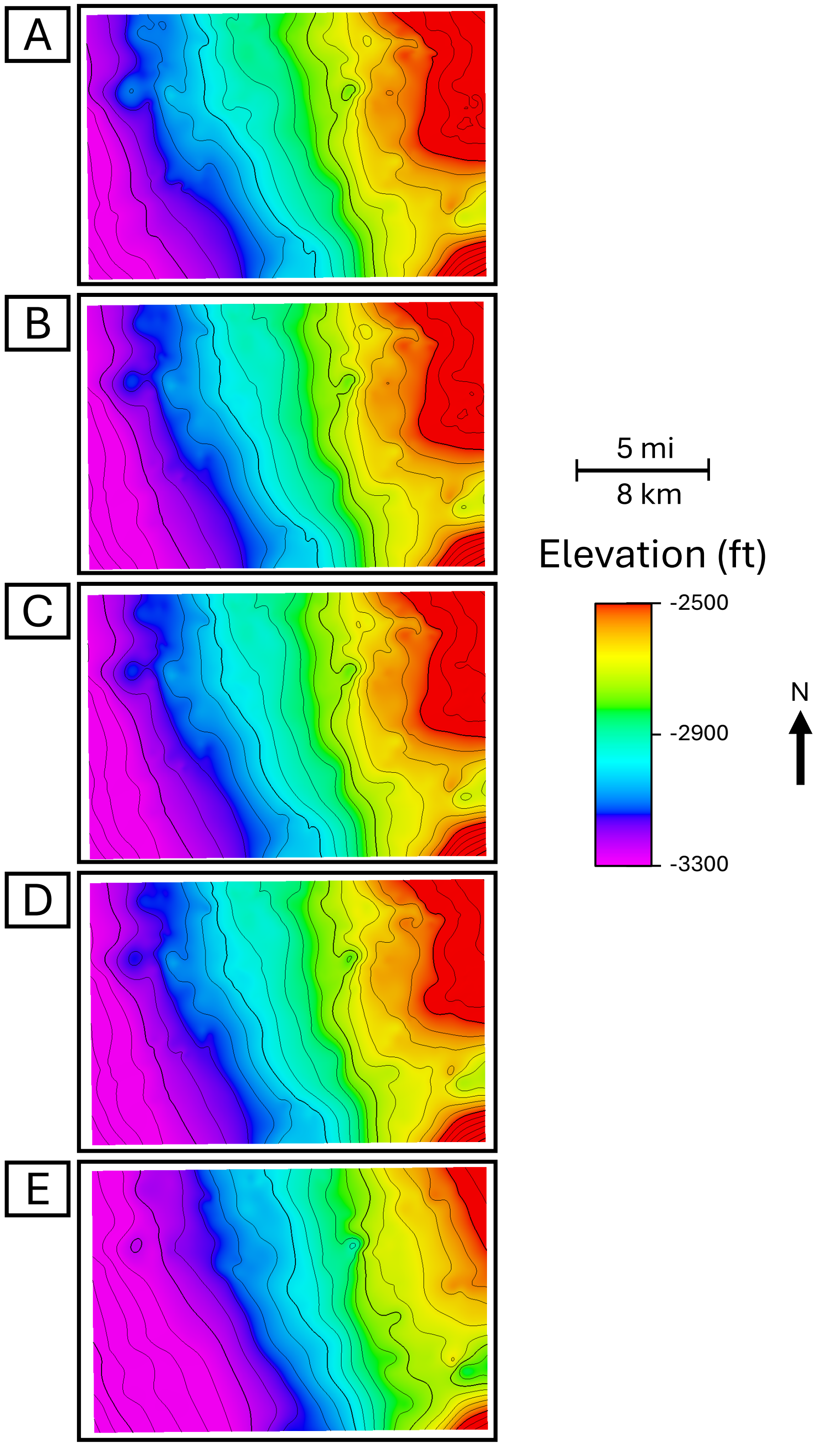

Figure 10: A) Structure-contour of the top of the Oswego Limestone , B) top of the Excello Shale, C) top of the Breezy Hill Limestone, D) top of the Prue Sandstone and E) top of the Verdigris Limestone. The highest elevations are to the northeast and southeast, with lowest elevations to the southwest.

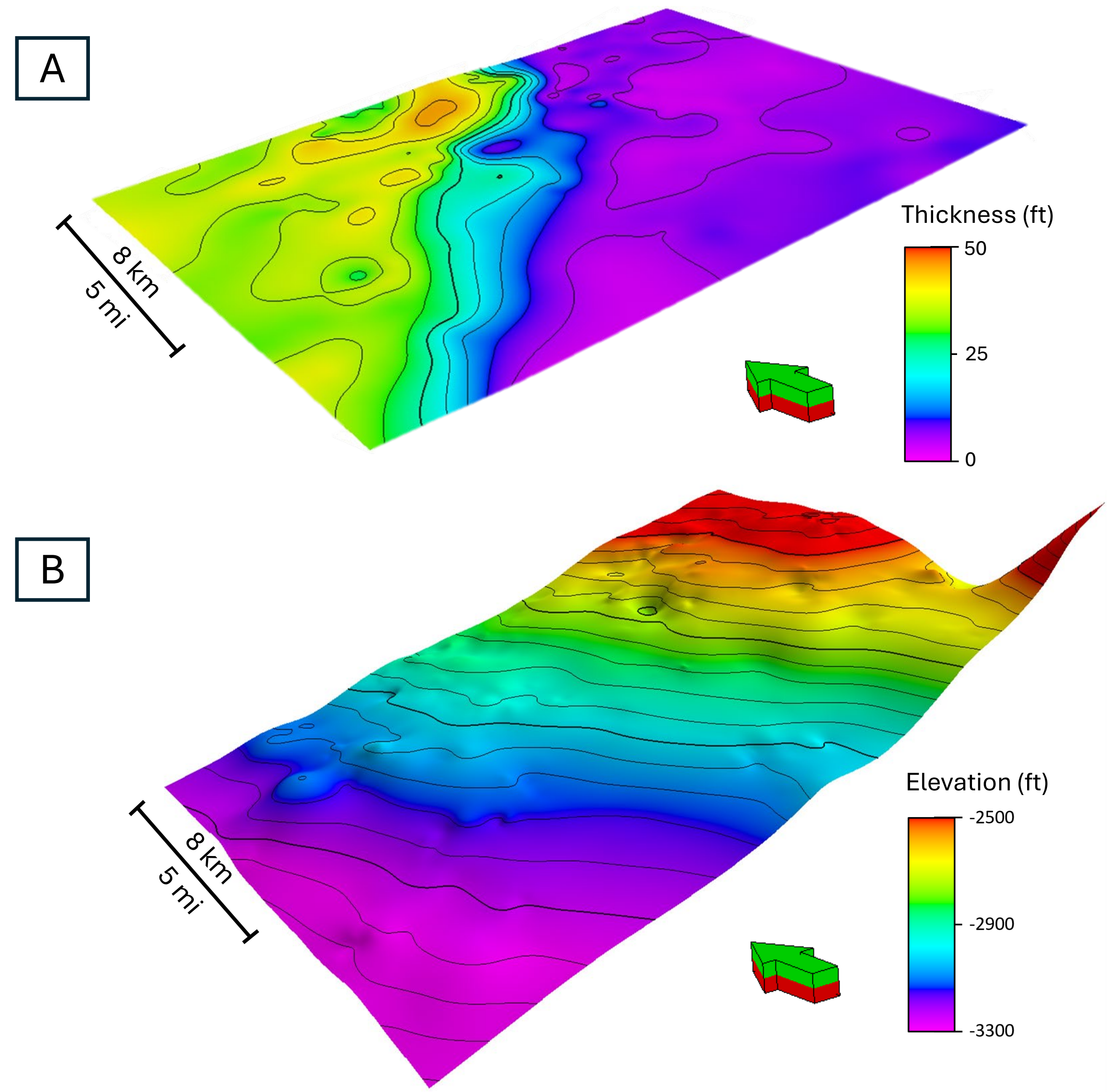

Figure 11: A) Oswego Limestone isopach and structure contour map. B) The Oswego Limestone dips to the west and the thickest Oswego Limestone is in the northwest.

Sandstone, they are not detectable from well logs (Puckette, 2021). The thickest Oswego Limestone is in the northwestern portion of the study area and it is thinnest in the southeast (Figure 11). The Excello Shale ranges in thickness from 1.3—8.4 ft (0.4-2.6 m) and is laterally and vertically continuous. The Breezy Hill Limestone ranges in thickness from 2.2–24.8 ft (0.7–7.6 m). The Prue Sandstone is the thickest mapped interval ranging from 53–147.4 ft (16.2–44.9 m) with elevations ranging from -3619– -2220 ft (-1103.1– -676.7 m) (Figure 12). The thinnest intervals in the Prue Sandstone are located to the east while the thickest portions of the study area are to the southeast. Thicker intervals are oriented primarily northeast to southwest or northwest to southeast. Thick portions of the interval are not heavily interconnected and separates thinner portions of the interval. Eighteen wells have signatures for saturated gas within the Prue Sandstone. The 18 wells are not distributed evenly and are concentrated in the northwestern corner (Figure 13). For these wells, the PHIE ranges from 7–28%, S_w in the gas saturated intervals ranges from 35–100%, and BVW ranges from 5–22%. BVH in these wells ranges from 0-13%.

3-D Reservoir Models

Lithology Models

Oswego Limestone

Limestone comprises 65.9% of the 3D Oswego Limestone lithology model with the remaining 34.2% being shale. Percentage and thickness maps were generated for the Oswego Limestone zone. Within the Oswego zone, limestone thickness ranges from 0–45 ft (0–13.7 m)

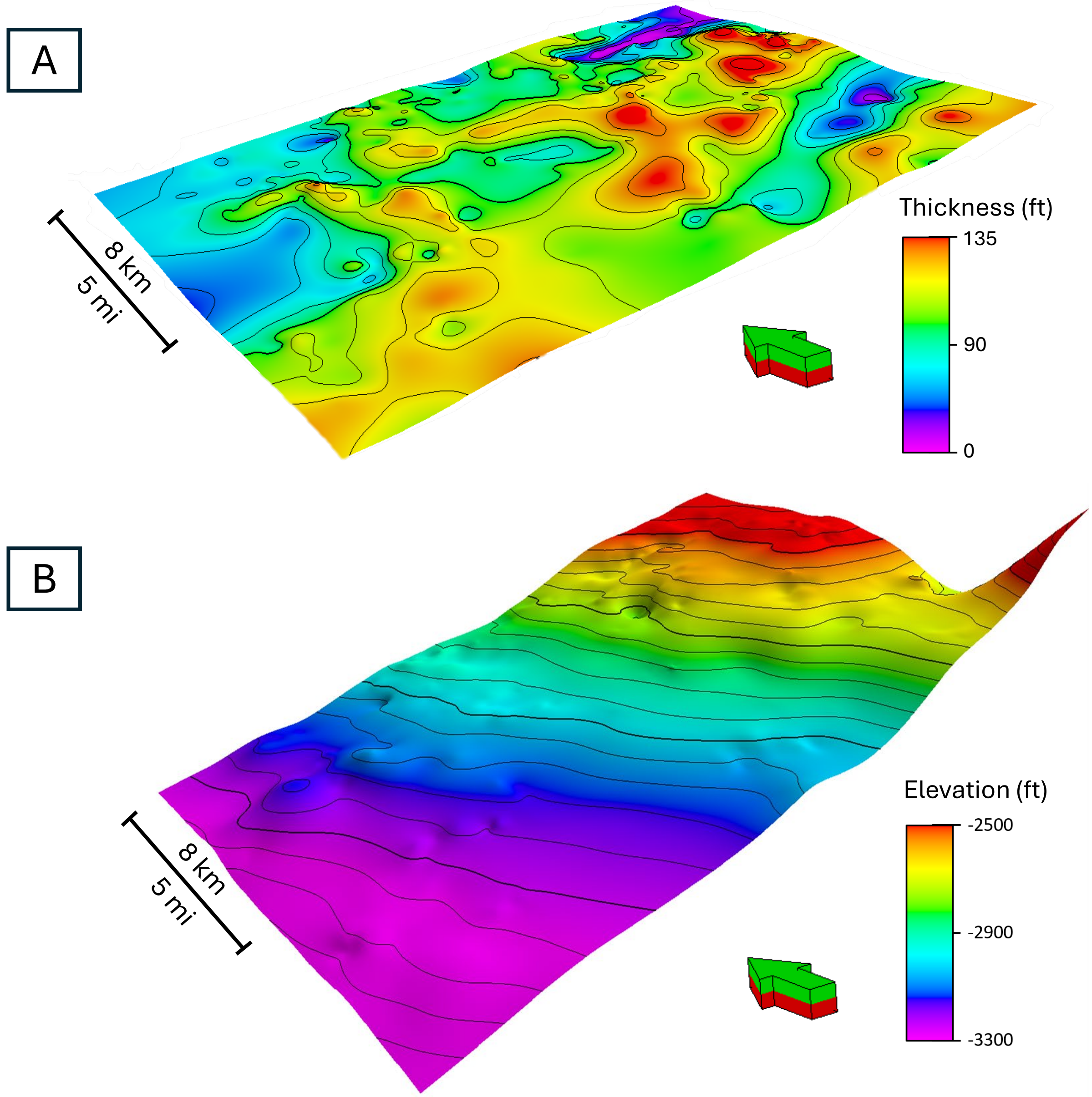

Figure 12: A) Prue Sandstone isopach and B) structure contour map. The Prue Sandstone dips to the west. The Prue Sandstone is thickest located to the east along a southwest-northeast trend.

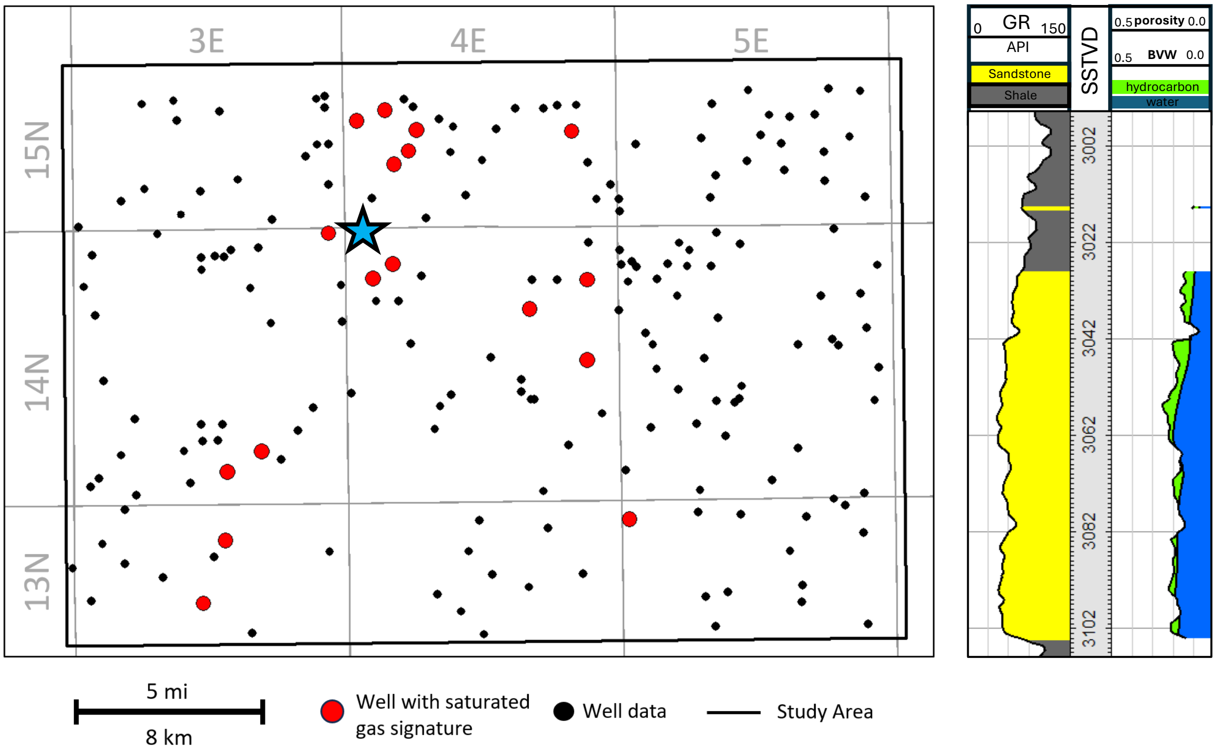

Figure 13: Wells with gas saturation (red circles). One well (Jay Petroleum Inc 1 Ella) is shown displaying the signature used. Gas saturation signature was determined by plotting both effective porosity and bulk volume water on the same reverse, fractional scale (0.50-0.0) on the same log track. A color fill was used between the porosity and bulk volume water to shade areas where bulk volume water is less than porosity, indicating the presence of hydrocarbons. The gas saturation signature is noted where the separation between the effective porosity curve and bulk volume water increases at the top of a sandstone package.

(Figure 14B), and shale thickness ranges from 0–23.45 ft (0–7.2 m) (Figure 14A). The thickest limestone is in the northwestern corner of the study area and shale thickens to the southeast.

Prue Sandstone

Within the Prue Sandstone, there is limited coal (1. 7%) which occurs as isolated beds with an average thickness of 1.7 ft (0.5 m) (Figure 15A). The thickest beds of coal range from 1.0–2.6-mi^2 (~2.6–6.8 km^2) in area. Shale makes up 70.5% lithologies and has an average thickness of 71.7 ft (21.8 m) and thickness range of 0-147.4 ft (0-44.9 m) (Figure 15B). Shale is thickest in the southeastern portion of the study area. Sandstone is the reservoir lithology for the Prue Sandstone and makes up 27.9% of the modeled interval (Figure 15C). The sandstone thickness ranges from 0–124.1 ft (0–37.84 m) with an average thickness of 29.3 ft (8.9 m). Elongate sandstones-oriented northwest-southeast range in thickness from 50-100 ft (~15.2-30.5 m), while more isolated sandstones range from 40-80 ft (~12.1-24.4 m) in thickness.

Prue Sandstone percent maps show that the sandstone distribution is highly variable and ranges from 0–100%. Similarly, shale within the Prue Sandstone is highly variable and ranges from 0–100%; coal percentage ranges from 0–26%. The thickest sandstones are to the north and thinner to the south and southeast.

Petrophysical Models

Oswego Limestone

Petrophysical modeling of total porosity for the Oswego Limestone resulted in a range of porosity in limestone from 0–16% with an average of 4% (Figure 16B). S_w ranges from 23–100% with an average of 82% (Figure 16C). Bulk volume water ranges from 0–16% with an average of 3% (Figure 16D). The maximum BVH is 0–12% (Figure 17B). An average porosity

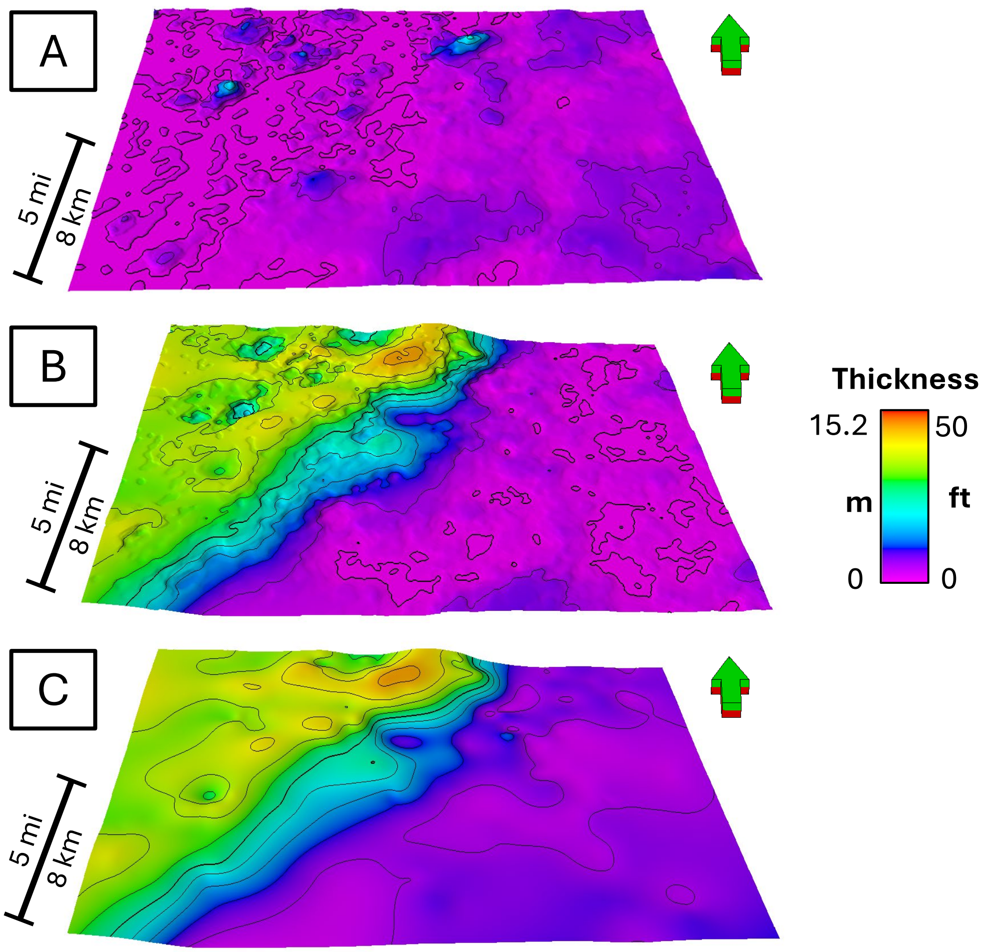

Figure 14: Oswego Limestone A) shale isopach; B) limestone isopach and C) total isopach. The Oswego Limestone is thickest and contains the most limestone to the northwest and thinnest containing the most shale to the southeast. Vertical exaggeration of 100x.

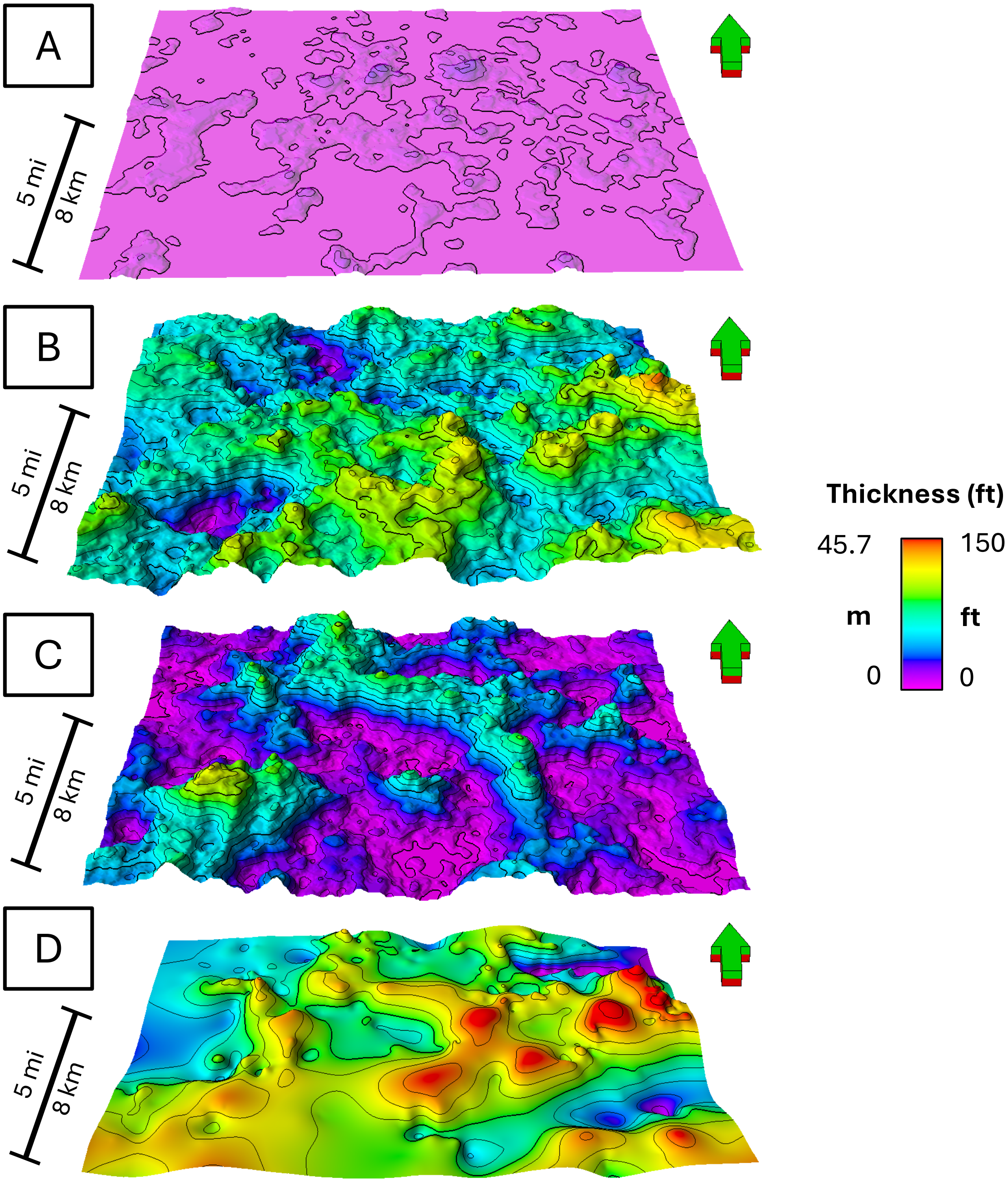

Figure 15: Prue Sandstone A) coal isopach; B) shale isopach; C) sandstone isopach, and D) total isopach. The Prue Sandstone is thickest to the southeast. Sandstone packages are thickest in isolated pockets and elongate bodies trending northwest to southeast. Coal thickness is evenly distributed. Vertical exaggeration of 100x.

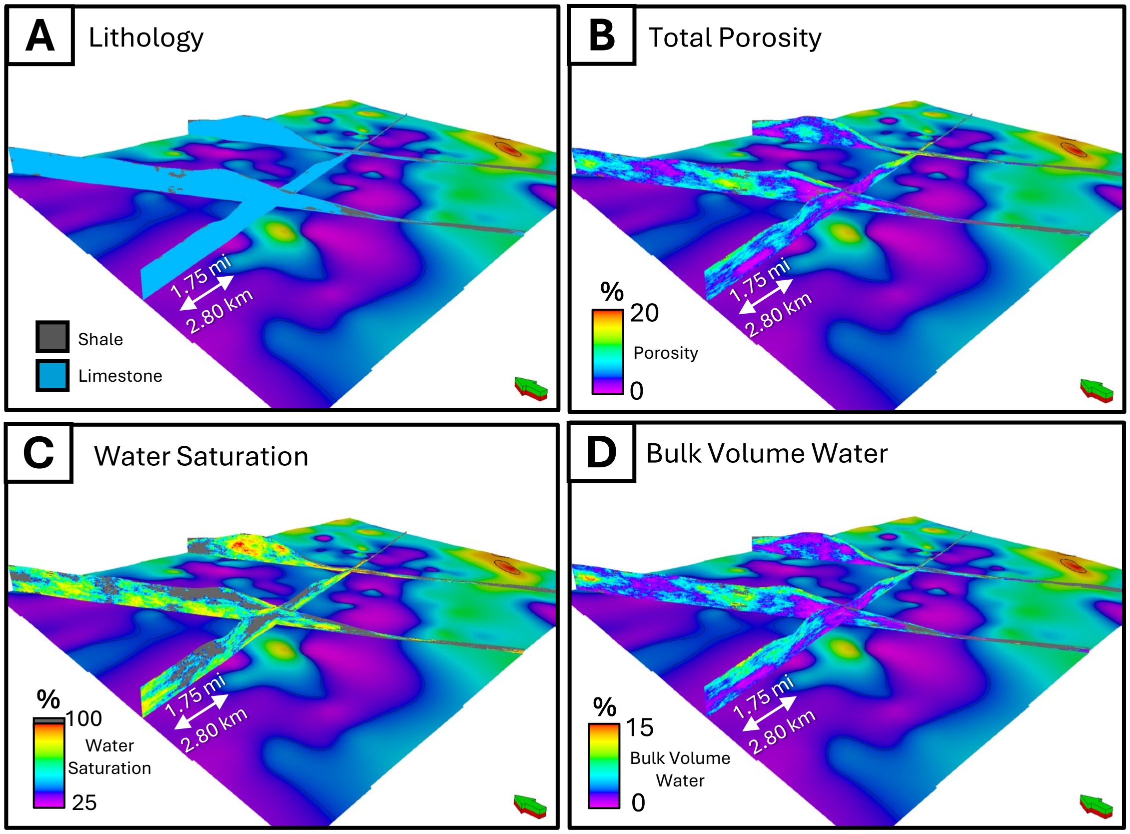

Figure 16: Northwest-southeast and southwest-northeast cross sections through 3d models of A) lithology, B) total porosity, C) water saturation and D) bulk volume water for the Oswego Limestone with the top of Excello Shale horizon show. The model and surfaces shown are adjusted to the flattened Top of Breezy Hill Limestone surface and with a vertical exaggeration of 125x. (B) Total porosity, (C) water saturation and (D) bulk volume water were only calculated within the limestone shown in (A).

map from the porosity model show that values range from 0–6% (Figure 17A). For the Oswego Limestone, hydrocarbons are present within 79.9% of the limestones and 6.9% of those limestones have BVH percentages >5%.

Prue Sandstone

PHIE for the Prue Sandstone ranges from 0–29% with an average of 15% (Figure 18B). Modeled S_w ranges from 24–100% with an average of 82% (Figure 18C). Bulk volume water ranges from 0–28% with an average of 12% (Figure 18D). BVH ranges from 0–15% (Figure 19B). An average BVH map shows that values range from 0–7% (Figure 19A). For the Prue Sandstone, hydrocarbons are present in 99.98% of the sandstones with 23% having BVH percentages >5%.

DISCUSSION

Stratigraphy

Subsurface mapping was performed with a high well density and completed at a fine scale, separating the Excello Shale and the Breezy Hill Limestone from the Oswego Limestone. Both the Excello Shale and the Breezy Hill Limestone are relatively thin in the study area and are not considered to be reservoirs. However, structural mapping of the Excello Shale and the Breezy Hill Limestone provides insight into sea levels at the time of deposition. The separation of the Breezy Hill Limestone from Oswego Limestone by the Excello Shale is interpreted to mark the presence of a minor regression and relative sea level rise over the entire study area preceding the deposition of the Oswego Limestone. Mapping the Excello Shale provides a known point of relative high sea level and even shale deposition on which structural models may be flattened to aid in understanding the paleogeography. Viewing the structural map of the

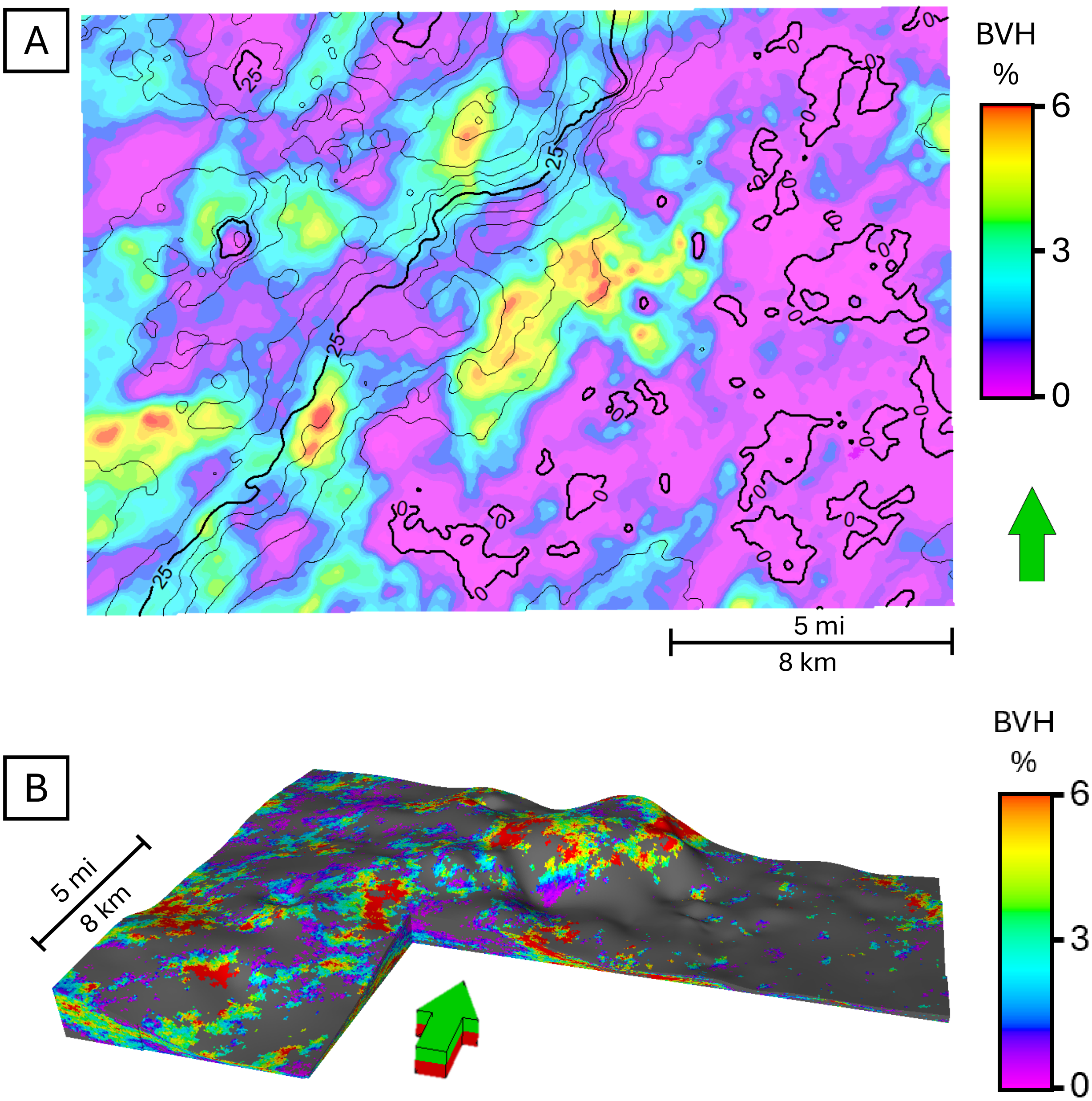

Figure 17: A) Average BVH percent map based on B) 3d BVH model within the Oswego Limestone. Contours shown indicate limestone thickness. The highest values of BVH are seen in and adjacent to areas of thicker limestone. BVH percentages were only calculated in limestone for the Oswego Limestone.

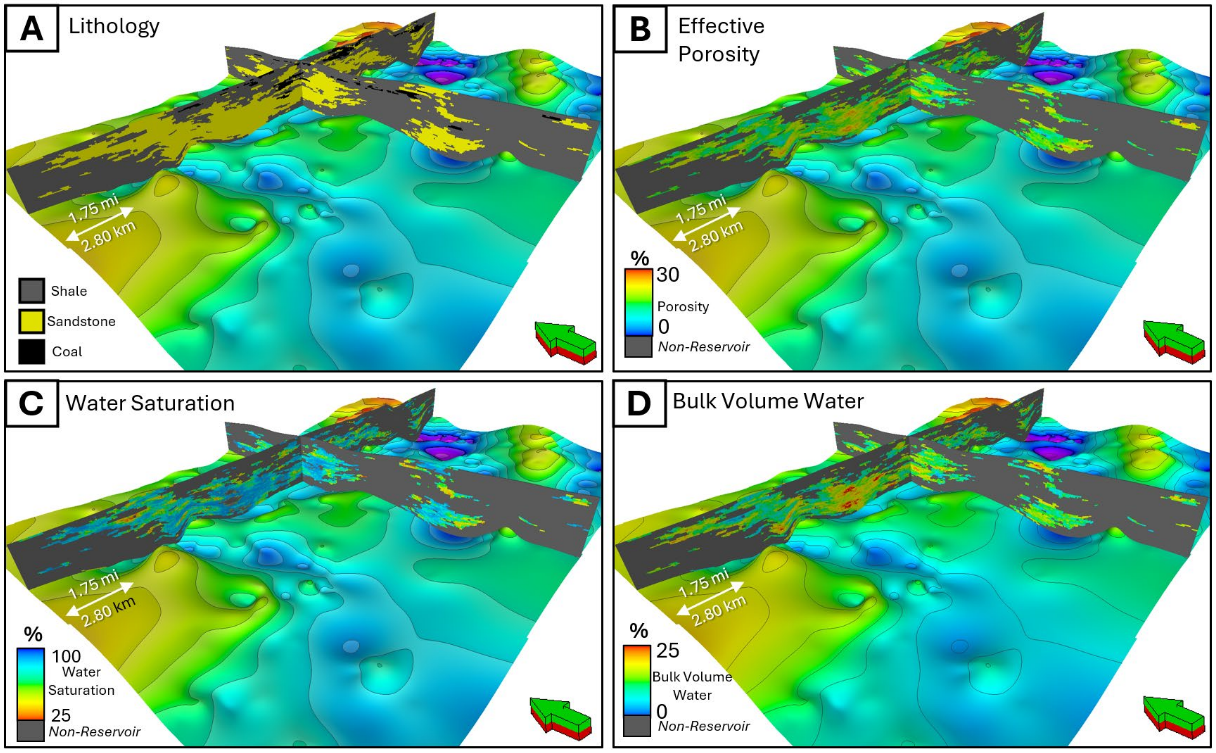

Figure 18: West-east and north-south cross sections through 3d model of A) lithology, B) effective porosity, C) water saturation and D) bulk volume water for the Prue Sandstone Interval with the top of Verdigris Limestone horizon shown. The model and surfaces shown are adjusted to the flattened Top of Breezy Hill Limestone surface and with a vertical exaggeration of 100x. (B) Effective porosity, (C) water saturation and (D) bulk volume water were only calculated within the sandstone petrofacies shown in (A).

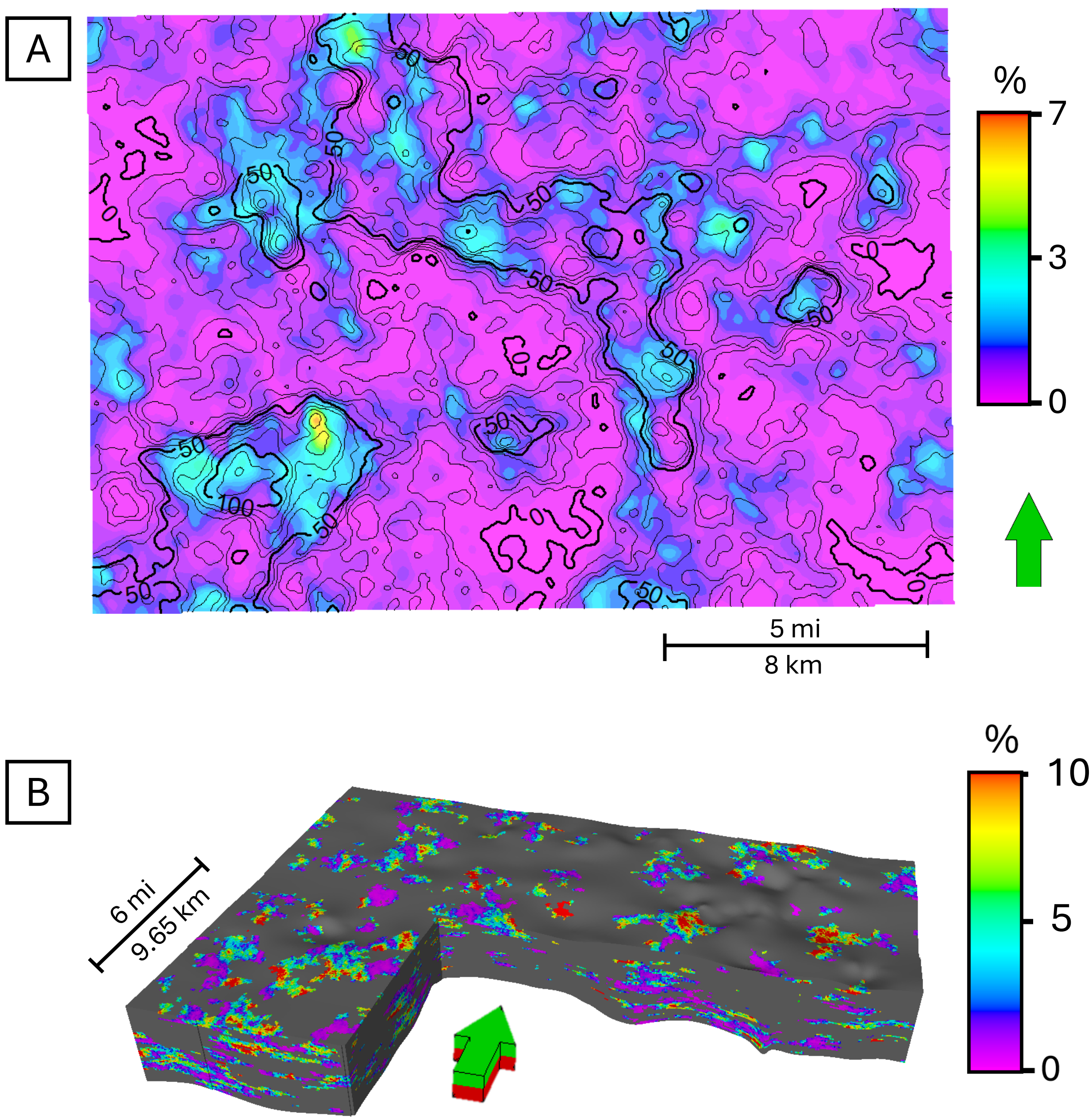

Figure 19: A) Average BVH percent map based on B) 3d BVH models of the Prue Sandstone. Contours represent sandstone thickness. Hydrocarbon percentages were only calculated in sandstone.

Oswego Limestone after flattening the model on the Excello Shale compensates for post-depositional structural changes and shows a significant change in Oswego Limestone depositional profile with decreasing depositional topography from the northwest to the southeast (Figure 20). The Oswego Limestone is thickest to the northwest and is interpreted to represent a carbonate shelf and shelf margin. The sharp change in slope along the carbonate shelf margin is apparent when viewing the Oswego Limestone depositional topography on the flattened model. The shelf margin corresponds with a change from shallow to deeper marine conditions and the transition to shale basinward. The thickness of limestone in the Oswego Limestone is positively related to the thickness of the formation (Figure 21). Average modeled water saturation and porosity show little relation to the thickness of limestone, suggesting high variability in reservoir quality (Figure 21).

When evaluating the Prue Sandstone, we see a similar change in slope following the same southwest to northeast trend of the Oswego Limestone when structural models are flattened on the Excello Shale. Sandstone percent increases to the west. The sandstones vary in thickness with elongate accumulations trending in a northwest to southeastern orientation. The thicker sandstone accumulations are interpreted as incised valley fill sandstones where the main delta channels are located. Smaller, thinner bodies of sandstones appear to be thinner and sporadic; this is consistent with findings by Brenner (1989). Smaller, more isolated bodies of sandstone are interpreted as being deposited by smaller distributary channels branching from the larger channels at the center of the delta (Figure 22). Within the Prue Sandstone, this is interpreted as the transition from shallow-deltaic to deeper-marine environments where shale is more likely to be deposited. The Sun Expl & Prod Co 3-6 Creiss Waterflood U core is interpreted to be along the margins of the delta where tidal influence is more pronounced allowing for herring-bone

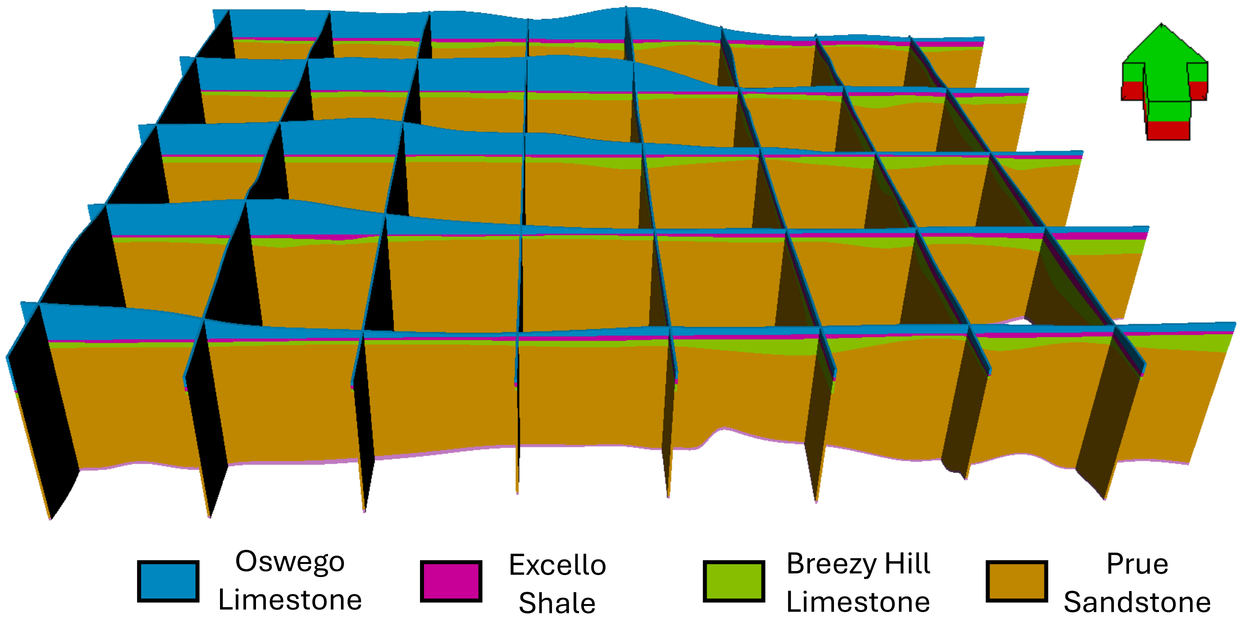

Figure 20: Structural model of the Oswego limestone, Excello Shale, Breezy Hill Limestone and Prue Sandstone shown flattened on the top of the Excello Shale at 100x vertical exaggeration. The Oswego Limestone shows decreasing thickness from northwest to the southeast.

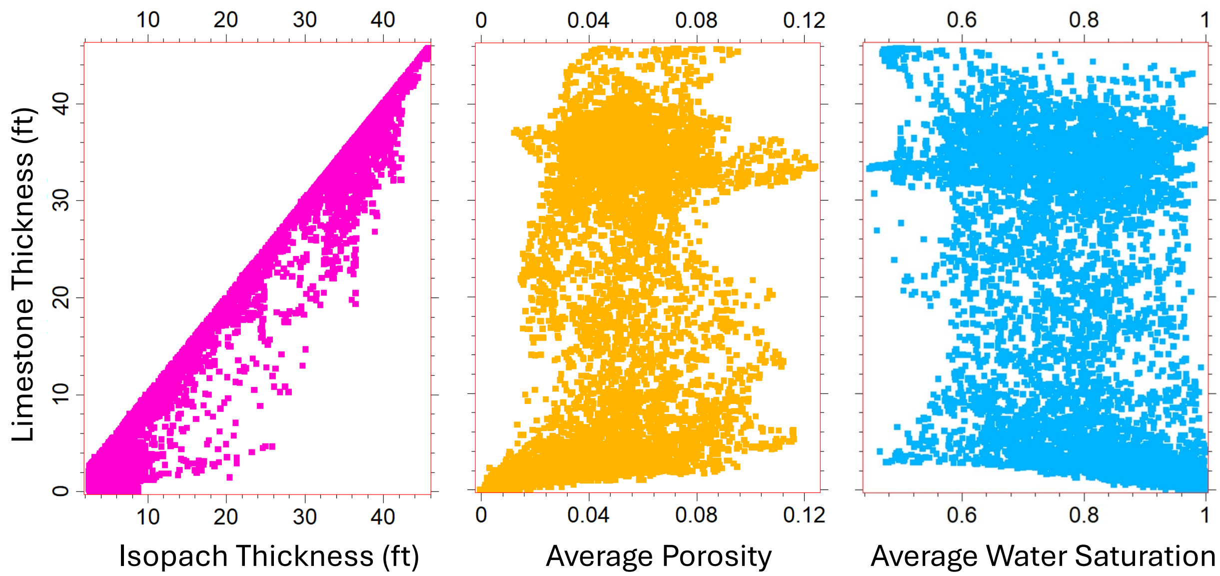

Figure 21: Cross plots comparing limestone thickness in the Oswego Limestone to total thickness of the Oswego Limestone, average porosity and average water saturation values from maps derived from property models. The thickness of limestone in the Oswego Limestone and the thickness of limestone are strongly positively corelated. There is little relation between the limestone thickness, average porosity and water saturation.

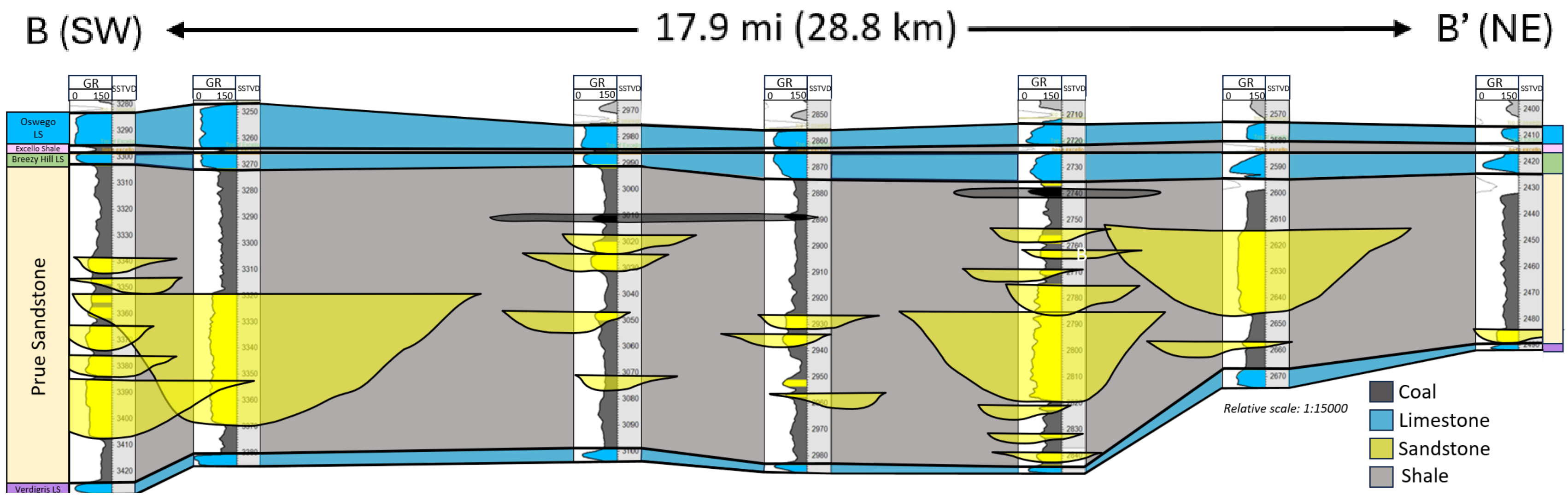

Figure 22: Interpreted relatively scaled cross section from southwest to northeast, perpendicular to channel flow direction. Larger, clean sandstone packages are interpreted as incised valley fill sandstones while smaller, more interbedded sandstone packages are deposited by distributary channels fills. Coals are laterally discontinuous and only present in the upper portions of the Prue Sandstone.

cross bedding. The interpreted shoreline in the Prue Sandstone is interpreted to be submerged by a minor rise in sea level, allowing for the deposition of the Breezy Hill Limestone. Following the deposition of the Breezy Hill Limestone, sea level is interpreted to continue to rise, flooding the carbonates of the Breezy Hill Limestone and allowing for the deposition of the Excello Shale, where the paleo-shoreline is outside the scope of the study area. Sea level then falls, creating a shallow water environment for the deposition of the Oswego Limestone to the northwest and shale to the southeast. Two cyclothems are identified within the Prue Sandstone interval. The first, more complete cyclothem, in ascending order, is represented by the Prue Sandstone, the Iron Pos Coal and followed by the Breezy Hill Limestone. The Excello Shale and the Oswego Limestone make up the second, partial cyclothems lacking sandstone components.

Depositional Interpretation

The sedimentary features that reflect the effects of bioturbation in both the Gulf Oil Corp 1 Hamm WF and Sun Expl & Prod Co 3-6 Creiss Waterflood U cores supports the interpretation of fluvial and shallow-marine environments of the Prue Sandstone. Herring-bone cross bedding in Prod Co 3-6 Creiss Waterflood U well indicates some level of tidal influence on the margins of what has been interpreted as a tidally influenced delta front. Isopach and structural mapping indicate that the sandstones deposited farthest north in the study area are incised valley fill sandstones and channel bars. These deposits are associated with the transition from a fluvial setting to a tidally influenced delta farther south and along the interpreted southwest-northeast trending shoreline (Figure 23). The presence of dark shales in core and the log-indicated presence of isolated coal supports the presence of organic material. Porosity within the Gulf Oil Corp 1 Hamm WF well is greater than in the Sun Expl & Prod Co 3-6 Creiss Waterflood U based on petrographic analysis. The elongated incised valley fill sandstones exhibit high

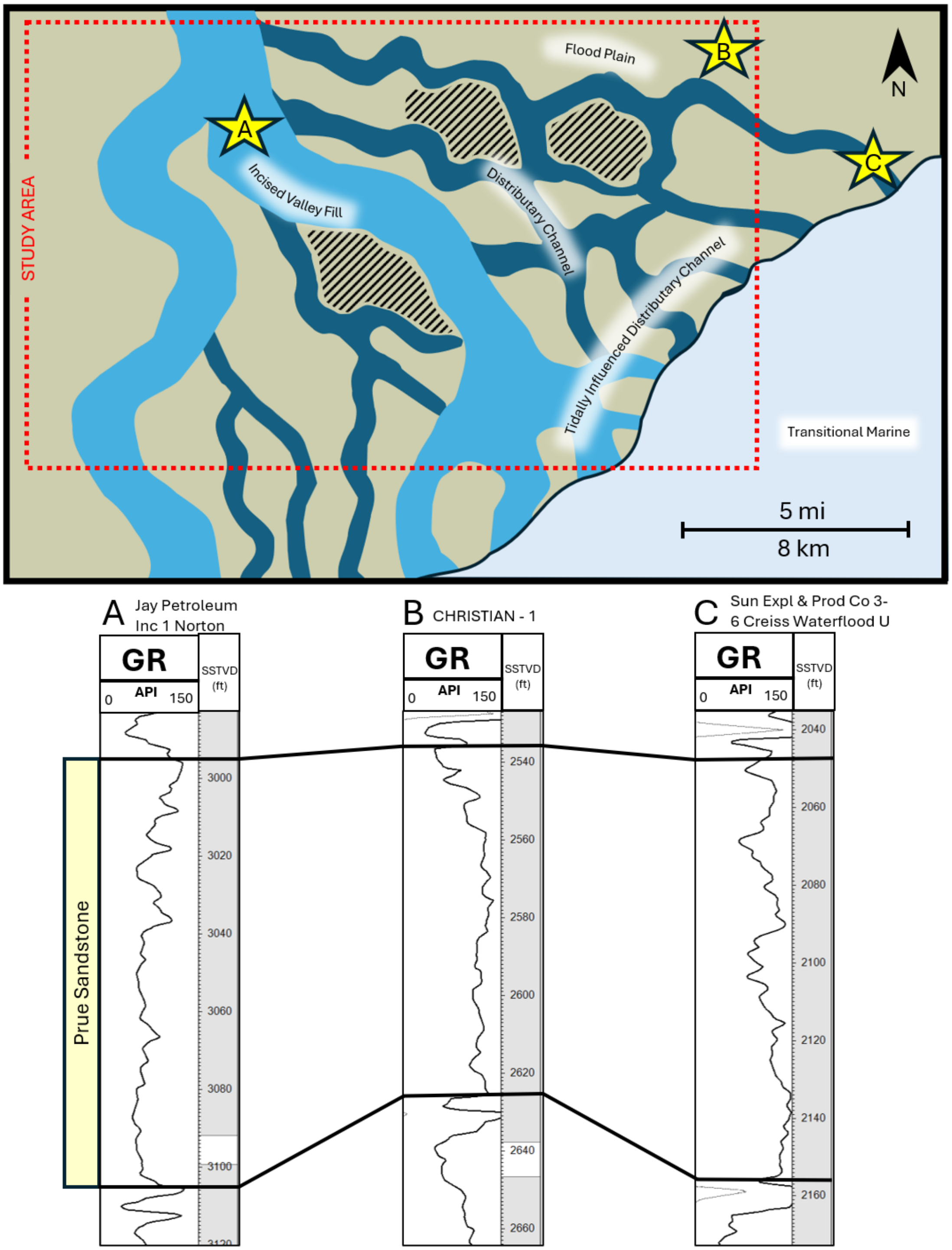

Figure 23: Diagrammatic Prue Sandstone paleogeographic map showing the presence of A) incised valley fill sandstones; B) Flood plain mudstones and C) tidally influenced sandstones (C). A) Incised valley fill sandstones represented by a fining upwards with increasing abounds of interbedded shale. B) Flood plain mudstones represented by a lack of significant sandstone packages. C) Tidally influenced sandstones represented by two separate coarsening upward sandstone packages stacked on top of one another.

porosity. The interbedding in the Sun Expl & Prod Co 3-6 Creiss Waterflood U coupled with the presence of organic material and mudstone indicates an environment with lower energy deposits of sandstones.

Deposition of the Oswego Limestone is interpreted as occurring after a fall in sea level following the deposition of the Excello Shale. The consistent thickening of Oswego Limestone to the northwest of the study area is interpreted as a limestone shelf. The limestone shelf trends northeast to southwest, to the east of which shale is more prevalent than limestone and the interval is overall much thinner. Thinner, more shale dominated areas are interpreted to be shallow marine environments of deposition (Figure 24).

Implications for Future Prue Sandstone and Oswego Limestone Development

Many of the wells evaluated in this project were originally completed in formations below both the Prue Sandstone and the Oswego Limestone. The wells with hydrocarbon indicators, particularly the mapped gas-saturated wells, may offer opportunities for recompletions in the Prue Sandstone. Updated, fine-scale mapping of the Prue Sandstone and Oswego Limestone utilizing data that was previously only available on raster logs provides the chance to better understand where and which portions of the reservoirs contain the best petrophysical qualities for further hydrocarbon development. Petrophysical comparisons of average porosity and average water saturation to the total thickness of the Prue Sandstone and the thickness of sandstone show that in thicker sandstone packages, higher porosity is positively related and lower water saturations is loosely inversely related (Figure 25). The lack of relationship seen between the thickness of the Oswego Limestone and petrophysical properties of water saturation and total porosity help to indicate that there may be other factors contributing to reservoir quality that could be benefit from the addition of core.

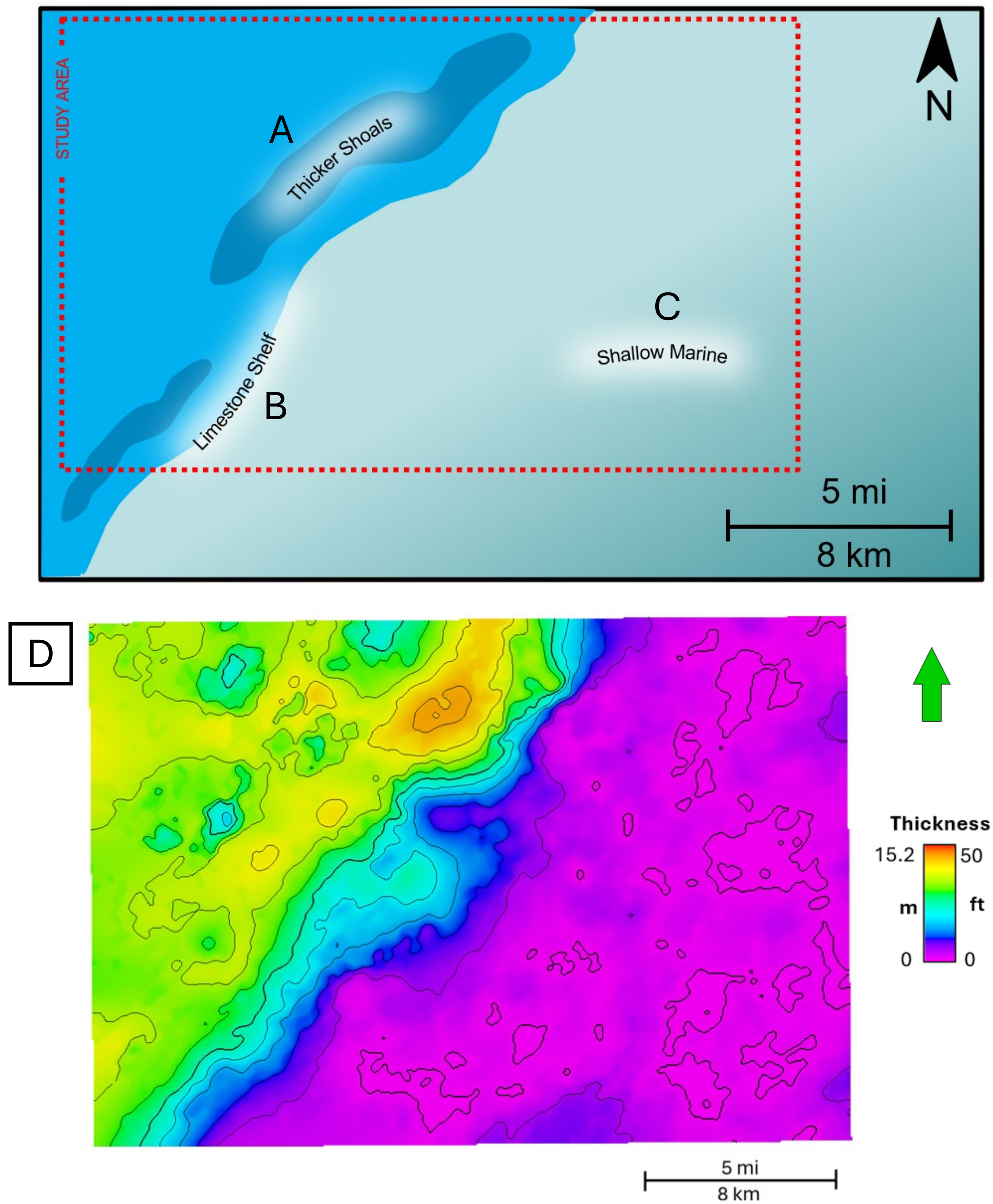

Figure 24: Diagrammatic Oswego Limestone paleogeographic map showing the presence of A) interpreted limestone shoals; B) Limestone shelf and C) shallow marine environment. D) Interpretation for the diagrammatic Oswego Limestone paleogeographic is based of the limestone thickness map.

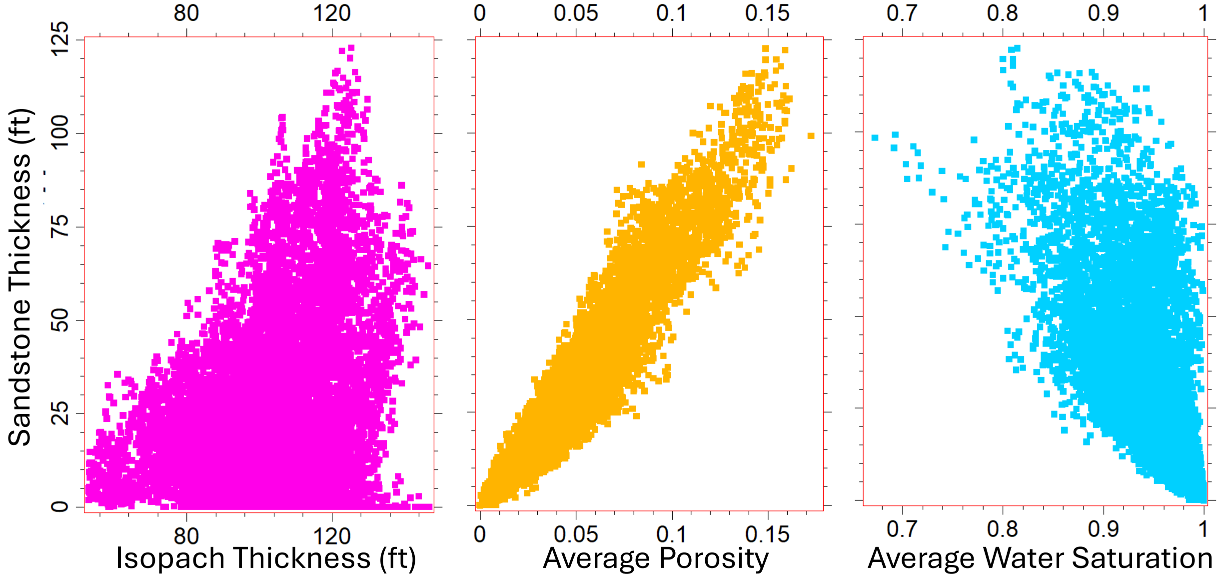

Figure 25: Cross plots comparing sandstone thickness in the Prue Sandstone to total thickness of the Prue Sandstone, average porosity and average water saturation values from maps derived from property models. The thickness of sandstone in the Prue Sandstone and the isopach thickness are somewhat positively corelated. There is a strong positive relationship between the average porosity and sandstone thickness. Water saturation and sandstone thickness are slightly inversely related.

Improved understanding of the stratigraphy outlined based on fine-scaled mapping of the Excello Shale and the Breezy Hill Limestone may also provide context for locations where both formations are thicker and may present as potential reservoirs.

Saturated Gas Mapping

The 18 wells mapped containing the signature for gas saturation were plotted to evaluate their spatial distribution. Of the18 wells, 13 are in the main northwest to southeast trending sandstone accumulation (interpreted as an incised valley fill). The 13 wells are located on the margins of the incised valley fill, in areas adjacent to the of greatest average porosity (Figure 26).

LIMITATIONS

Petrophysical Values

The calculation of porosity, S_w and, in turn, BVW and BVH were using assumptions for values of matrix and water resistivity. The assumption for a singular value across the study area may lead to inaccuracies where water resistivity may be different.

A clean sandstone matrix value of 2.65 g/cm^3 was chosen for the Prue Sandstone to adjust neutron porosity and to calculate both porosity (total and effective) and S_w. While sandstone in the Prue Sandstone appears as clean sandstone in core, there is significant interbedded shale within some sandstones. The grain density of 2.65 g/cm^3 was chosen based on the observed clean, consolidated sandstone in core. The petrophysical calculations in the interbedded sandstones could be affected using a clean sandstone matrix. To mitigate the effects of the presence of shale within some sandstone packages, PHIE was calculated for the Prue Sandstone interval using a shale volume calculation.

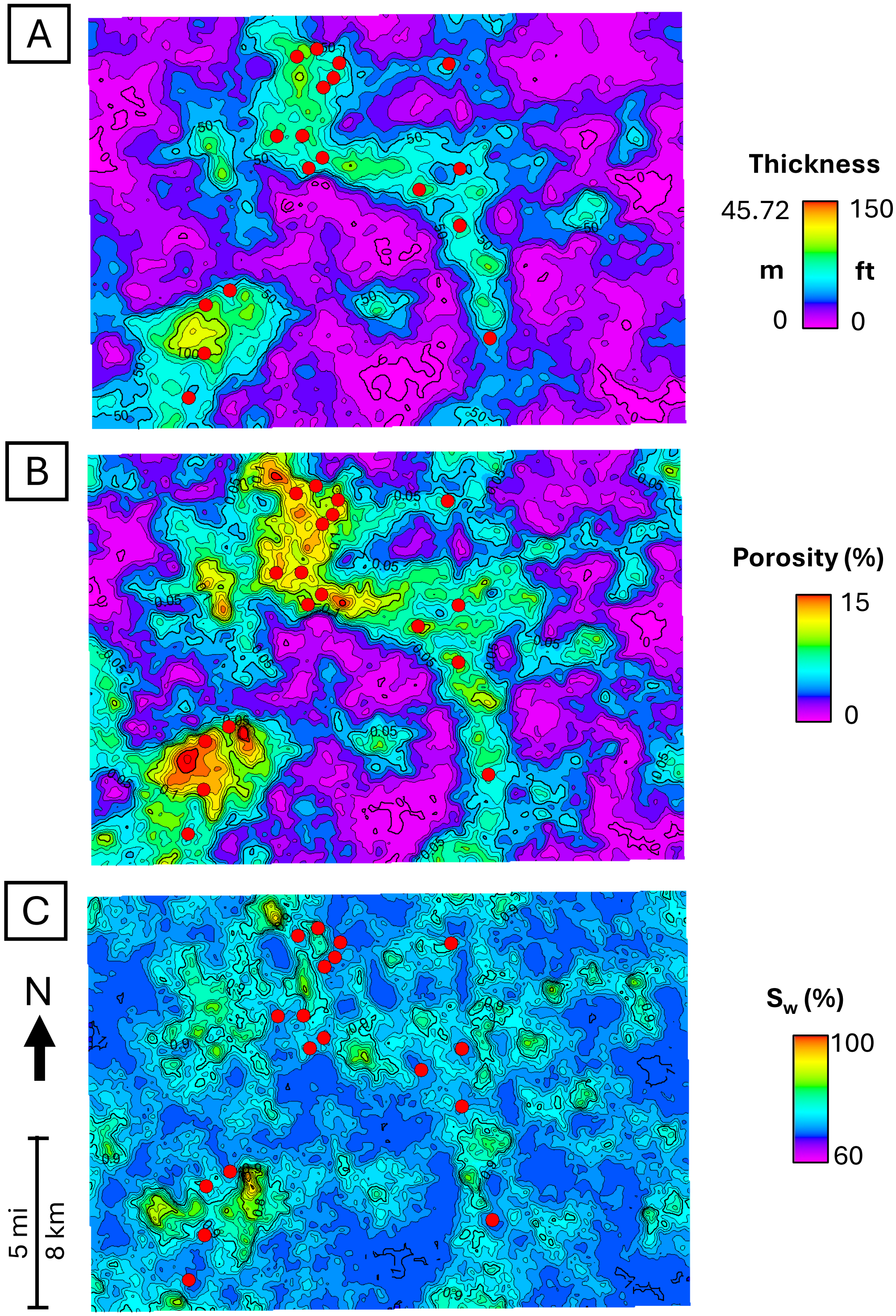

Figure 26: Locations of wells identified to exhibit saturated gas signature on A) sandstone thickness map derived from 3d model, B) average porosity map derived from 3d model, and C) average water saturation map derived from 3d model. The locations of saturated gas wells are separated between two main modeled sandstone bodies. The locations are located outside of the highest porosity values and outside of the lowest water saturation values.

A clean limestone matrix was assumed and was used for the Oswego Limestone in the calculation of density porosity, total porosity, and S_w. This was chosen in the absence of core data. In areas where the Oswego Limestone may not be clean limestone, the petrophysical calculations could be affected. However, based on analysis of well-logs, namely GR, the thick limestones exhibit a very low gamma-ray signature; thus, supporting the interpretation of a clean limestone. The absence of core in the Oswego Limestone also limits the degree of interpretation for the environment of deposition.

Implication of Petrophysics-based Lithology Classification

Lithology estimation of sandstone, shale, coal, or limestone was based solely on preexisting knowledge of formation lithologies and log-based classifications using GR, RESD, RHOB, and NPHI values. From observations of Prue Sandstone core, stratigraphic variability of lithology is more prominent as compared to the stratigraphic variability from log-based lithology classification. Fine-scale laminations of sandstone and shale observed in core are not captured on well logs, therefore the level of stratigraphic variability is limited by the vertical well-log resolution. The impact of the vertical changes in lithology are perhaps better represented by the stratigraphic variability of porosity within sandstones of the Prue Sandstone. Higher porosity values are commonly associated with cleaner sandstones that lack interbedded shales. Fine-scale shale laminations may not be resolved but might impact the calculated neutron porosity or density porosity.

Reservoir Modeling

Reservoir modeling for this study was completed from a log-based approach, utilizing well-log calculations followed by upscaling prior to reservoir modeling using both sequential-Gaussian- and sequential-indicator simulations. When considering model results, it is important to understand the implications of the vintage of well logs used in this study. Well logs in the study area used are all dated as 1980 or newer; however, differences between tools, operations, and other factors can impact the values that are measured. Therefore, there is always uncertainty in the modeling results that is variable based on the input data. To explore this further, a more detailed uncertainty assessment could be conducted to report a range of model outcomes versus a single model for each parameter.

Hydrocarbon Volumes

The calculation of the presence of hydrocarbons was completed using calculated values of BVW and porosity. The assumption was made that any pore space not calculated to be filled with water represents the presence of hydrocarbons. It is important to note that this would calculate only the presence of hydrocarbons in place at the time the well was logged, not the current presence of hydrocarbons in the Prue Sandstone.

CONCLUSIONS

The Prue Sandstone consists of sandstone, shale, and coal within the study area. Prue Sandstone thickness ranges from 53–147.4 ft (16.1–44.9 m). The Oswego Limestone is 2.4–45.7 ft (0.7–13.9 m) thick and consists of limestone and shale. Log signatures indicate thicker portions of the Oswego Limestone to be dominated by clean limestone.

Prue sandstones lack lateral and vertical connectivity, creating a heterogenous reservoir. The thickest sandstone packages are in the northern portion of the study and are interpreted to be incised valley fill sandstones. These elongate sandstone bodies trend northwest to southeast, are 50-100 ft (~15.2-30.5 m) thick, have an PHIE ranging from 1-15%, and BVH values of 0-20%. A gas saturation signature was identified in 18 wells located within the interpreted incised valley fill sandstones. Smaller, less elongate sandstone bodies ranging from 40-80 ft (~12.1-24.4 m) were deposited by deltaic distributary channels and are more isolated between shales and coals. Shale is present both interbedded with distributary channel fills, at the top of incised valley fill sandstone packages and in larger laterally continuous intervals as part of flood plains. Coal is present at the top of the Prue Sandstone on the margins of sandstone packages and is not laterally continuous or vertically continues, ranging in thickness from 1.0–2.6-mi^2 (2.6–6.8~km^2). The dark, rich organic nature of the shale observed in core, the presence of coal and burrows in core indicate an organic-rich environment of deposition.

Limestone is the main reservoir lithology in the Oswego Limestone. Limestone is the most abundant to the northwestern and is thinner to the southeast. A distinct northeast-southwest trending shelf margin is associated with the change in thickness. To the east of the interpreted shelf margin is predominantly shale, indicating a deeper water environment of deposition. The best reservoir potential in the Oswego Limestone is located to the west of the interpreted shelf margin where limestones are the thickest (10-43 ft (~3-13.1 m)) and exhibit total porosities from 0–26%.

Porosity, S_w, BVW, and BVH are related stratigraphically to the best reservoir lithologies within the Prue Sandstone and Oswego Limestone. Within the Prue Sandstone, the highest porosity and lowest S_w are within incised valley fill sandstones. Based on petrophysical property analyses and stratigraphic mapping, the greatest reservoir potential for the Oswego Limestone is in thicker limestones to the northwest of the study area along the interpreted shelf environment.

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APPENDIX

Appendix A

~400 raster well-logs were used to assign formation tops for the Prue sandstone interval and the Oswego Limestone interval. Of these raster logs, ~198 were selected for digitization to be used in petrophysical calculations. The criteria used for rater log selection was based on the logs available for digitization, spacing between digitized wells and quality of raster logs. Digitization was only performed over the intervals of interest.

Appendix B

A high choice for sandstone qualification of 80 API was used so that sandstones bodies with laminations of shale would be included in singular sandstone packages as opposed to small individual sandstone packages. The mica seen in core was also a factor in choosing a higher gamma ray reading of 80 API to define a sandstone due to the high potassium content of mica.

Prue Sandstone Interval Lithology Classification	
Lithology	*Classification*
Sandstone	GR>=80 API
Shale	GR=<80 API
Coal	2.1 g/cm3

Appendix C

Oswego Lithology Classification	
Lithology	*Classification*
Limestone	GR>=50 API
Shale	GR=<50 API

Appendix D

$$NPHI_{ss} = 1.035(NPHI) + 0.0351$$

Appendix E

Prue Sandstone Interval Lithologies							
Lithologies	**Nugget**	**Sill**	**Major Range**	**Minor Range**	**Vertical Range**	**Major Azimuth**	**Minor Azimuth**
Sandstone	0	0.999	9000	8000	20	75	345
Shale	0	0.999	9000	8000	15	75	345
Coal	0	0.990	7000	6000	10	75	345

Oswego Limestone Interval Lithologies							
Lithologies	**Nugget**	**Sill**	**Major Range**	**Minor Range**	**Vertical Range**	**Major Azimuth**	**Minor Azimuth**
Limestone	0	0.999	15000	12000	15	40	310
Shale	0	0.999	15000	12000	15	40	310

Appendix F

Prue Sandstone Interval Lithologies							
Lithologies	**Nugget**	**Sill**	**Major Range**	**Minor Range**	**Vertical Range**	**Major Azimuth**	**Minor Azimuth**
Sandstone	0	0.999	5000	3000	10	335	245

Oswego Limestone Porosity							
Lithologies	**Nugget**	**Sill**	**Major Range**	**Minor Range**	**Vertical Range**	**Major Azimuth**	**Minor Azimuth**
Limestone	0	0.999	10000	7000	10	40	310

Appendix G

Prue Sandstone Interval Water Saturation							
Lithologies	**Nugget**	**Sill**	**Major Range**	**Minor Range**	**Vertical Range**	**Major Azimuth**	**Minor Azimuth**
Sandstone	0	0.999	5000	3000	10	335	245

Oswego Limestone Water Saturation							
Lithologies	**Nugget**	**Sill**	**Major Range**	**Minor Range**	**Vertical Range**	**Major Azimuth**	**Minor Azimuth**
Limestone	0	0.999	3500	2500	10	40	310

Appendix H

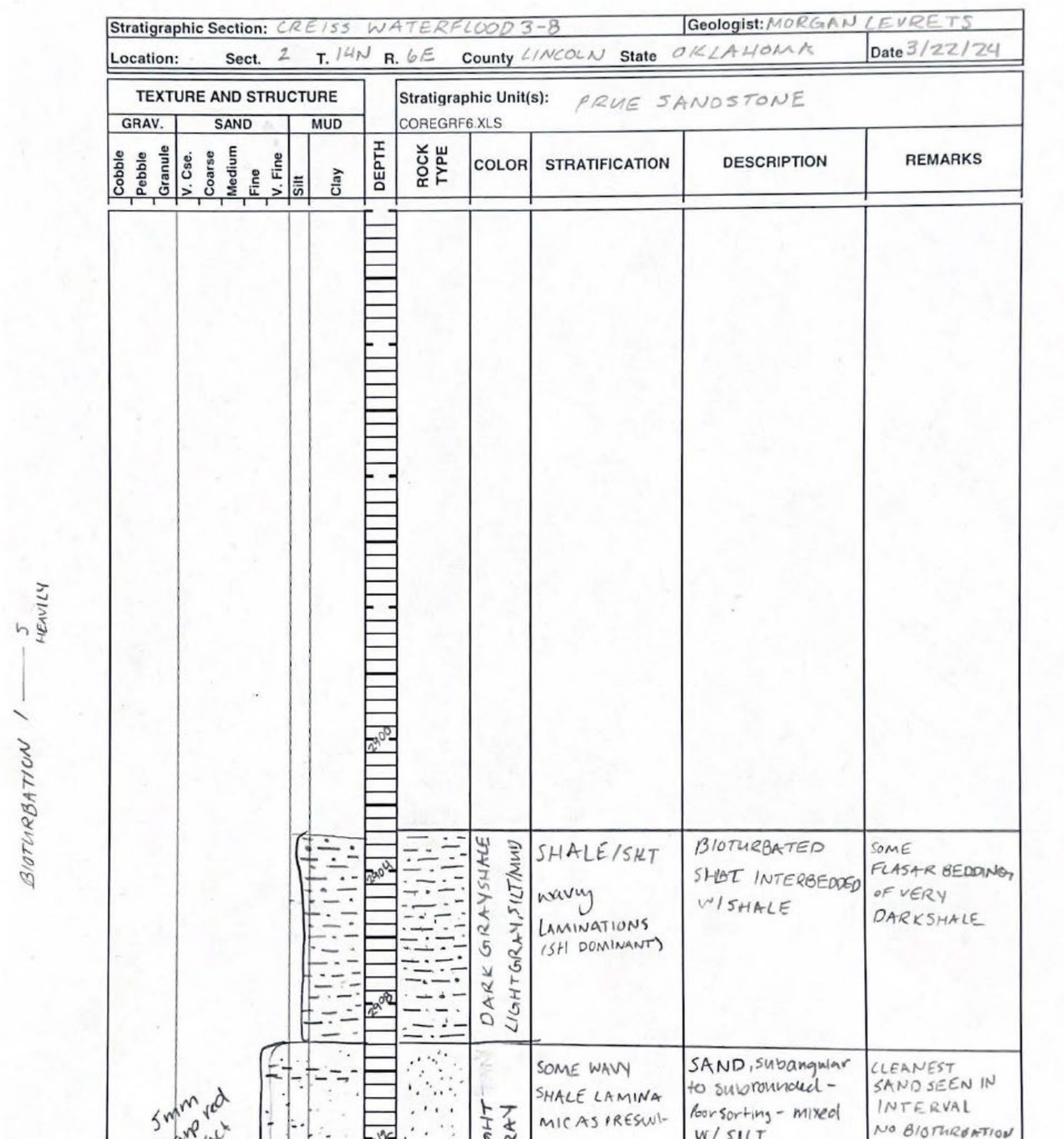
Appendix H1: Sun Expl & Prod Co 3-6 Creiss Waterflood U Core, boxes 1-8 of core. Depths 2903-2927 ft.

Appendix H2: Sun Expl & Prod Co 3-6 Creiss Waterflood U Core, boxes 9-16 of core. Depths 2927-2949 ft.

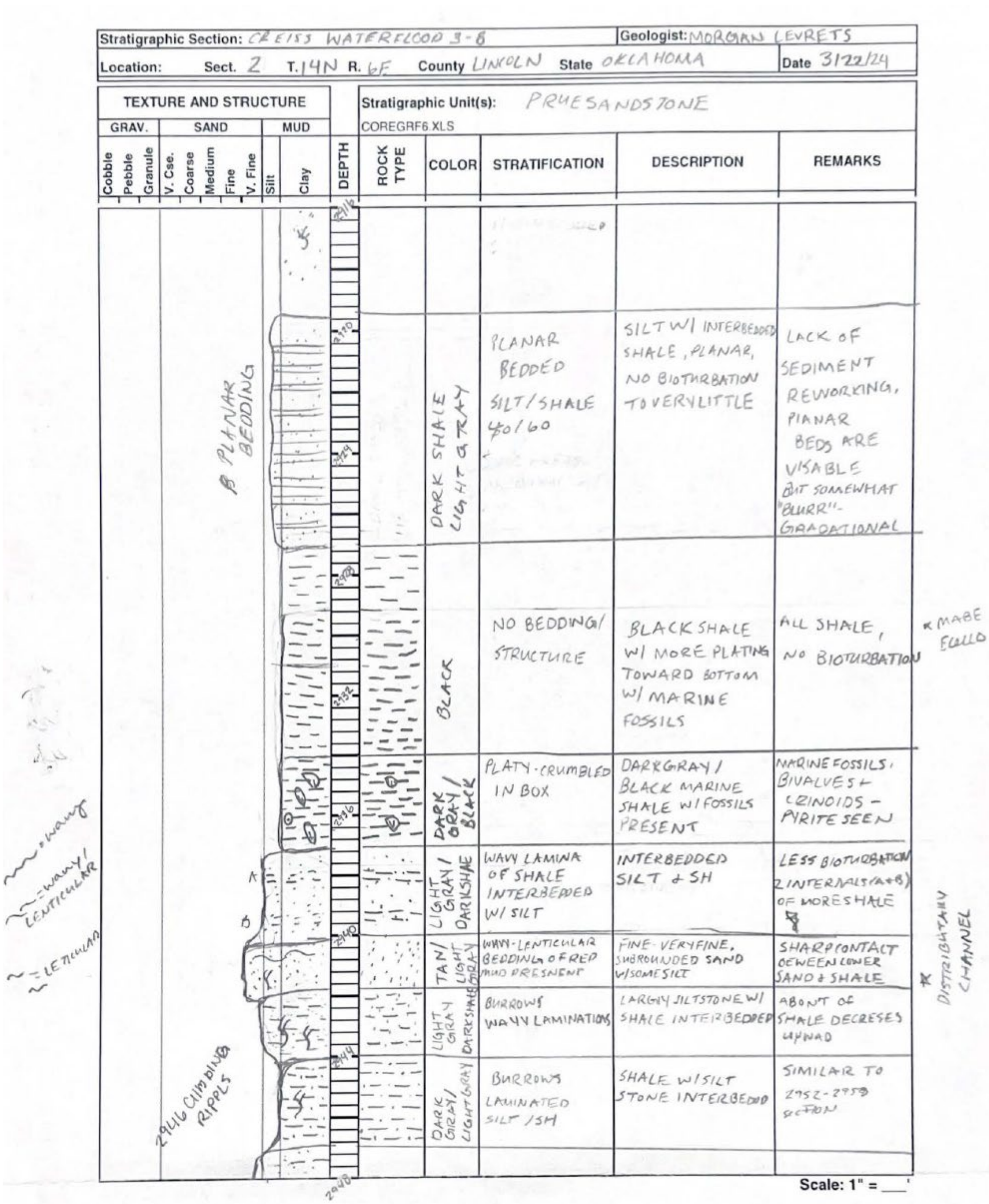
Appendix H3: Sun Expl & Prod Co 3-6 Creiss Waterflood U Core, boxes 17-24 of core. Depths 2949-2973 ft.

Appendix H4: , boxes 25Sun Expl & Prod Co 3-6 Creiss Waterflood U Core-32 of core. Depths 2973-2992 ft.

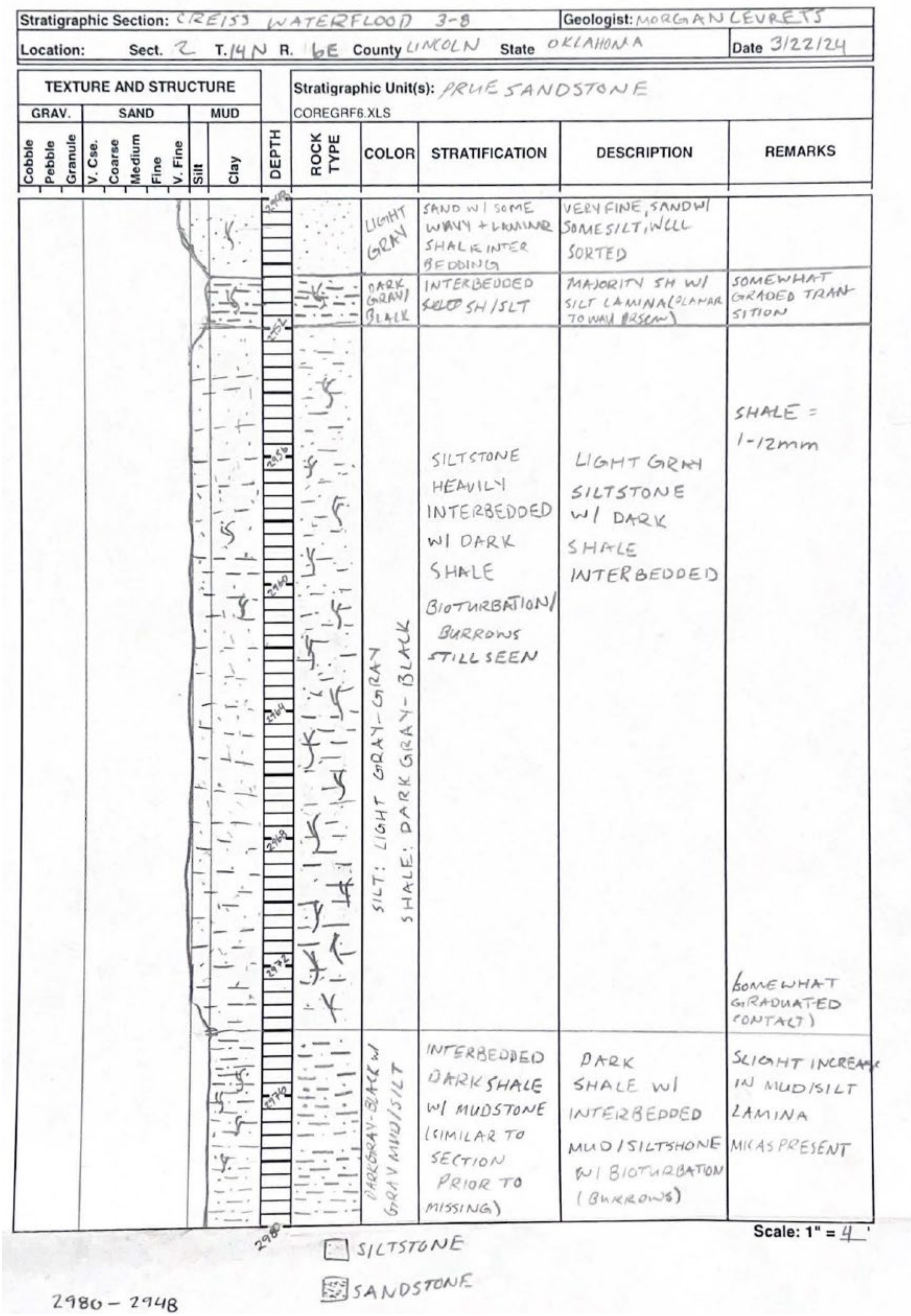
Appendix H5: Sun Expl & Prod Co 3-6 Creiss Waterflood U Core, boxes 1-8 of core. Depths 2992-3012 ft.



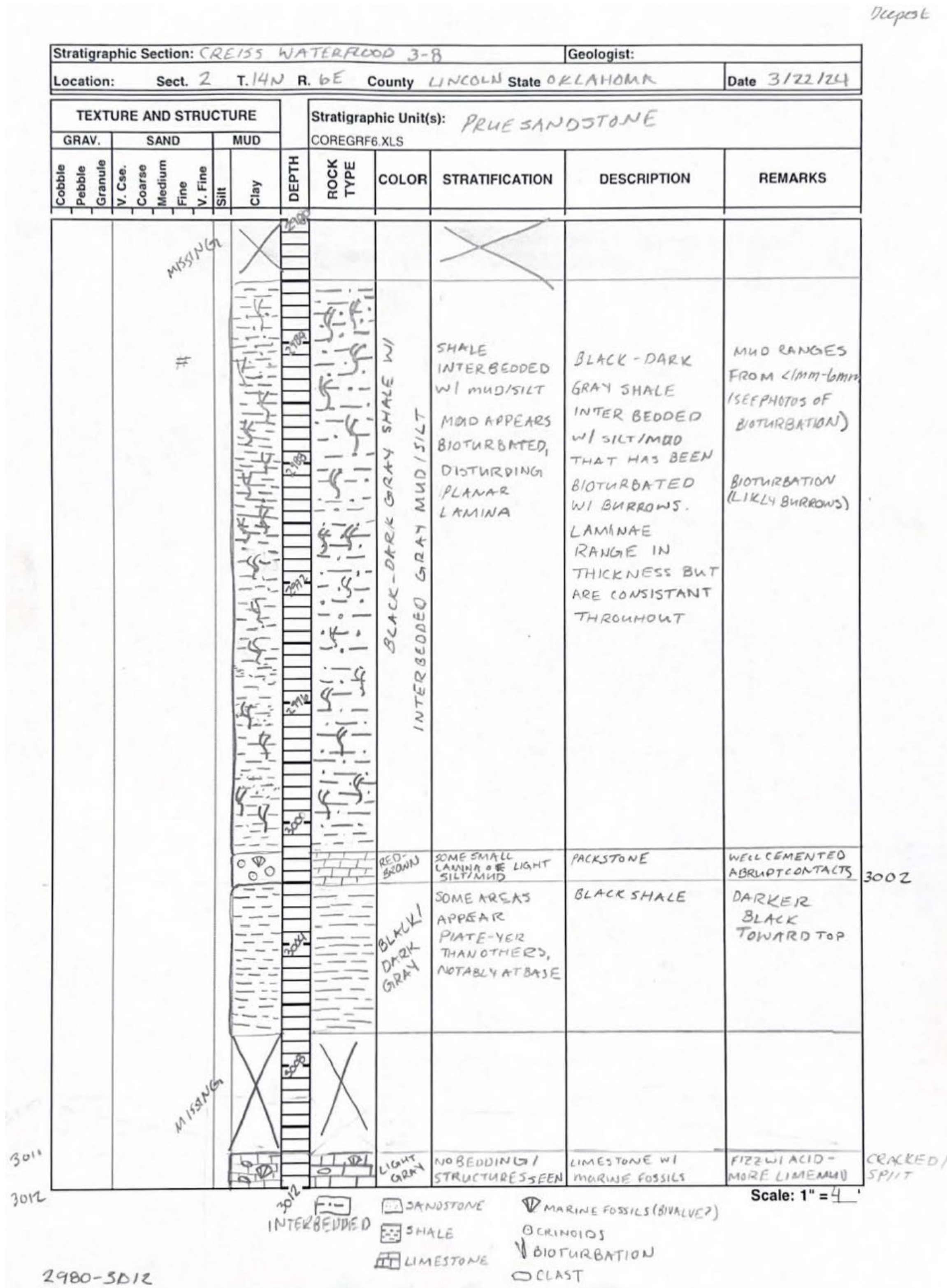
Appendix H6: Core description for Sun Expl & Prod Co 3-6 Creiss Waterflood U.



Appendix H7: Core description for Sun Expl & Prod Co 3-6 Creiss Waterflood U.



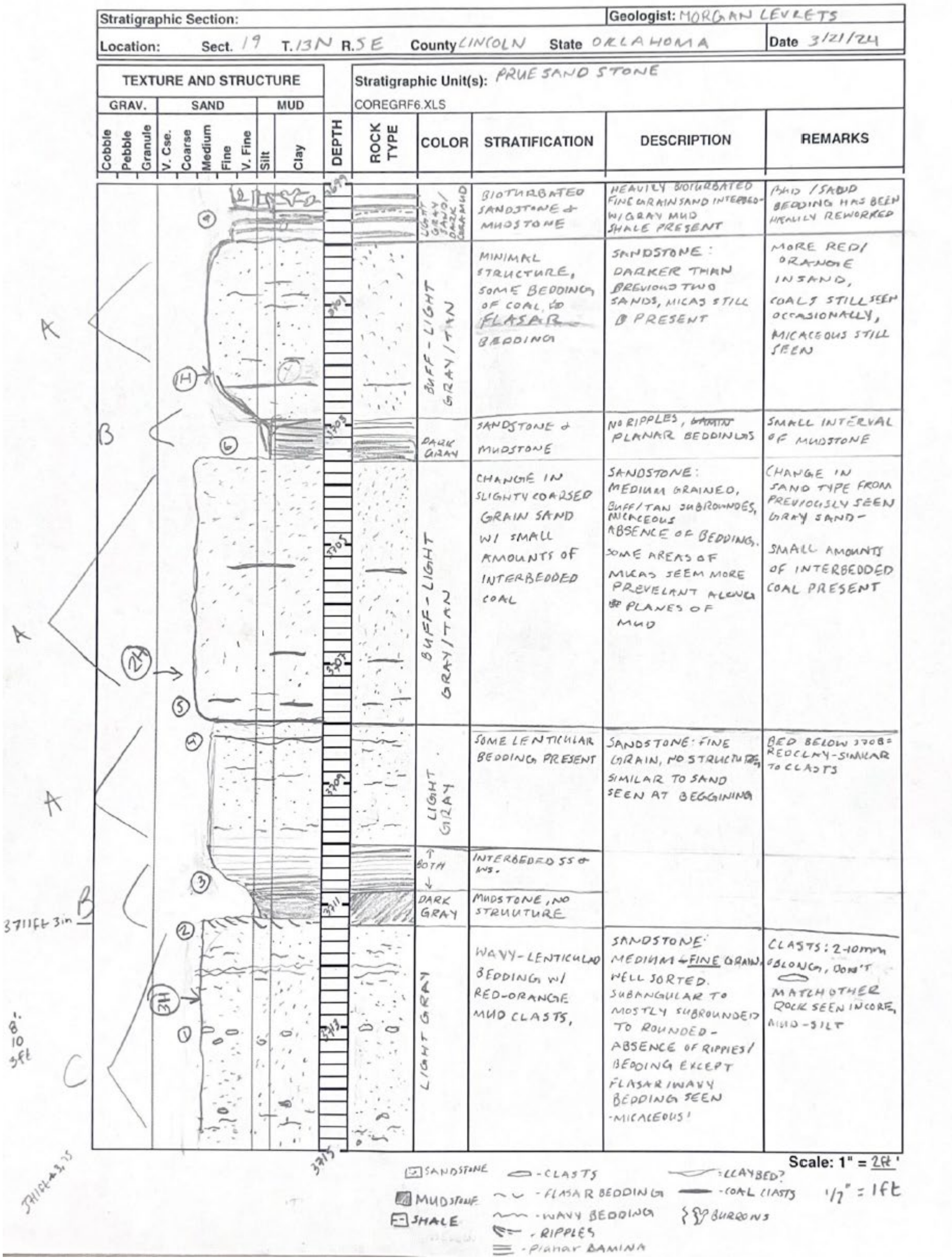
Appendix H8: Core description for Sun Expl & Prod Co 3-6 Creiss Waterflood U.



Appendix H9: Core description for Sun Expl & Prod Co 3-6 Creiss Waterflood U.

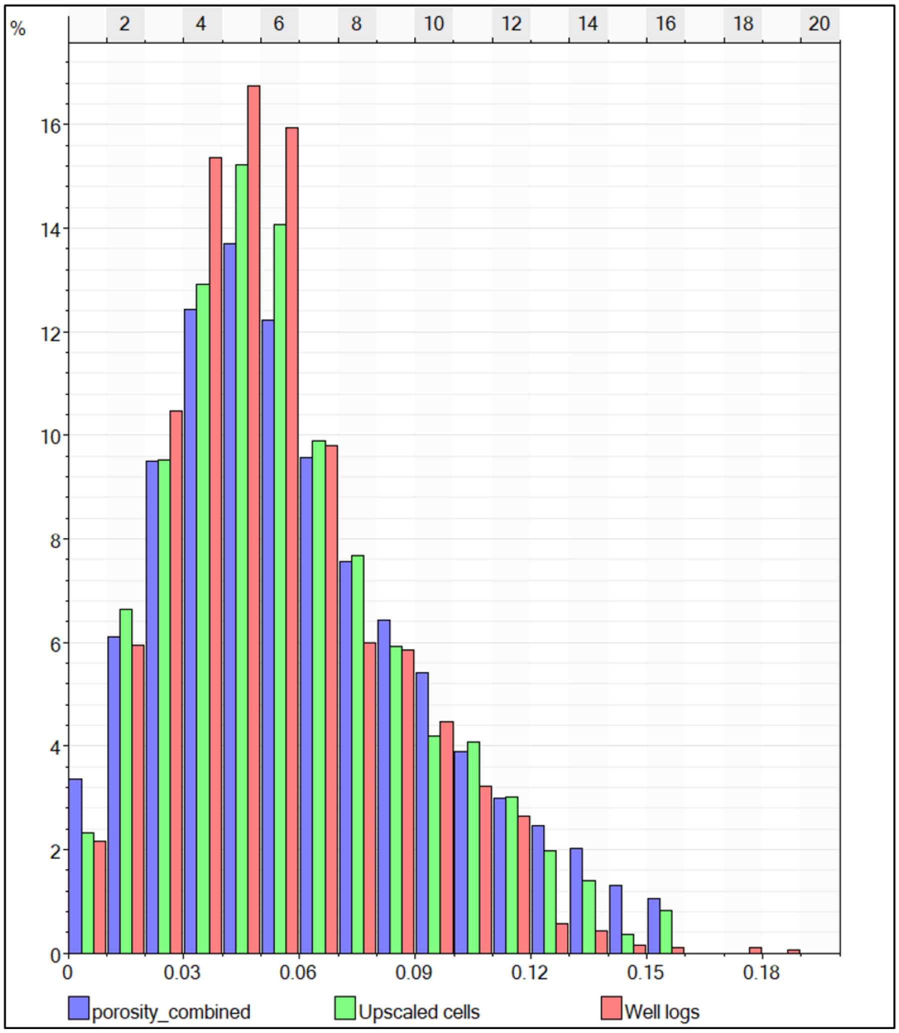
Appendix I

Appendix I1: Image showing Gulf Oil Corp 1 Hamm WF core previously interpreted by Ropp 1991.



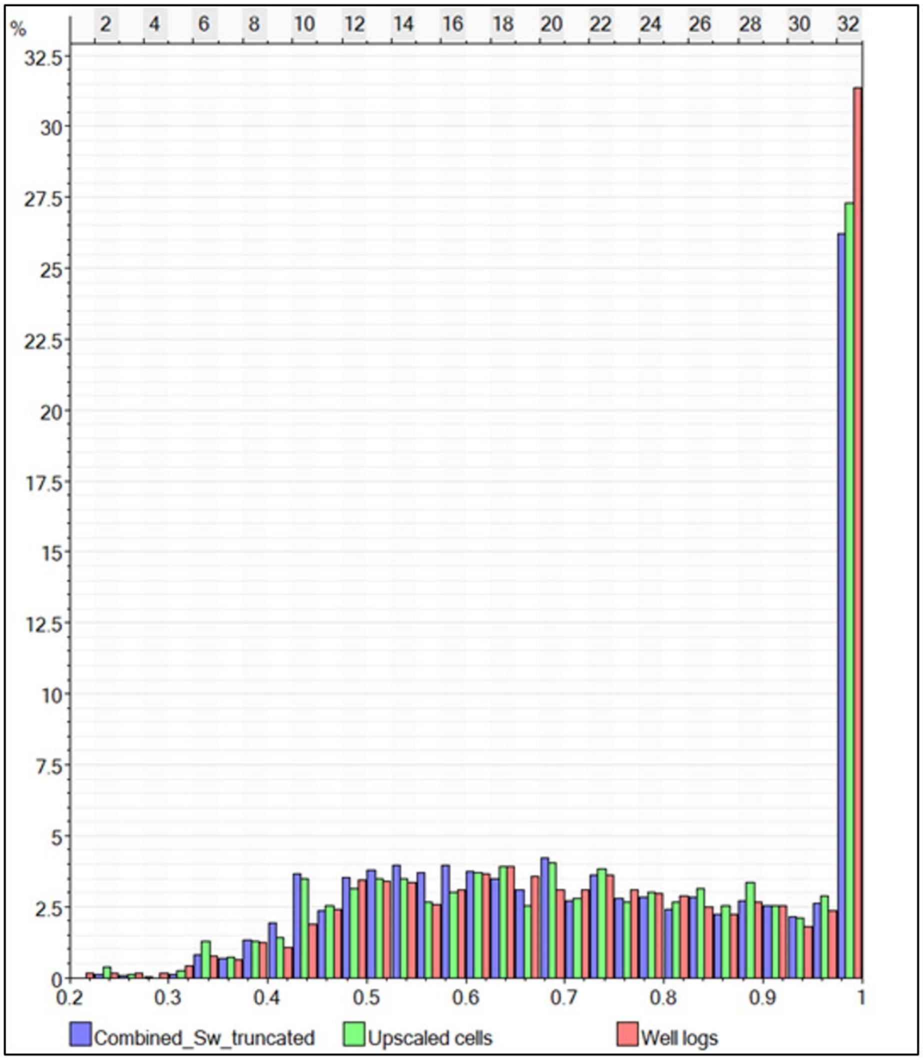
Appendix I2: Core description for Gulf Oil Corp 1 Hamm WF core.

Appendix K



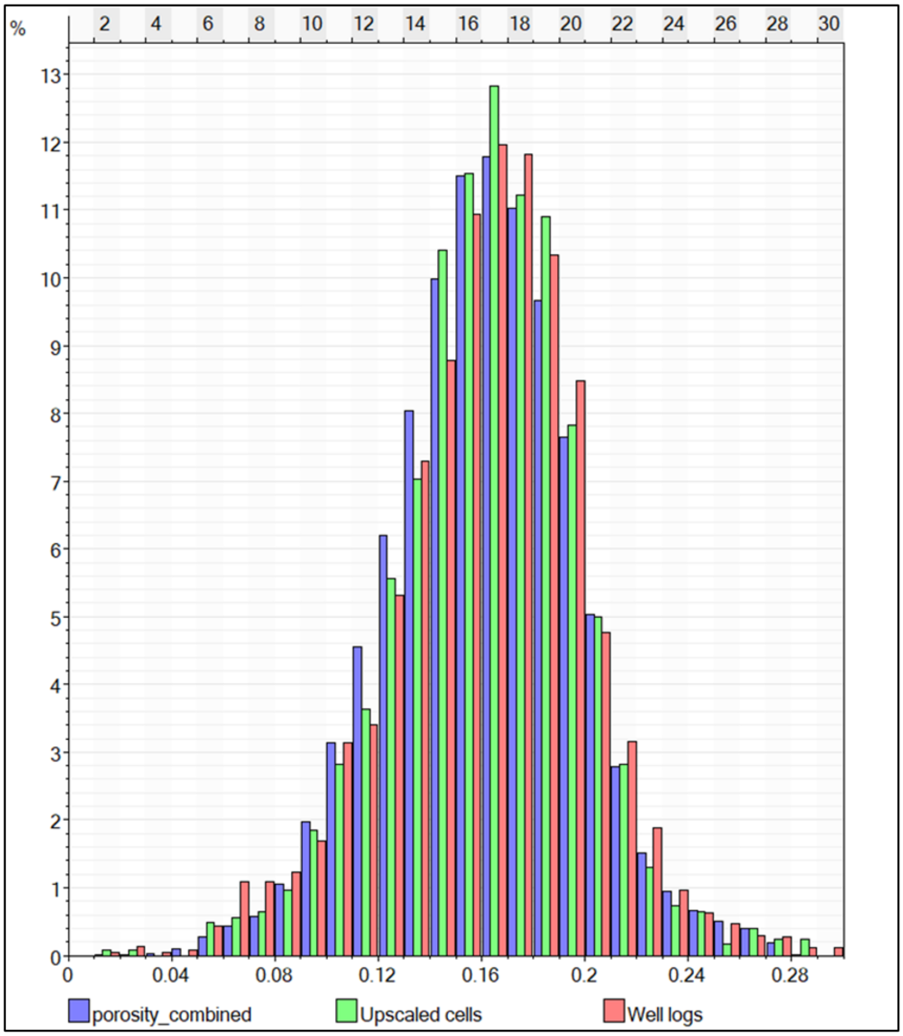
Appendix K1: Histogram showing values for well-values, upscaled well-logs, and modeled total porosity in the Oswego Limestone.

Appendix L



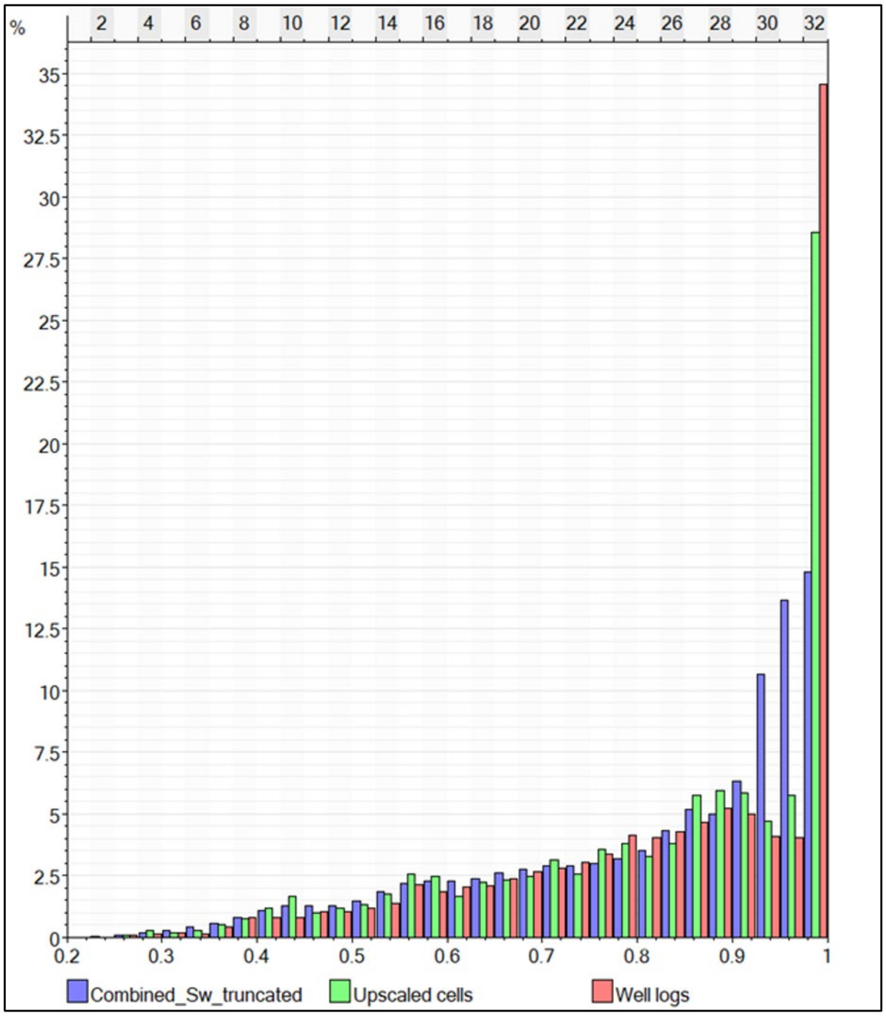
Appendix L1: Histogram showing values for well-values, upscaled well-logs, and modeled water saturation in the Oswego Limestone.

Appendix M



Appendix M1: Histogram showing values for well-values, upscaled well-logs, and modeled effective porosity in the Prue Sandstone.

Appendix N



Appendix N1: Histogram showing values for well-values, upscaled well-logs, and modeled water saturation in the Prue Sandstone.