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REGIONAL STRATIGRAPHY AND DEPOSITIONAL CHARACTERISTICS OF THE PENNSYLVANIAN PRUE SANDSTONE, LINCOLN COUNTY, OKLAHOMA

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REGIONAL STRATIGRAPHY AND DEPOSITIONAL CHARACTERISTICS OF THE PENNSYLVANIAN PRUE SANDSTONE, LINCOLN COUNTY, OKLAHOMA

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ABSTRACT

The Pennsylvanian Prue Sandstone in northeastern Oklahoma represents fluvial and deltaic deposits that formed across a gently dipping shelf margin. The Prue Sandstone is predominantly well-sorted, fine to medium-grain sandstones that are light grey to tan in color within a stratigraphic interval of sandstone and shale.

To evaluate the Prue Sandstone regional stratigraphy and depositional characteristics for the 990 mi^2 (1593 km^2) study area of Lincoln County, Oklahoma, cross sections and subsurface maps were generated to illustrate the spatial variability of the Prue Sandstone. Raster logs from 1724 wells were used for subsurface correlation and to generate geological maps. LAS logs from 95 wells were used to generate a 3D lithology model. Two wells totaling 126 ft (38.4 m) of Prue Sandstone core spanning the selected interval were examined, along with the petrographic analysis of ten thin sections. Subsurface maps combined with well-log signatures, core descriptions, and literature review were used to further define the Prue Sandstone depositional environment, stratigraphy, and reservoir characteristics.

The Prue Sandstone is bounded at the top by the Excello Shale and at the base by the Verdigris Limestone. The Excello and Verdigris are easily recognized on well-logs and form excellent stratigraphic markers given their lateral continuity. Iron Post Coal and Breezy Hill Limestone deposits are observed intermittently throughout the study area.

Top and base Prue Sandstone structure maps illustrate the gradual southwesterly dip across the study area. Isopach and net sandstone maps reveal thickness trends that are oriented from northeast to southwest and are consistent with a sediment source from the northeast. In central Lincoln County, interval thickness increases toward the southeast and ranges from 20 – 160 ft (6.1 – 48.8 m) across the county. Prue net sandstone thickness ranges from 0 – 116 ft (35.4 m) and displays similar trends as the isopach. Porosity ranges from 0 – 0.24 within the main depositional trend. By incorporating core, log-signature analysis, and subsurface maps, three key environments are interpreted: fluvial channels, distributary channels, and floodplain environments. Fluvial and distributary channel fill are both characterized by well-sorted, medium to fine-grain sandstones. Using gamma-ray logs, fluvial channels were distinguished from distributaries by their blocky sandstone appearance. Distributary channel signatures displayed stacking, thinner sandstone packages, and an increased amount of interbedded shale. Interpreted floodplain deposits are predominantly shale with a non-distinct or serrated well-log signature. Lithology proportion maps indicate a central-southeastern trend of sandstone deposition with isolated pockets of coal occurring intermittently throughout the study area. Modeled sandstone trends are representative of fluvial and distributary channel-fill deposits. Channel geometry and heterogeneity affect vertical sandstone variability, while changes in the depositional environment are the primary control for spatial variability.

INTRODUCTION

The Pennsylvanian-age Prue Sandstone is the uppermost siliciclastic interval of the Cabaniss Group and has been a considerable contributor to Oklahoma oil and gas production since the 1930s. Pennsylvanian reservoirs have been credited as the most prolific reservoirs for oil and gas in Oklahoma (Johnson, 2008). Several studies explored the stratigraphy of the Krebs and Cabaniss groups and have interpreted the Prue Sandstone depositional system as a fluvial-deltaic complex and shallow-marine environments (Blumenthal, 1956; Krumme, 1981; Brenner, 1989; Ropp, 1991; Cecil, 2003).

A study by Ropp (1991) used well-logs, scout tickets, production data, and core to investigate the Prue's stratigraphy, diagenetic history, and spatial distribution. Observations of dissolution from petrographic analysis contribute to increased porosity values seen in the Prue. Two sequences of cyclothems were observed from correlations across the study area, and sandstone reservoir deposits were interpreted as deltaic and incised valley fill deposits (Ropp, 1991). Brenner (1989) studied the stratigraphy and paleogeography of the upper Cherokee Group across eastern Kansas and northeastern Oklahoma. The Prue Sandstone Formation studied in this thesis corresponds to Brenner's informal Banzet formation. Gamma-ray, neutron, and density well-logs were utilized to correlate, differentiate lithologies, and delineate sandstone body geometries. Thick sandstone bodies with blocky, bell-shaped signatures were observed to have sharp basal contacts. Sandstones are observed to have been deposited in northeast-to-southwest trending channels within fluvial-dominated deltaic lobes (Brenner, 1989). Research conducted by Boucher (2007) and Puckette (1990) focus on Cabaniss Group formations in the Anadarko Basin in east-central Oklahoma. Boucher studied the Cabaniss for the depositional environment, hydrocarbon zones, and to establish sandstone distribution patterns using well-logs, core, and generated subsurface maps (2007). The Prue was observed as a single continuous unit lacking multistory development. Signature analysis suggests distributary channel, delta front, marginal marine, and prodelta depositional environments. Reservoir deposits of the Cabaniss Group are largely interpreted as incised-valley fill, distributary channels, and channel mouth bars (Boucher, 2007). Puckette utilized well-logs, core, thin sections, well cuttings, and generated maps to study reservoir geometry, depositional facies, effects of cyclicity on deposition, and describe diagenetic events (1990). Prue sandstones are absent across the study area, and the underlying Verdigris Limestone was used to define shelf and basin facies. Migration and distribution of the Verdigris Limestone compared to that of the older Pink Limestone suggest an up-dip shelf migration over time. Overall, the Cabaniss Group was interpreted to have been deposited in a stable shelf setting with deposition strongly affected by cyclic sea level changes (Puckette, 1990). Johnson (2008) addresses the structural development and paleogeography of Oklahoma extensively. Much of Oklahoma's present-day topography has been attributed to periods of mountain building, subsidence, and erosion, most of which occurred during the Pennsylvanian. The mid-continent during this time was heavily influenced by glacial eustatic sea-level fluctuations, with numerous studies detailing transgressive and regressive cyclothems from shales and limestones within the Prue Sandstone (Boardman and Nestell, 1993; Brenner, 1995; Marshall, 2002). Dominant lithologies include sandstone, limestone, shale, and coal.

This study explores the regional Prue stratigraphy and depositional characteristics through the analysis of core, thin sections, well-logs, subsurface maps, and 3D models to address the following questions:

1. What are the common lithologies and sedimentary structures of the Prue Sandstone?
2. What are the dominant framework grains, grain size, and pore types?

3. How do structure, thickness, and sandstone percent trends vary spatially?
4. What do the thickness, sandstone percent trends, well-log signatures, and sedimentological characteristics suggest about the depositional setting of the Prue Sandstone?

The study area of Lincoln County, Oklahoma encompasses approximately 990 mi^2 (1593 km^2) and 30 townships (Figure 1). Lincoln County is in east-central Oklahoma on the Cherokee Platform. Formation tops were interpreted and correlated using raster logs for 1724 wells. A subset of 879 wells was interpreted for sandstone thickness, with 123 wells further used to estimate average porosity. Digital LAS logs for 95 wells were also interpreted, correlated, and used to generate a 3D lithology model (Figure 2).

Through this study, the Prue Sandstone's depositional system is further defined as a deltaic plain with interpreted fluvial channels, interdistributary channels, and floodplain environments. The spatial variability of the Prue is highly dependent on the depositional environment, while vertical variability is primarily controlled by channel geometries and heterogeneity within the interval. Information gathered in this study resulted in a diagrammatic paleogeographic reconstruction and an enhanced understanding of the Prue's regional stratigraphy that can be applied to future sedimentology and economic development projects.

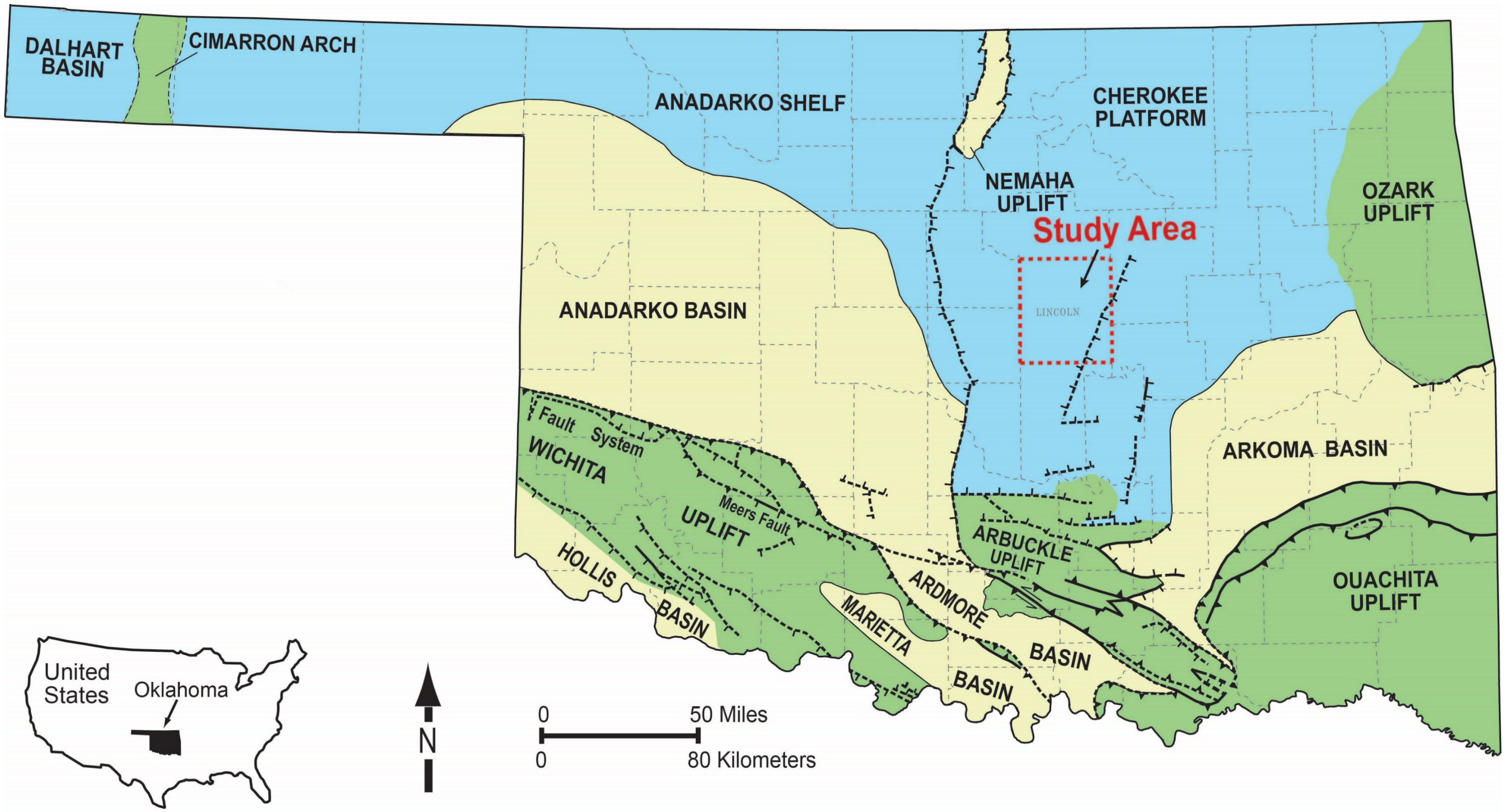


Figure 1: Map of Oklahoma illustrating the tectonic settings of the study area location (Modified from Northcutt & Campbell, 1995).

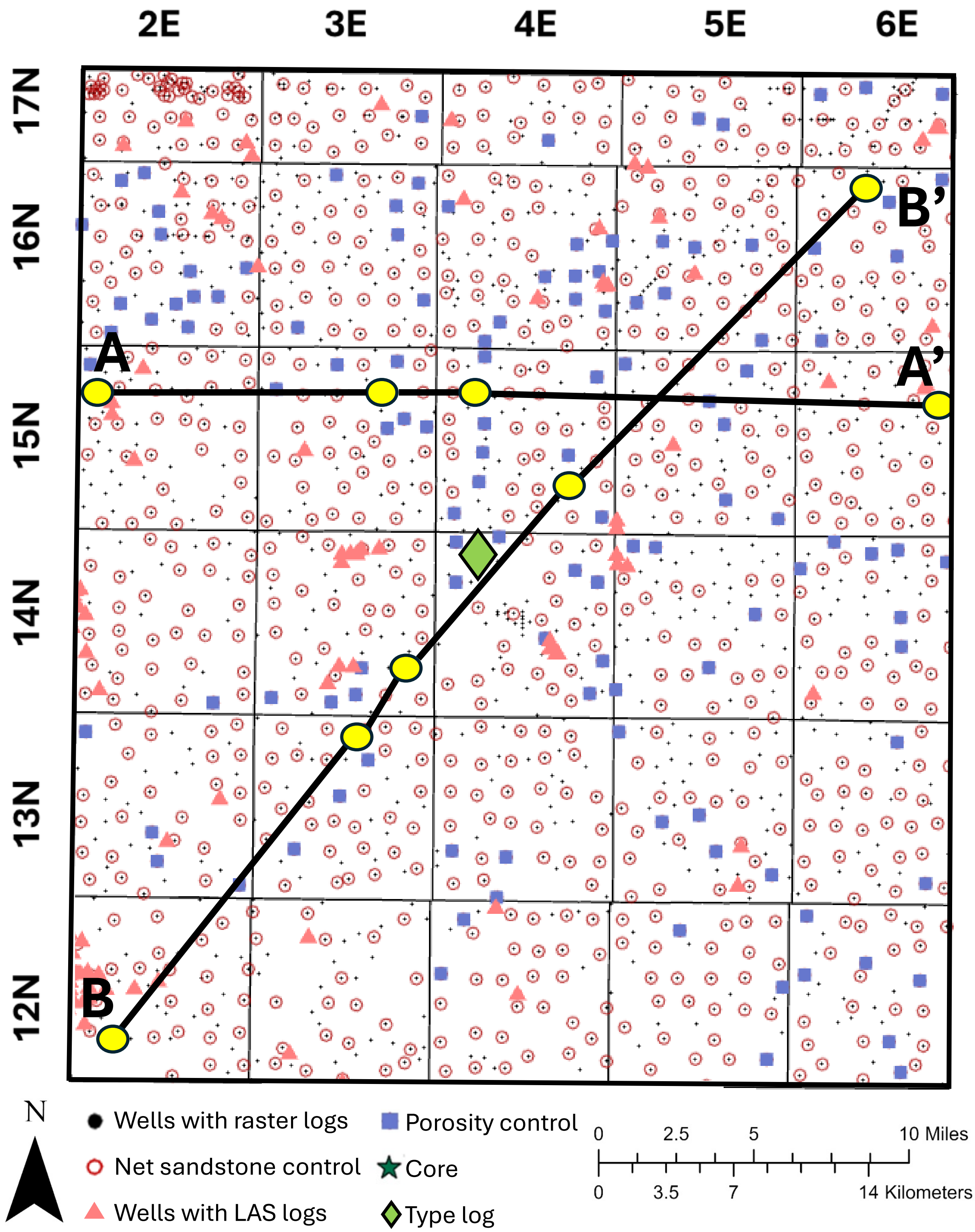


Figure 2: Basemap of Lincoln County, Oklahoma displaying distribution of wells with interpreted formation tops from raster logs (black), net sandstone correlations (red), average porosity estimations (blue), type log (green), and the locations of core (stars). Cross sections A-A’ and B-B’ of Figure 6 are shown.

GEOLOGIC SETTING

The study area of Lincoln County, Oklahoma, is in east-central Oklahoma and is positioned on the southern portion of the gently dipping Cherokee Platform. Structural surroundings include the Wichita uplift to the southwest, the Ozark uplift to the northeast, the Nemaha uplift to the northwest, and the Ouachita uplift to the southeast (Figure 1). The Arbuckle uplift is south of the study area and was not present at the time of Prue Sandstone deposition (Johnson, 2008). The region is bound by two major fault systems: the Nemaha Ridge Fault System and the Wilzetta Fault System.

The Pennsylvanian (Desmoinesian; ~308 Ma) Prue Sandstone is the youngest siliciclastic member of the Cabaniss Group (Figure 3). It is important to note that the Prue Sandstone is commonly referred to in early Oklahoma literature as a member of the informal "Cherokee Group." The move to more formal nomenclature was proposed by Krumme (1981), in which he extensively addressed the stratigraphic terminology of the group and proposed to replace the Cherokee term with two subgroups previously defined for the Desmoinian strata of Oklahoma. The terms Krebs and Cabaniss have since been adopted. Refer to Appendix A for additional information regarding Prue nomenclature.

The interval is overlain by the Excello Shale and conformably lies above the Verdigris Limestone. The base of the Oswego Limestone and the top of the Excello Shale separate Cabaniss stratigraphy from the overlying Marmaton Group. The Verdigris and Oswego limestones have been interpreted to represent small-scale transgressive cycles (Heckel, 1983; Ropp, 1991). Present in the Prue interval are sandstones, shales, and minor amounts of coal. The Prue was deposited in a fluvial-deltaic depositional environment (Ropp, 1991; Broker, 2000; Ahmadian, 2019). Lagonda Sandstone serves as the surface equivalent terminology to the subsurface Prue nomenclature.

Both the Excello and Verdigris units are laterally continuous across the study area and have distinct well-log signatures. The Excello Shale has been described as light grey to black, organic-rich shale, and is 2 – 4 ft (0.6 – 1.2 m) thick (Ropp, 1981). It is a “hot” shale with a gamma-ray (GR) value greater than 85 API. The Verdigris Limestone is a microcrystalline dolomitic limestone and is easily identified by low GR values and high RESD values (Ropp, 1981).

The Breezy Hill Limestone and the Iron Post Coal are irregularly distributed across the study area. The Breezy Hill Limestone is a massive crinoidal biosparite at the base of the Excello Shale (Ropp,1981) with a low GR log signature and is up to 5 ft (1.5 m) thick. Where present, the Iron Post Coal has a variable GR signature and bulk density (RHOB) values <2 g/cm^3.

METHODS

Core and Thin Section Analyses

Prue Sandstone cores from two wells within the study area, Gulf Oil Corp. 1 – Hamm WF and Sun Oil Exploration and Production Co. 3–6 Creiss Waterflood, were described for their lithology, grain size, grain sorting, color, and sedimentary structures. The Gulf Oil Corp. 1 – Hamm WF core is in southeast Lincoln County in township 13N–5E, section 19, and is 17 ft (5.2 m) in length (Appendix B). The Sun Oil Exploration and Production Co. Creiss Waterflood 3-6 core is in 14N–6E, section 2, and is 109 ft (33.2 m) long (Appendix C). Ten samples (3 from 1–Hamm WF; 7 from 3–6 Creiss Waterflood) were acquired from the cores for thin-section petrographic analysis to analyze the framework grains and pore types. Thin sections were treated with alizarin red stain and impregnated with methylene blue epoxy to aid in the identification of calcite and

System	Series	Group	Subsurface Formation Name
Pennsylvanian	Desmoinesian	Marmaton	Big Lime
			Little Osage Shale
			Oswego Limestone
		Cabaniss	Excello Shale
			Breezy Hill Limestone
			Iron Post Coal
			Prue Sandstone
			Verdigris Limestone
			Oakley Shale
			Skinner Sandstone
		Krebs	Pink Limestone
			Red Fork Sandstone
			Inola Limestone
			Bartlesville Sandstone
			Brown Limestone
Mississippian	Meramecian		Mayes Limestone

Figure 3: Stratigraphic column of Late Mississippian and Early–Mid Pennsylvanian strata. (Modified from Krumme (1981) and Ropp (1991)).

pore space, respectively. All samples were analyzed in plain and cross-polarized light with 4x and 10x magnification. An increased magnification power of 40x was used as needed to aid in interpretation and imaging.

Stratigraphic Correlation

Sedimentological and stratigraphic characteristics observed from core, thin sections, and well-log signatures were used to identify and map the stratigraphic units of the Prue Sandstone interval. Cross-sections were created to correlate the top and base of the Prue interval for 1724 wells using raster logs. The underlying Pink Limestone was also interpreted to assist in correlating areas where the Verdigris Limestone was not as easily recognizable.

A regional cross-section grid comprised of six segments was used to understand well-log signature trends and create the foundation for additional correlations (Appendix D). Stratigraphic markers were interpreted primarily from gamma-ray (GR) and spontaneous-potential (SP) logs. Resistivity (RESD), bulk-density (RHOB), neutron-porosity (NPHI), and density-porosity (DPHI) logs were also considered. Key stratigraphic surfaces interpreted include the Pink Limestone, Verdigris Limestone, and the Excello Shale. These formations are easily distinguished and form distinctive stratigraphic markers due to their spatial continuity (Figure 4). Log signatures at the base of the Prue are low GR and high RESD. Signatures at the top of the interval display high GR values and low RESD. The underlying Pink Limestone exhibits low GR values and a very pronounced high RESD deflection.

Wells with RHOB logs (N=123) were used to identify and correlate the Iron Post Coal and to determine its thickness. Coal density typically ranged from 1.1 – 1.5 g/cm^3. The Iron Post Coal was manually identified using RHOB values in the Prue <2 g/cm^3.

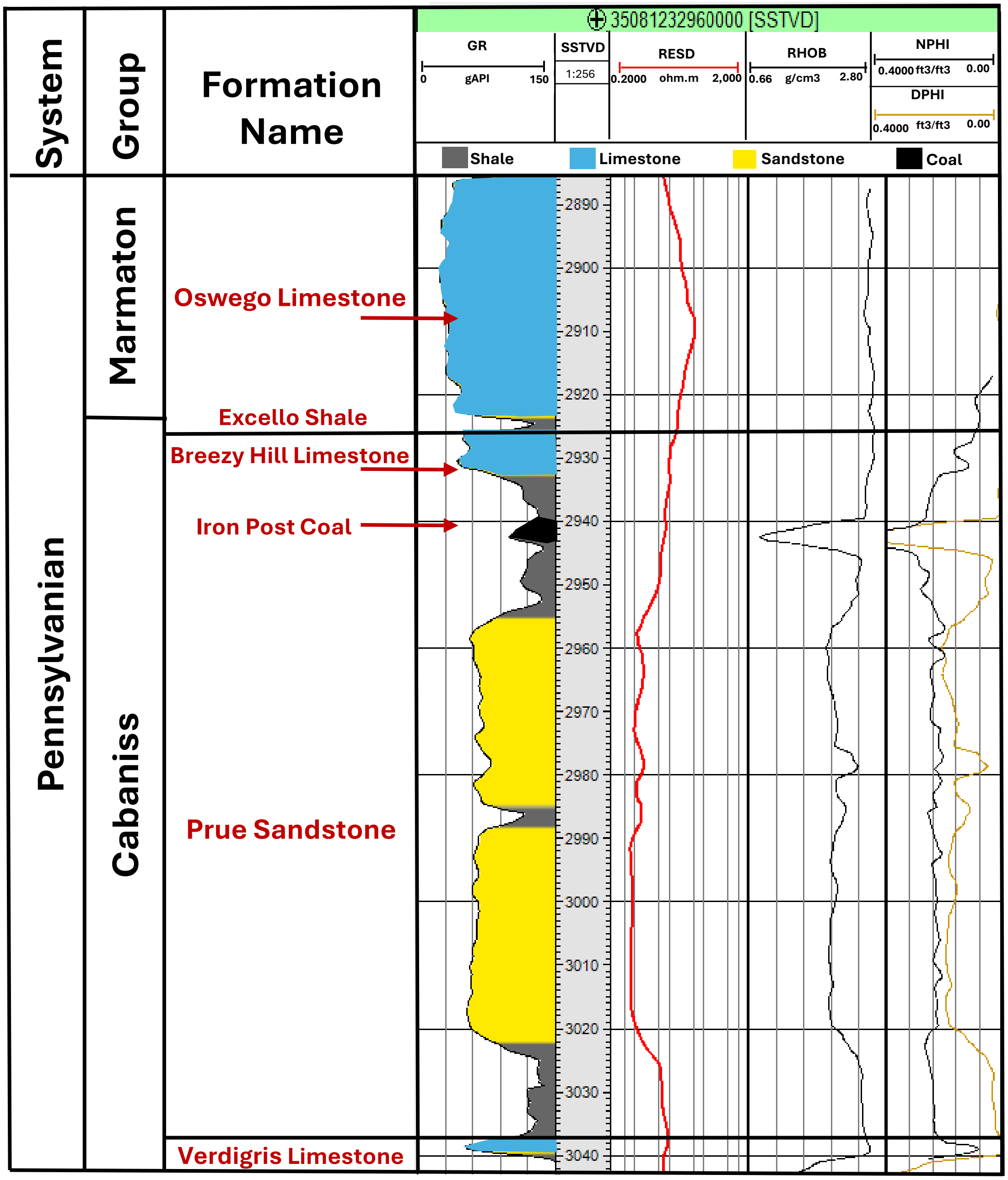
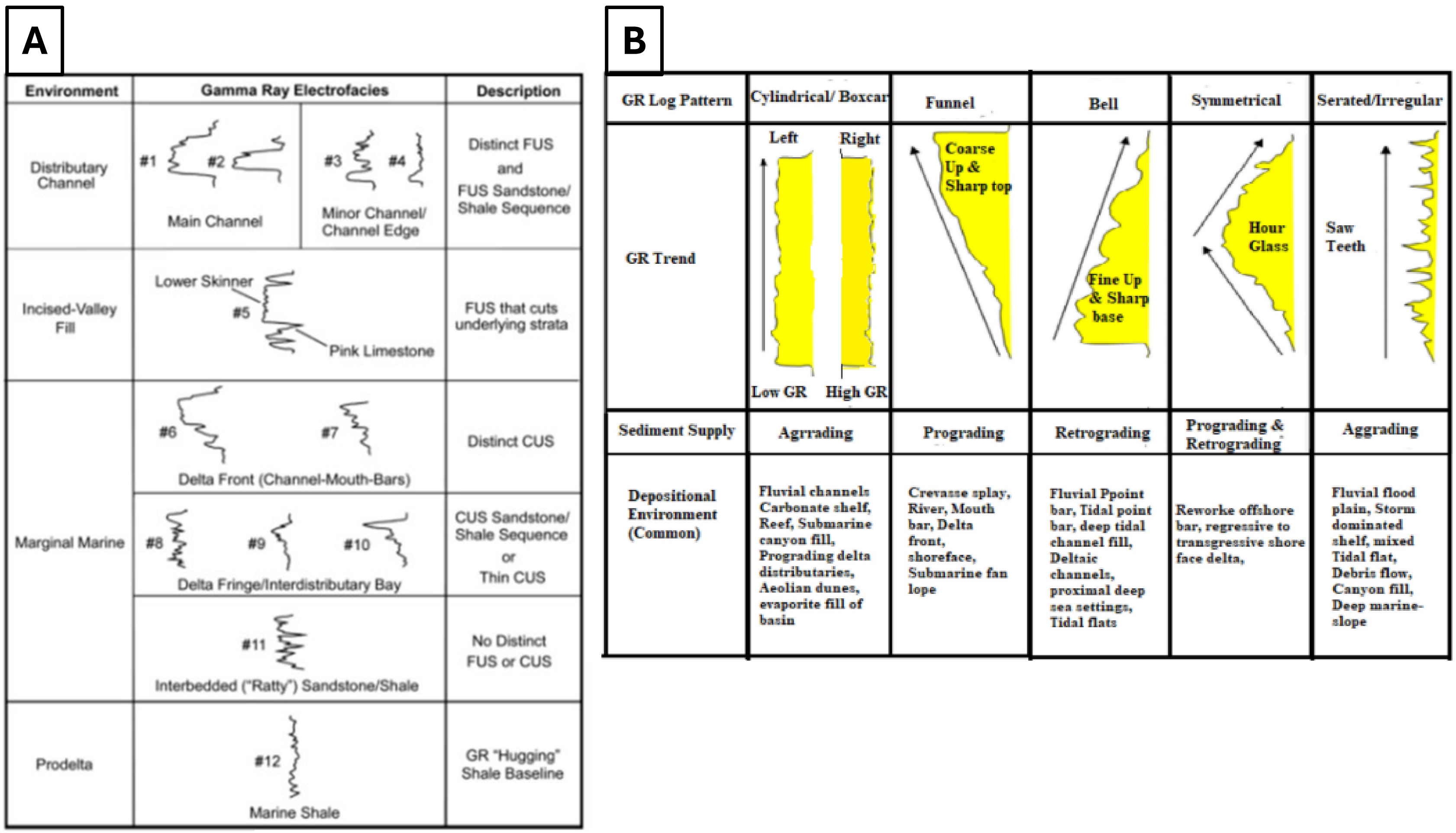


Figure 4: Type log showing Prue Sandstone stratigraphy from Geoquest Energy Inc. 1–Marcia. Wireline logs include gamma-ray (GR), deep resistivity (RESD), bulk-density (RHOB), neutron-porosity (NPHI), and density-porosity (DPHI). Formations and bounding surfaces are labeled (left) and correlate to their wireline signature (right).

Well-log Signature Analysis

The general shape and trends of GR and SP log signatures were used to interpret depositional characteristics and environments for the Prue Sandstone interval. Terminology and concepts from Rider (1990), Cant (1992), Boucher (2007), and Torrado (2020) were used to analyze log signatures and establish facies trends. Terms used to describe the log patterns include fining upward sequence, coarsening upward sequence, serrated, symmetrical, and cylindrical. The inferred lithologies and vertical succession of lithologies associated with each log pattern are explored and assigned a depositional environment consistent with the log signature.

GR logs measure the natural radioactivity of a rock based on the concentrations of uranium, thorium, or potassium isotopes. Higher radioactivity results in a higher GR value and is commonly indicative of shale. A lower GR value indicates less radioactivity and is commonly associated with lithologies such as sandstone, limestone, or coal. Certain circumstances such as an increased amount of radioactive minerals, clays, or interbedding in sandstones may result in high API values and misinterpretation as a shale. Additionally, the shape of the GR log signature (Figure 5) is a direct response to upward-coarsening successions (e.g., interpreted as progradational) and upward-fining successions (e.g., interpreted as retrogradation). Funnel-shaped signatures (Figure 5) can represent upward-coarsening successions that occur during periods of progradation. Bell-shaped signatures (Figure 5) can represent upward-fining successions that occur during periods of retrogradation. Common upward-fining sequences include point bars, tidal channel fills, and delta distributary channels. Other common signatures include cylindrical and symmetrical trends. Cylindrical shapes (Figure 5) exhibit uniform GR values associated with aggradation. A similar aggradational pattern observed with significant serration or irregularity within the sediment package indicates an environment with extreme small-scale cyclicity. These responses are typically



FUS – Fining Upward Sequence
CUS – Coarsening Upward Sequence
GR – Gamma Ray

Figure 5: Example gamma-ray signatures, associated terminology, and potential depositional environment interpretations from A) Boucher (2007) and B) Radwan (2020); modified after Cant (1992).

associated with fluvial flood plains, storm-dominated shelves, and tidal flat deposits. The symmetrical pattern (Figure 5) is defined by a coarsening upward sequence transitioning to a fining upward sequence with little or no aggradational response. This pattern is indicative of offshore reworking or transgressive delta shoreface environments.

Thirty wells (well spacing = 6 mi; 9.7 km) were considered for well-log signature analysis. Log signatures of the Prue Sandstone were described independently of each other and assigned a depositional environment interpretation. Wells were compared to each other, core, a sandstone percent map, and the paleogeographic trends of Krumme (1981) to develop depositional environment interpretations.

Subsurface Mapping

Formation tops were interpreted from well logs to generate structure-contour maps for the top and base of the Prue Sandstone. The structure maps were generated using a kriging algorithm and are displayed using a 50 ft (15.2 m) contour interval. An isopach map of the Prue Sandstone was calculated by subtracting the Verdigris Limestone surface from the Excello Shale surface to create a map representative of the Prue Sandstone's gross thickness.

A subset of 879 wells (Figure 2) distributed approximately every 1 mi (1.6 km) was selected to map net sandstone thickness of the Prue Sandstone. Sandstones were identified based on log signatures displaying low GR values and high RESD values (Figure 6). Due to the low quality of the raster logs, sandstones were interpreted for each well individually rather than using a specified cut-off value across the entire study area. Interpretations were based on shale baselines and typical signature values observed throughout the well-log for other known sandstone units. Following the

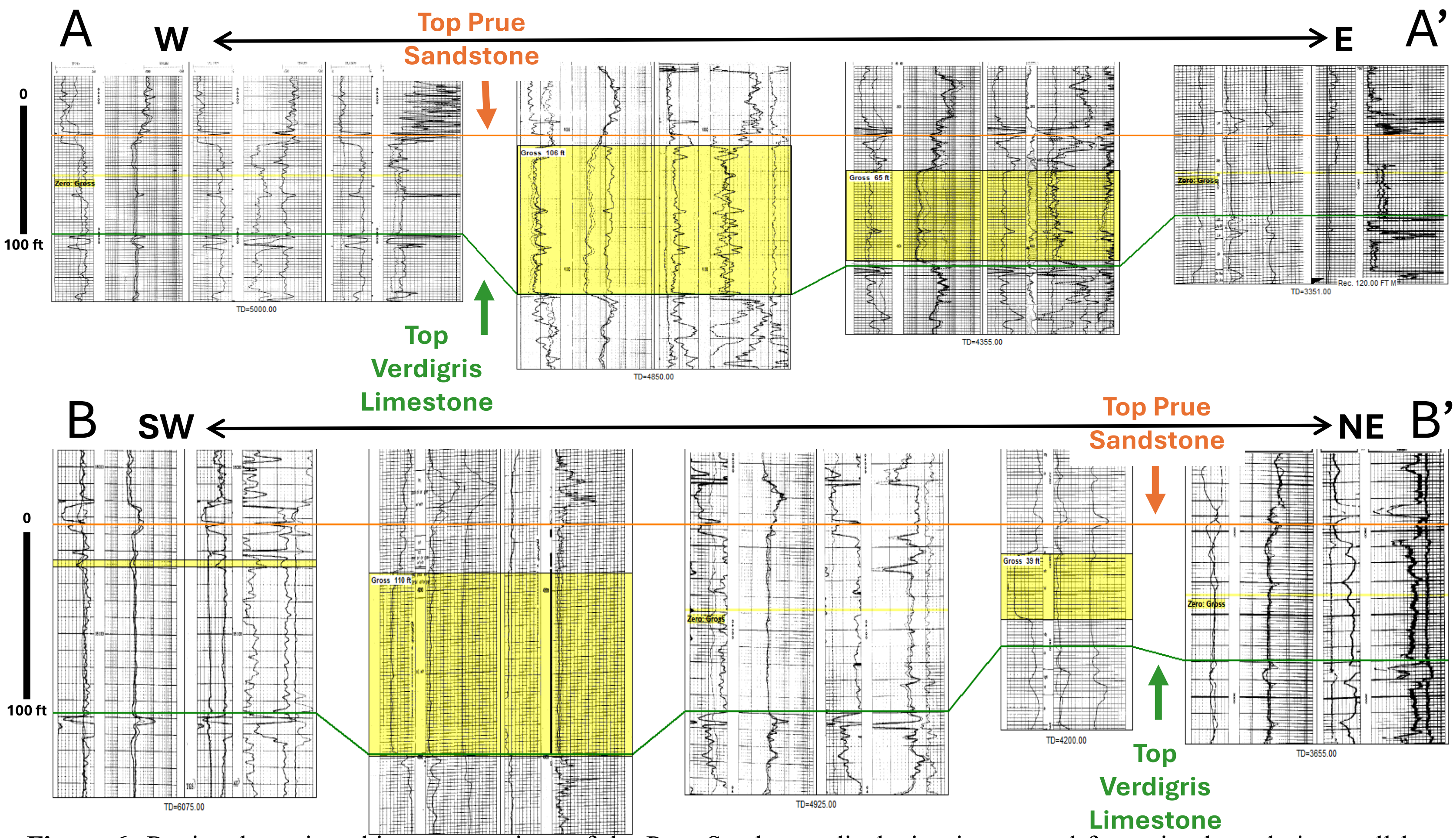


Figure 6: Regional stratigraphic cross-sections of the Prue Sandstone displaying interpreted formation boundaries, well-log signatures, and calculated net sandstone values. Bounding surfaces are shown at the top (orange) and base (green) of the Prue Sandstone. Yellow corresponds to net sandstone estimations. Cross-sections indicate an overall decrease in gross thickness towards the east and northeast. Sandstones are thickest in the central portion of north Lincoln County but show more variability SW–NE across the study area.

interpretation of sandstone packages within the Prue Sandstone, net sandstone and sandstone percent maps were generated using a kriging algorithm.

For the wells (N=123; Figure 2) with manually interpreted Prue sandstones with net sandstone thickness values >10 ft (3 m), the average porosity was estimated. The average porosity of the Prue interval in a well was estimated by determining the approximate mean density-porosity log (DPHI) value within the interpreted sandstone. The average sandstone porosity was mapped within the sandstone's main depositional trend using a kriging algorithm.

Property Calculation and Lithology Modeling

Calculations for 95 wells with digital logs were used to define and model Prue Sandstone lithology. GR and RESD logs are present in all wells. Sandstone was defined by a GR cut-off of <80 API; shale is defined by GR values ≥80 API. Bulk density logs were used to define coal in 123 wells by applying a cut-off of <2 g/cm^3.

Structure maps of the top and base of the Prue Sandstone generated from the initial dataset were used to create a 3D grid across the study area. The aerial cell dimensions used to create the structural framework largely depend on the availability and distribution of wells with LAS logs. The modeling framework was established using an aerial cell size of 1000 ft x 1000 ft (304.8 m x 304.8 m) and 75 proportional layers. The number of proportional layers (75) resulted in a layer thickness of ≤2.1 ft (0.64 m). The generated framework is comprised of approximately 2 million total cells. Well-logs were correlated at the base of the Breezy Hill Limestone, where present, to prevent the inclusion of the limestone in the Prue lithology model. Generated lithology logs were upscaled to the 3D grid (Appendix E). The accuracy of the log upscaling was checked on numerous cross-sections by comparing the upscaled log to the defined lithology log and GR curves.

The 3D lithology model was generated using sequential indicator simulation. The 3D stratigraphic framework (3D grid), vertical lithology proportion curves, upscaled lithology logs, variogram parameters (Appendix F), and net sandstone thickness map (trend surface) were used to constrain the lithology model.

RESULTS

Sedimentary Characteristics and Pore Types

Gulf Oil Corp. 1–Hamm WF is cored 17 ft (5.2 m) through the Prue Sandstone and is primarily composed of well-sorted, fine to medium-grained sandstone with small mudstone beds and clasts (Figure 7). The sandstone exhibits planar, wavy, and flaser laminations. Laminations within the sandstone are composed of shale and coal with minor amounts of mica and mudstone distributed throughout the length of the core. The Prue Sandstone is primarily light grey to grey with some sections appearing more tan or reddish brown. Additional images of the core are in Appendix G. Petrographic analysis of three thin sections revealed subangular–subrounded, moderately well–sorted quartz grains exhibiting intergranular and channel porosity (Figure 8). Trace amounts of calcite and feldspar were noted from the analysis with greater amounts of muscovite and organic matter.

The Sun Oil Exploration and Production Co 3–6 Creiss Waterflood core consists of very-fine to fine-grained sandstone with large amounts of interbedded shale and siltstone (Appendix H). The core is 109 ft (33.2 m) in length (Figure 9). Sedimentary structures include planar and wavy laminations and bedding, disturbed bedding, burrows, climbing ripples, and herringbone cross-stratification. Seven thin sections were analyzed to reveal a framework of subangular–rounded quartz grains that are moderately well-sorted and very-fine to fine-grained in size (Figure 8).

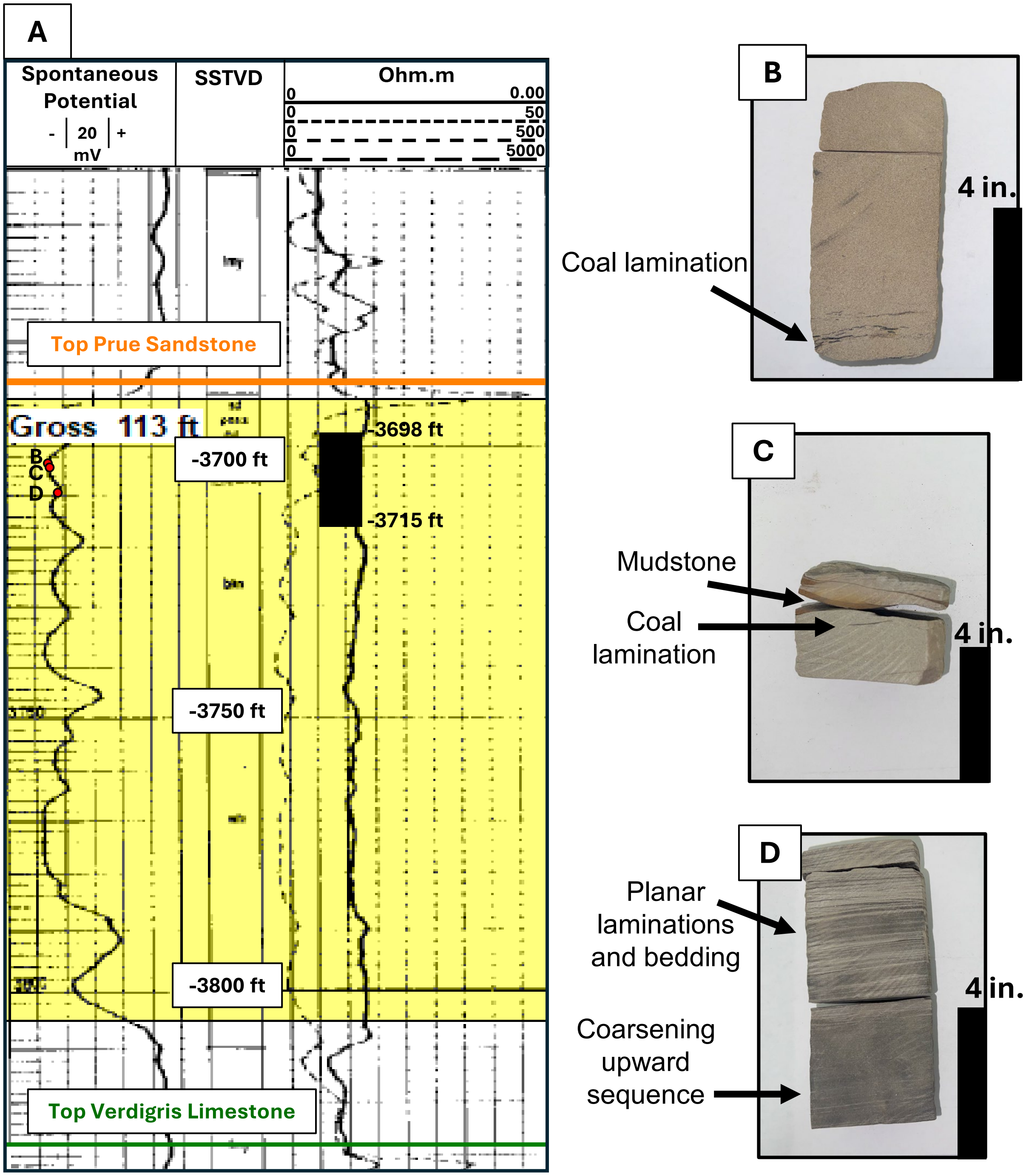
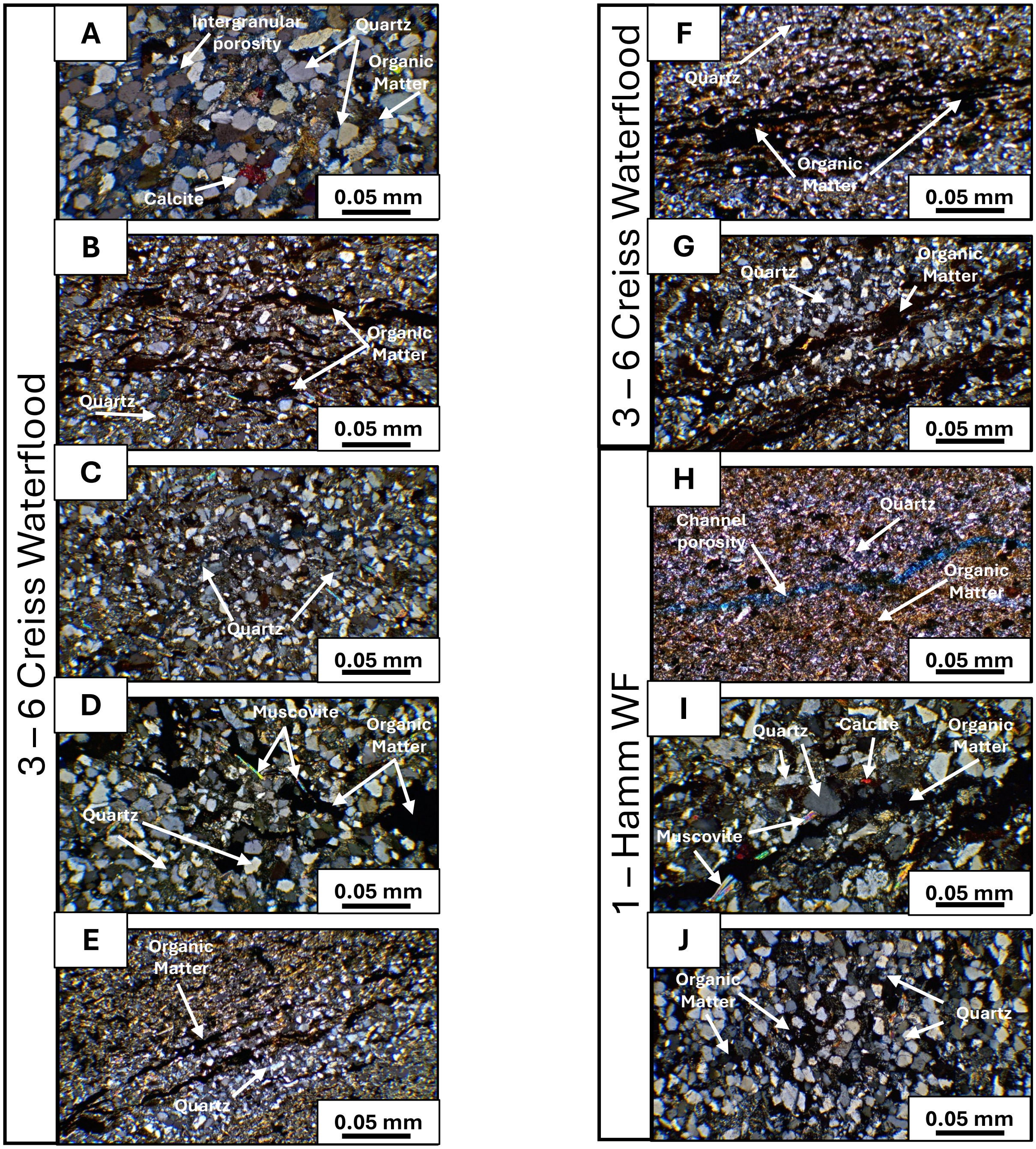


Figure 7: A) Gulf Oil Corp. 1 – Hamm WF cored interval (-3698 – -3715 ft) indicated on the well-log by a black bar. B) Photograph of massive sandstone with coal laminations at -3704 ft. C) Photograph of massive fine-grained sandstone with mudstone and thin coal laminations -3705 ft. D) Photograph of planar laminations and bedding, siltstone, and shale exhibiting a coarsening upward sequence at -3710 ft.



3 – 6 Creiss Waterflood
A
Intergranular porosity
Quartz
Organic Matter
Calcite
0.05 mm
B
Organic Matter
Quartz
0.05 mm
C
Quartz
0.05 mm
D
Muscovite
Organic Matter
Quartz
0.05 mm
E
Organic Matter
Quartz
0.05 mm
3 – 6 Creiss Waterflood
F
Quartz
Organic Matter
0.05 mm
G
Quartz
Organic Matter
0.05 mm
1 – Hamm WF
H
Channel porosity
Quartz
Organic Matter
0.05 mm
I
Quartz
Calcite
Organic Matter
Muscovite
0.05 mm
J
Organic Matter
Quartz
0.05 mm

Figure 8: Thin-section images from Sun Exploration and Production 3–6 Creiss Waterflood (7 samples) and Gulf Oil Corp. 1–Hamm WF (3 samples) shown in cross-polarized light at 4x magnification. A) Subangular – subrounded, fine – medium grain sandstone displaying intergranular porosity, and inclusions of calcite, muscovite, and organic matter. B) Well cemented subround–round, very fine to fine-grain sandstone with organic matter inclusions. C) Well cemented, subangular–subrounded, fine to medium–grain sandstone displaying fracture porosity and organic matter inclusions. D) Subangular – subrounded, fine – medium grain sandstone with inclusions of muscovite, feldspar, and organic matter. E) Very fine, subrounded sandstone displaying intergranular and fracture porosity, feldspar, and organic matter laminations. F) Subangular – subrounded, very fine to fine-grained sandstone with feldspar and muscovite inclusions. G) Fine–medium grain, subrounded quartz displaying fracture porosity and organic matter laminations. H) Moderately well-sorted, very-fine grained, subangular – subrounded sandstone. Displays intergranular porosity and inclusions of muscovite, feldspar, and organic matter laminations. I) Well cemented, subangular – subrounded, fine to medium grained sandstone. Displays intergranular and fracture porosity, calcite, feldspar, and organic matter. J) Well cemented, subangular–subround, fine to medium grained sandstone displaying intergranular porosity and inclusions of feldspar, muscovite, and organic matter.

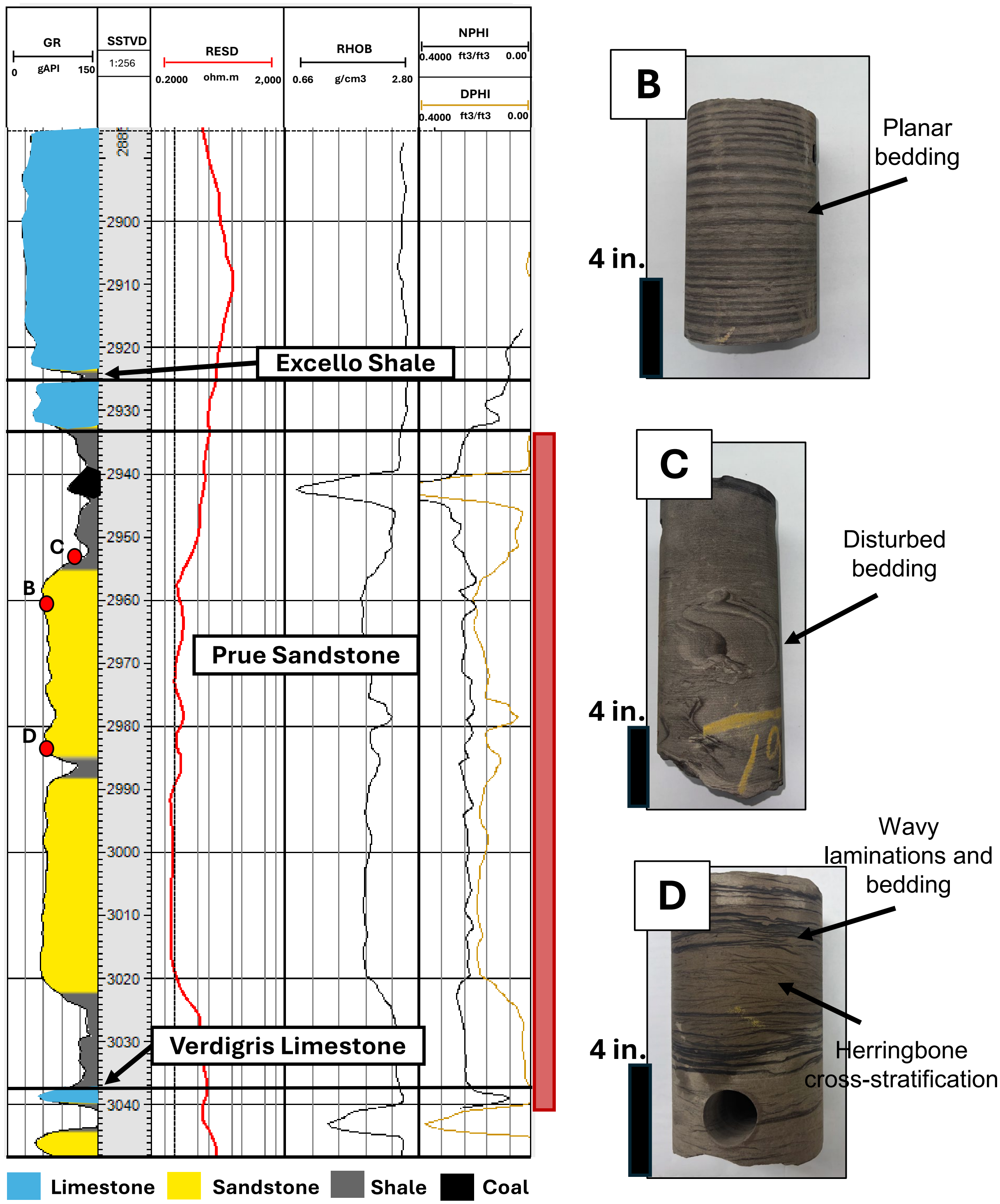


Figure 9: A) Sun Exploration and Production Co. 3 – 6 Creiss Waterflood cored interval (-2903 – -3011 ft; 2934 – 3042 SSTVD) indicated on the well-log by a red bar. Formation interpretations are shown and labeled by black arrows. B) Image of planar bedding at -2927 ft. C) Image of disturbed bedding at -2918 ft. D) Image of wavy laminations, bedding, and herringbone cross-stratification at -2954 ft.

Where present, porosity is primarily intergranular or channel porosity. Trace amounts of calcite, muscovite, feldspar, and organic matter are observed, as well as mudstone and organic matter laminations. Some organic matter laminations and bedding (e.g., sample #7) are visible in the thin section and measure approximately 0.4 in (1 cm) thick. A table summarizing thin-section observations is in Appendix I.

Depositional Signatures and Stratigraphic Variability

The log response of the Prue Sandstone consists of low GR (<85 API) at the base of the formation and high (>85) API values at its upper bounding surface. Many wells display consistent RESD values between 2 – 10 ohm.ms. Some wells display values greater than 15 ohm.ms and likely indicate the presence of oil or gas.

Common well-log patterns observed include fining-upward sequence, blocky, and serrated patterns. Thin coarsening upward sequences were observed a lesser amount and typically occurred as part of a serration pattern. Blocky signatures were further investigated for erosion or incision into underlying strata. Sequences displaying extremely irregular well-log signatures, or "serration," are the most common for Lincoln County (Figure 10). Serration patterns are typically shale but may include thin sandstone bodies within. Sandstone dominant serration patterns and serration association with block signatures have also been observed. Compared to net sandstone maps, shale-dominated serration patterns correspond to areas of low sandstone thickness compared to generated net sandstone and sandstone percent maps. Fining upward sequences, cylindrical, and sandstone-dominated serration signatures are located in areas with higher net sandstone values.

It is important to note that faults are hypothesized to affect the Prue but cannot be properly addressed with the data available. Faults were not observed in the well-logs but should be expected due to the presence of the fault system in the overlying Marmaton Group. A previous study by Toth

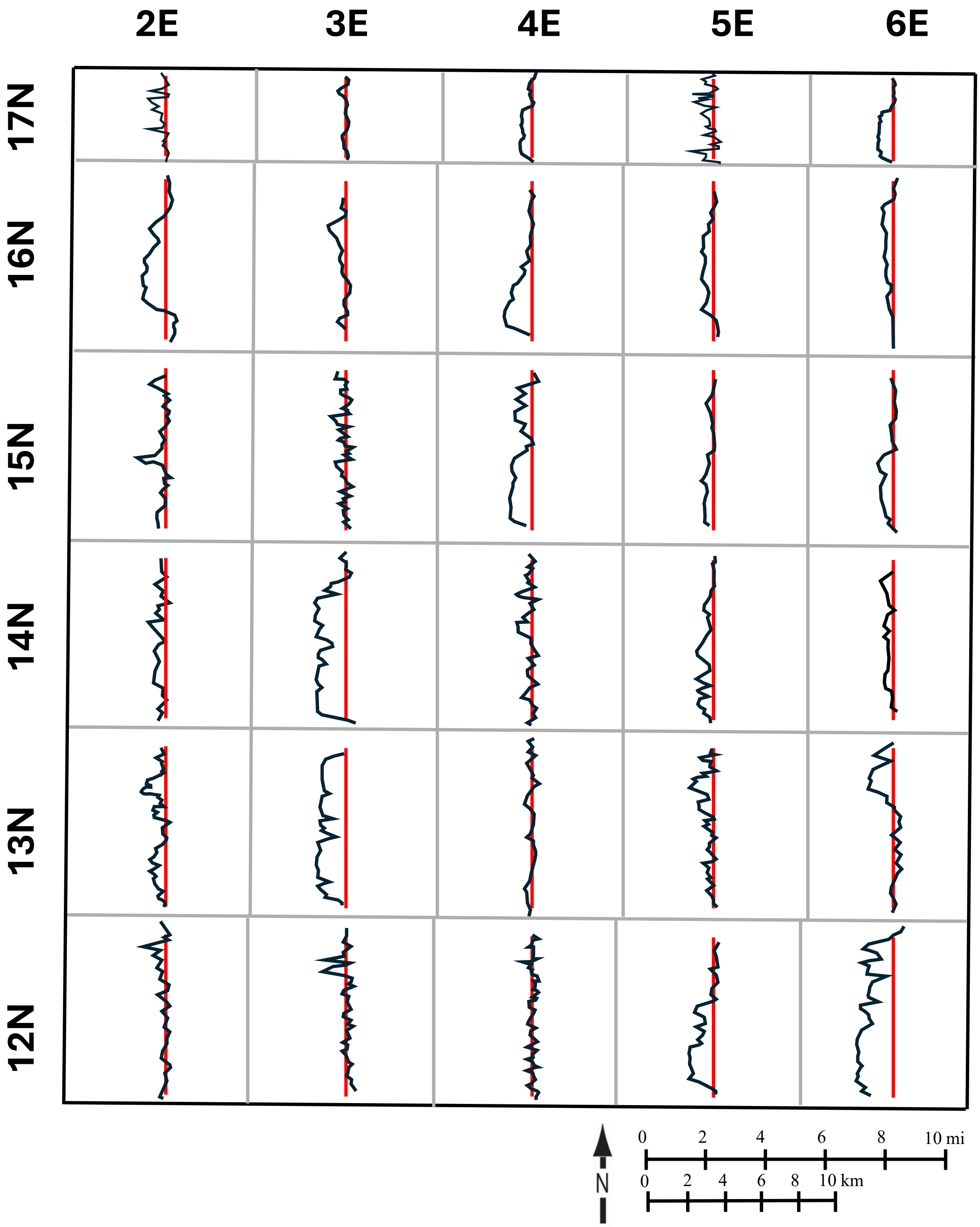


Figure 10: Basemap of Lincoln County, Oklahoma displaying gamma-ray well log signatures observed across the study area. Township lines (grey) and interpreted shale baseline (red) are shown.

and Puckett (2021) addressed the structural issue in detail stating that the distribution of Cherokee sandstones can be difficult to map using only wireline control and that a seismic volume is necessary to delineate faults affecting Cherokee deposition.

Structure, Isopach, Sandstone Thickness, and Porosity Trends

The top Prue structure map (Figure 11A) displays elevations ranging from -1525 ft to -3975 ft (-464.2 m – -1211.6 m). Elevation is greatest to the east with a gradual decrease in elevation towards the west. The base Prue structure contour map exhibits the same general trends but ranges in elevation from -1650 ft to -4200 ft (-502.9 m – -1249.7 m) (Figure 11B).

Prue Sandstone isopach values range from 20 – 160 ft (6.1 – 48.8 m). The Prue isopach map displays its lowest gross thickness values in the northwest corner of Lincoln County and increases in thickness towards the southeast (Figure 12).

Net sandstone values range from 0 to 116 ft (35.4 m) and display thicker sandstone trends towards the center and southeast corner of Lincoln County (Figure 13A). The average net sandstone thickness is 23.2 ft (7.1 m) and increases to 27.9 ft (8.5 m) when zero values are disregarded. The range of sandstone percent is 0 – 100% (Figure 13B).

Prue Sandstone average porosity values range from 0 – 0.24 within the main sandstone depositional trends observed in the net sandstone map (Figure 14). Porosity values are highest in the northwest and southeast corners of Lincoln County, with an additional isolated area of high porosity to the southwest. The mean value of the calculated average porosity is 7%. Forty percent of wells exhibit no porosity. Excluding zero porosity values from the dataset, the average porosity of the Prue Sandstone is 11%.

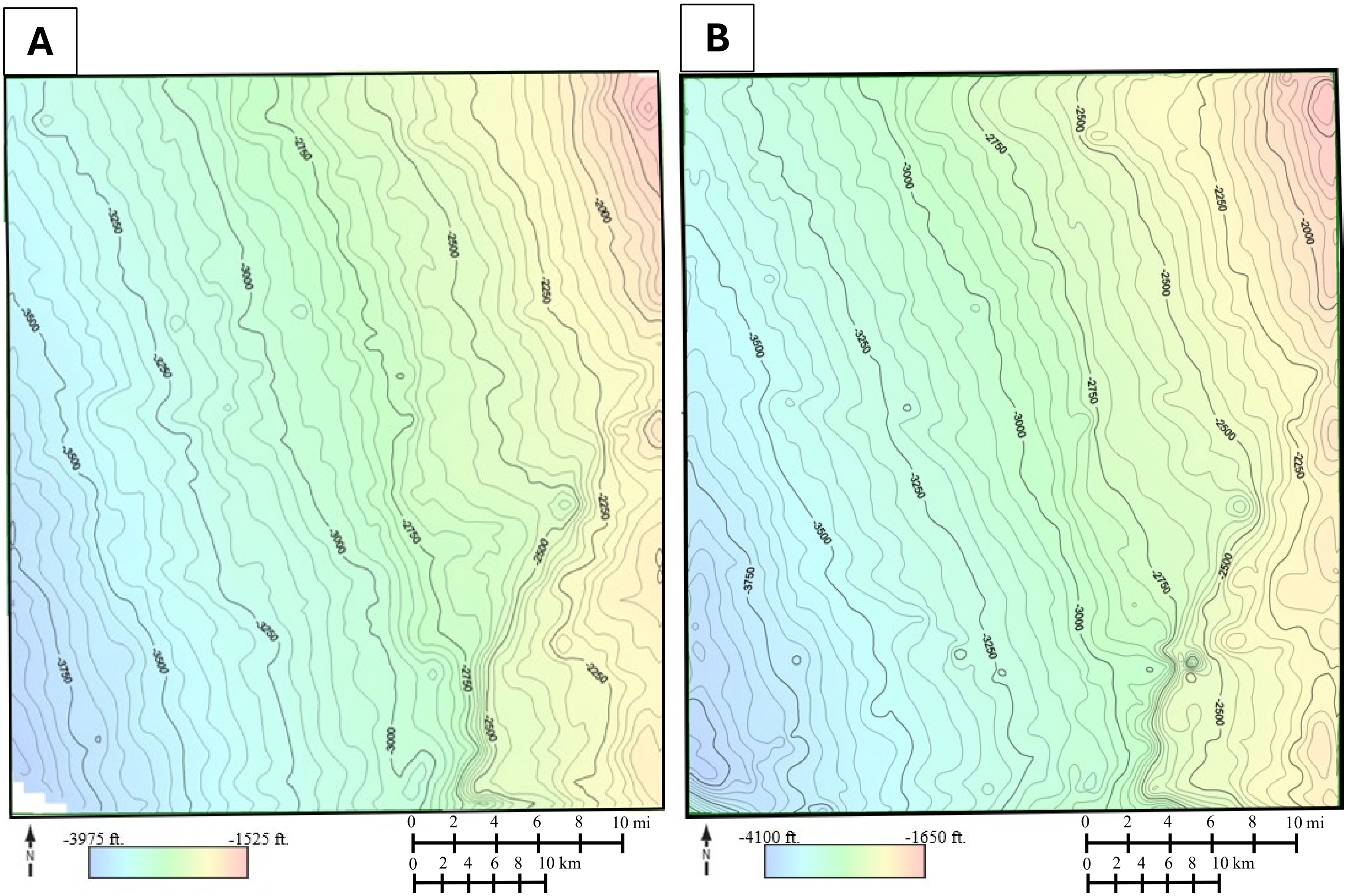


Figure 11: A) Top Prue Sandstone structure contour map. Generated from correlated formation tops at the base of the Excello Shale. B) Top Verdigris Limestone structure contour map. Generated from correlated formation tops at the top of the Verdigris Limestone. Maps indicate uniform structural dip towards the west – southwest.

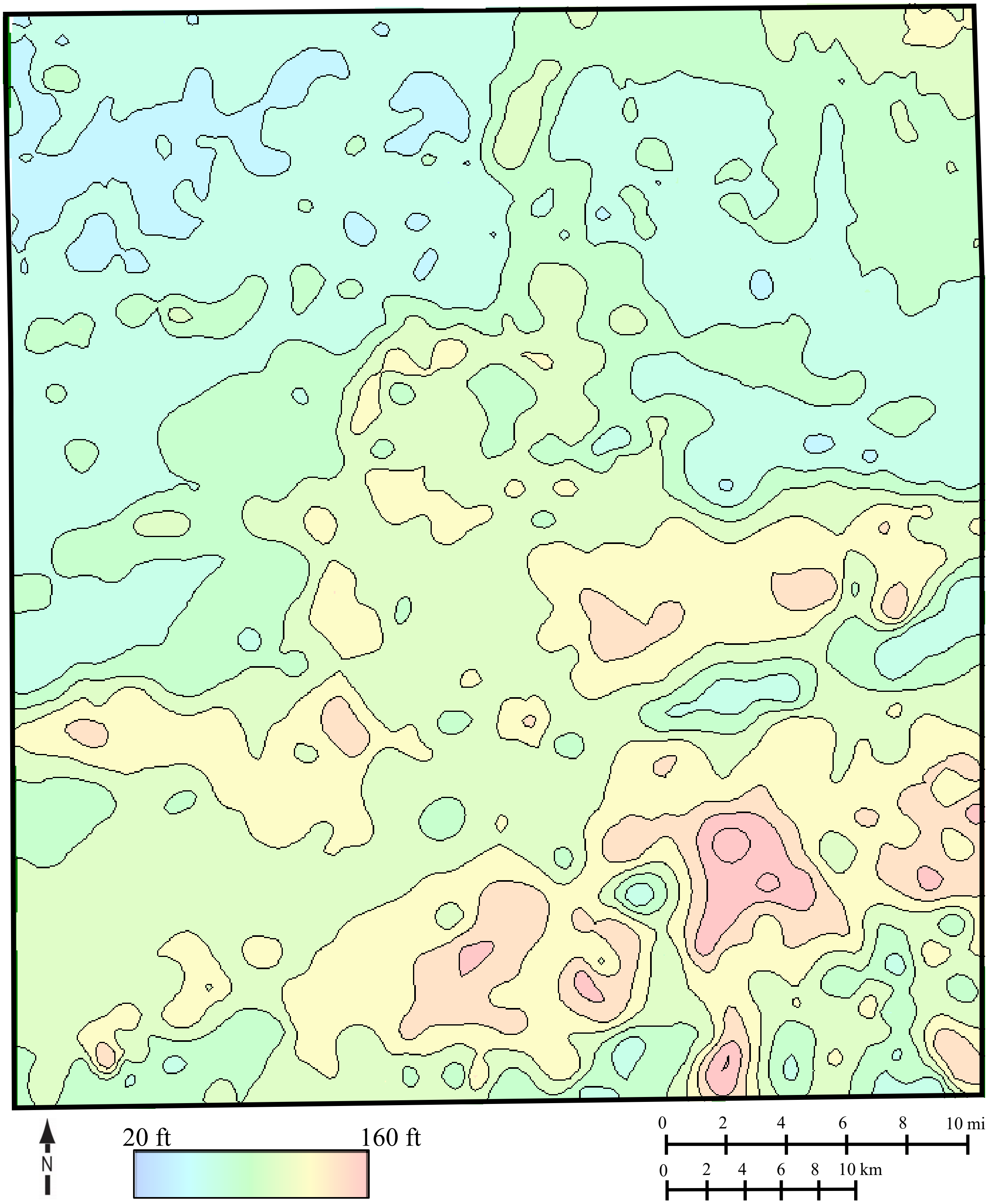


Figure 12: Prue Sandstone isopach map displaying thickness trends across Lincoln County. Map exhibits an increase in thickness south across the study area with the highest gross thickness values towards the southeast.

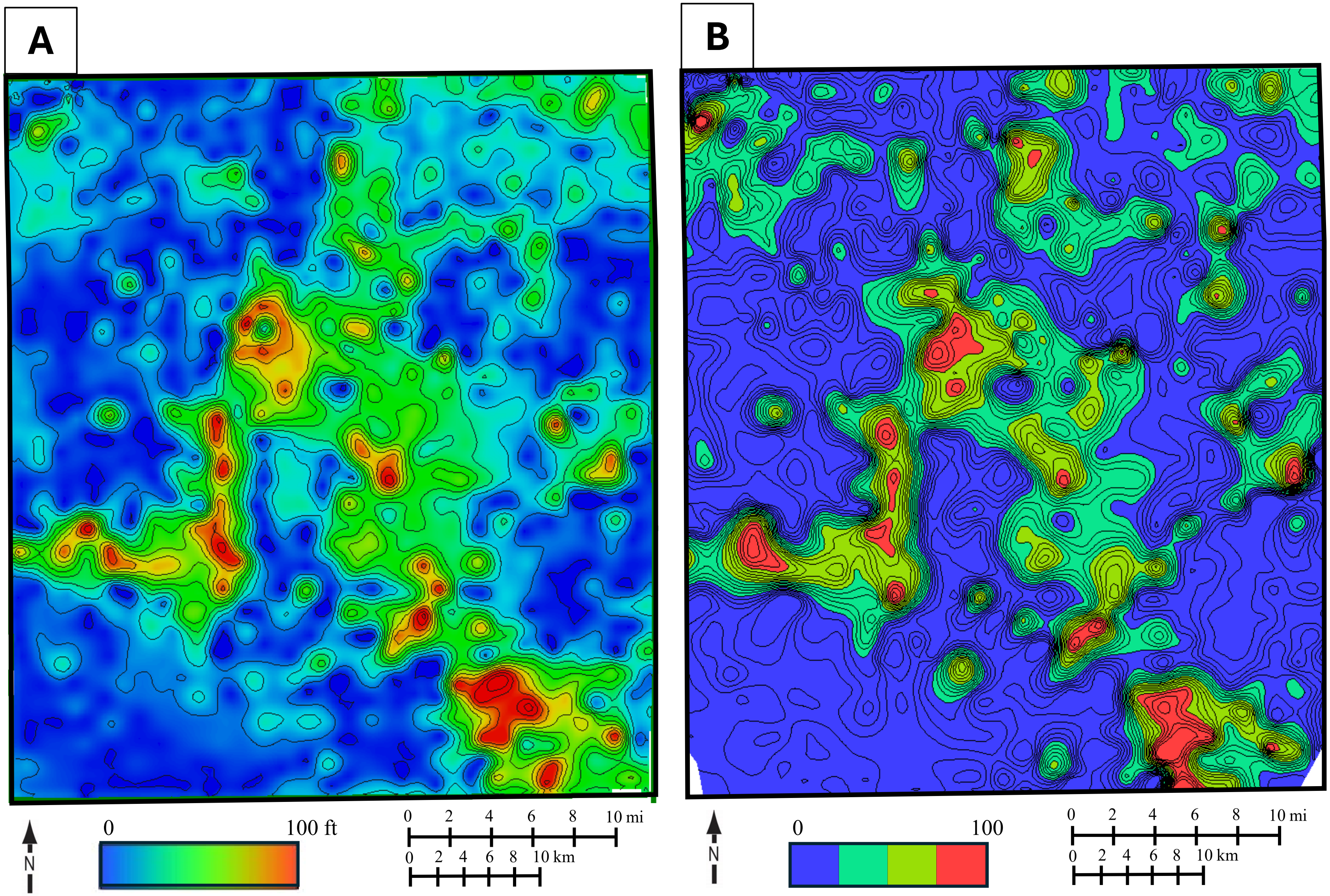


Figure 13: A) Prue Sandstone net sandstone thickness map. Map displays sandstone thickness within the Prue and indicates an increase in thickness towards the west and southeast. B) Prue Sandstone sandstone percent map. Displays sandstone thickness compared to gross interval thickness.

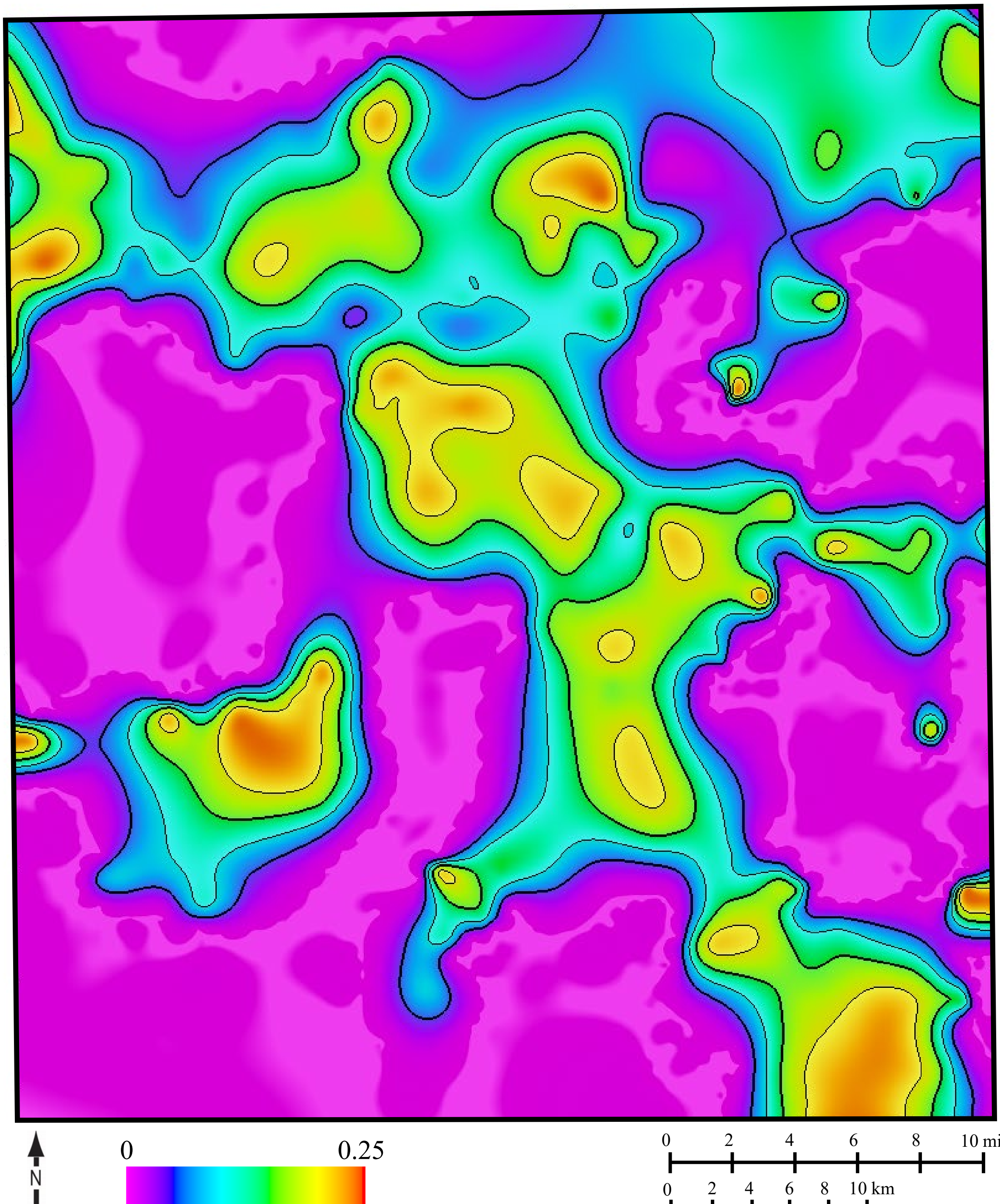


Figure 14: Prue Sandstone average porosity map. Porosity distribution trends northwest to southeast with high porosity values located on the north–central, northwest, and southeast edges of the study area.

The Prue lithology model displays the spatial and vertical distribution of shale, sandstone, and coal. The modeled lithologies include 85.3% shale, 14.3% sandstone, and 1.5% coal (Figure 15). The Iron Post Coal is discontinuous and exists in the uppermost portion of the interval. Shale is laterally continuous across the model and is the most predominant lithology within the Prue Sandstone. Sandstones are laterally discontinuous and exhibit a somewhat sinuous pattern across the modeled area.

DISCUSSION

Stratigraphy

Sedimentary and petrographic characteristics observed from Gulf Oil Corp. 1–Hamm WF and Sun Exploration and Production Co. 3–6 Creiss Waterflood, including grain size, shape, sorting, porosity, and structures, provide valuable insights into the depositional environment, energy conditions, and sources of transported sediments. Gulf Oil Corp. 1–Hamm WF samples are fine to medium-grained, well-sorted massive sandstone with minor amounts of feldspar and muscovite present. Core obtained from the Sun Exploration and Production Co. 3–6 Creiss Waterflood is predominantly very fine to fine-grained sandstone with large amounts of interbedded shale and siltstone. Disturbed bedding and burrows observed in both cores form from bioturbation and disruption of sediment by organisms. Herringbone cross-stratification was also observed and forms from current reversals depositing stacked sediments at an incline. This type of cross-stratification is typically observed in tidally influenced environments (Ojo and Akande, 2012). Burrows and disturbed bedding can occur in streams, shallow marine, and tidally influenced environments. The information obtained from Gulf Oil Corp. 1–Hamm WF supports the interpretation of fluvial channel-fill deposits. This interpretation is similar to the results of Ropp

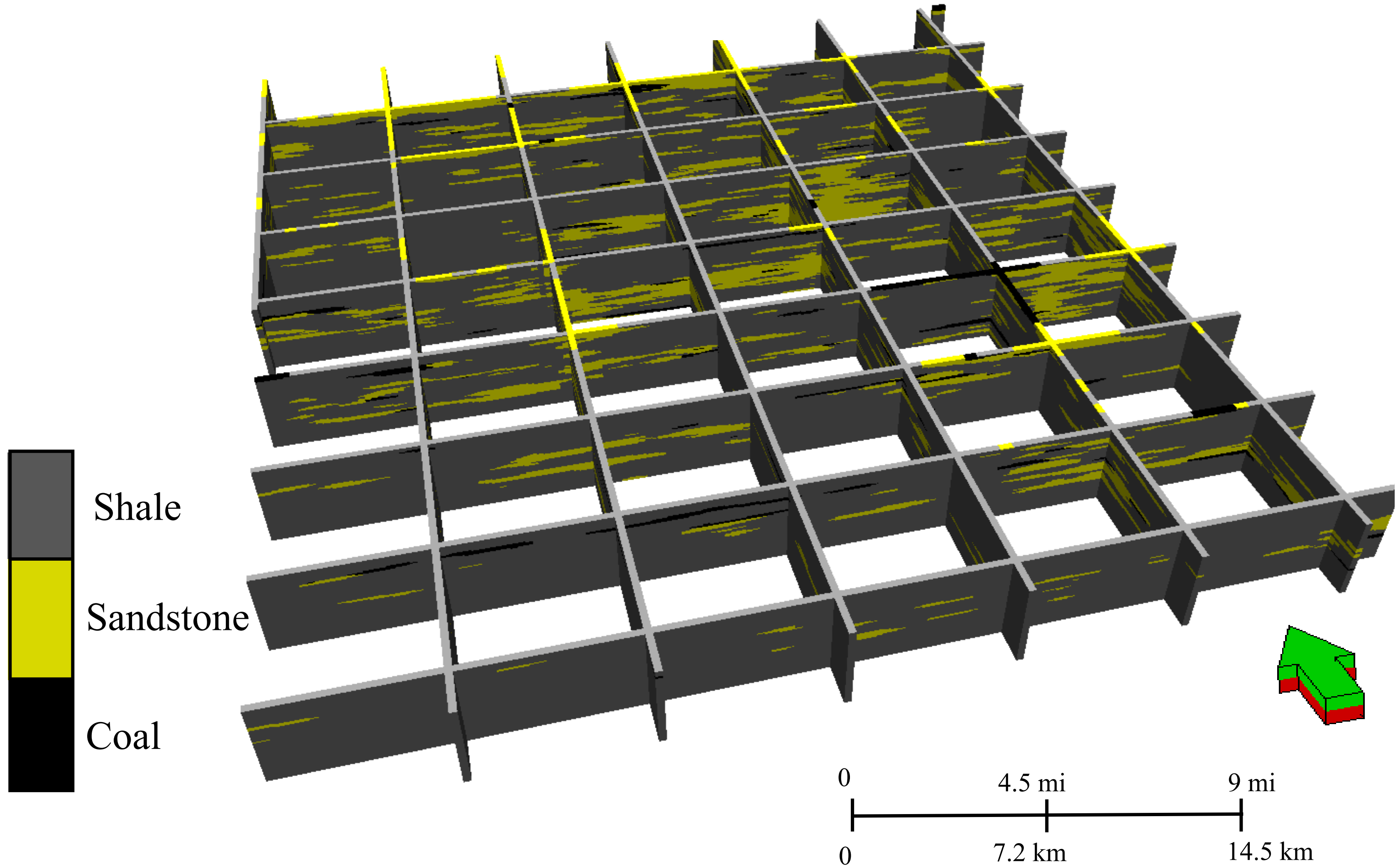


Figure 15: Three-dimensional lithology model of the Prue Sandstone across Lincoln County, Oklahoma. The formation is composed of 84% shale, 14% sandstone, and 1.5% coal. Model displays vertical and lateral sandstone distribution across the study area.

(1991) who noted channels as well as incised valley fill deposits. Sun Exploration and Production Co. 3–6 Creiss Waterflood deposits are interpreted to have been deposited in a tidally influenced floodplain environment. Although the well consists of a predominantly sandstone lithology, the interbedded sandstones at this location differ significantly to the channel sandstone deposit observed from Gulf Oil Corp. 1–Hamm WF core. Additional evidence supporting the interpretation includes herringbone cross-stratification.

Framework grain characteristics and clasts observed in the sandstones indicate a moderate to prolonged period of transport in a high-energy environment. A previous study has identified clast composition as siderite (Ropp, 1991). Intergranular porosity observed from petrographic analysis of the thin sections is common in well-sorted sediments and supports the interpretation of prolonged transport. While this study does not directly research sediment sources, detrital zircon studies conducted by Jesus (2021) and Kushner (2022) determined the sediment age of Pennsylvanian deposits to be approximately 1300 – 1800 Ma (Paleoproterozoic – Mesoproterozoic eras) and suggested the Midcontinental Ridge as the likely provenance for northern Oklahoma. The presence of muscovite, an easily eroded metamorphic mineral, suggests an additional provenance. Ropp (1991) suggests that the mineral has been sourced from erosion of the Transcontinental Arch north of the study area, however, provenance cannot be confidently addressed without additional research.

A singular cyclothem is observed from the stratigraphic sequence of the Verdigris Limestone, Prue Sandstone, and Excello Shale deposits seen in well-logs. The Verdigris Limestone underlying the Prue was deposited in a transgressive cycle of increased sea-level, allowing for limestone deposits to accumulate in a shallow sea environment. The study area then underwent a regressive period where sea-level decreased and remained stable throughout the deposition of the

Prue Sandstone. As sea level rose, portions of Lincoln County experienced a transgressive episode that allowed for the deposition of the Breezy Hill Limestone, seen intermittently across the study area. The sea level continued to rise, allowing the laterally continuous Excello Shale to be deposited in a marine environment.

Depositional Environment

Well-log signatures observed throughout the study area are interpreted to represent fluvial channels, distributary channels, and floodplain deposits. Compared to the generated net sandstone map, areas with high net sandstone values correspond to fluvial and deltaic distributary channels with shale zones representative of floodplain deposits (Figure 16). Fluvial channels are distinguished from distributaries by their blocky, cylindrical signatures. Cylindrical patterns are quite defined compared to neighboring strata and have relatively consistent API values throughout the interval. This stacking pattern requires continuous deposition of a lithology with little depositional change to the area over time. Fining upward sequences occur when coarser-grained sediments are deposited first, with sediments becoming more fine-grained over time. This type of sediment deposition can represent a period of retrogradation or lateral channel migration. Channel signatures observed across the study area follow net sandstone depositional trends, with cylindrical well-log signatures most commonly observed in the center of the interpreted channel trends. An isopach of the Prue and Calvin sandstones across eastern Oklahoma from Krumme (1981) provides additional context to the depositional trends observed in Lincoln County (Figure 17).

While the Verdigris Limestone is considered laterally continuous, studies by Brenner (1989) and Ropp (1991) documented incision into underlying mudstones, shales, and limestones, as well as sharp basal contacts. In this study, sharp basal contacts have also been observed and correspond to channel trends with high sandstone percent values. It is possible that incision

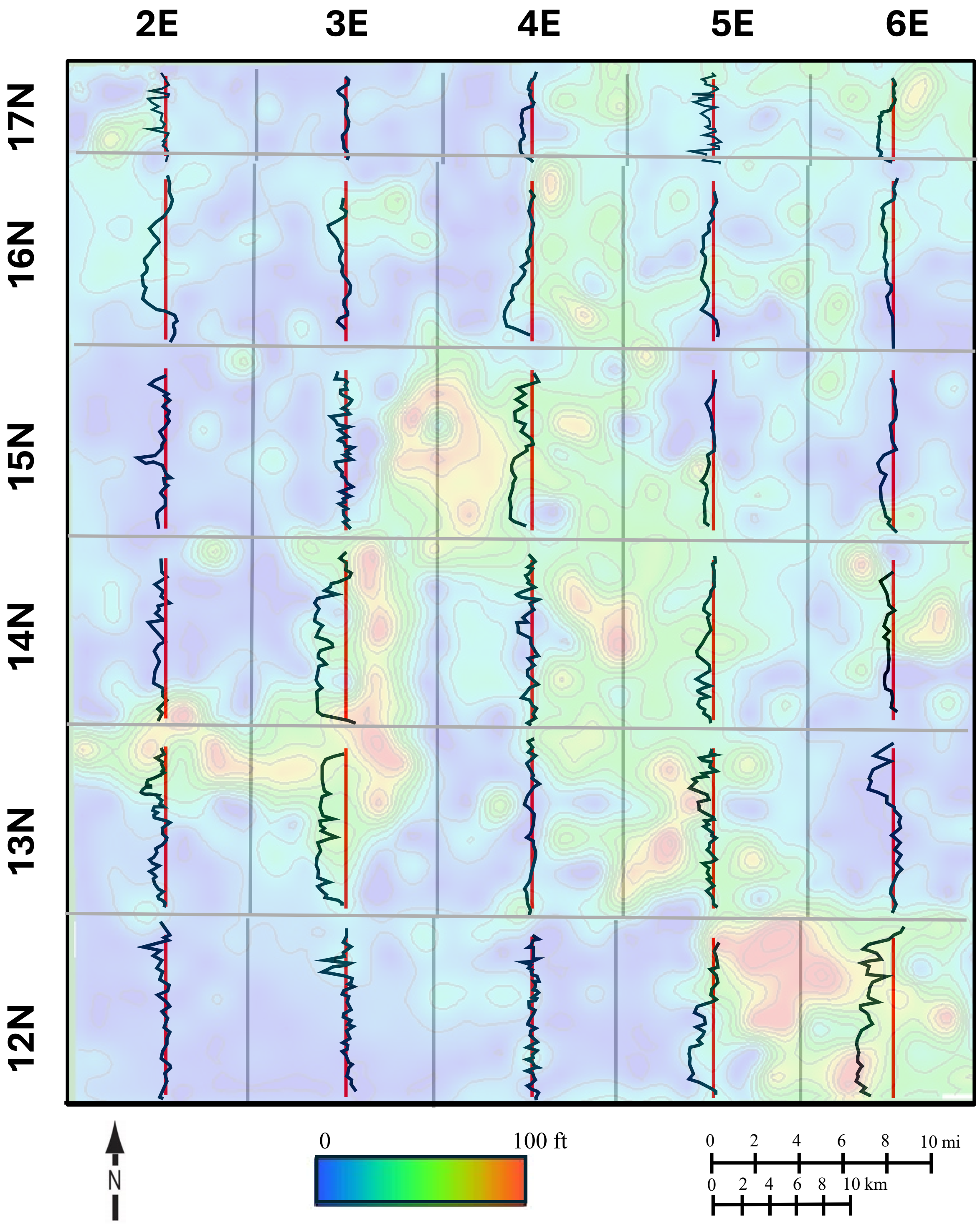


Figure 16: Basemap of Lincoln County, Oklahoma displaying gamma-ray well log signatures overlain on the Prue Sandstone's net sandstone thickness map (Figure 13A). Township lines (grey) and shale baseline (red) are shown.

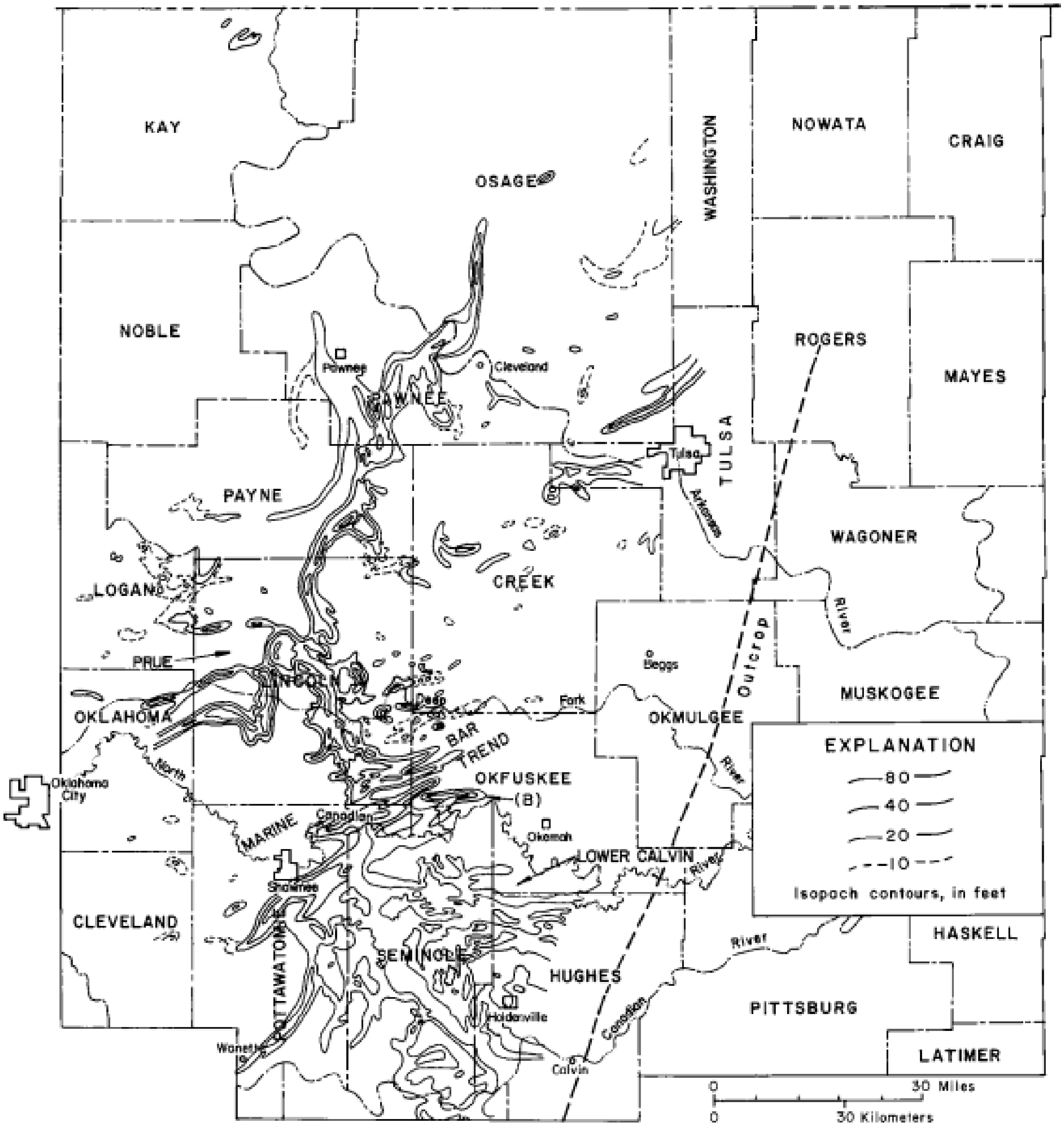


Figure 17: Isopach map of the Prue Sandstone and lower Calvin Sandstone in eastern Oklahoma. Regional depositional trends and spatial distribution of the Prue are shown for Lincoln County, Oklahoma, and surrounding counties (Krumme, 1981). Map displays Krumme's interpreted depositional system across northeastern Oklahoma, including channels, distributary channels, and distributary mouth bar complexes. The figure provides a broader context for the study area and highlights regional depositional trends significant to understanding the spatial variability within the study.

occurred into the underlying sediments as the study area transitioned into a regressive cycle, as suggested by Ropp (1991), however, the interpretation of incised valley fill deposits cannot be made with confidence without additional subsurface mapping.

Serrated signatures are the most common signature observed for the Prue Sandstone and are interpreted as floodplain deposits and interdistributary channels based on predominant lithology. It is composed of very thin, sandstone–shale sequences or a high GR aggradational stacking pattern representative of rapid depositional changes. Fluvial and deltaic floodplains can be difficult to differentiate from each other due to the similar geologic processes used to deposit sediments in both environments. Distributary channel signatures exhibit stacked patterns, thinner sandstone packages, and a higher proportion of interbedded sandstone compared to serrated floodplain deposits, which are predominantly composed of shale. Distinct fining upward sequences observed with a sandstone and shale series are also interpreted as distributary channels but are not as common compared to other signatures.

The southern portion of the study area is interpreted to be tidally influenced as suggested by observations from the Sun Exploration and Production Co. 3–6 Creiss Waterflood core. Distributary channels are present across Lincoln County with fluvial-dominated channels present in the northern and western portions of the study area. Tidal fluctuations in the southern portion of the study area result in the deposition of deltaic floodplain deposits. The overall depositional environment of Lincoln County is consistent with that of a deltaic plain (Figure 18). The main channel enters from the north-central portion of the study area. Herringbone cross-stratification observed from the 3–6 Creiss Waterflood well located in township 14N–6E and paleogeographic Blakey (2013) maps reconstructing early and late Pennsylvanian paleogeography support shoreline interpretations towards the southeast. While the Iron Post Coal is not extensively addressed in this study, it is important to note that coal is commonly observed in deltaic plains due to both floodplain and tidal influence creating swamp-like conditions suitable for the generation of isolated coal pockets.

Limitations

It is important to note the qualitative nature of well-log signature analysis. While well-log analysis of gamma-ray responses can be an extremely quick and useful tool for aiding in the interpretation of depositional environments, the signatures and patterns observed are not always unique to the depositional environment assigned. The scientific study of wireline signature analysis relates established locations to commonly observed patterns. The patterns observed are not always unique and can be caused by geologic processes that occur in multiple environments.

Additionally, the well-log signature analysis portion of this study was initially conducted using well-logs from sections 15, 16, 21, or 22 of each respective township. Due to this, the signatures shown in Figures 10 and 17 best represent the geology at the center of each township and may not be the best representation of the township as a whole. The comparisons and interpretations made in the Discussion and Results sections include additional well-log observations from within the township that may not be shown on Figures 10 and 17.

In regard to the 3D lithology model, many of the wells with digital LAS logs lack RHOB. Therefore, the presence of coal could not be calculated and used in the lithology model at every control point. Due to limited well-log availability and the coal's spatial variability, the margin of error is greater for the coal distribution than in other modeled lithologies.

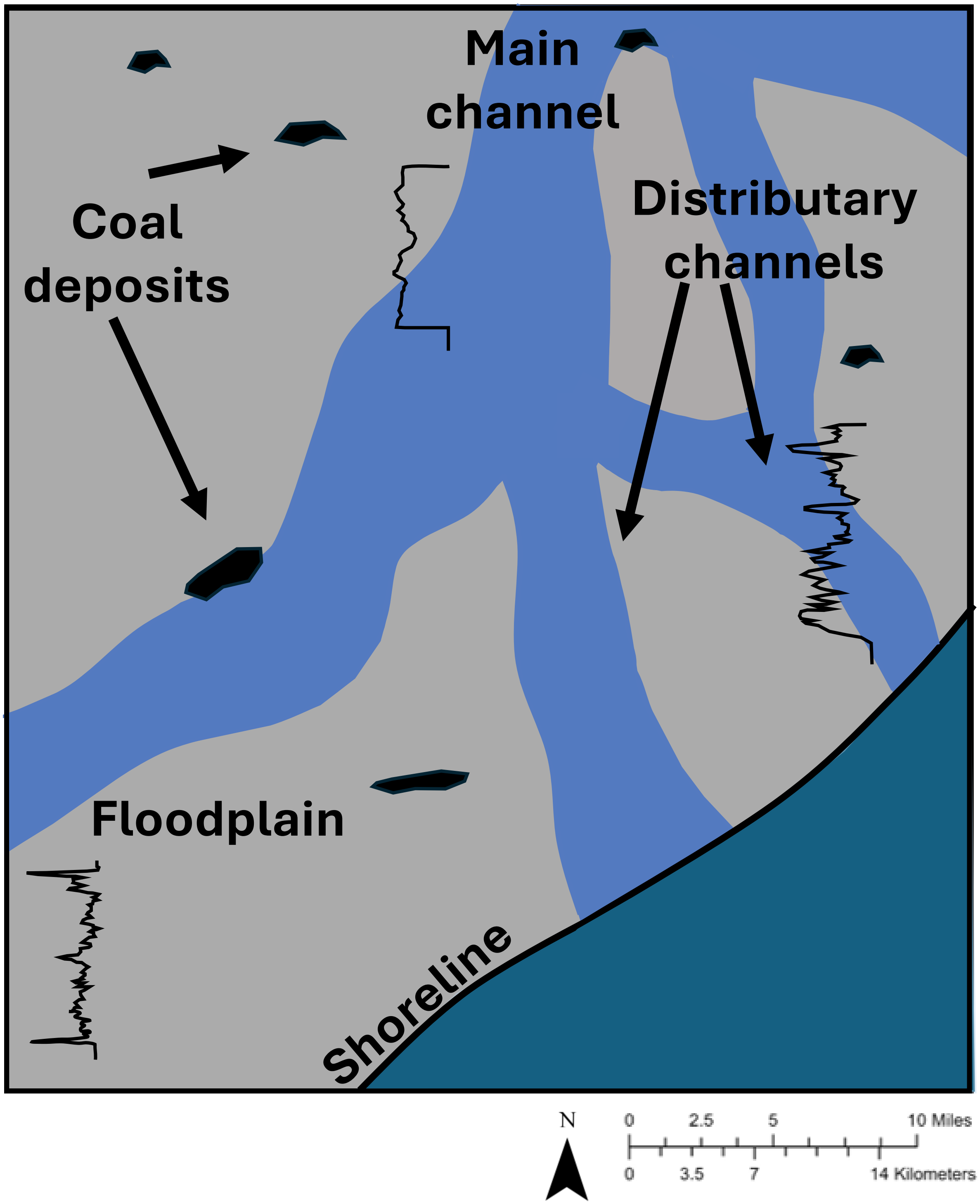


Figure 18: Paleogeographic reconstruction schematic at the time of Prue Sandstone deposition. Map depicts a deltaic plain environment with fluvial channels, distributary channels, and floodplain environments. Includes gamma-ray signatures observed from logs of each environment. Interpreted channel signatures consist of thick, blocky sandstone packages, while floodplain environments are characterized by serrated shale signatures. Interdistributary channel signatures are serrated sequences of interbedded sandstone.

CONCLUSIONS

The integration of structure, isopach, and net sandstone maps with core and log analyses provides a comprehensive understanding of the Prue Sandstone's stratigraphy, depositional environments, and spatial variability, reinforcing its significance in regional geological studies.

Common lithologies of the Prue include sandstone, shale, and coal. Predominant framework grains observed include quartz and organic matter, with minor amounts of muscovite, feldspar, and calcite also identified. The grains range from very fine to coarse-grained in size and are subangular to round in shape. The dominant pore types observed include intergranular and channel porosity. From core, sedimentary structures such as disturbed bedding, planar, wavy, and flaser laminations and bedding, herringbone cross stratification, climbing ripples, and burrows were recognized.

Structure maps at the top and base of the Prue Sandstone exhibit a westerly and southwesterly dip to the Prue, and the net sandstone thickness map displays depositional trends towards the southeast. The Prue Sandstone structure ranges from -1525 ft to -4100 ft (-464.2 m – -1249.7 m) with gross thickness values ranging from 20 to 160 ft (6.1 – 48.8 m). The Prue interval displays a general southernly increase in thickness across the county with net sandstone values increasing south to southeast. Net sandstone thickness ranges from 0 to 116 ft (25.4 m) with the largest values occurring in the center of the interpreted channels. Similarly, the average porosity of the Prue ranges from 0 – 0.24 with the highest average porosity values aligned in the center of the interpreted channels.

The combination of core, well-log signatures analysis, and subsurface maps support a deltaic plain depositional environment. From well-log signature analysis, fluvial channels, distributary channels, and floodplain environments have been interpreted. Channel and floodplain environments are further supported by core and cored well locations relative to mapped net sandstone thickness. While the Iron Post Coal is not studied extensively in this study, its presence in the Prue Sandstone compliments the interpretation of deltaic plain environment, as well. Additionally, herringbone cross-stratification identified in Sun Exploration and Production 3–6 Creiss Waterflood well forms from alternating currents and is a very strong indicator of a tidal influence in the southern portion of the study area.

The spatial variability of the Prue Sandstone across the study area is largely dependent on the depositional environments observed. Sandstone deposits rely on sediment transport from fluvial and distributary channels and are laterally connected only within its channel. Floodplain environments separate the channels and are predominantly shale. Evidence supports floodplain deposits having a tidal influence, further affecting the heterogeneity and connectivity. Vertical sandstone variability is primarily controlled by channel geometries and stratigraphic changes within the Prue gross thickness.

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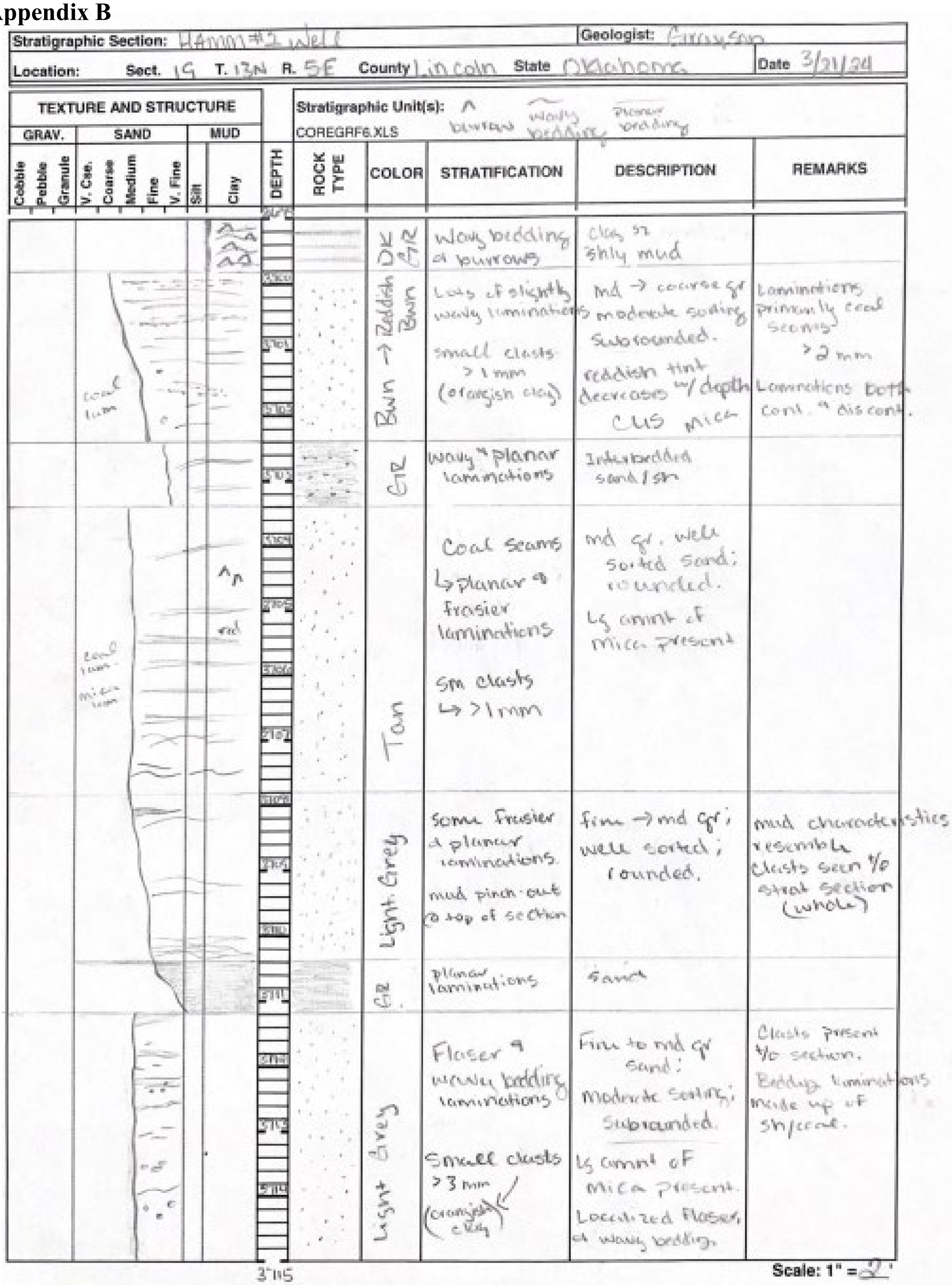
APPENDIX

Appendix A

It is important to note that early Oklahoma literature and studies north of Oklahoma refer to Prue Sandstone as a member of the Cherokee Group. In 1953, a vote was held to rename the Cherokee into the Cabaniss and Krebs Groups for the North Midcontinent region. The renaming was never fully accepted by Oklahoma geologists who believed formations should be named after the most prominent unit in the formation regardless of lithology. Midcontinent states north of Oklahoma later readopted the original nomenclature and demoted the Cabaniss and Krebs groups to subgroups to remain consistent with Oklahoma nomenclature and oil and gas industry standards (Kansas Geological Society, 2003). In 1981, an Oklahoma study advocated for the readoption of the Cabaniss and Krebs groups (Krumme, 1981). The renaming has since become standard for Prue research in Oklahoma despite the lack of acceptance from other states of the northern midcontinent region. Only formal nomenclatures are used in this study.

Appendix B


Stratigraphic Section: Hamm #1 Well — Geologist: Grayson
Location: Sect. 15 T. 13N R. 5E County Lincoln State Oklahoma — Date 3/21/24

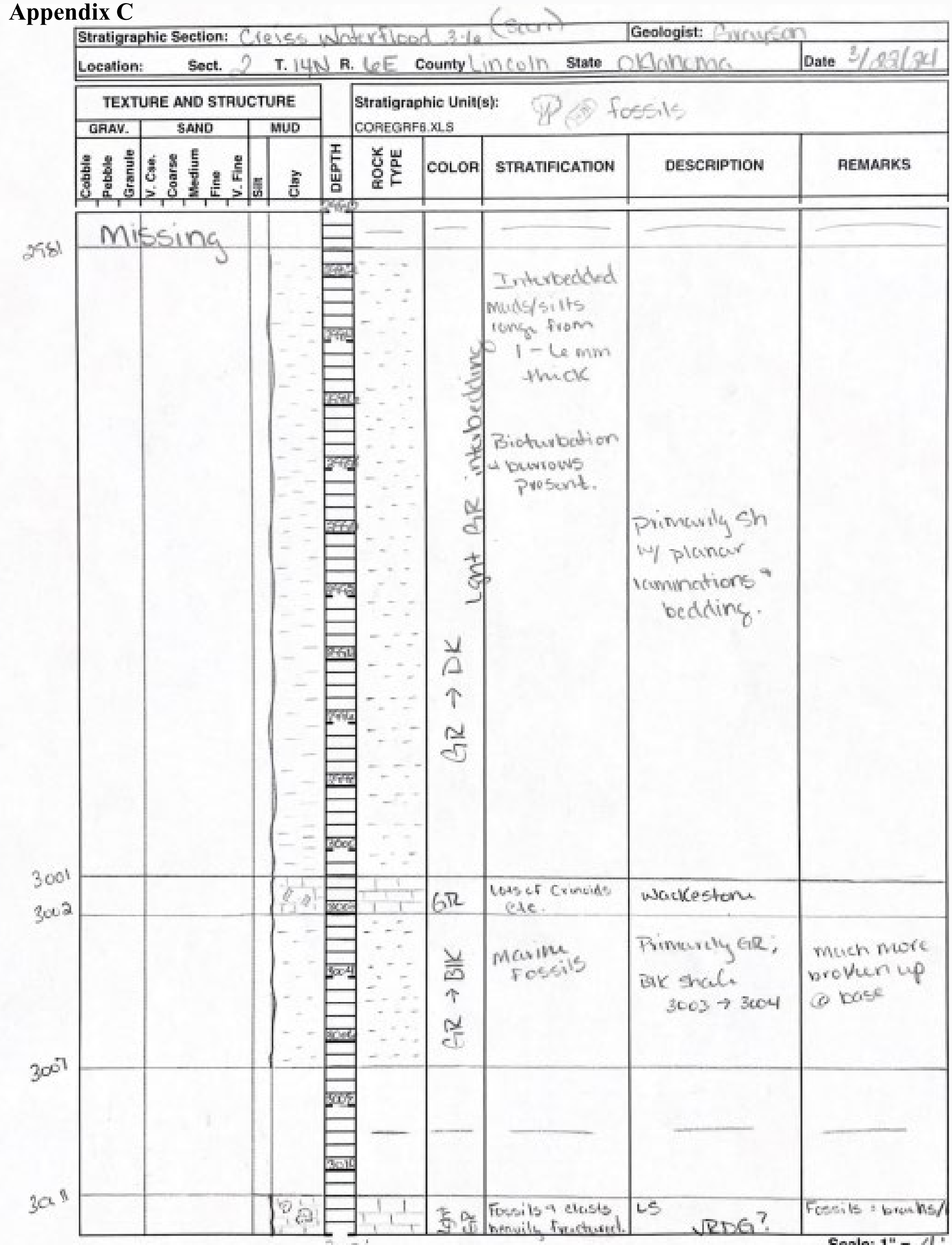
Stratigraphic Unit(s): COREGRF6.XLS

Color	Stratification	Description	Remarks
DK GR	Wavy bedding & burrows	Clay sz shly mud	
Bwn → Reddish Bwn	Lots of slightly wavy laminations; small clasts > 1 mm (orangish clay)	md → coarse gr; moderate sorting; subrounded. reddish tint decreases w/ depth. CUS mica	Laminations primarily coal seams > 2 mm. Laminations both cont. & dis cont.
GR	Wavy & planar laminations	Interbedded sand / sh	
Tan	Coal seams ↳ planar & frasier laminations; sm clasts ↳ > 1 mm	md gr, well sorted sand; rounded. Lg amnt of mica present	
Light Grey	Some frasier & planar laminations. mud pinch-out @ top of section	fine → md gr; well sorted; rounded.	mud characteristics resemble clasts seen t/o strat section (whole)
GR	planar laminations	Sand	
Light Grey	Flaser & wavy bedding laminations. Small clasts > 3 mm (orangish clay)	Fine to md gr sand; moderate sorting; subrounded. Lg amnt of mica present. Localized flaser & wavy bedding.	Clasts present t/o section. Bedding laminations made up of sh/coal.

Scale: 1" = 2'

Appendix B: Gulf Oil Corp. No. 1 Hamm WF core description sheet (-3698 ft – -3715 ft).

Appendix C



Stratigraphic Section: Creiss Waterflood 3-6 (Sun) Geologist: Grayson

Location: Sect. 2 T. 14N R. 6E County Lincoln State Oklahoma Date 3/23/21

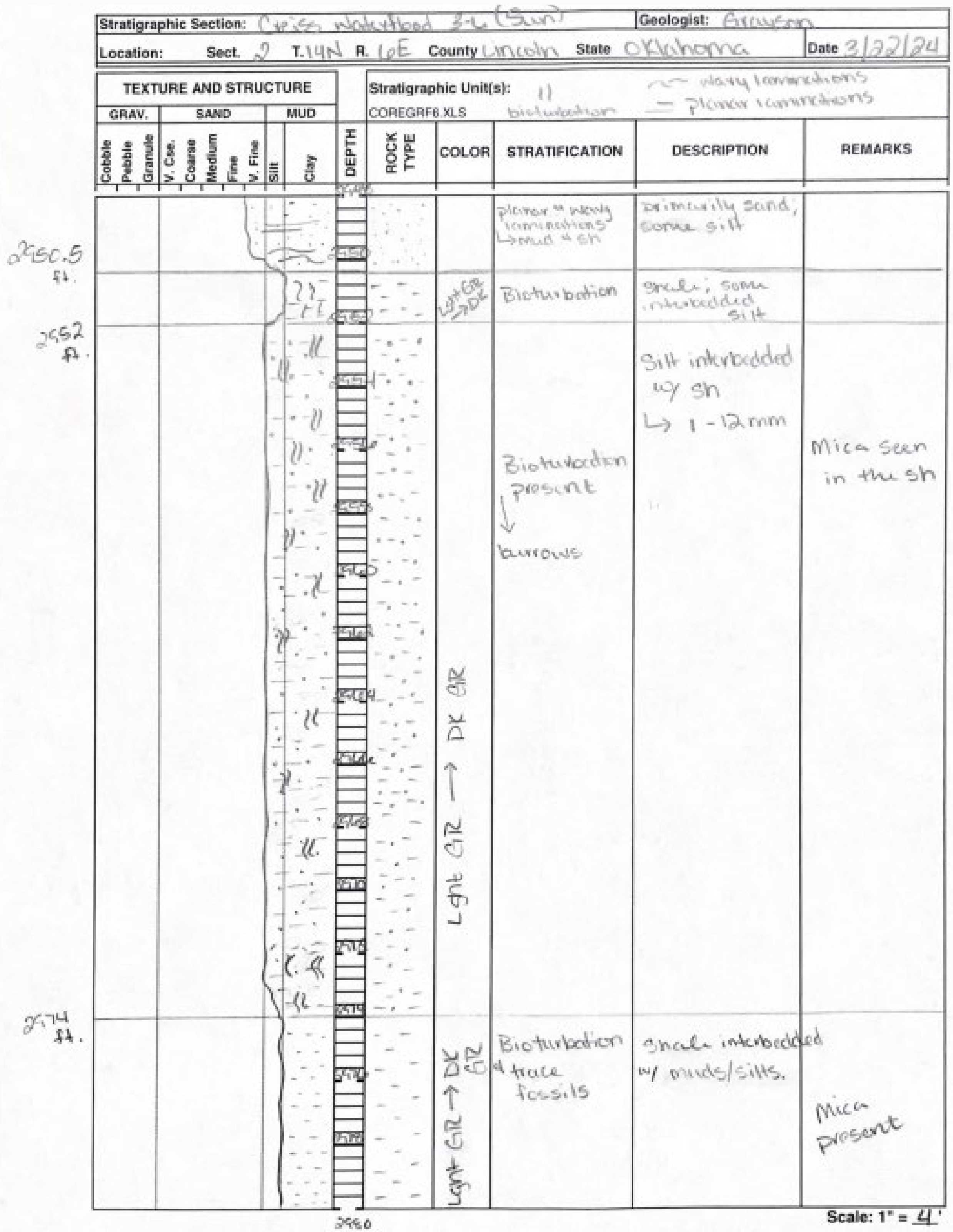
Stratigraphic Unit(s): fossils

COREGRF6.XLS

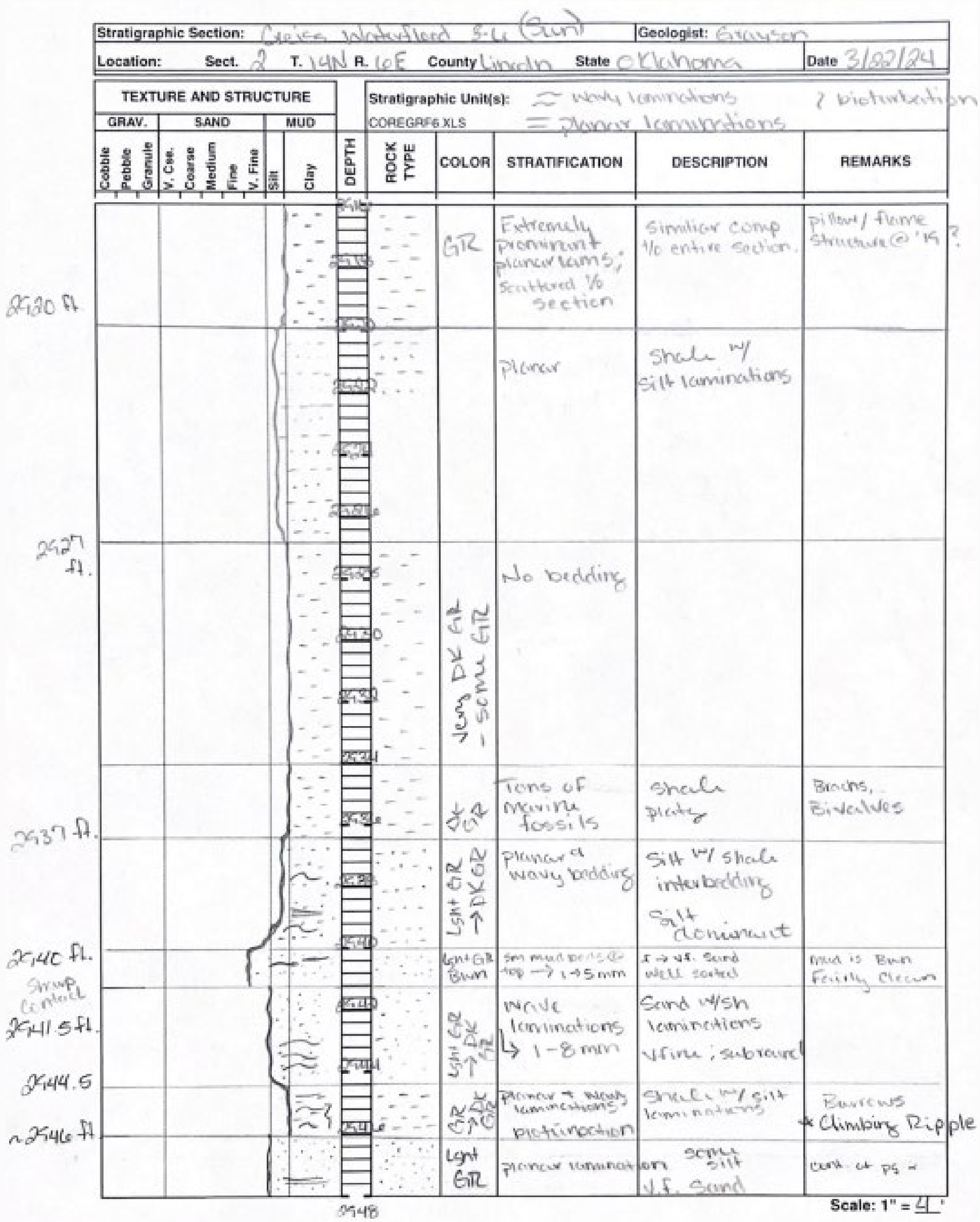
Depth	Texture and Structure	Rock Type	Color	Stratification	Description	Remarks
2981	Missing					
2981–3001	Clay		Lght GR interbedding GR → DK	Interbedded muds/silts range from 1 – 6 mm thick. Bioturbation & burrows present.	Primarily sh w/ planar laminations & bedding.	
3001–3002			GR	Lots of Crinoids etc.	wackestone	
3002–3007	Clay		GR → Blk	Marine Fossils	Primarily GR; Blk shale 3003 → 3004	much more broken up @ base
3007–3011						
3011–3012			Lght GR	Fossils & clasts heavily fractured.	LS RDG?	Fossils : brachs/

Scale: 1" = 4'

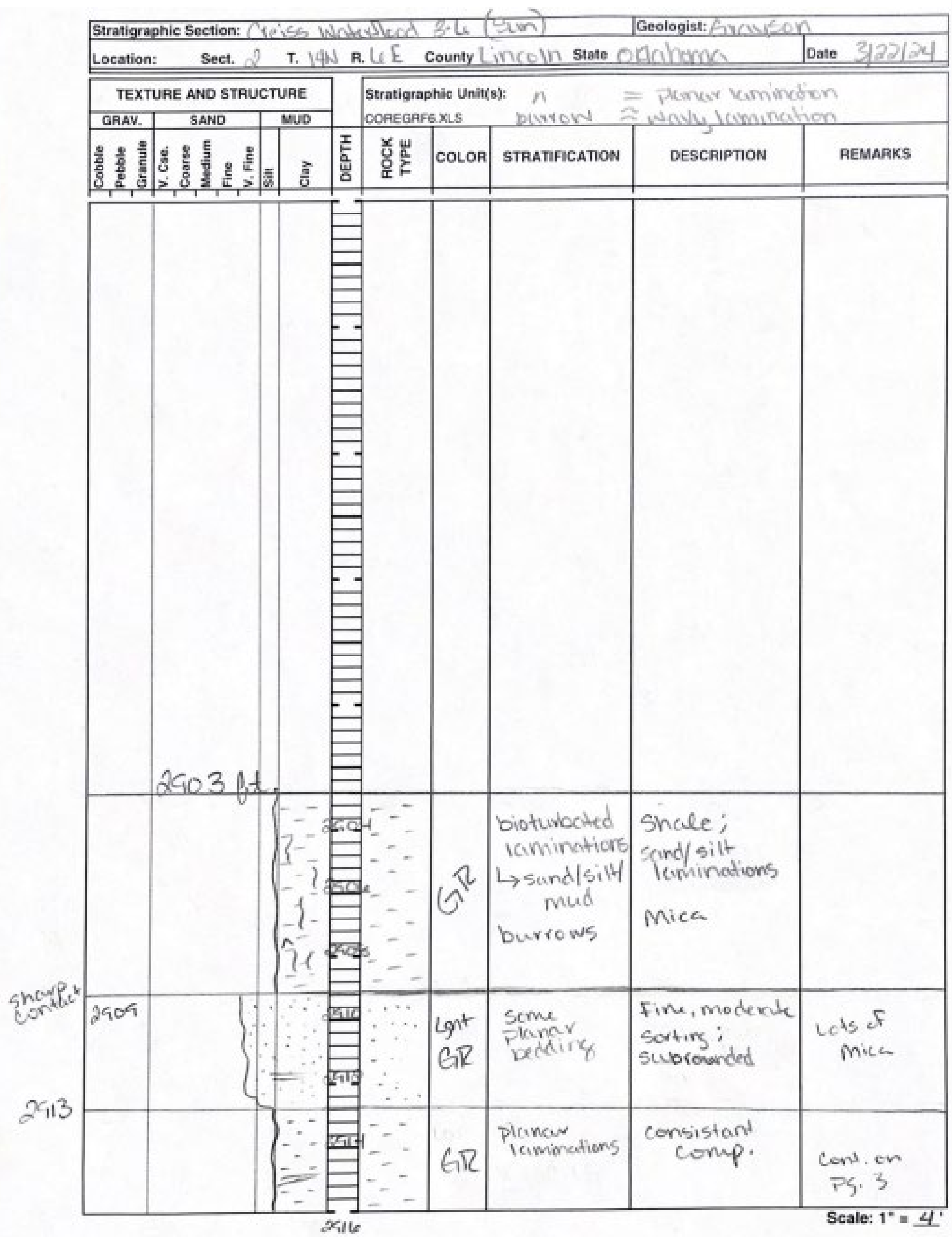
Appendix C: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood core description sheet (-3012 ft – -2981 ft)



Appendix C: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood core description sheet (-2980 ft – -2948 ft)

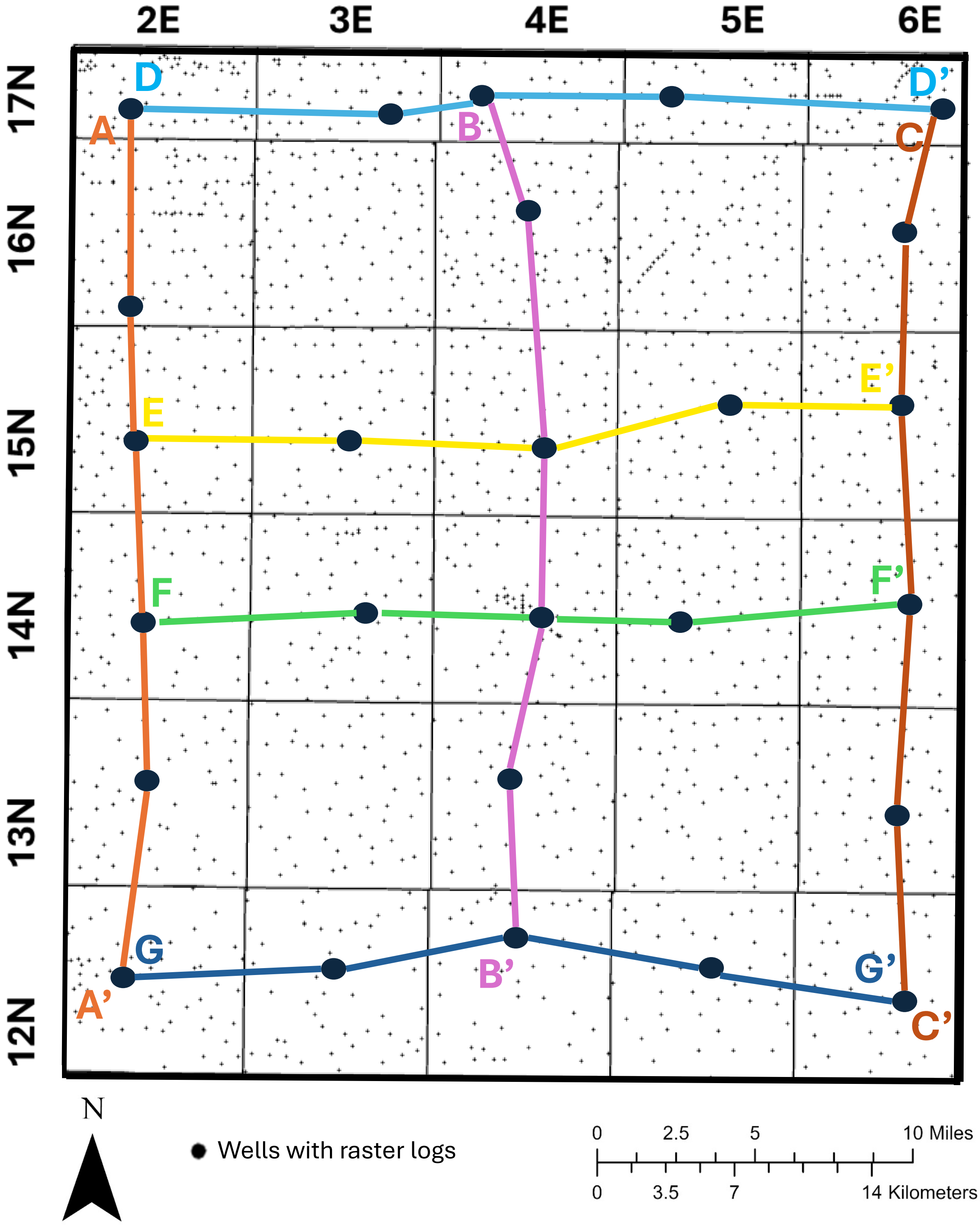


Appendix C: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood core description sheet (-2948 ft – -2916 ft)

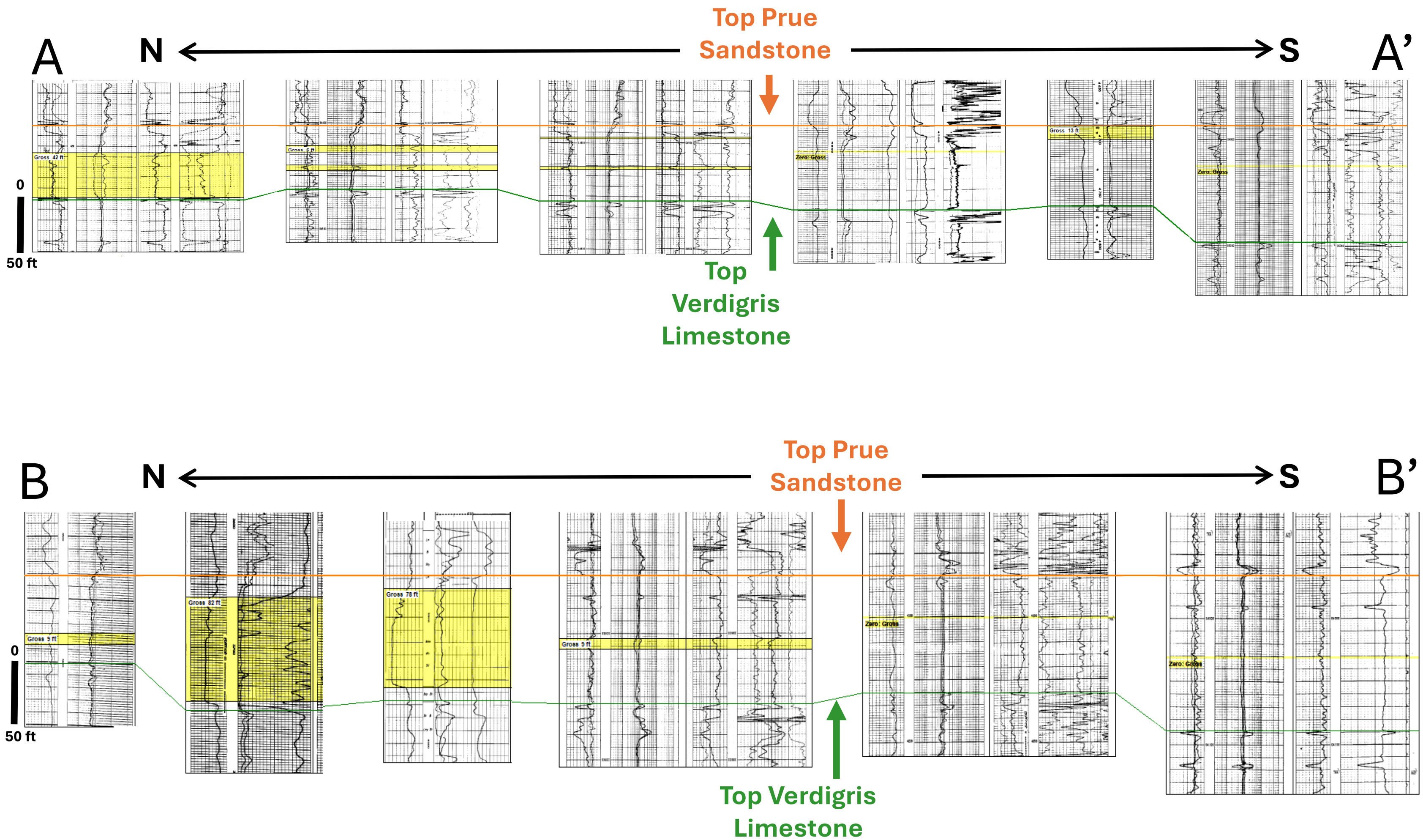


Appendix C: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood core description sheet (-2916 ft – -2903 ft)

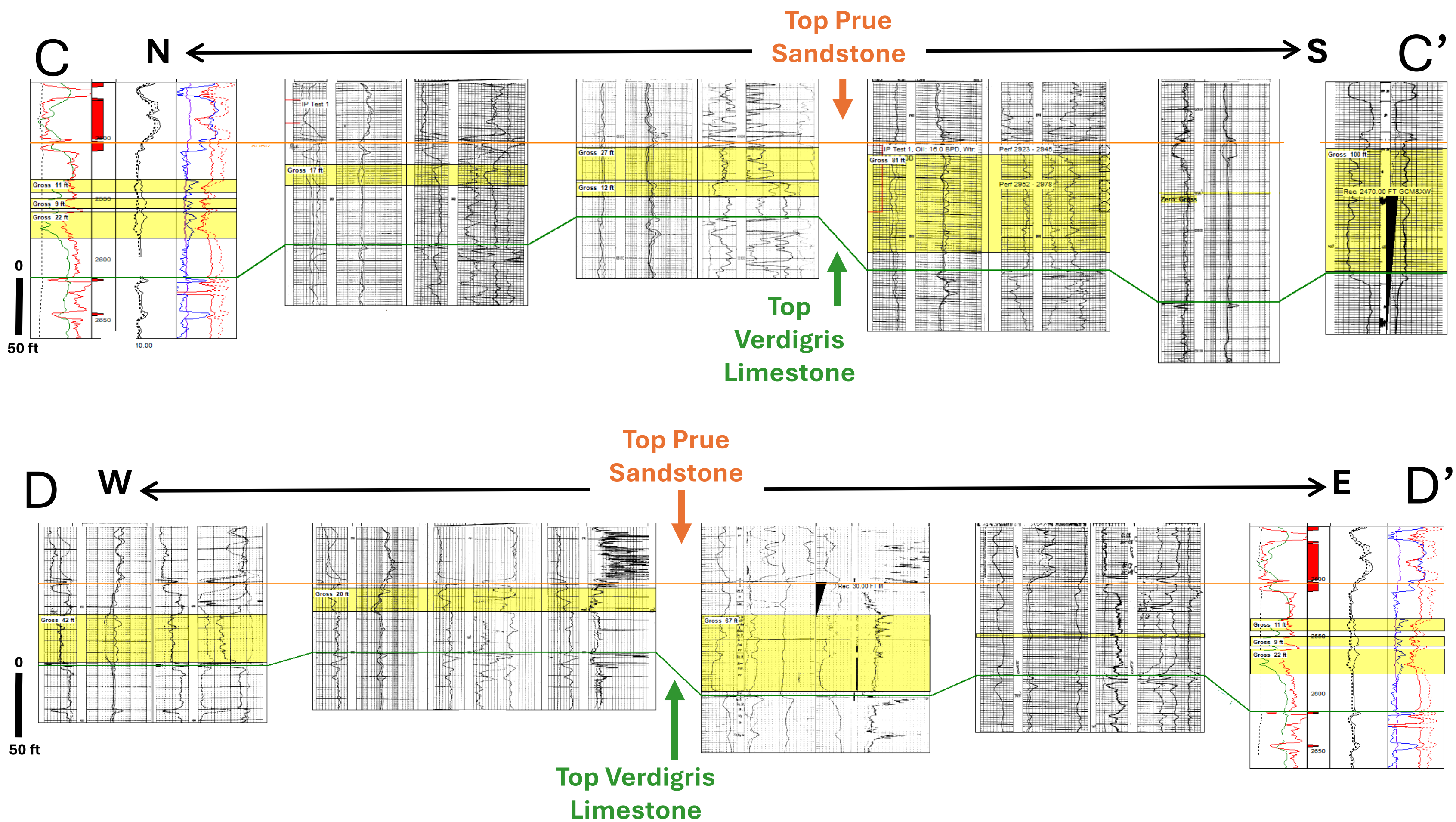
Appendix D



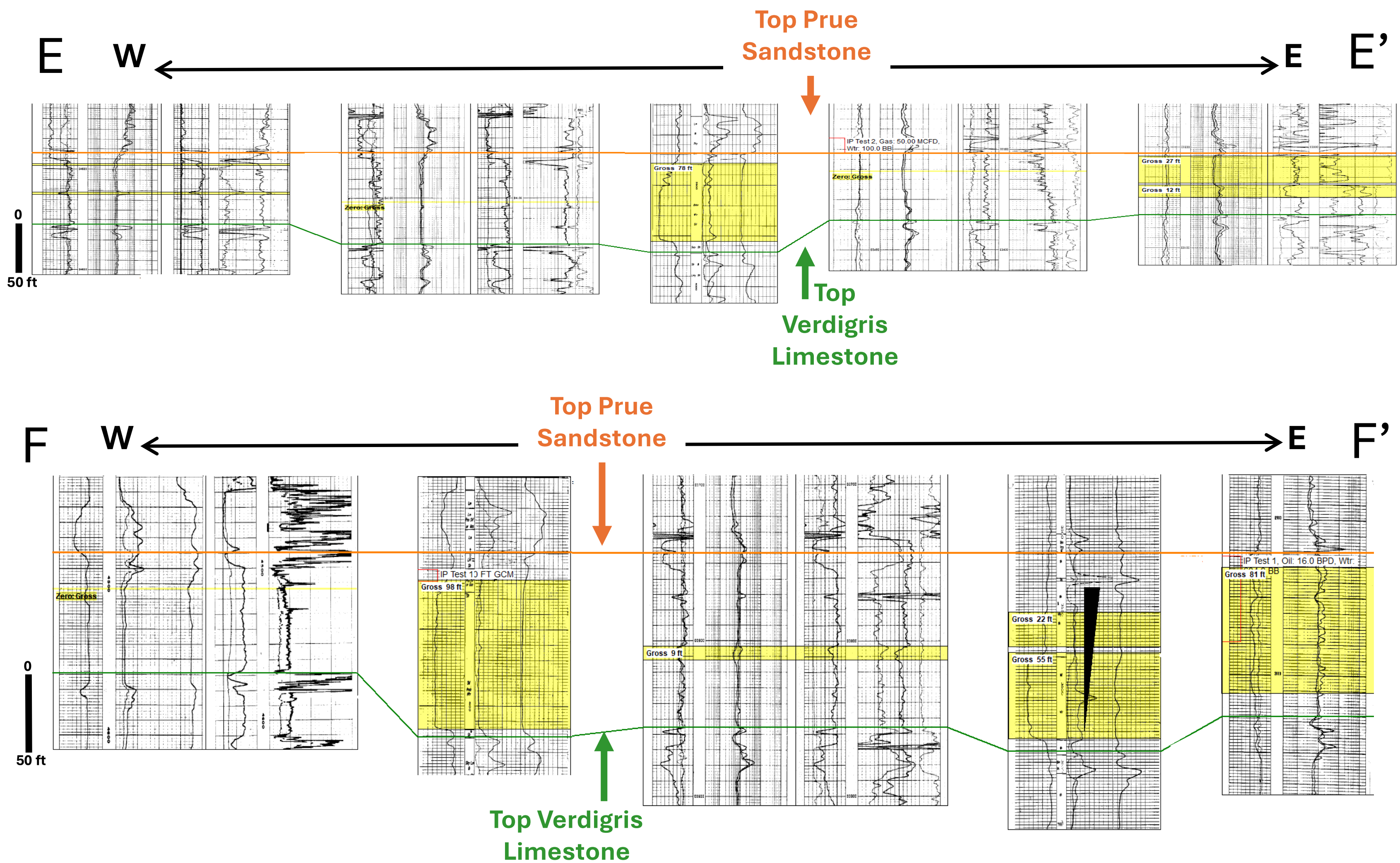
Appendix D: Basemap of Lincoln County, Oklahoma displaying distribution of wells with interpreted formation tops from raster logs (black) and cross-sections A – G of Appendix D.



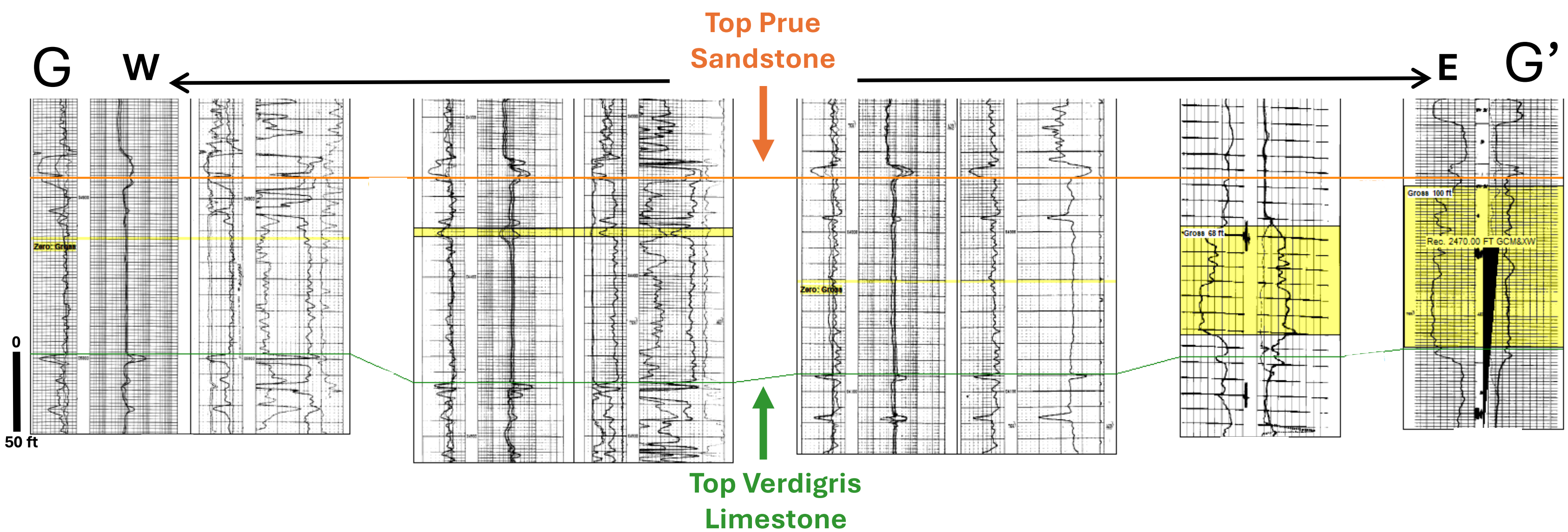
Appendix D: Regional stratigraphic cross-sections of the Prue Sandstone displaying interpreted formation boundaries, well-log signatures, and calculated net sandstone values. Bounding surfaces are shown at the top (orange) and base (green) of the Prue Sandstone. Yellow corresponds to net sandstone estimations.



Appendix D: Regional stratigraphic cross-sections of the Prue Sandstone displaying interpreted formation boundaries, well-log signatures, and calculated net sandstone values. Bounding surfaces are shown at the top (orange) and base (green) of the Prue Sandstone. Yellow corresponds to net sandstone estimations.

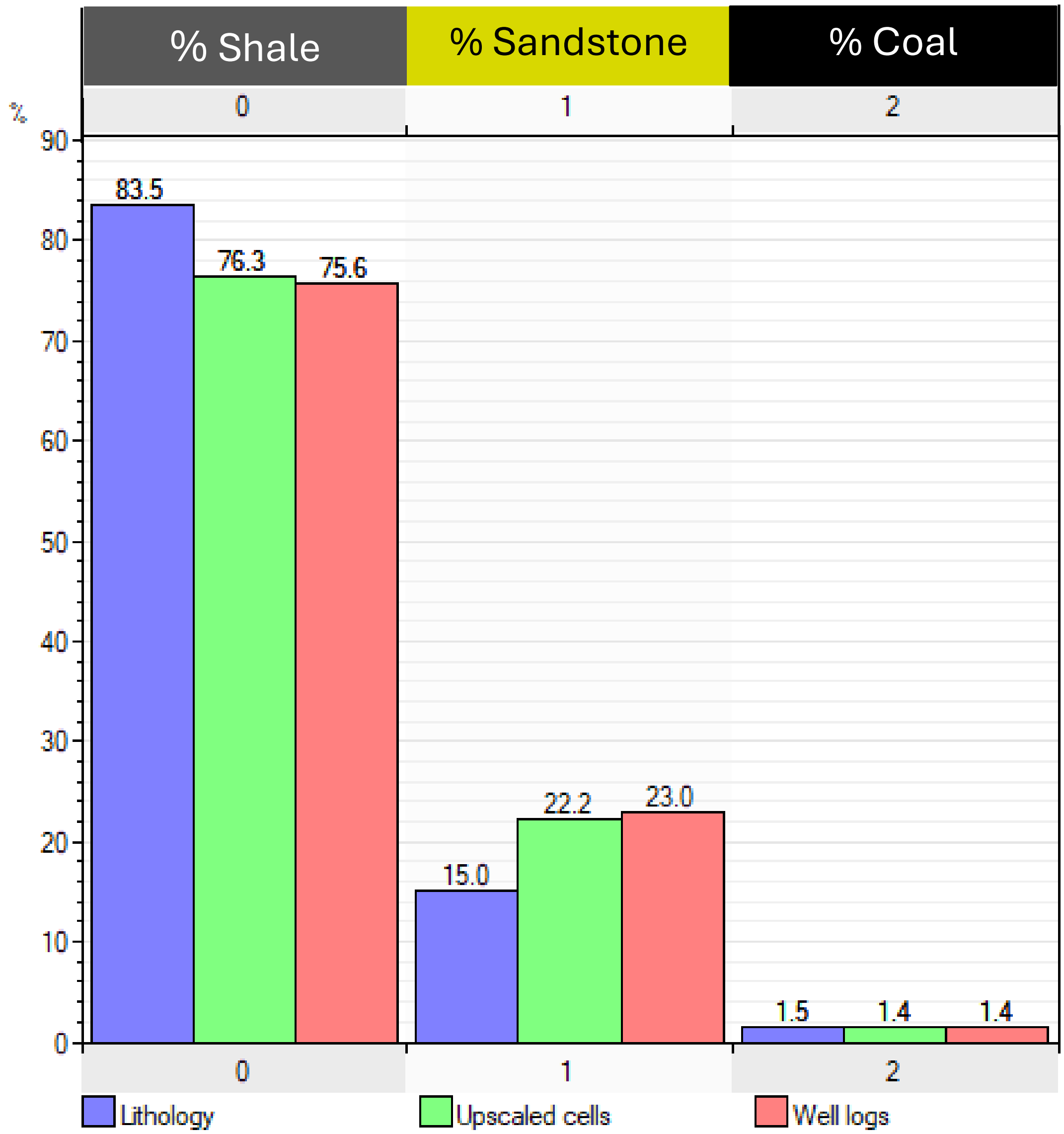


Appendix D: Regional stratigraphic cross-sections of the Prue Sandstone displaying interpreted formation boundaries, well-log signatures, and calculated net sandstone values. Bounding surfaces are shown at the top (orange) and base (green) of the Prue Sandstone. Yellow corresponds to net sandstone estimations.



Appendix D: Regional stratigraphic cross-sections of the Prue Sandstone displaying interpreted formation boundaries, well-log signatures, and calculated net sandstone values. Bounding surfaces are shown at the top (orange) and base (green) of the Prue Sandstone. Yellow corresponds to net sandstone estimations.

Appendix E



Appendix E: Histogram of upscaled lithology log values compared to original well log lithology percentages. Histogram of original well-logs, upscaled well-logs, and 3D lithology model shale, sandstone, and coal lithologies.

Appendix F

Lithology Model Variogram Values					
Lithology	**Nugget**	**Sill**	**Major Range**	**Minor Range**	**Vertical Range**
Sandstone	0	1	20000	20000	15
Shale	0	1	75000	75000	20
Coal	0	1	15000	15000	5

Appendix F: Variogram values used to define sandstone, shale, and coal distribution within the 3D lithology model.

Appendix G

Appendix G: Gulf Oil Corp. No. 1 Hamm WF cored interval (-3698 ft – -3715 ft).

Appendix H

Appendix H: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood cored interval (-2903 ft – -2927 ft)

Appendix H: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood cored interval (-2927 ft – -2955 ft)

-2955 ft

-2981 ft

Appendix H: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood cored interval (-2955 ft – -2981 ft)

Appendix H: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood cored interval (-2981 ft – -2993 ft)

-2993 ft

-3012 ft

Appendix H: Sun Exploration and Production Co. 3 – 6 Creiss Waterflood cored interval (-2993 ft – -2912 ft)

Appendix I

	Sample Number	Framework Grains	Porosity	Other observations
Sun Exploration and Production Co. 3 – 6 Creiss Waterflood	1	Quartz: subangular - subrounded; undulating	Intergranular	Minor amounts of muscovite, calcite, & organic matter
	2	Quartz: subround - rounded; undulating; well cemented	Minimal porosity observed	Singular calcite grain
	3	Quartz: subangular - subrounded; undulating; well cemented	Minimal pore space; potential fracture/channel porosity	Minor amounts of organic matter; unidentified grey grain
	4	Quartz: subangular - subround; undulating; well cemented	Minimal intergranular porosity	Minor amounts of feldspar, muscovite, & organic matter
	5	Quartz: subrounded grains; undulating; very-fine	Minimal intergranular porosity; some fracture porosity	Minor amounts of feldspar. Laminations of mud and organic matter also present
	6	Quartz: subangular - subrounded; undulating	Minimal porosity	Minor amounts of felspar, slighty increased amount of muscovite
	7	Quartz: subrounded grains; undulating	Fracture porosity	Laminations of organic matter; laminations macroscopically visable in slide
Gulf Oil Corp. 1 – Hamm WF	8	Quartz: subangular - subrounded; undulating; moderately well sorted	Intergranular; increased porosity compared to samples #9 & #10	Minor amounts of organic material, feldspar, & muscovite; small brown grain (clast)
	9	Quartz: subangular - subrounded; undulating; well cemented	intergranular; channel/fracture porosity also present; decrease in porosity from sample #8	Minor amounts of organic material (elongate), feldpar, & calcite
	10	Quartz: subangular - subround; undulating; well cemented	Intergranular; decrease in porosity from sample #8	Minor amounts of muscovite, feldspar, & organic material

Appendix I: Summary of Prue Sandstone petrographic characteristics. A total of ten samples from Sun Exploration and Production Corp. 3 – 6 Creiss Waterflood (7 samples) and Gulf Oil Corp. 1 – Hamm WF (3 samples) were analyzed.