GEOLOGIC CHARACTERIZATION OF CRETACEOUS SANDSTONE AT THE KEMPER COUNTY ENERGY FACILITY, MISSISSIPPI: A WORLD-CLASS SITE FOR CO_2 STORAGE

By

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Abstract: With anthropogenic CO_2 being of growing concern, the Department of Energy's Carbon Storage Assurance Facility Enterprise (CarbonSAFE) program is designed to explore the possibility of saline storage of CO_2 at and around the Kemper County, energy facility in east-central Mississippi. The natural gas combined cycle (NGCC) generation facility rests upon a thick succession of Mesozoic strata that contains numerous saline reservoirs that hold significant potential for carbon sequestration. To further characterize these reservoirs and evaluate their storage capacity, an integrated approach was used combining data from cores and geophysical well logs.

Mesozoic strata thicken to the southwest and unconformably overlie Paleozoic strata in Kemper County. Cretaceous units, such as the Paluxy Formation, Washita-Fredericksburg interval, and the lower Tuscaloosa Group are lithologically similar in that they are composed of sandstone and conglomerate that fine upward into interbedded sandstone and mudrock. Furthermore, the sandstone units contain saline water (>10,000 mg/L TDS), have high porosity (~30%), and have Darcy-class permeability making them particularly attractive for geologic storage.

To better understand sediment provenance and reservoir quality, petrologic analysis was used to determine framework grain composition, which was then plotted on Dickinson provenance diagrams. Furthermore, petrologic analysis was used to document diagenetic alterations and the resulting sedimentary fabrics influencing porosity. Lastly, geophysical well logs were used to identify reservoir quality packages using gamma ray and porosity cutoffs of $\leq$ 75 API units and $\geq$ 15%, respectively. The resulting net reservoir sandstone thickness and average porosity values for selected reservoirs was mapped and used to calculate CO_2 storage capacity.

Results from routine core analysis suggest that Cretaceous sandstone was deposited as channel and bar deposits in bedload-dominated fluvial systems. Subsequent bifurcation of channels left deposits stranded and subaerially exposed, thus allowing vegetation, burrowing, and feldspar dissolution to occur. Significant feldspar dissolution created an abundance of secondary porosity in the form of moldic and oversized pores and left behind only minor amounts of pore-filling kaolinite. Ultimately, this enhanced the original porosity and permeability of sandstone reservoirs resulting in a P_{50} storage resource of 428 Mt in the Paluxy Formation, 753 Mt in the Washita-Fredericksburg interval, and 182 Mt in the lower Tuscaloosa Group.

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CHAPTER I

INTRODUCTION

Statement of Purpose

Over the last two decades, climate change as a result of atmospheric CO_2 emissions from anthropogenic sources has become a major concern. According to the Environmental Protection Agency (EPA), fossil fuel combustion in 2016 accounted for 93.5 percent of CO_2 emissions in the United States. These emissions came from five major sectors: commercial, residential, industrial, transportation, and electric power generation. Electric power generation was responsible for the largest amount of CO_2 emitted in the United States, producing 1.809 billion metric tons of CO_2 equivalent in 2016. Permanent subsurface CO_2 storage is becoming an increasingly attractive option for reducing atmospheric CO_2 emissions, especially since the Internal Revenue Service established a Section 45Q tax credit of $50/ton for geological storage of CO_2 in saline formations.

The Kemper County energy facility in Kemper County, Mississippi rests upon a thick Mesozoic section containing abundant saline formations. Pashin et al. (2008) estimated that the sandstone of the Lower Cretaceous Paluxy Formation has the capacity to store between 4 and 22 million short tons of CO_2 per mi^2. Mississippi Power had designed and built a large integrated gasification combined cycle power plant (IGCC) and natural gas combined cycle plant (NGCC) that would supply CO_2 for enhanced oil recovery in association with the U.S. Department of

Energy's Clean Coal Power Initiative. Subsequent funding under the Department of Energy's Carbon Storage Assurance Facility Enterprise (CarbonSAFE) program included drilling of test wells to explore the possibility of saline formation storage of CO_2 at and around the plant site, and this thesis was supported by that program. Although the IGCC is not likely to operate commercially, the Kemper Energy Facility includes combined cycle natural gas generation, which can supply CO_2 for emissions reduction through geological storage.

Cretaceous saline reservoirs in the Paluxy Formation, the Washita-Fredericksburg interval, and the Tuscaloosa Group appear suitable for commercial storage in the area of the Kemper County energy facility. In addition, underground sources of drinking water (USDW) exist in the area and therefore must be protected to comply with the Underground Injection Control (UIC) provisions of the Safe Drinking Water Act (Pashin et al., 2008). The CarbonSAFE program, which is funded by the U.S. Department of Energy through the Southern States Energy Board (SSEB) and Advanced Resources International (ARI), aims to determine the feasibility of a CO_2 storage complex at the Kemper Energy Facility. Accordingly, this study focuses on characterizing potential Lower Cretaceous sandstone reservoirs, documenting their petrologic characteristics, and estimating their storage capacity at the energy facility.

The hypothesis of this study is that Cretaceous sandstone within the net acreage of the Kemper Energy Facility is capable of storing CO_2 at a gigatonne scale. Therefore, goal of this research is to characterize Cretaceous sandstone reservoirs and evaluate their storage capacity of CO_2 within the net acreage controlled by Southern Company around the energy facility by employing a multidisciplinary approach to understanding reservoir architecture, sandstone composition, sediment source, and diagenetic alteration. A series of objectives were executed in order to test the hypothesis. (1) Geologic data were compiled. (2) Thin sections from the research area were point counted and plotted on Folk (1980) and Dickinson (1983) diagrams to determine sandstone composition and aid in provenance interpretation. (3) Well log analysis was performed and routine core analyses was used to identify potential reservoirs within the Kemper energy facility acreage. (4) Regional maps and cross-sections were constructed using the wells within the energy facility acreage. (5) Porosity, net thickness, and CO_2 compressibility under hydrostatic conditions were used to calculate the storage resource for each prospective reservoir zone. (6) A potential storage strategy was suggested based on storage resource and potential hazards.

Regional Setting

Figure 1 shows the location of the Kemper County energy facility power plant and the location of the three exploratory wells drilled for this study. The exploratory wells were cored and logged, and samples were taken from the cores to make thin sections for petrologic analysis.

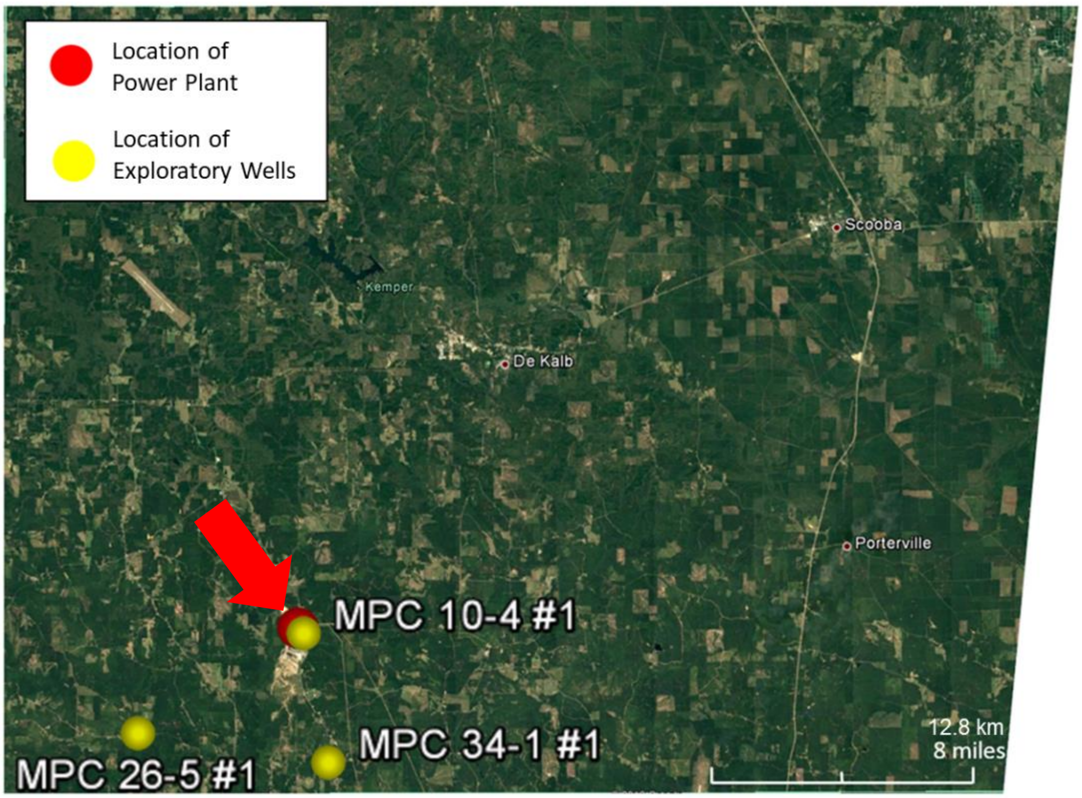

Figure 1. Satellite image of Kemper County Mississippi showing the location of the IGCC facility and exploratory well (Arrow points to the plant location).

Sedimentary rocks in Kemper County range in age from Cambrian through Tertiary and reach a thickness of more than 5 mi (Hale-Erlich and Coleman, 1993). The base of the Paleozoic section is thought to nonconformably overlie Precambrian basement. However, no significant sequestration potential was identified in Paleozoic rocks during the initial assessment by Pashin et al. (2008), and so the Paleozoic section will therefore be considered as effective basement for this study. Mesozoic-Cenozoic strata dip gently southwestward and overlie the Paleozoic section with a distinct angular unconformity (Pashin et al., 2008).

Mesozoic-Cenozoic strata form a wedge of sedimentary rock that thickens to the southwest and is deposited near the eastern edge of the Mississippi Embayment of the Gulf of Mexico Basin. These strata disconformably overlie Paleozoic strata in Kemper County, with the oldest Mesozoic strata being Early Cretaceous in age (Figure 2). The Naheola and Nanafalia Formations are of Tertiary age and are exposed at the surface in Kemper County. Mesozoic strata onlap the Paleozoic section toward the northeast, and Jurassic through Lower Cretaceous strata are concealed in the subsurface (Pashin et al. 2008).

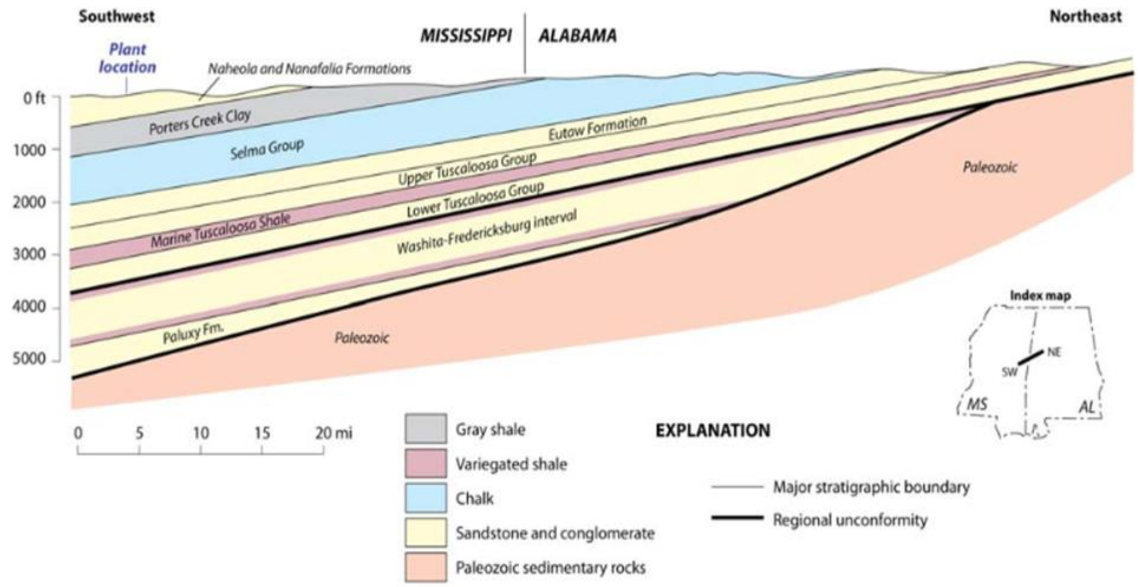

Figure 2. Schematic cross-section showing regional stratigraphy in east-central Mississippi and west-central Alabama (Pashin et al., 2008).

Figure 3 shows a schematic stratigraphic column based on wireline logs and sample descriptions within the study area. In Kemper County, the Lower Cretaceous Mooringsport and Paluxy Formations make up the base of the Mesozoic section and overlies Paleozoic rocks with a pronounced angular unconformity. The Paluxy is overlain by the Lower Cretaceous Washita-Fredericksburg interval. Both the Paluxy Formation and Washita-Fredericksburg interval are composed predominantly of sandstone and variegated shale, with some conglomerate found near the base of the sandstone bodies. Compositionally, the sandstone is quartz-rich and the conglomerate contains pebbles of vein quartz, chert, and quartzite. The sandstone bodies thicken southwest along with the host formations and exhibit fining-upward sequences with sharp, conglomeratic bases that grade upward into mudrock (Pashin et al., 2008).

The Washita-Fredericksburg interval is unique in that the primary portion of the interval consists of several stacked conglomeratic sandstone bodies that thicken and become more frequent towards the center of the interval. This portion of the Washita-Fredericksburg is nicknamed the Big Fred sand, is composed of about 90 percent sandstone, and approaches a thickness of about 300 feet (Pashin et al., 2008).

Directly above the Washita-Fredericksburg interval lies the Tuscaloosa Group, which has a sharp contact that marks a major unconformity at the base of the Upper Cretaceous section. The Tuscaloosa Group is formally divided into two Formations (Coker and Gordo Formations) and contains three distinctive intervals known as the Massive sand (lower Tuscaloosa Group; Coker Formation), the Marine shale (basal Gordo Formation), and the upper Tuscaloosa Group (upper Gordo Formation).

The base of the Tuscaloosa is often referred to as the Massive sand due to its characteristic blocky signature in well logs. Much like the Paluxy Formation and the Washita-Fredericksburg interval, the lower Tuscaloosa contains sandstone intervals that fines upward from a conglomeratic base and is composed entirely of a large sand body informally referred to as the Massive sand (Pashin et al., 2008).

The Marine shale is interpreted as a nearshore deposit and is principally a variegated shale in Kemper County, and regionally a widespread marker. Additionally, the marine shale is thickest in the area of the Kemper County energy facility. The upper Tuscaloosa Group overlies the Marine shale with a contact that can be either sharp or gradational. The upper Tuscaloosa consists of a thick succession of interbedded sandstone, conglomerate, and shale and appears to be nonmarine in the study area (Planert et al., 1993; Cook, 1993; Pashin et al., 2008).

The Eutaw Formation disconformably overlies the Tuscaloosa Group. It is composed of interbedded sandstone and shale and forms an overall fining upward sequence. The Eutaw Formation contains an abundance of glauconite and marine fossils, and has been interpreted as a marginal-marine to shelf facies that formed during a major marine transgression (Cook, 1993; Mancini et al., 1996; Pashin et al., 2000, 2008).

The uppermost part of the Cretaceous section in the study area is the Selma Group, which overlies the Eutaw Formation. The Selma is dominantly chalk and marl deposited in a marine shelf setting and exhibits a uniform thickness throughout the study area (Pashin et al. 2008).

Tertiary age strata assigned to the Midway Group and the Wilcox Group disconformably overlie the Selma Group and contain the formations that crop out at the surface in Kemper County (Clayton Formation, Porters Creek Clay, Naheola Formation, and Nanafalia Formation). The Clayton Formation is a thin calcareous and arenaceous limestone, the Porters Creek clay is a thick shale, and the Naheola and Nanafalia Formations contain interbedded sand, claystone, and lignite. Furthermore, the Naheola and Nanafalia Formations contain the principal fresh-water aquifers in this area (Pashin et al., 2008).

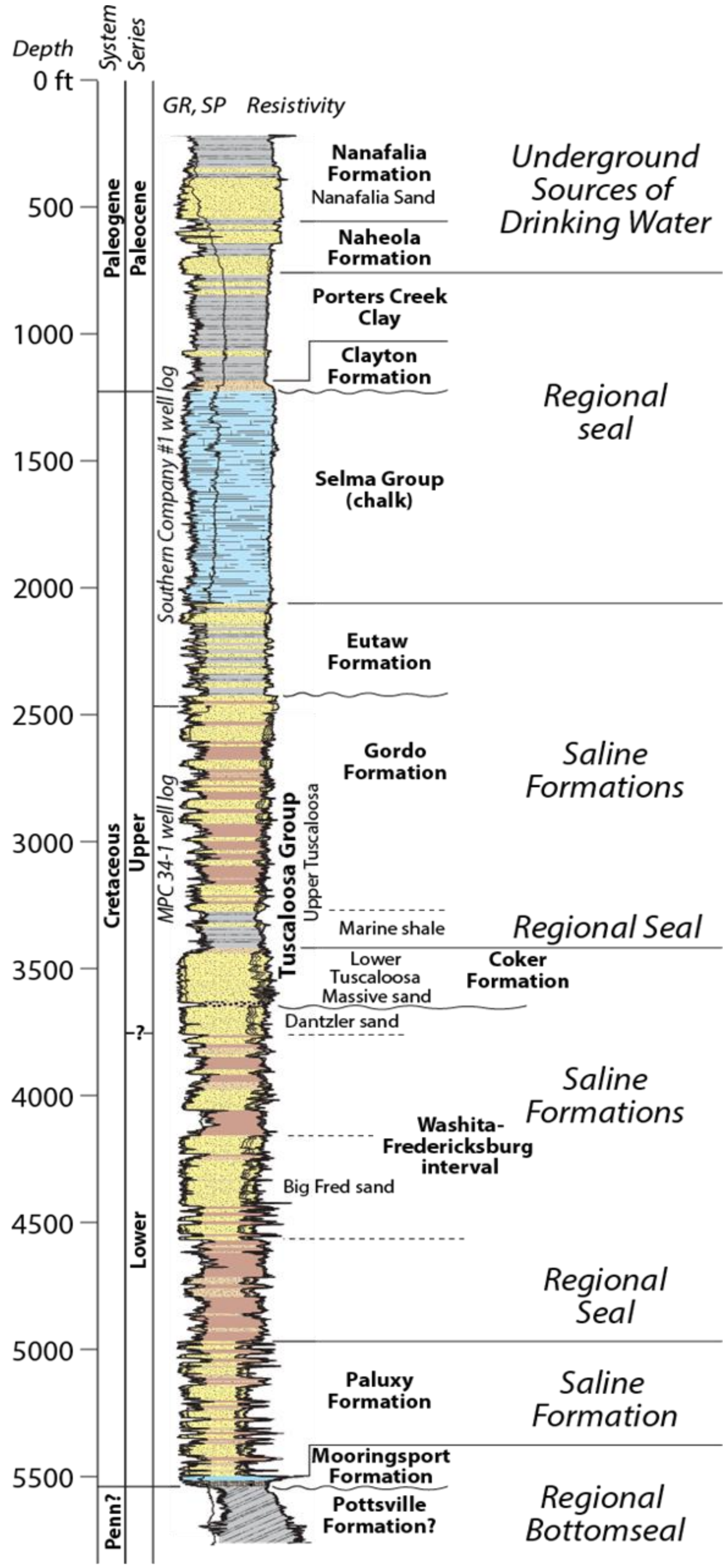

Figure 3. Schematic stratigraphic column and geophysical well logs of strata near the Kemper County energy facility.

CHAPTER II

METHODOLOGY

Core and Petrologic Analysis

Cores were acquired from three exploratory wells that were drilled within the Kemper County energy facility acreage. These are the MPC 26-5, MPC 34-1, and MPC 10-4 wells (Figure 1). The cores recovered from the three exploratory wells are from the Cretaceous formations being evaluated as potential reservoirs and seals for CO_2 storage. In well MPC 10-4, core was recovered from the Paluxy at depths of 5,038-5,137 ft and the Marine Tuscaloosa shale at 3,170-3,210 ft. In well MPC 34-1, core was recovered from the Paluxy Formation at 5,300-5,340 ft as well as the Washita-Fredericksburg interval at 4,850-4,867 ft. Well MPC 26-5 recovered core from the Washita-Fredericksburg interval at depths of 4,331-4,335 ft as well as the lower Tuscaloosa at depths of 3,588-3,592 ft and 3,645-3,655 ft, which was not slabbed and described in detail because the sandstone is very poorly consolidated and was liquified during recovery. Standard stratigraphic and sedimentologic techniques were implemented when describing core in order to define lithofacies and interpret depositional environment. More specifically, this was accomplished by creating graphical logs and describing rock types, bedding types, sedimentary structures, and biogenic structures. Grain size was determined using a hand lens and a graphical comparator.

Standard thin sections were made by Wagner Petrographic from 26 core samples of sandstone in the Paluxy Formation, the Washita-Fredericksburg interval, and the Lower Tuscaloosa Group. Blue epoxy was used to impregnate all thin sections in order to identify porosity. Thin sections were also stained with alizarin red to identify carbonate minerals. An additional potassium ferricyanide stain was used for MPC 26-5 thin sections to aid in feldspar identification, however, it was not used for thin sections in wells MPC 10-4 or MPC 34-1. Thin section analysis was performed to determine framework grain composition, size, fabric, and diagenesis as well as, pore geometry and pore fillings. Due to abundant porosity, a modified Chayes point counting method was used resulting in a minimum of 500 points per thin section and 300 points from framework grains. Proportions of various rock-forming minerals and porosity were calculated for each thin section. However, rock-fabric from thin sections obtained from well MPC 26-5 are not indicative of in-situ fabric as they were prepared as grain mounts. Standard Folk (1980) ternary diagrams were used to classify sandstone composition such that polycrystalline and monocrystalline quartz were summed to calculate total quartz content, while chert is quantified as a lithic fragment. Furthermore, Dickinson (1979 and 1983) ternary diagrams were used to interpret provenance. Though, to better interpret provenance, quartz content was calculated from monocrystalline quartz summed alone and all other quartz varieties were plotted as lithic fragments following the procedures of Graham et al. (1976). A large quantity of feldspar was dissolved from the sandstone, and so modified provenance diagrams also were made by counting grain-size voids as feldspar grains to get a better feel for the character of the source areas.

Reservoir Characterization

In addition to the cores from the exploratory wells, a full suite of digital geophysical well logs was run to aid in the characterization of the potential reservoir and seal rocks. Well log data span the top of the Paleozoic section through the Nanafalia Formation. Digital LAS well headers and log curves were compiled and loaded into IHS Petra software along with a Mississippi land grid. The key steps involved with reservoir characterization were (1) interpreting rock types, (2) characterizing the structural and stratigraphic framework of the area, (3) calculating thickness and average porosity of the sandstone units, and (4) identifying and characterizing potential carbon storage reservoirs.

Geophysical logs were used to determine rock types as well as identify potential sandstone reservoirs and their properties. The primary log curves used were mud logs, gamma-ray logs, spontaneous potential logs, induction logs, and density and neutron porosity logs. Additionally, cores obtained from these wells were used as a guide to confirm the interpretation of rock types in well logs. After the rock types and sandstone bodies were defined, effective porosity was determined from the porosity logs. The density porosity log was used and needed no correction as it was scaled to a sandstone matrix and because the neutron density logs give no indication of gas effect. A given sandstone was considered to be of reservoir quality if it had a gamma ray value ≤ 75 API units and a density porosity value ≥15 percent.

Once the well logs were interpreted, major stratigraphic boundaries were correlated among the three wells. The boundaries were identified on well logs via characteristic stratigraphic relationships and well log signatures described by (Pashin et al., 2008). Subsequently, a regional cross-section was constructed in order to demonstrate the structural and stratigraphic architecture. Furthermore, depth and thickness data of the various sandstone bodies were used to construct hand contoured geologic maps that honor the data obtained from each exploratory well.

Volumetric Analysis

Based on exceptionally low resistivity values (1-4 ohm-m) and TDS content between 23,000 and 115,000 mg/L in chloride-rich samples pulled from the wells in the target reservoirs (Pashin et al., 2020), Cretaceous sandstone in the area of the Kemper County energy facility contains saline water. Therefore, the CO_2 storage resources were estimated using methods defined by Goodman et al. (2011) as:

$$G_{CO2} = A_t h_n \phi_{tot} \rho E_{saline}$$

Where,

G_{CO2} is the reservoir CO_2 storage resource

A_t is the reservoir area

h_n is the net sandstone thickness

Φ_{tot} is the total porosity

ρ is the CO_2 density

E_{saline} is the CO_2 storage efficiency factor

The storage efficiency factor (E_{saline}) is the fraction of total pore space that is occupied by injected CO_2 and was determined by Monte Carlo sampling techniques by Goodman et al. (2011). This factor is dictated by numerous geological parameters such as total area, net reservoir thickness, net porosity, and the range of E_{saline} values that are determined statistically by studying numerous reservoirs of varying rock types. In this study, the system is well constrained, and values were determined for total area, net sandstone thickness, and total porosity. Therefore, E_{saline} values for displacement in well-characterized siliciclastic systems can be used to calculate the storage resource and range from 7.4 to 24% over a 10-90% probability range, such that P_{10} is 7.4%, P_{50} is 14%, and P_{90} is 24% (Goodman et al., 2011).

CHAPTER III

RESULTS

Geologic Framework

Rock types identified in well logs in the area of the Kemper County energy facility are predominantly sandstone and shale. Plate 1 shows a regional cross section that illustrates the stratigraphic architecture, and reservoir geometry of sedimentary units ranging from the base of the Paluxy Formation to the top of the Marine Tuscaloosa shale.

The oldest stratigraphic unit evaluated for this study is the Paluxy Formation. The Paluxy lies directly above a thin limestone assigned to the Mooringsport Formation, dips gently (~0.9°) to the southwest (Figure 4), and is composed of interbedded sandstone and shale (Plate 1). The thickness of the Paluxy ranges from approximately 540 to 740 feet (Figure 5), with the thickness being the greatest in the northwestern portion of the study area. Even with the relative close well spacing (5-6 mi), the Plauxy shows a high degree of internal variability and poses difficulty in correlating individual sandstone bodies. Gamma ray and density porosity log characteristics vary from blocky to bell shaped. Blocky log signatures reflect little to no vertical change in grain size and porosity, whereas the bell shaped log signatures reflect a fining-upward grain-size trend and an overall decrease in porosity.

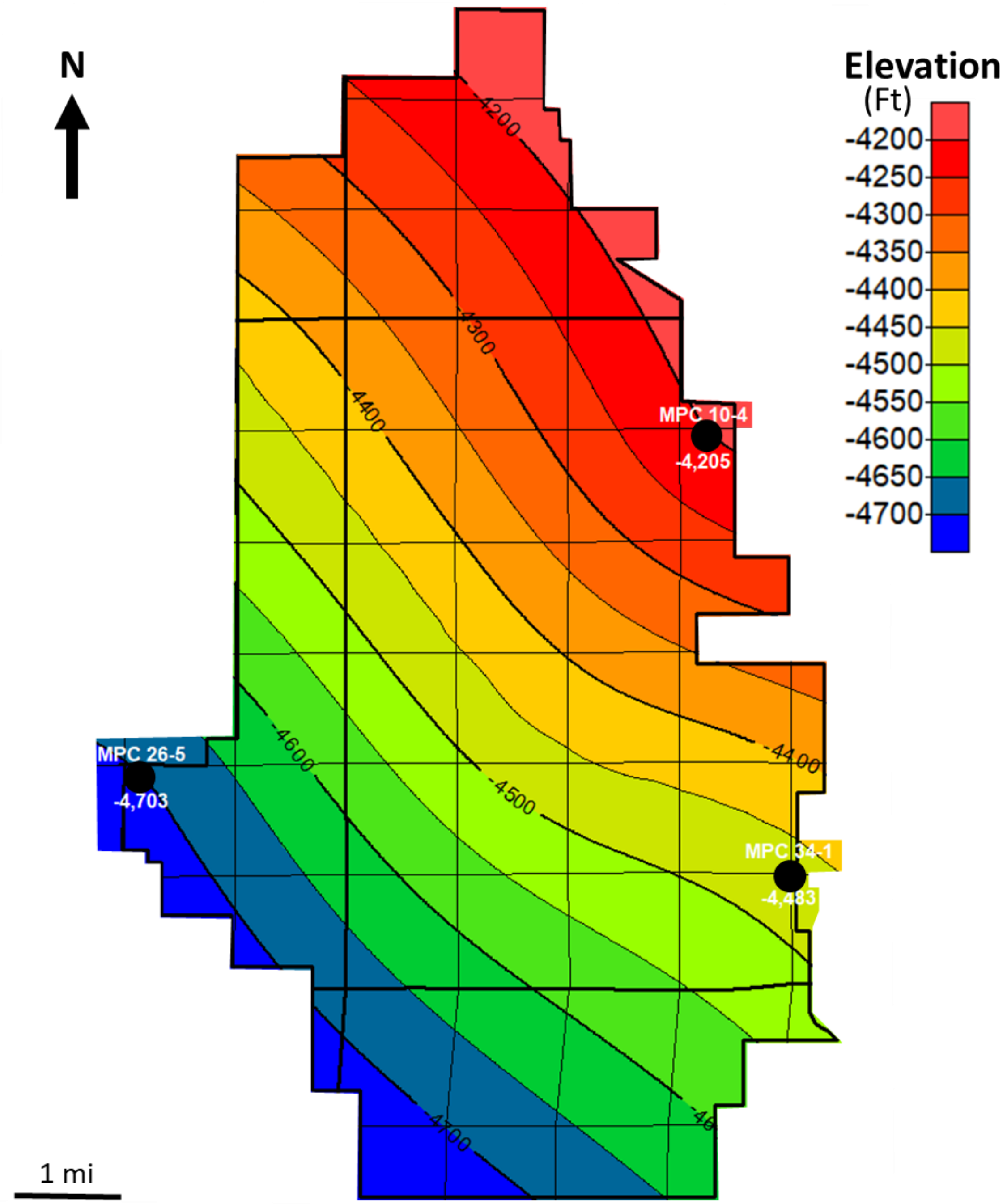

Figure 4 Structural contour map of the top of the Paluxy Formation. The Paluxy dips to the southwest at approximately 0.9° in the area of the Kemper County energy facility. Contour interval = 50 ft.

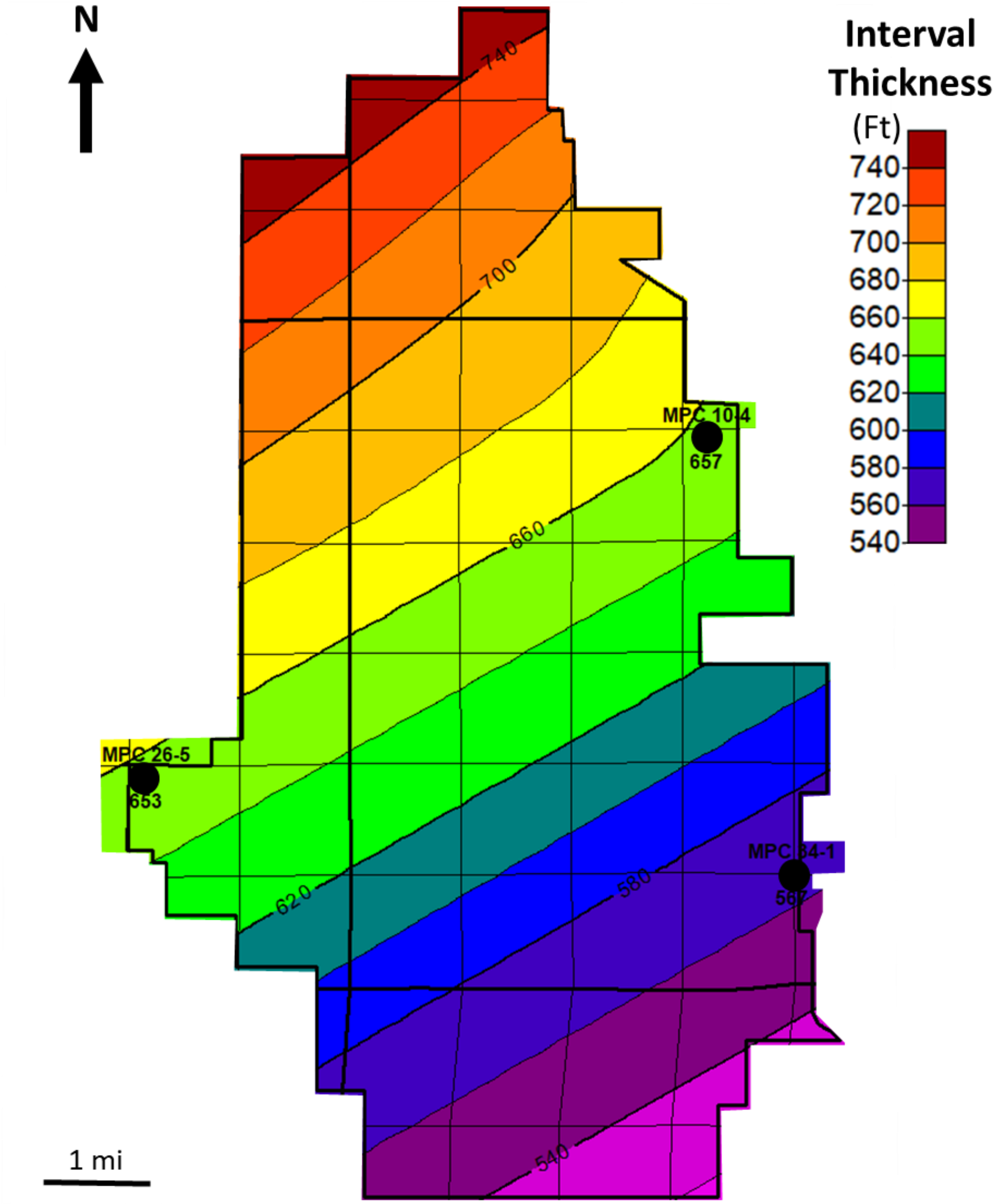

Figure 5. Isopach map of the Paluxy Formation. In the area of the Kemper County energy facility, the Paluxy thickens to the northwest. Contour interval = 20 ft.

Directly overlying the Paluxy Formation is the Washita-Fredericksburg interval; the basal Washita-Fredericksburg section is dominated by variegated shale. Much like the Paluxy, the Washita-Fredericksburg also dips southwest (Figure 6) but at a slightly lower gradient (~0.6°). The Washita-Fredericksburg is composed of interbedded sandstone and shale. However, unlike the Paluxy Formation, the Washita-Fredericksburg contains some stratigraphic intervals that can be correlated within the study area. Basal Washita-Fredericksburg strata are dominated by mudstone (Plate 1). The Washita-Fredericksburg contains sandstone bodies that increase in frequency and thickness and reach a maximum towards the middle of the interval. This portion of the Washita-Fredericksburg is informally known at the Big Fred sand. Moving up section, the thickness and frequency of sand bodies decreases and become more shaly until an upper sandstone zone is reached referred to as the Dantzler sand which throughout the study area ranges from about 100 to 150 ft in thickness. The Washita-Fredericksburg interval overall ranges in thickness from approximately 1,000 to 1,400 ft, with the thickest part of the section being in the southern portion of the study area (Figure 7). Log signatures within the Big Fred are characteristically blocky, whereas the sandstone units above and below the central portion of the section typically have a bell-shaped profile. The Dantzler sandstone is the upper most sandstone body within the Washita-Fredericksburg interval and sits directly above a prominent shale layer with a sharp contact.

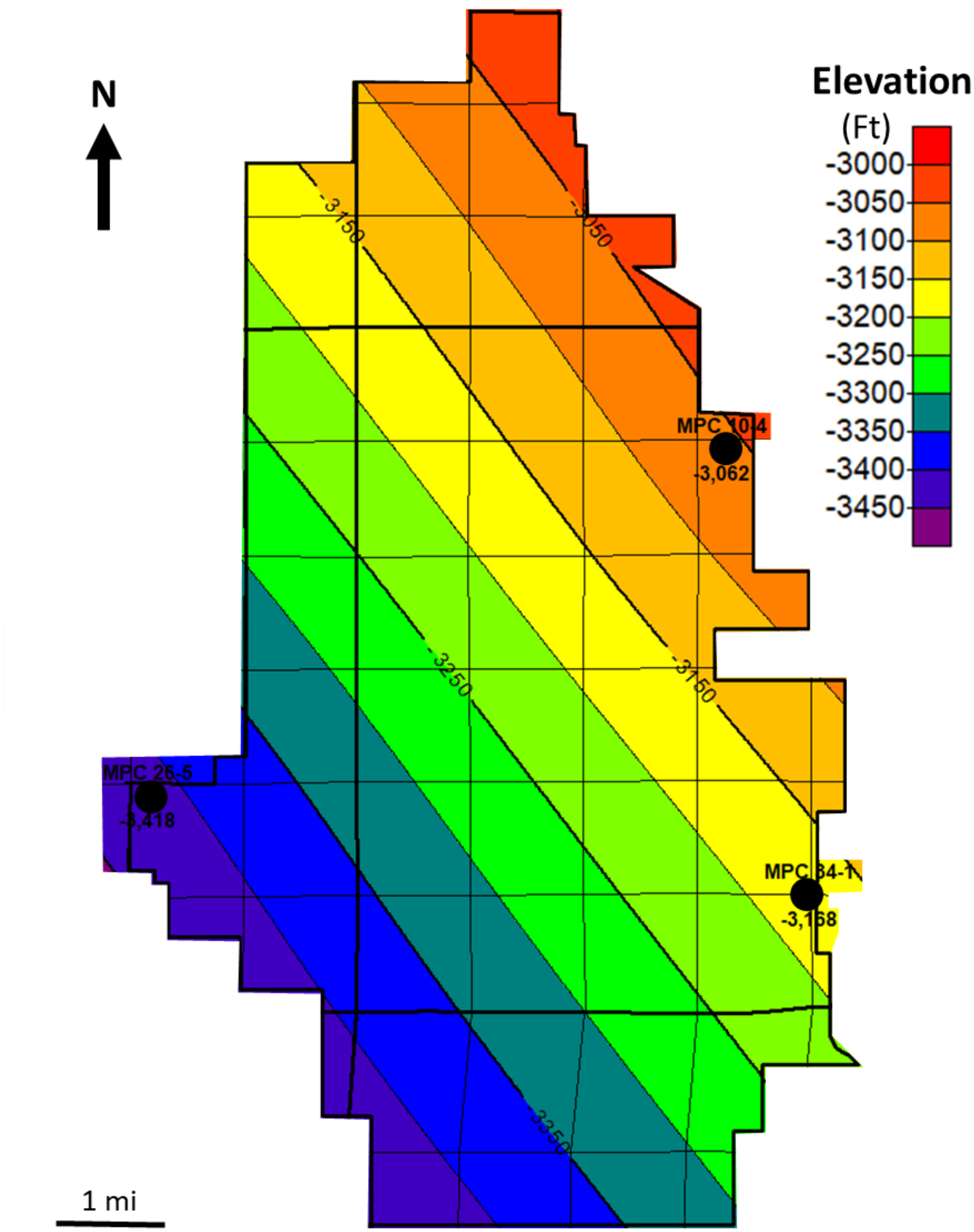

Figure 6. Structural contour map of the top of the Washita-Fredericksburg interval. The Washita-Fredericksburg dips to the southwest at approximately 0.6° in the area of the Kemper County energy facility. Contour interval = 50 ft.

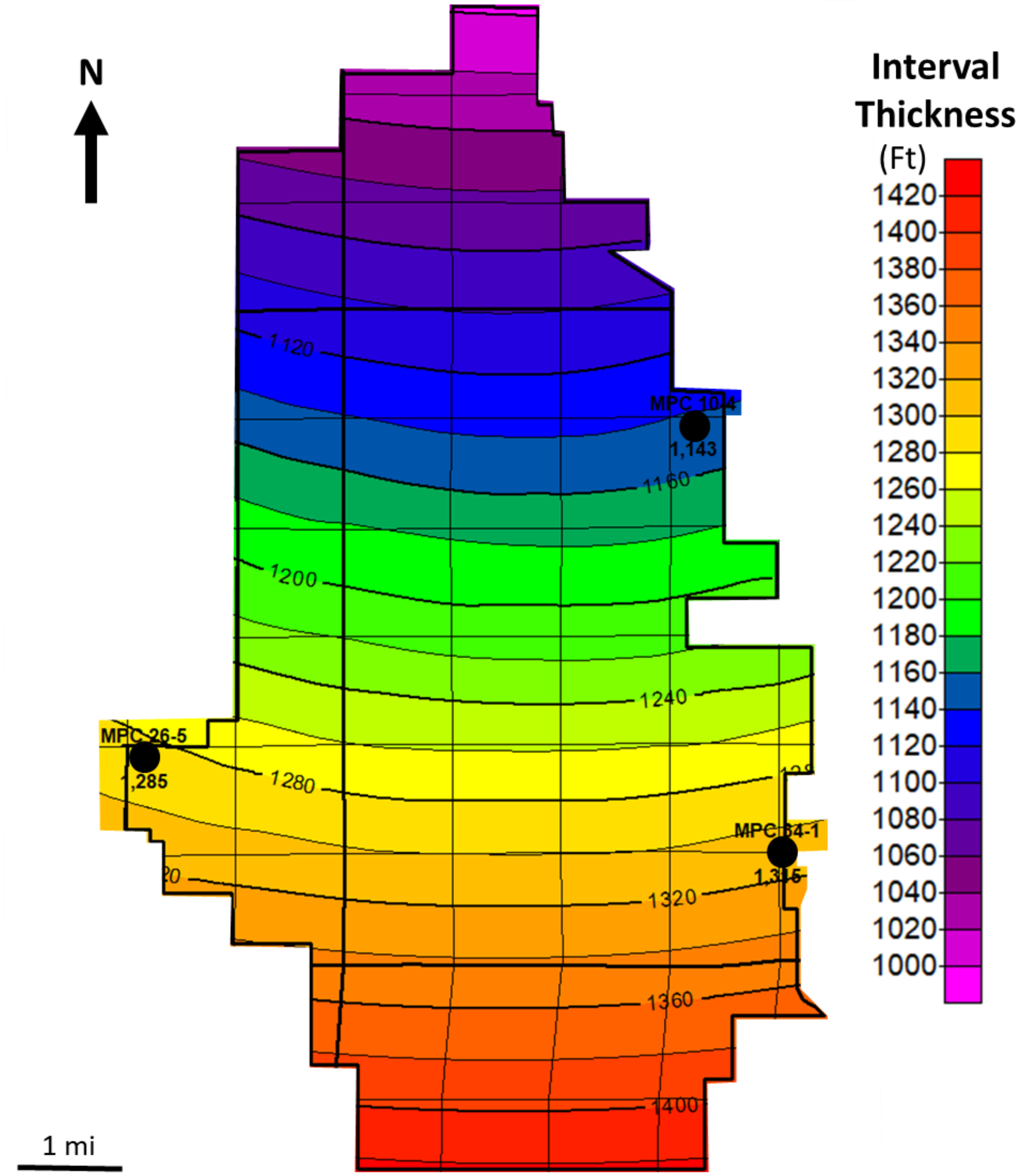

Figure 7. Isopach map of the Washita-Fredericksburg interval. In the area of the Kemper County energy facility, the Washita-Fredericksburg thickens to the south. Contour interval = 20 ft.

Sharply overlying the Dantzler sand of the Washita-Fredericksburg interval is the Massive sand of the lower Tuscaloosa Group with a sharp conglomeratic base that grades into a medium sand. The thickness of the lower Tuscaloosa in the study area ranges from approximately 120 to 240 ft (Figure 8). The Massive sand is readily recognized on wireline logs by low gamma count and a blocky signature in gamma ray and porosity logs, suggesting relatively consistent grain size and porosity. Much like the Lower Cretaceous formations below, the lower Tuscaloosa dips southwest at ~0.5° (Figure 9). Overlying the lower Tuscaloosa Group is the Marine Tuscaloosa shale. The Marine shale is regionally extensive and is correlative throughout the study area (Pashin et al., 2008).

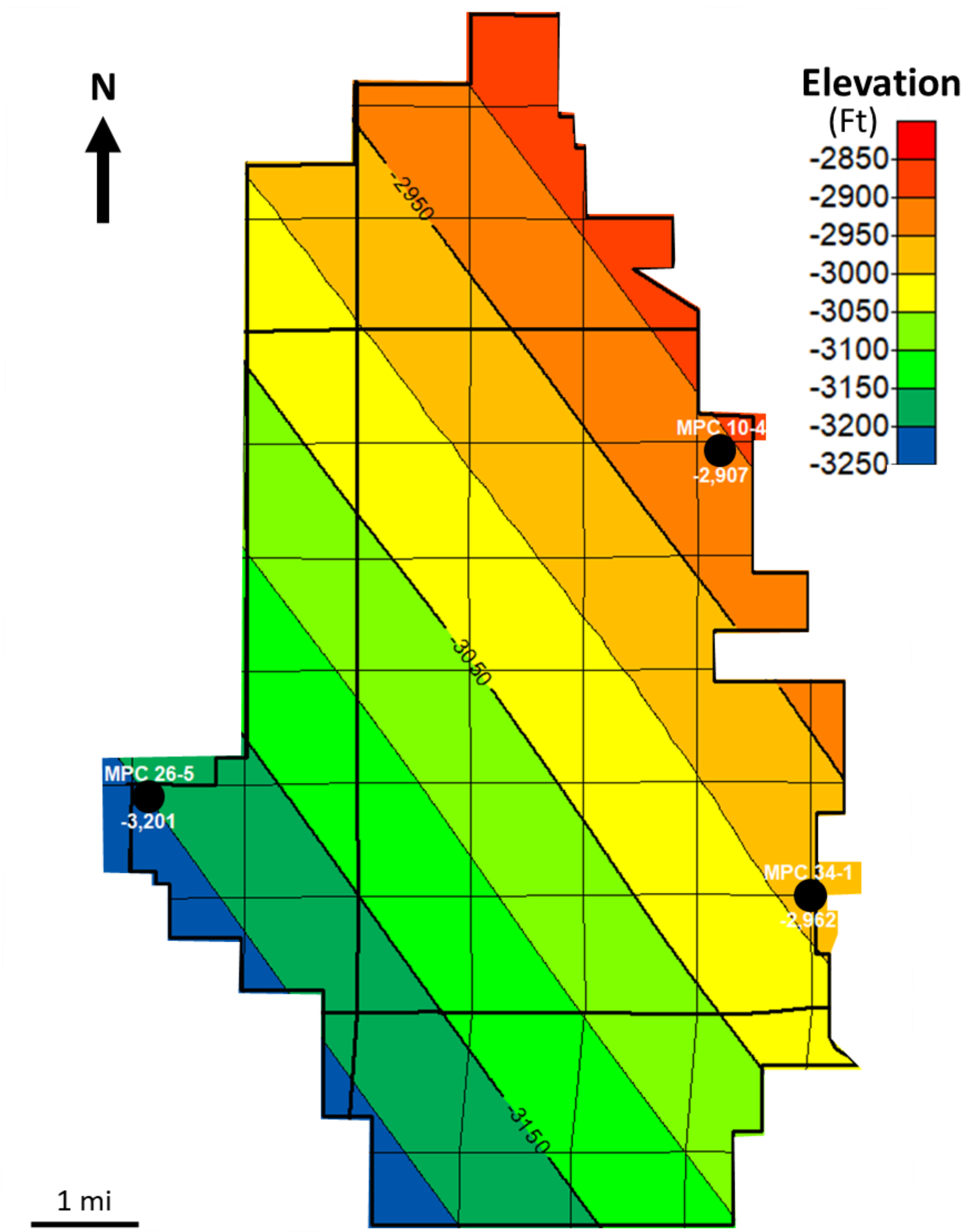

Figure 8. Structural contour map of the top of the lower Tuscaloosa Group. The lower Tuscaloosa dips to the southwest at approximately 0.5° in the area of the Kemper County energy facility, the. Contour interval = 50 ft.

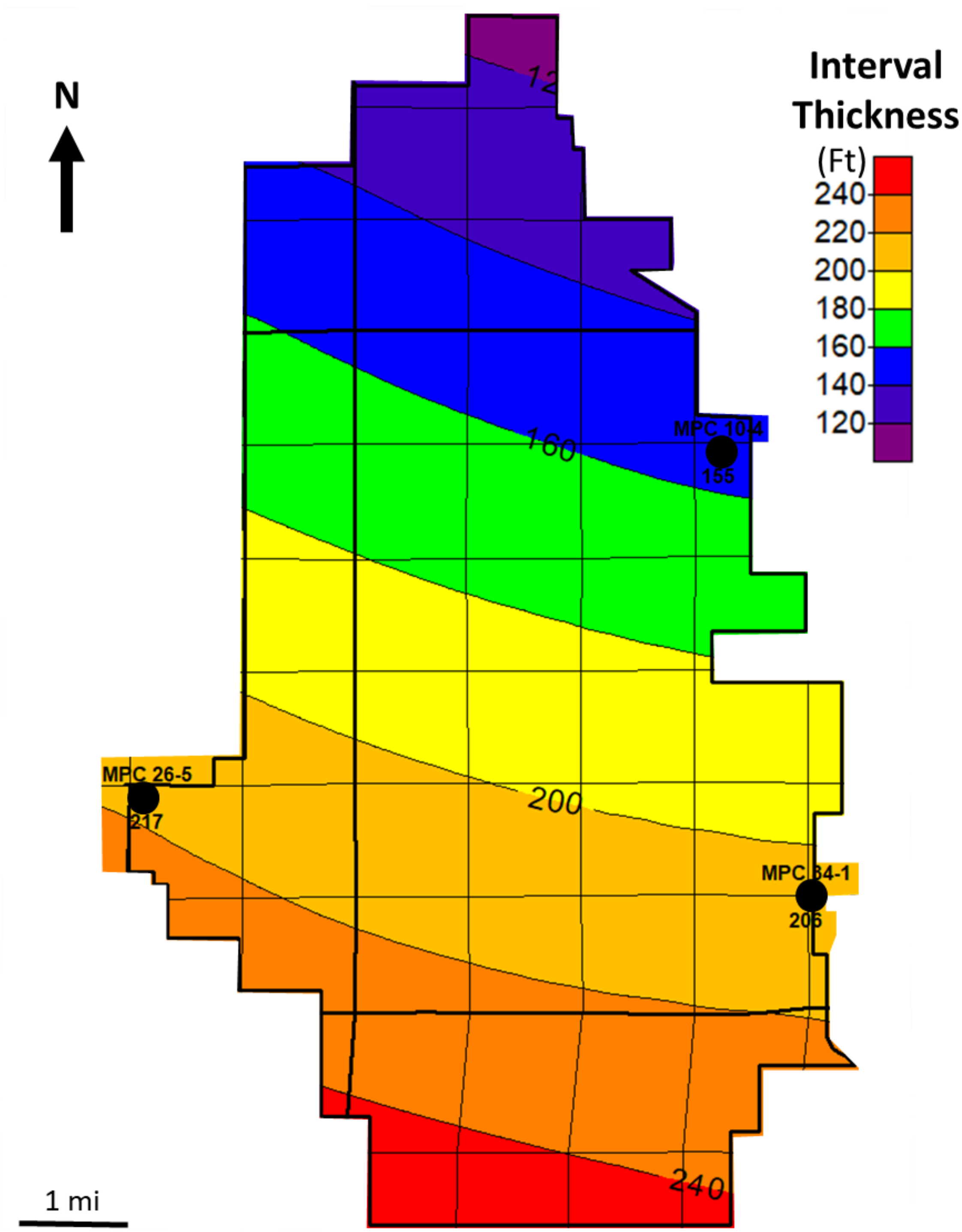

Figure 9. Isopach map of the lower Tuscaloosa Group. In the area of the Kemper County energy facility, the lower Tuscaloosa thickens to the southwest. Contour interval = 20 ft.

Core Description

Cretaceous sandstones were cored and logged graphically in the MPC 10-4 and MPC 34-1 wells (Figures 10-12). Only the Paluxy Formation was cored in the MPC 10-4 well, whereas the Washita-Fredericksburg interval and the Paluxy Formation were cored in the MPC 34-1 well.

The color of Paluxy sandstone in core is typically reddish-brown to light grey. Though it should be noted that the sandstone commonly appears red from infiltration of drilling fluid. Grains are weakly cemented and grain size is most commonly in the medium sand range and consistent throughout a given sand body until being abruptly capped by a shale layer. However, some sandstone bodies grade upward from a conglomeratic base through coarse-grained sandstone into fine-grained sandstone. High-angle cross-beds are the dominant sedimentary structure observed, particularly within sand bodies that had little to no change in grain size. Other sedimentary structures include horizontal laminae, and current ripple cross-laminae (Figure 13). Sedimentary accessories in the Paluxy sandstones include coal spars, quartz granules and pebbles; mudstone pebbles forming angular to rounded clasts, that were commonly smashed and deformed; and granule- to pebble-size calcite concretions (typically in local clusters), (Figure 14).

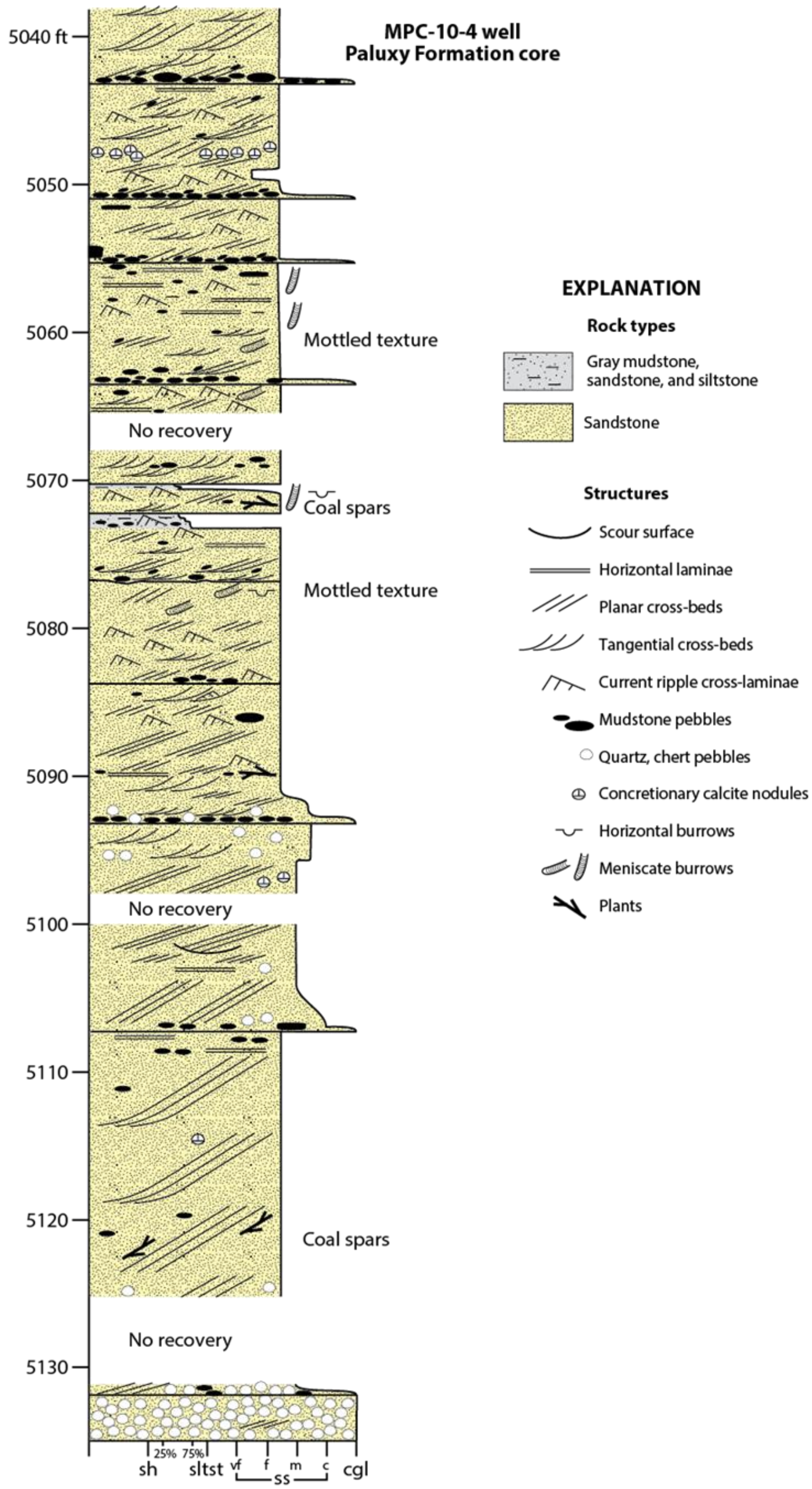

Figure 10. Schematic core log showing lithology, sedimentary structures, biogenic features, and footage of the Paluxy core recovered from well MPC 10-4 (after Pashin et al., 2020).

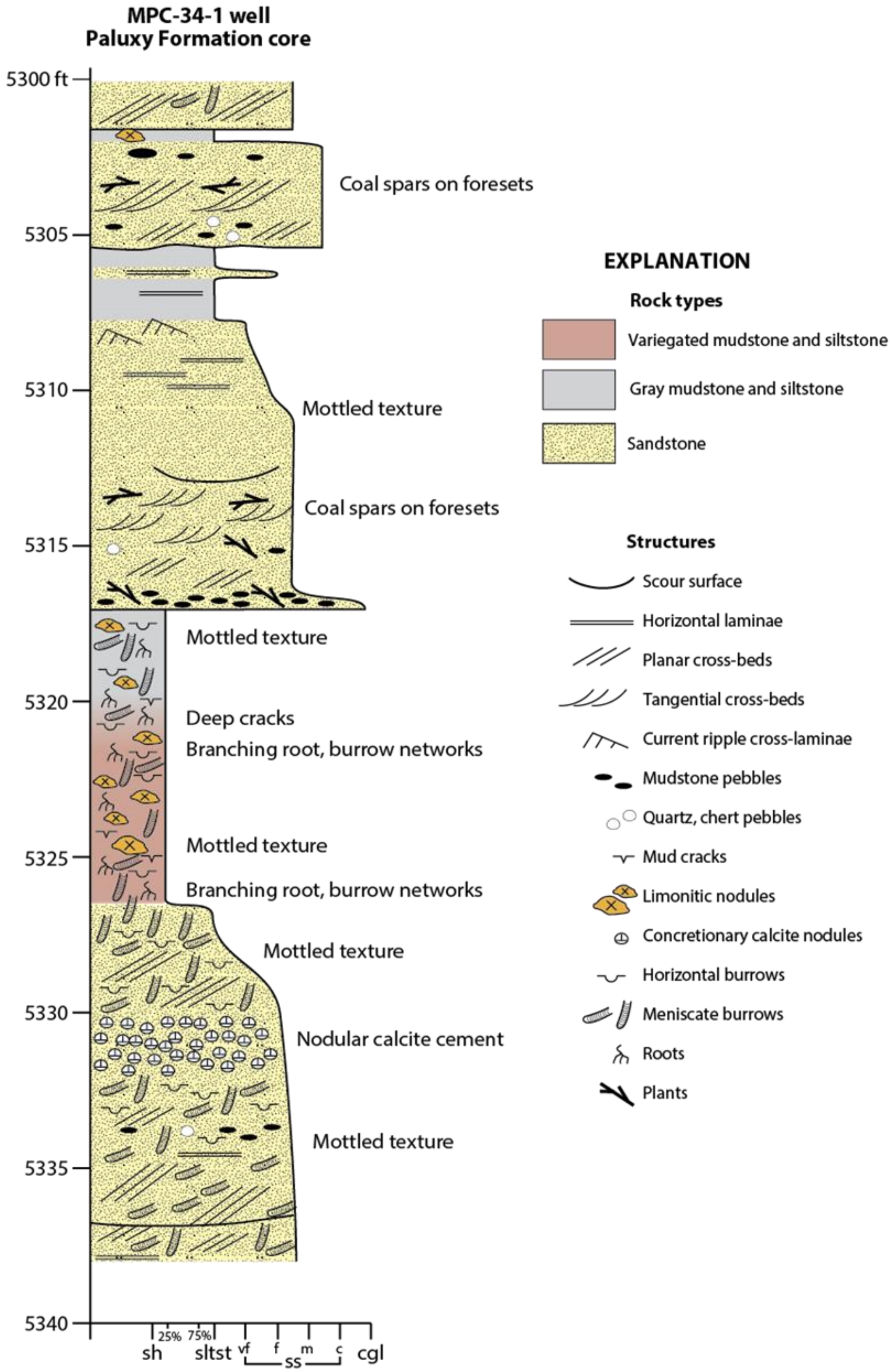

Figure 11. Schematic core log showing lithology, sedimentary structures, biogenic features, and footage of the Paluxy core recovered from well MPC 34-1 (after Pashin et al., 2020).

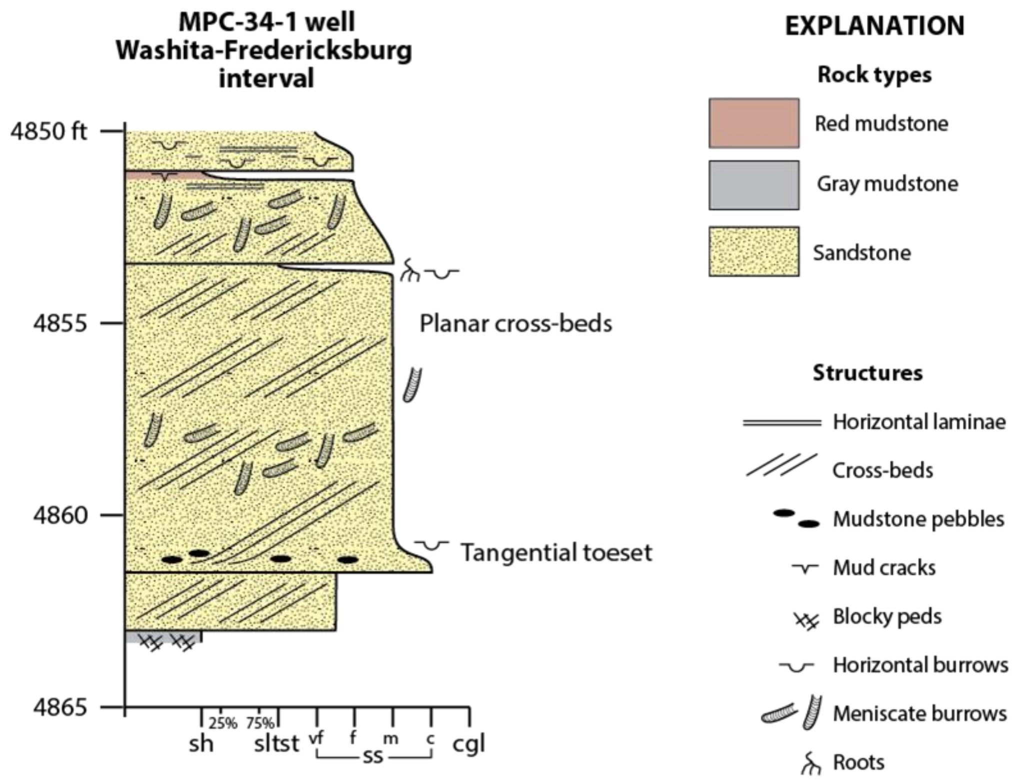

Figure 12. Schematic core log showing lithology, sedimentary structures, biogenic features, and footage of the Washita-Fredericksburg core recovered from well 34-1 (after Pashin et al., 2020).

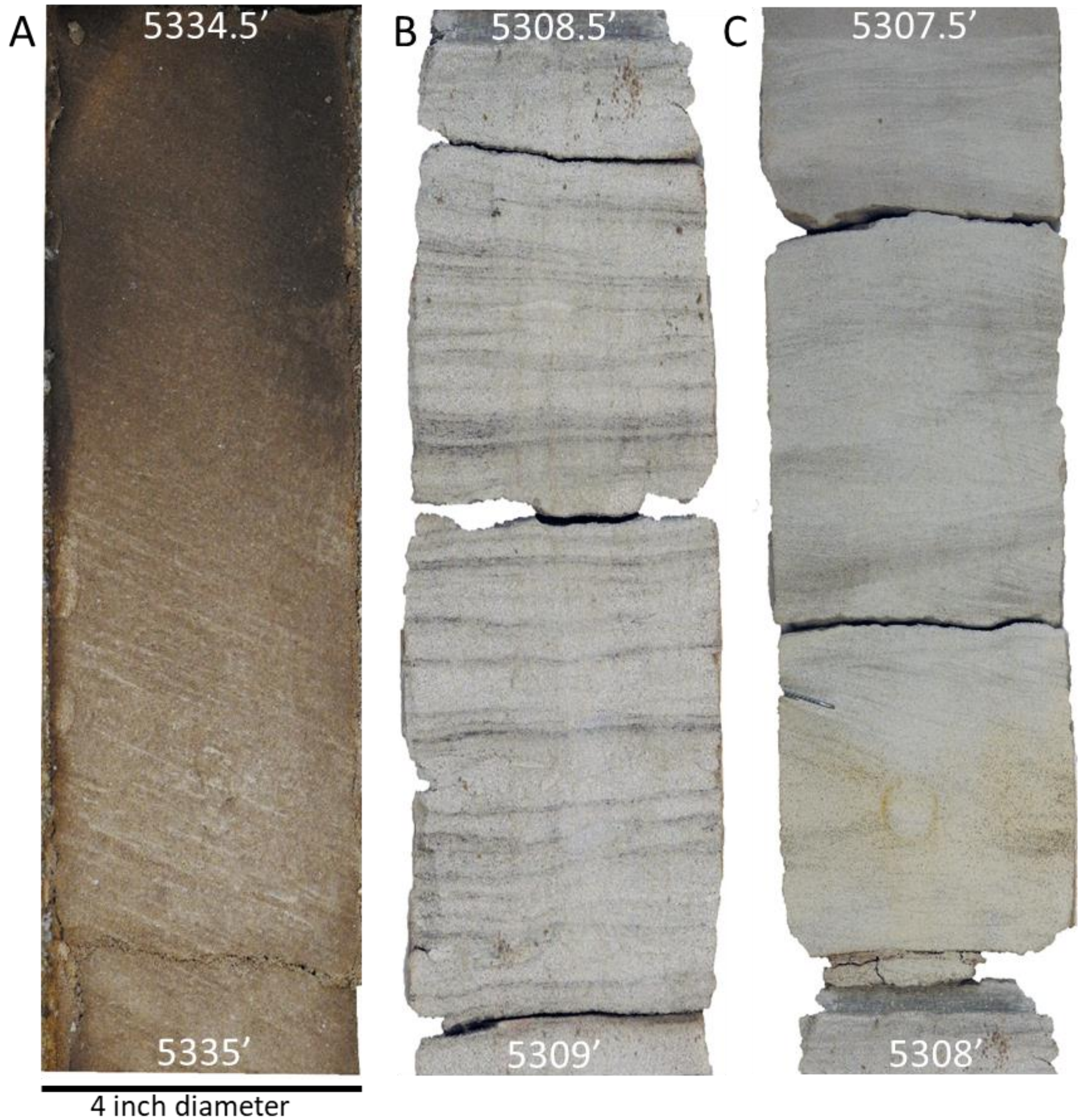

Figure 13. Slabbed core photographs of Paluxy sandstone from the MPC 34-1 well. A) High- and low-angle cross-bedded sandstone. B) Horizontally laminated sandstone with faint, silty and micaceous partings. C) Ripple cross-stratified sandstone with faint, silty and micaceous partings.

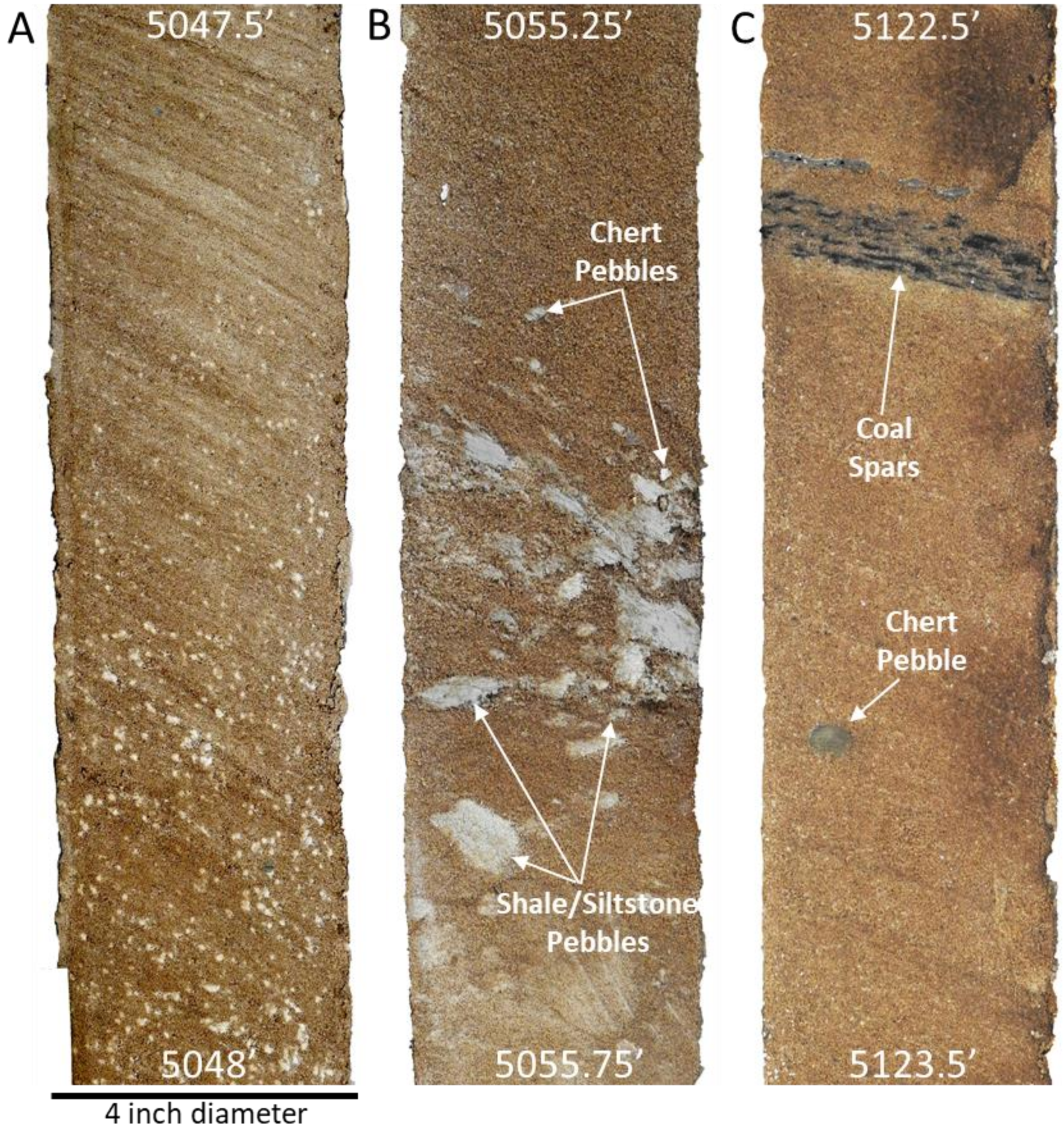

Figure 14. Slabbed core photograph of the Paluxy sandstone from well MPC 10-4. A) Medium grained, cross-bedded sandstone with concretionary calcite nodules. B) Medium grained, cross-bedded sandstone with chert pebbles and shale/siltstone pebbles, often smashed and deformed between grains. C) Medium grained, cross-bedded sandstone with concentrated layer of coal spars and chert pebbles.

Washita-Fredericksburg sandstone has similar characteristics to that in the Paluxy Formation, although there are a few notable differences. Sandstone from the Washita-Fredericksburg has colors ranging reddish-brown to light grey. Much like the Paluxy sandstone, the red and red-brown sandstones observed from the Washita-Fredericksburg appear to derive their color from infiltration of drilling fluid, however, some of the red coloring does indeed appear to be primary. The Washita-Fredericksburg sandstone grades upward from medium-grained to very fine-grained sandstone and is generally weakly cemented. The remainder of the sandstone contains sedimentary structures much like those in the Paluxy with high-angle cross-beds being the most common followed by horizontal laminae, and current ripples. The upper 3 ft of the sandstone is varicolored, has limonitic stain, and is mottled/burrowed (Figure 15). Likewise, sedimentary accessories observed in the Washita-Fredericksburg include coal spars, calcite concretions, shale/siltstone pebbles, and the aforementioned burrows.

Figure 15. Slabbed core photo of the varicolored Washita-Fredericksburg sandstone containing some remnant ripples that were persevered from lack of burrowing, meniscate burrows contributing to mottled texture as well as limonitic staining (Well MPC 34-1).

Petrologic Analysis

The present-day composition of sandstone within the Paluxy Formation, Washita-Fredericksburg interval, and lower Tuscaloosa Group is similar with framework grains composed of quartz, feldspar, and lithic fragments. The majority of the samples plot as subarkose on the Folk (1980) diagram (Figure 16). However, composition is variable, ranging from arkose to feldspathic litharenite. Table 1 summarizes the point count data used for the compositional ternary diagram in Figure 16 and Table 2 summarizes the point count data used for the ternary provenance diagram in figure 32.

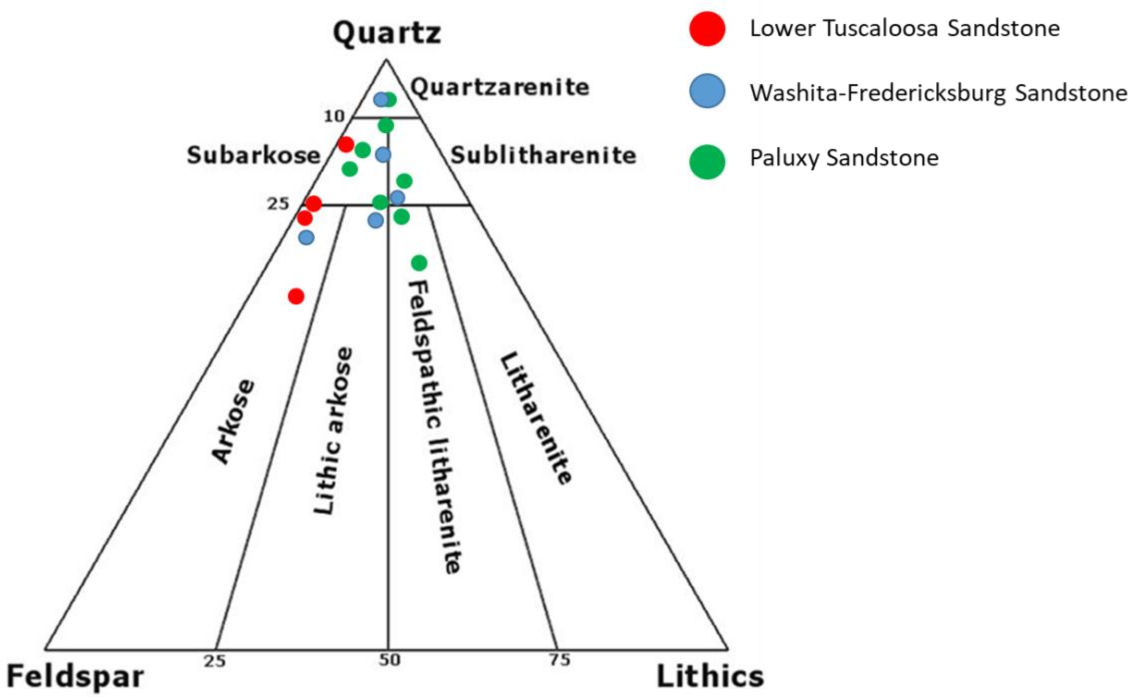

Figure 16. Ternary diagram showing classification of sandstone in the Paluxy Formation, Washita-Fredericksburg interval, and the lower Tuscaloosa Group (diagram modified from Folk, 1980).

Table 1. Results of point count data used to plot in-situ Cretaceous sandstone composition.

Well	Thin Section	Formation	Quartz (%)	Feldspar (%)	Lithics (%)
MPC 26-5	3645	lower Tuscaloosa	86.8	12.2	1
MPC 26-5	3647	lower Tuscaloosa	70.7	26.1	3.2
MPC 26-5	3649	lower Tuscaloosa	73.9	23.3	2.8
MPC 26-5	3651	lower Tuscaloosa	59.1	32.6	8.3
MPC 34-1	4852.6	Washita-Fredericksburg	74.8	15.3	9.9
MPC 34-1	4855.3	Washita-Fredericksburg	85.4	7.6	7
MPC 34-1	4858	Washita-Fredericksburg	70.2	28	1.8
MPC 34-1	4861.75	Washita-Fredericksburg	77	9.5	13.5
MPC 34-1	4863	Washita-Fredericksburg	96	0	4
MPC 10-4	5042	Paluxy	83.3	15.7	0
MPC 10-4	5084	Paluxy	74	11.3	14.7
MPC 10-4	5102	Paluxy	65	12.6	22.4
MPC 10-4	5110	Paluxy	89.6	6.3	4.1
MPC 34-1	5312.2	Paluxy	84.2	10.2	5.6
MPC 34-1	5314.5	Paluxy	76.4	13.8	9.8
MPC 34-1	5331.5	Paluxy	80.3	8.5	11.2
MPC 34-1	5335.2	Paluxy	94.8	0	5.2

Table 2. Results of point count data used to plot in-situ Cretaceous sandstone provenance.

Well	Thin Section	Formation	Quartz (%)	Feldspar (%)	Lithics (%)
MPC 26-5	3645	lower Tuscaloosa	52.6	13.2	34.2
MPC 26-5	3647	lower Tuscaloosa	47.7	26.1	26.2
MPC 26-5	3649	lower Tuscaloosa	53.8	23.2	23
MPC 26-5	3651	lower Tuscaloosa	31.2	32.6	36.2
MPC 34-1	4852.6	Washita-Fredericksburg	74.8	15.3	9.9
MPC 34-1	4855.3	Washita-Fredericksburg	57.8	7.6	34.6
MPC 34-1	4858	Washita-Fredericksburg	55	28	17
MPC 34-1	4861.75	Washita-Fredericksburg	53.6	9.5	36.9
MPC 34-1	4863	Washita-Fredericksburg	84.2	0	15.8
MPC 10-4	5042	Paluxy	56	17	27
MPC 10-4	5084	Paluxy	61	11.3	27.7
MPC 10-4	5102	Paluxy	65	12.6	32.4
MPC 10-4	5110	Paluxy	62.5	6.3	31.2
MPC 34-1	5312.2	Paluxy	51	10.2	38.8
MPC 34-1	5314.5	Paluxy	38	14	48
MPC 34-1	5331.5	Paluxy	80.3	8.5	11.2
MPC 34-1	5335.2	Paluxy	63	0	37

In the Paluxy Formation, monocrystalline quartz is the dominant framework quartz grain with polycrystalline quartz, which has several forms, being a close second (Figure 17). Quartz content in the Paluxy ranges from 65 to 95%. Grains are angular to subround, and sphericity ranges from slightly elongate (oblate) to spherical. Monocrystalline quartz grains are commonly fractured and have undulatory extinction. Polycrystalline quartz grains have internal crystals ranging from straight to weakly sutured, and some are composed of crystals that are elongate in one direction. Average grain size ranges from fine (~0.2 mm) to coarse sand (~0.4 mm), and the sandstone is commonly poorly sorted.

Lithic rock fragments and feldspar constitute the remainder of the framework grains and have variable but similar proportions. Both orthoclase and plagioclase feldspar were identified in the Paluxy sandstone, and potassium feldspar can easily be misidentified when it lacks characteristic twinning, such as tartan twinning observed in microcline and Carlsbad twinning commonly observed in orthoclase. Point counting indicates that feldspar concentration ranges from 2 to 16%. Feldspar is often partially dissolved or vacuolized. Furthermore, clay coats that commonly bridge grains reveal remnant grain shapes that were likely feldspar or perhaps other types of labile grains that have been completely dissolved (Figures 17, 18). The partial and complete dissolution of feldspar and other chemically unstable grains results in secondary porosity such as intraparticle and moldic pores, which are commonly observed in Paluxy sandstone.

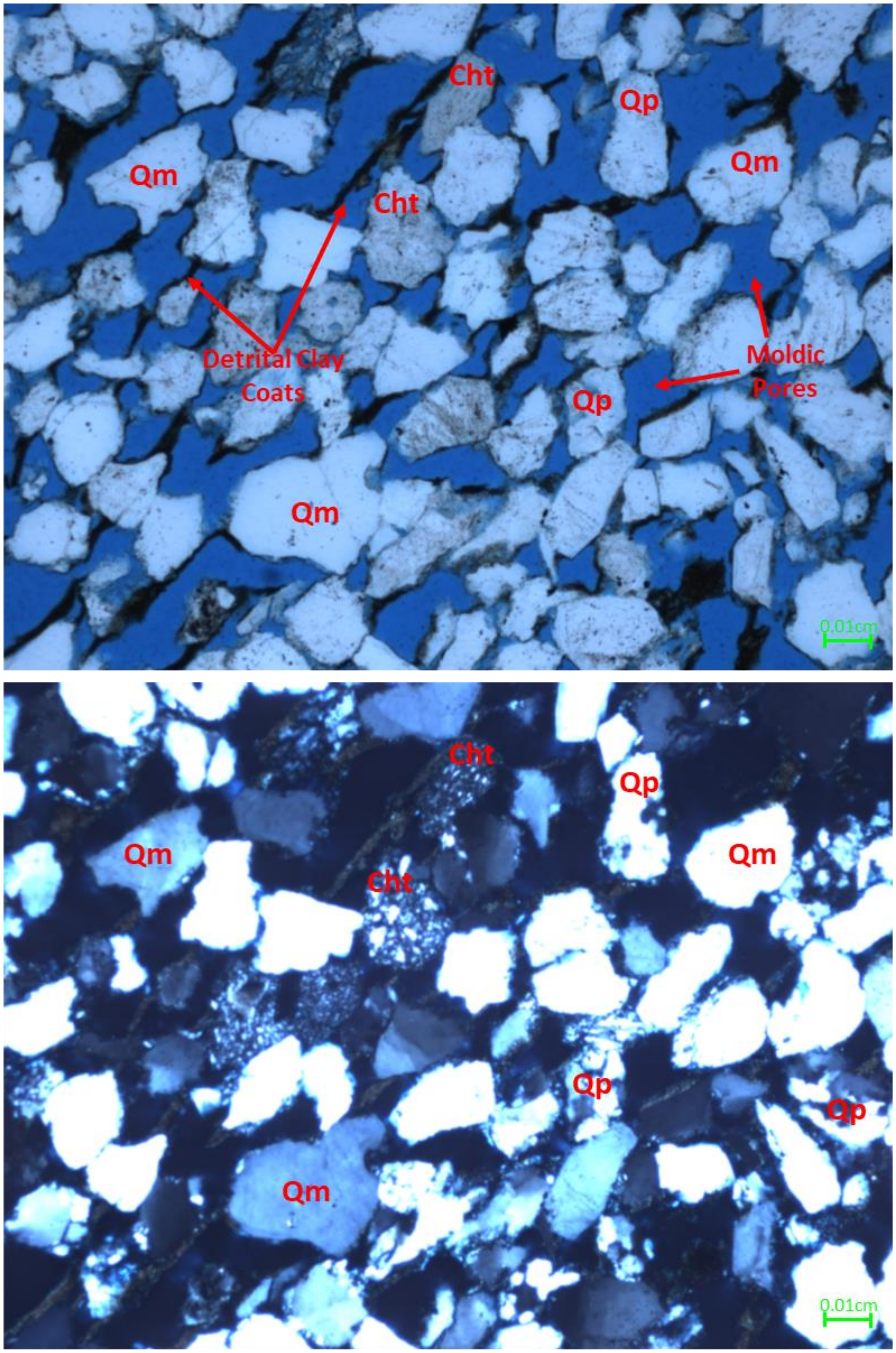

Figure 10. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of Paluxy sandstone (MPC 34-1, 5335.2 ft., 5x) showing abundant monocrystalline (Qm) and polycrystalline (Qp) quartz framework grains, as well as some detrital chert grains (Chrt). Note the dark clay coats that bridge grains, which appear to mark pores left by grain dissolution. The complete dissolution of feldspars results in moldic pores.

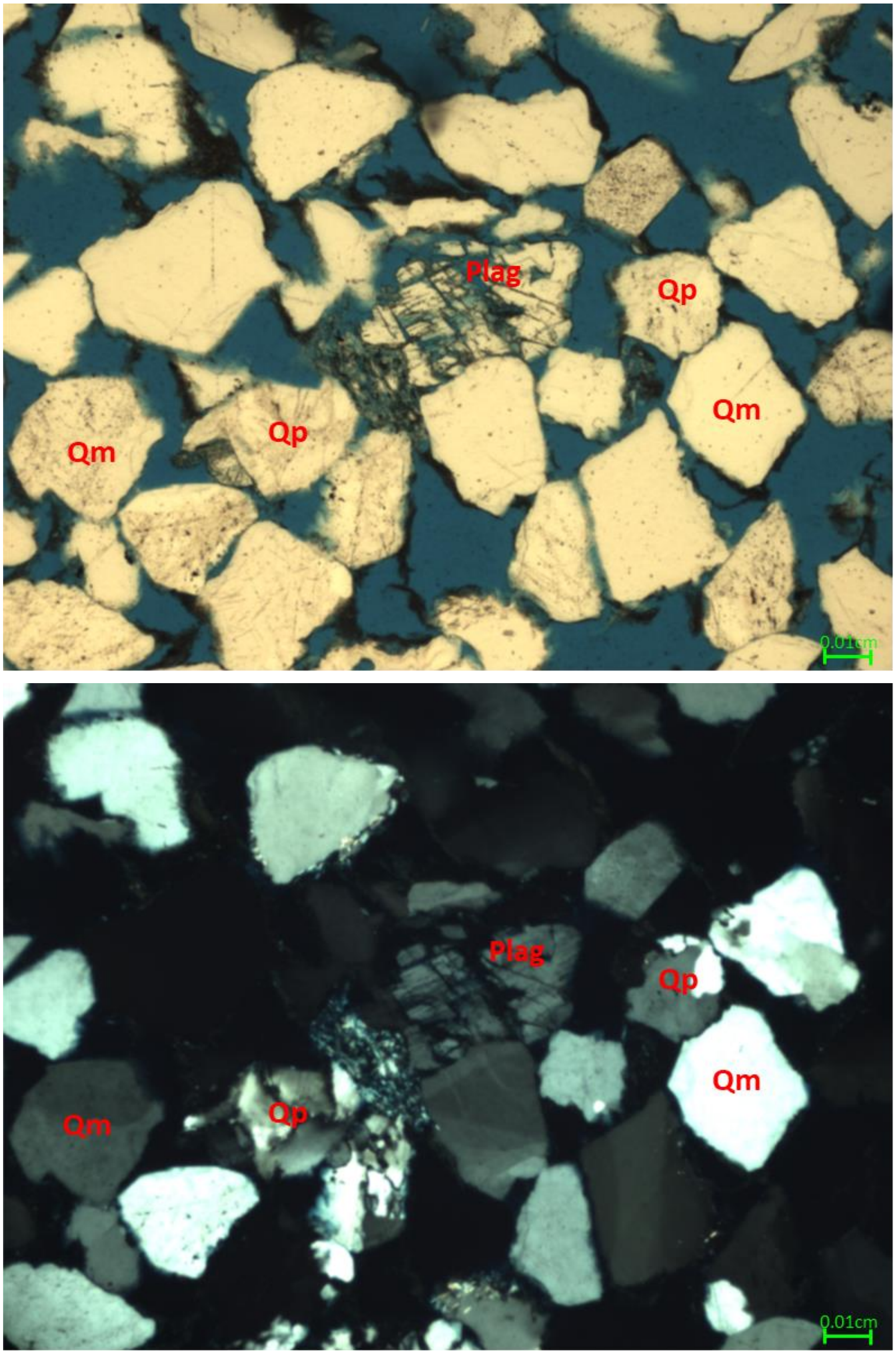

Figure 18. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of Paluxy sandstone (MPC 10-4, 5110 ft., 5x) showing a partially dissolved and vacuolized feldspar showing polysynthetic twinning. Abundant quartz and clay coats are also present in this thin section.

Lithic fragments are common in Paluxy sandstone in quantities comparable to feldspar (4-22%). Lithic grains include metamorphic rock fragments, such as grains of schist (Figure 19) and quartzite, and sedimentary rock fragments such as chert (Figure 17), as well as igneous rock fragments. A few grains of oolitic chert also were observed (Figure 20). Metamorphic rock fragments are the dominant lithic fragment observed. Accessory minerals are predominantly muscovite, and several zircons were observed in thin section but did not fall within any of the point counts. Paluxy sandstone generally lacks authigenic minerals and cement. Only one thin section contains minor amounts (~5%) of calcite cement which occurs throughout the thin section in small patches; a minimal amount of pore-filling kaolinite was observed.

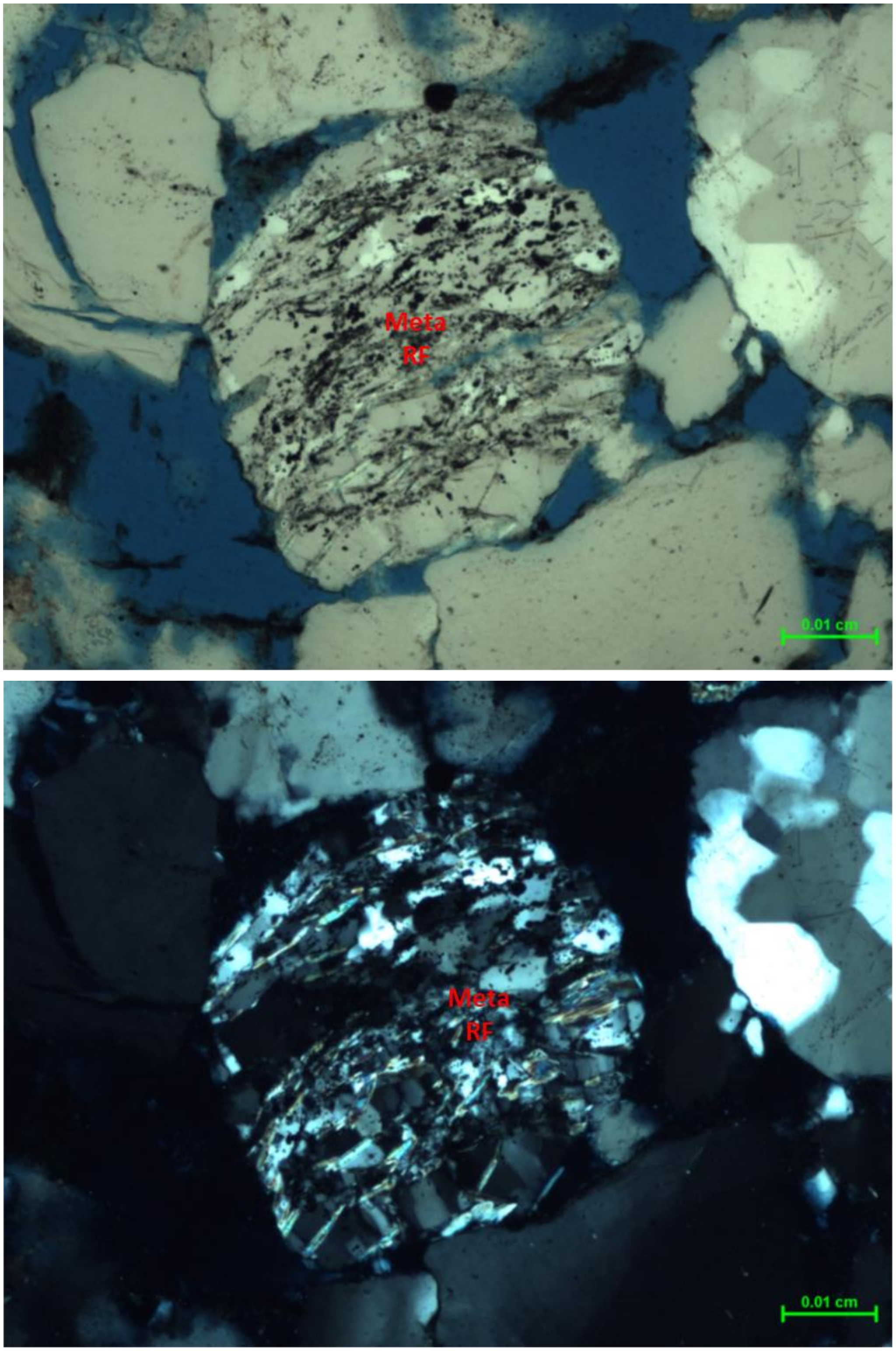

Figure 19. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of Paluxy sandstone (MPC 10-4, 5102 ft., 10x) showing a schistose metamorphic rock fragment surrounded by monocrystalline and polycrystalline quartz. The monocrystalline quartz grain below the metamorphic rock fragment displays undulatory extinction, which is common in Paluxy sandstone.

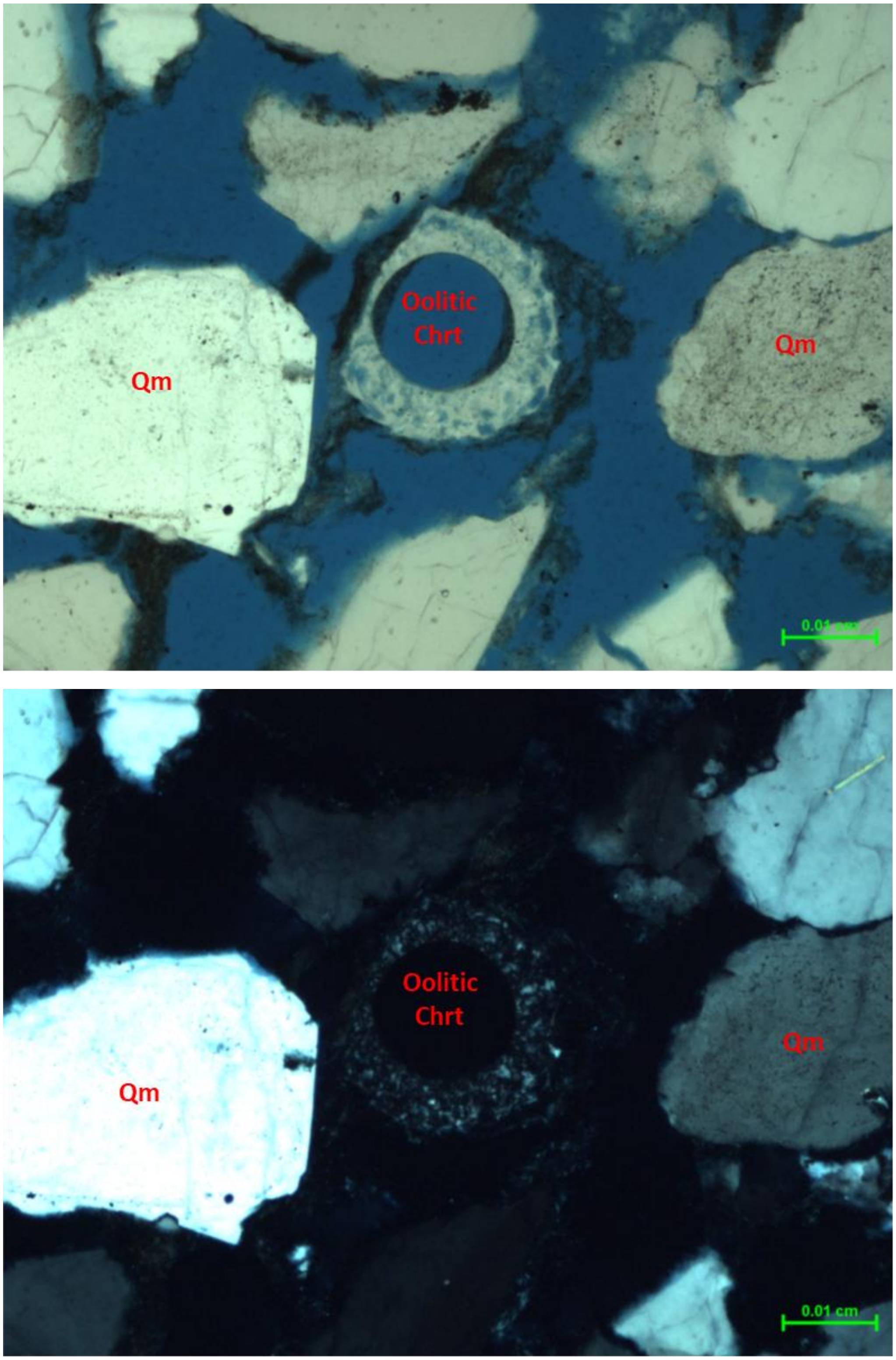

Figure 20. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of Paluxy sandstone (MPC 10-4, 5110 ft., 10x) showing an oolitic chert grain surrounded by monocrystalline quartz grains (Qm).

The Washita-Fredericksburg interval, much like the Paluxy Formation, is a poorly to moderately sorted quartz-rich sandstone that has grains that range from sub-angular to sub-round with variable sphericity. Monocrystalline quartz is the dominant variety of quartz; it is commonly fractured and displays undulatory extinction. Polycrystalline quartz is also very common and has internal grain boundaries that vary from straight to sutured to elongate in a single direction. Quartz content ranges from 70 to 96% (Figure 21). Average grain size for the Washita-Fredericksburg sandstone ranges from very fine (~0.1mm) to medium sand (~0.25mm).

The second most abundant type of framework grain in the Washita-Fredericksburg is feldspar (0-15%). Feldspar in the Washita-Fredericksburg while still commonly partially dissolved and vacuolized appears to be slightly less common and extensive than that in the Paluxy. Additionally, feldspar with sericitic alteration was observed (Figure 22).

Lithic fragments are the third most abundant class of framework grain (4-14%). Lithic fragments observed in decreasing order of abundance are: metamorphic rock fragments, chert, igneous rock fragments, and argillaceous rock fragments. Metamorphic rock fragments are dominantly schistose with a few quartzite grains and a significant number of polycrystalline quartz grains that showed evidence of marginal metamorphism. Igneous rock fragments appear granitic due to felsic mineral constituents and argillaceous rock fragments are commonly compacted between other framework grains and thus appear as matrix (i.e., pseudomatrix) (Figure 23).

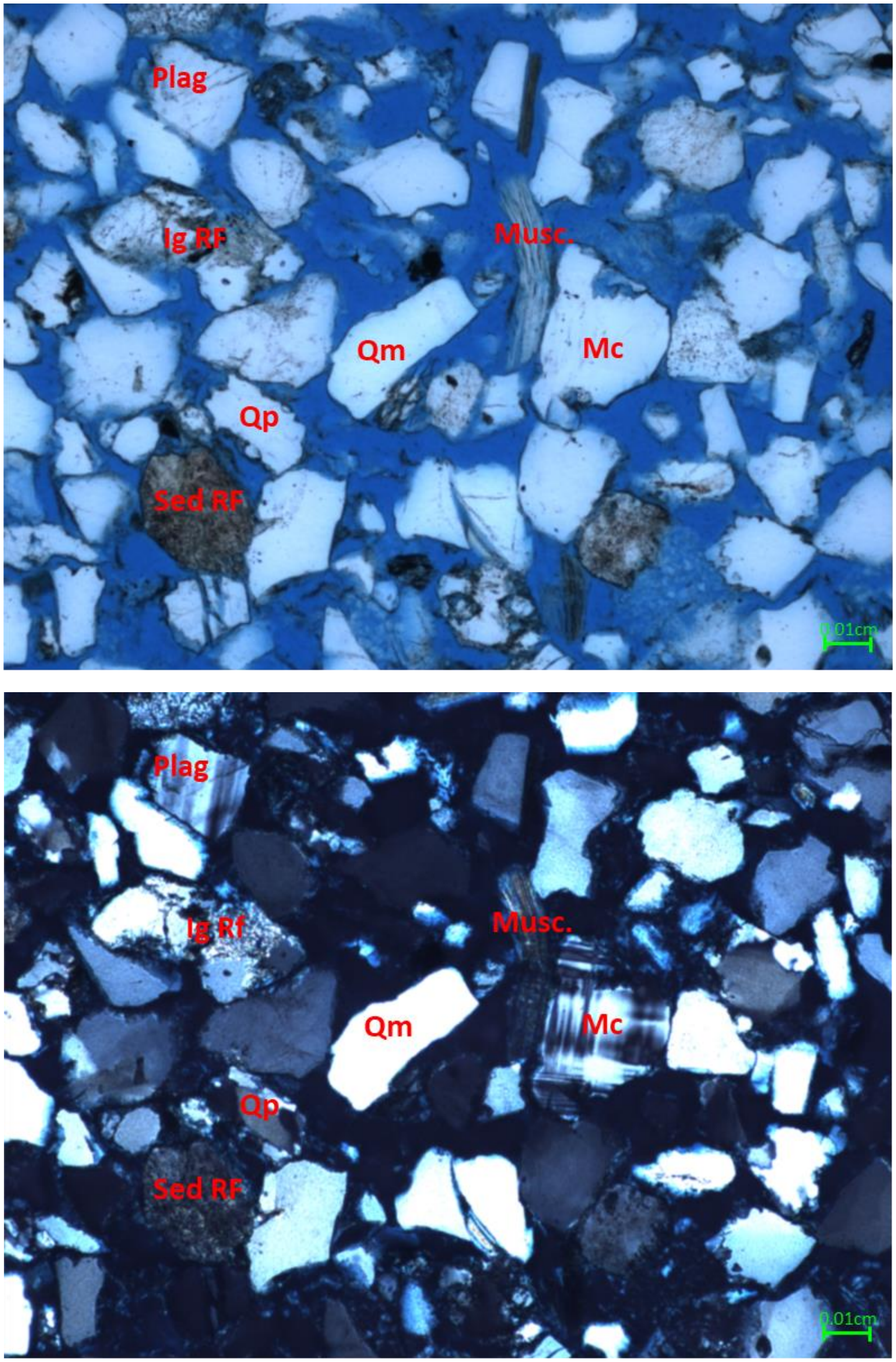

Figure 21. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of Washita-Fredericksburg sandstone (MPC 34-1, 4855.3 ft., 5x) showing abundant monocrystalline (Qm) and polycrystalline (Qp) quartz as well as other common framework grains (Plag=plagioclase, Ig RF=igneous rock fragment, Musc.=muscovite, Sed RF=sedimentary rock fragment, Mc=microcline).

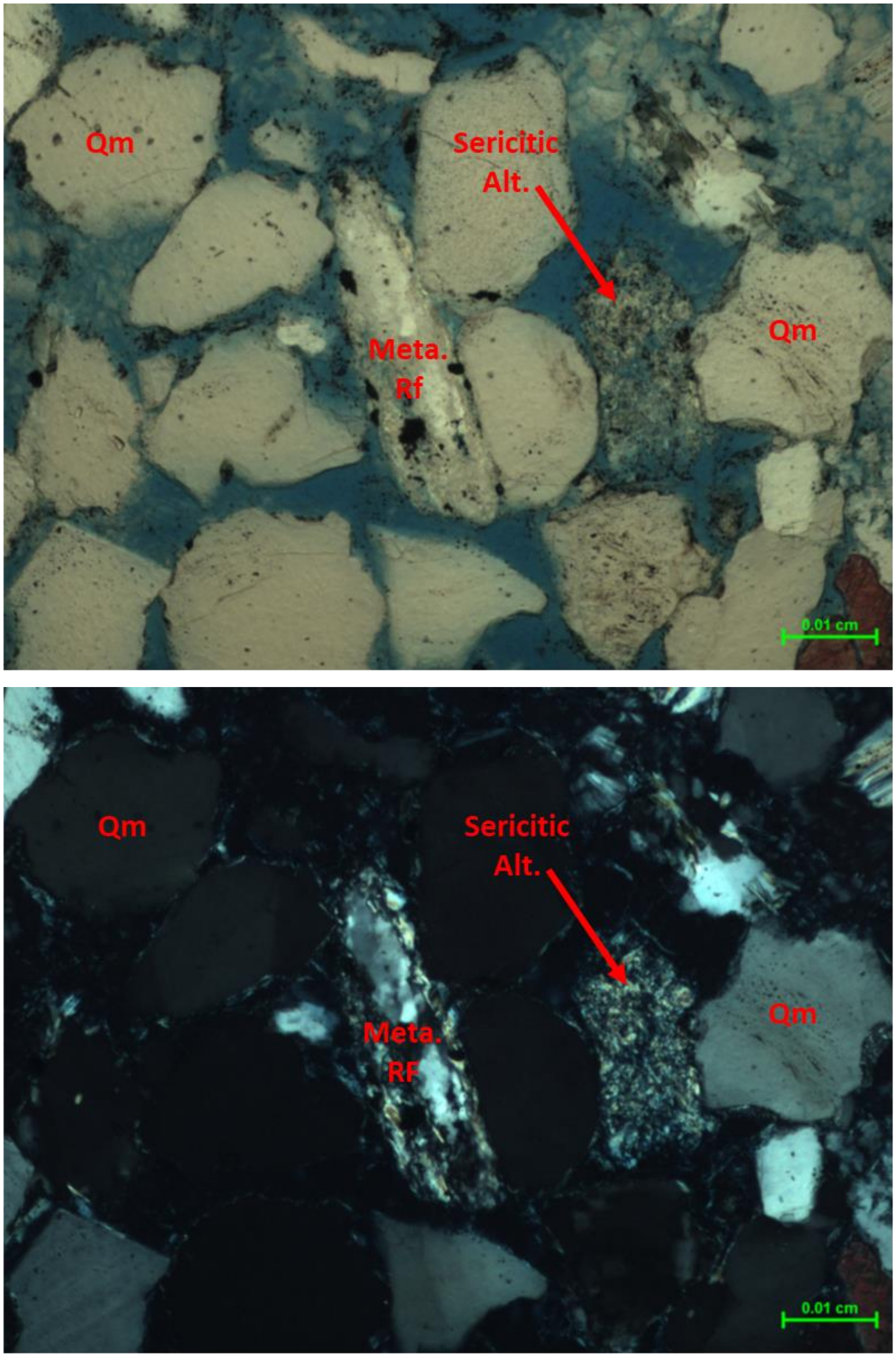

Figure 22. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of Washita-Fredericksburg sandstone (MPC 34-1, 4858 ft., 10x) showing a sericitized feldspar grain and a schistose metamorphic rock fragment surrounded by monocrystalline quartz grains.

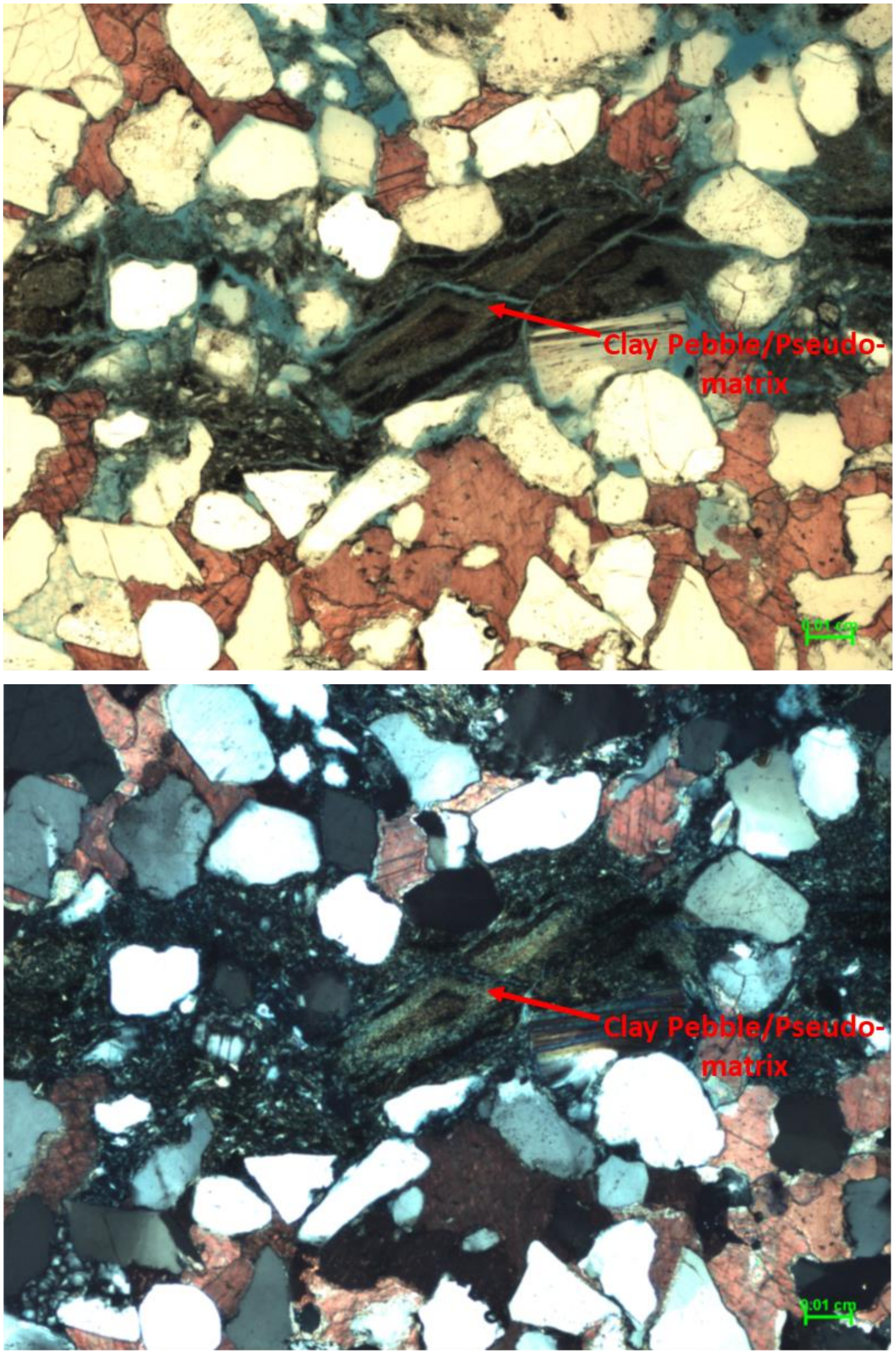

Figure 23. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of Washita-Fredericksburg sandstone (MPC 34-1, 4861.75 ft., 5x) showing an argillaceous rock fragment that has been compacted between framework grains. Most intergranular space is filled with interparticle calcite cement that appears pink from alizarin staining.

Muscovite is the most common accessory mineral observed in the Washita-Fredericksburg interval. Muscovite is commonly bent at the margins of other framework grains (Figure 24). Calcite cement is more abundant in the Washita-Fredericksburg interval than in the Paluxy Formation, although it was not observed in every thin section. Where observed, the calcite cement is in patches. Furthermore, some thin sections contain sandstone with a notable amount fine-grained matrix. Thin sections with intergranular argillaceous matrix commonly occur in samples with a significant amount of calcite cement (Figure 25).

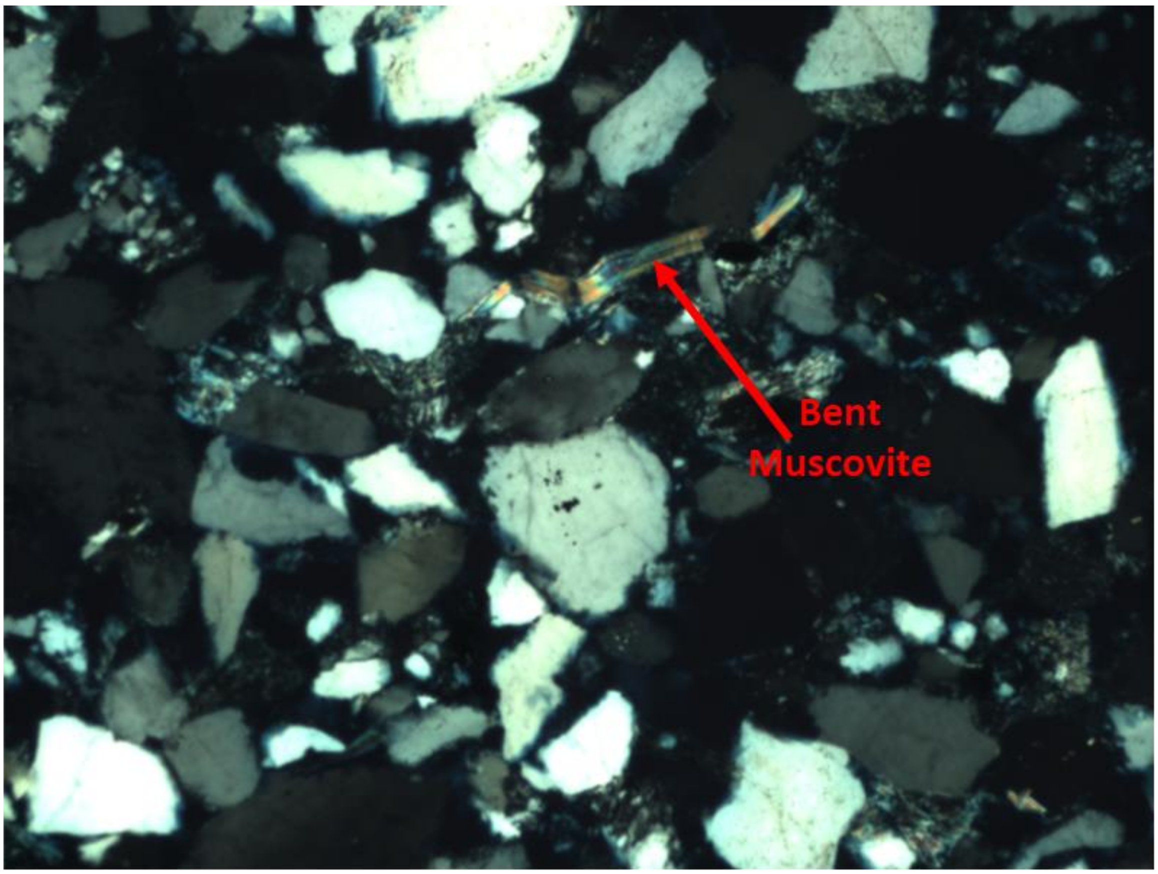

Figure 24. Cross-polarized thin section photomicrograph of Washita-Fredericksburg sandstone (MPC 34-1, 4858 ft., 5x) with a grain of muscovite being bent between quartzose framework grains.

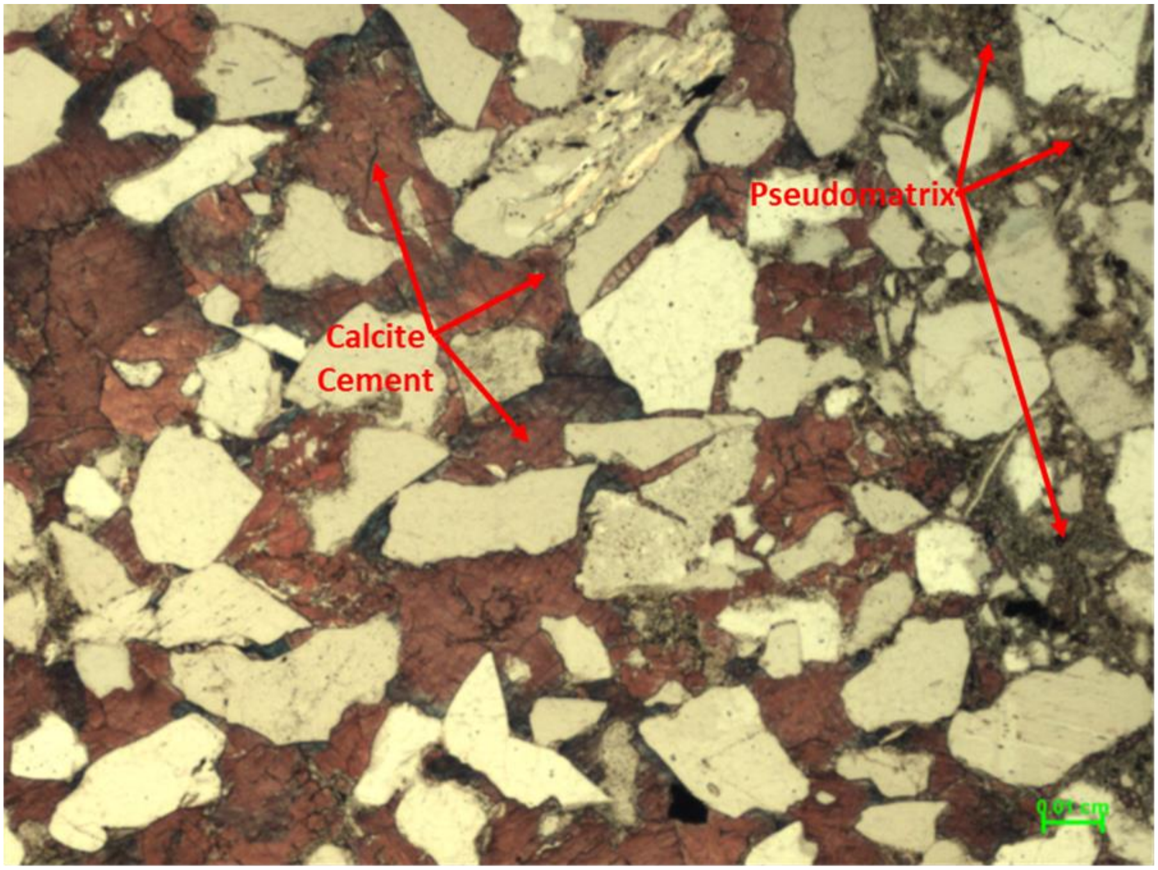

Figure 25. Plane-polarized thin section photomicrograph of Washita-Fredericksburg sandstone (MPC 34-1, 4863 ft., 5x) with an abundance of calcite cement and fine-grained pseudomatrix.

The Massive sand of the lower Tuscaloosa Group (Figure 26) was also point counted. However, due to the unit being effectively unconsolidated and liquefied during coring, original fabric was not preserved in the thin sections. Thus, lower Tuscaloosa thin sections are only useful for analyzing sandstone composition and grain alteration.

Grain sizes range from very fine (0.1mm) to medium sand (0.23mm), and the grains are typically subangular to subround. The thin sections dominantly contain monocrystalline and polycrystalline quartz (59-87%). Much like the other Cretaceous sandstone units, monocrystalline quartz commonly has undulatory extinction, and polycrystalline quartz grains commonly have sutured internal boundaries.

Feldspar is the second most abundant framework grain type in the lower Tuscaloosa. Thin sections of the lower Tuscaloosa were stained with potassium ferricyanide, which was not done for thin sections of the other Cretaceous sandstones. Feldspar content ranges from 13 to 33%. Dissolution and vacuolization of feldspar was observed that is similar to that in the Washita-Fredericksburg interval.

The lower Tuscaloosa contains the smallest percentage of lithic fragments (1-8%) of the formations studied. Though the types of lithic fragments observed were similar to those in the Paluxy and Washita-Fredericksburg and consist of metamorphic rock fragments, chert, and igneous rock fragments. Muscovite is a common accessory mineral, and no cement or detrital matrix was observed within the Massive sand.

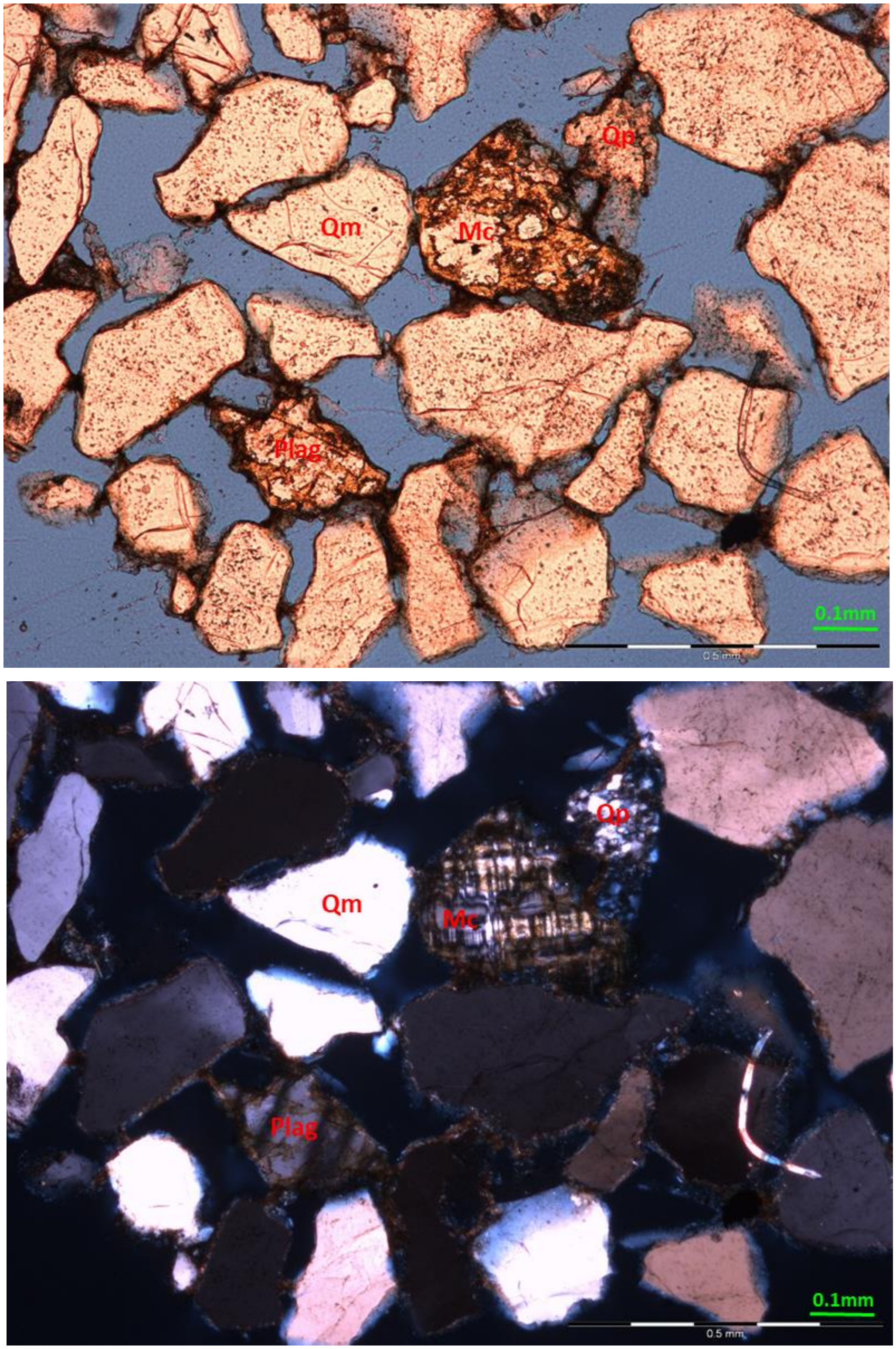

Figure 26. Plane-polarized (top) and cross-polarized (bottom) thin section photomicrographs of the the Massive sand of the lower Tuscaloosa Group (MPC 26-5, 3645 ft., 10x) showing feldspar stained brown by potassium ferricyanide, polycrystalline quartz (Qp), and an abundance of monocrystalline quartz (Qm).

Reservoir Properties

As previously mentioned, sandstone is qualified as reservoir in this study if it has a gamma-ray value of less than 75 API units and a density porosity value ≥15%. Figure 27 is a net reservoir sandstone isolith map of the Paluxy. In the study area, the Paluxy averages 74% sandstone, with an average net reservoir sandstone to gross sandstone ratio of 0.83. Sandstone bodies range from >5 feet thick to ~125 feet. Sandstone porosity is exceptionally high, with values ranging from 13% to more than 30% and an average porosity of 26.3%. While Paluxy sandstone generally is of reservoir quality, variable thickness and inability to correlate sandstone units between wells reflects a high degree of lateral heterogeneity.

Overall, the Washita-Fredericksburg interval is sand-rich but contains more mudstone than in the Paluxy with the average sandstone content in the study area being 63%. However, the average net reservoir sandstone to gross sandstone ratio is slightly higher for the Washita-Fredericksburg at 0.87. Figure 28 shows net reservoir sandstone thickness. Sandstone bodies range in thickness from >5 feet to ~130 feet. Porosity exceeds 35% in some sandstone bodies and averages 27.4% in the study area.

The Massive sand is easily correlated throughout the study area. The Massive sand in the study area is on average 90% sandstone, with a net reservoir sandstone to gross sandstone ratio of 0.95. Figure 29 shows the net thickness of reservoir sandstone in the lower Tuscaloosa. The thickest body of sandstone in the Massive sand is ~195 feet thick. The lower Tuscaloosa has the overall highest porosity with values ranging from 20 to nearly 40% with an average of 28.8%.

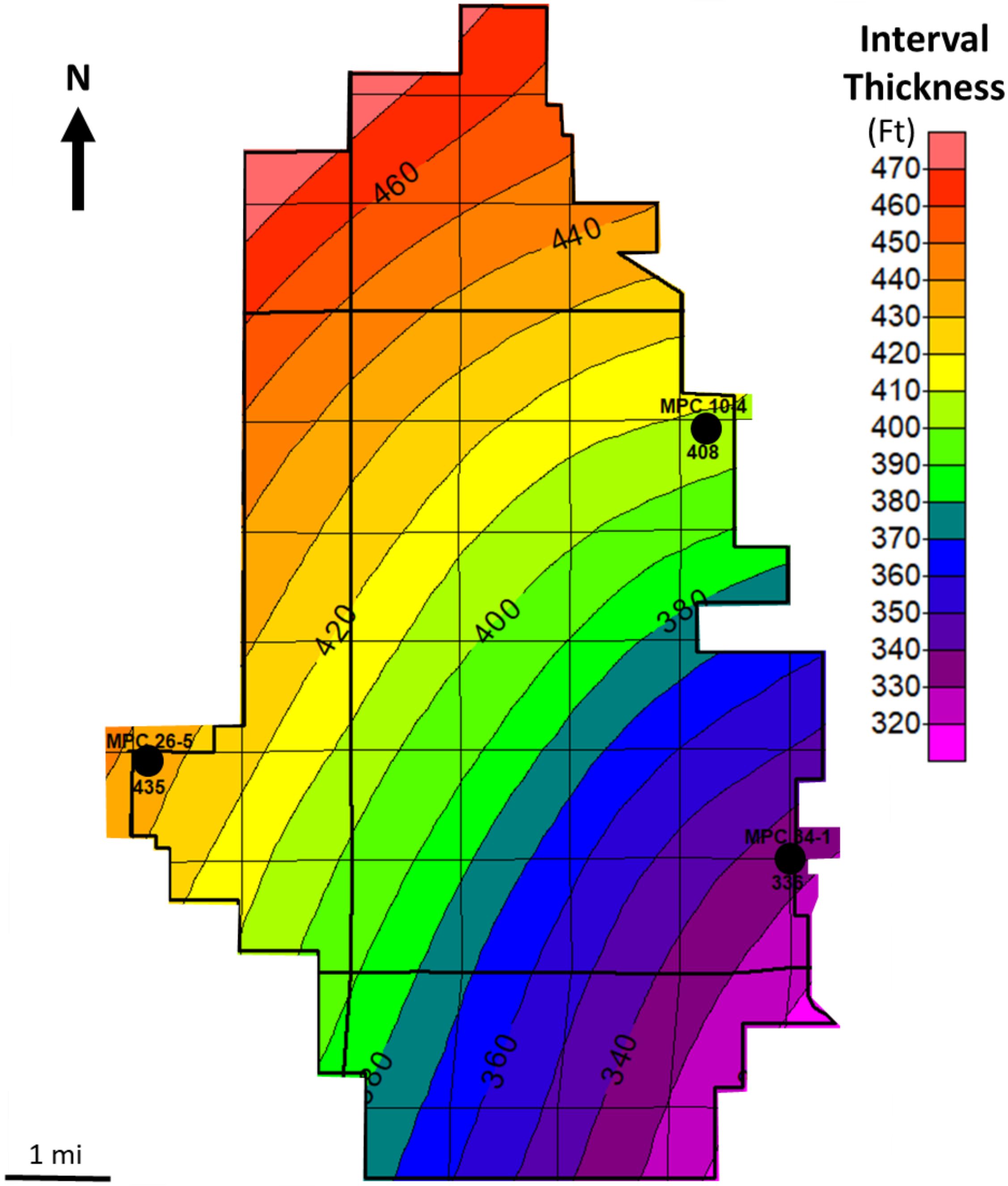

Figure 27. Net reservoir sandstone isolith map of the Paluxy Formation. Reservoir quality sandstone increases in thickness to the northwest, with the most reservoir sandstone occurring in well MPC 26-5. Contour interval = 10 ft.

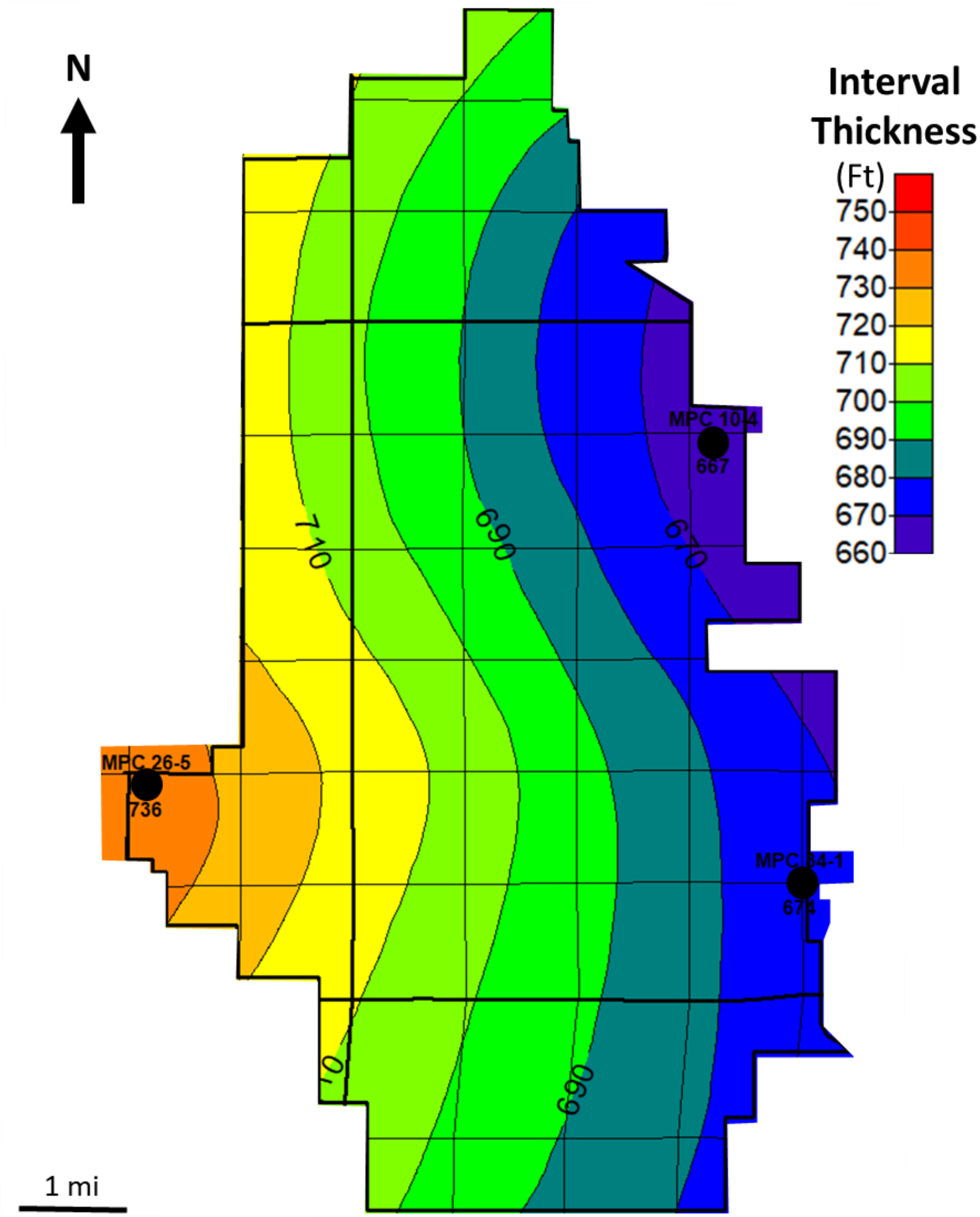

Figure 28. Net reservoir sandstone isolith map of the Washita-Fredericksburg interval. Reservoir quality sandstone increases in thickness to the west, with the most reservoir sandstone occurring in well MPC 26-5. Contour interval = 10 ft.

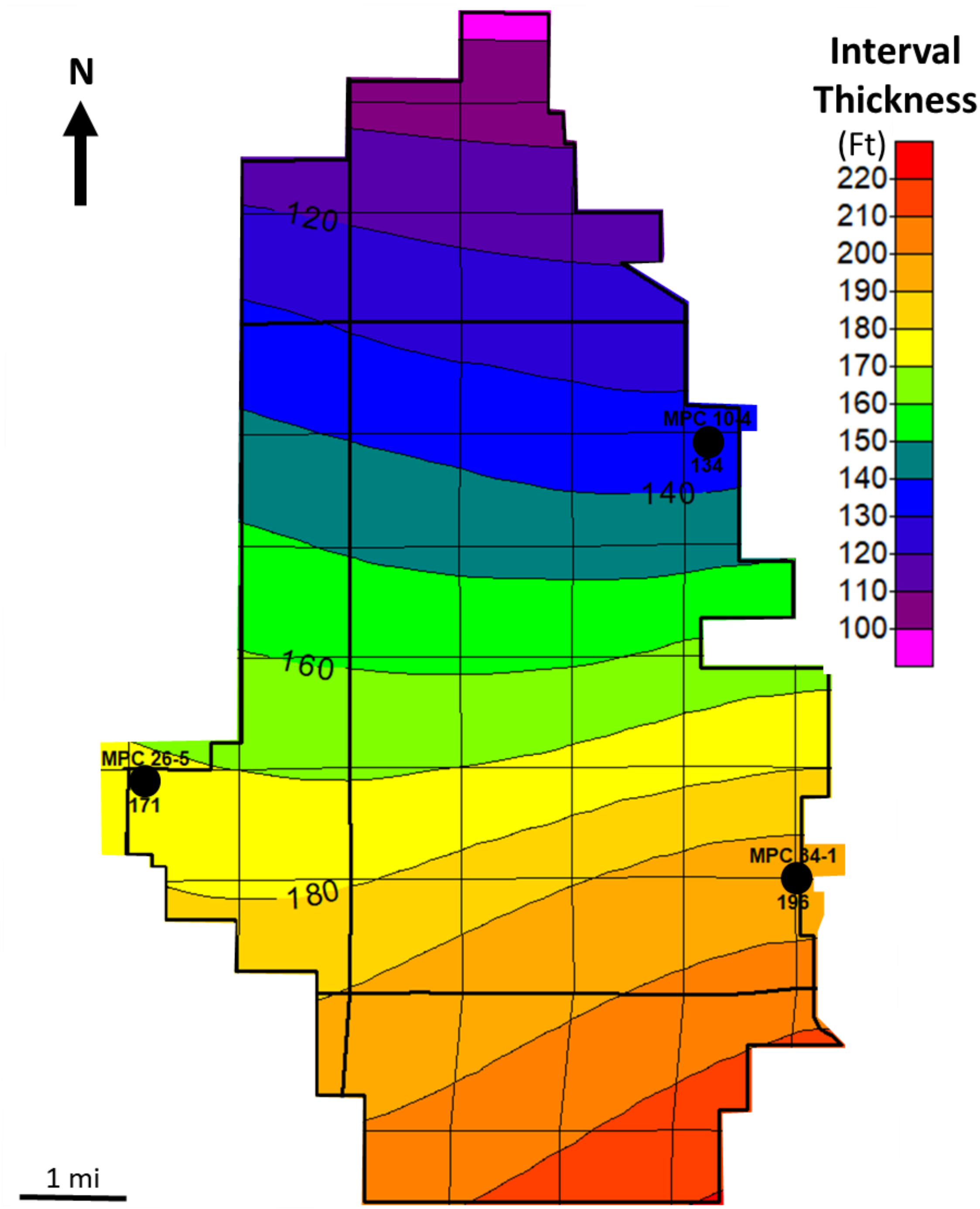

Figure 29. Net reservoir sandstone isolith map of the lower Tuscaloosa. Reservoir quality sandstone increases in thickness to the south/southeast, with the most reservoir sandstone occurring in well MPC 34-1. Contour interval = 10 ft.

Volumetric Analysis

CO_2 reaches the critical point (31.1°C and 7.38 MPa) at approximately 2,480 feet under normal geothermal and hydrostatic gradients; therefore, CO_2 is expected to be stored as a supercritical fluid within all zones being considered for storage (Figure 30). Average reservoir temperature for

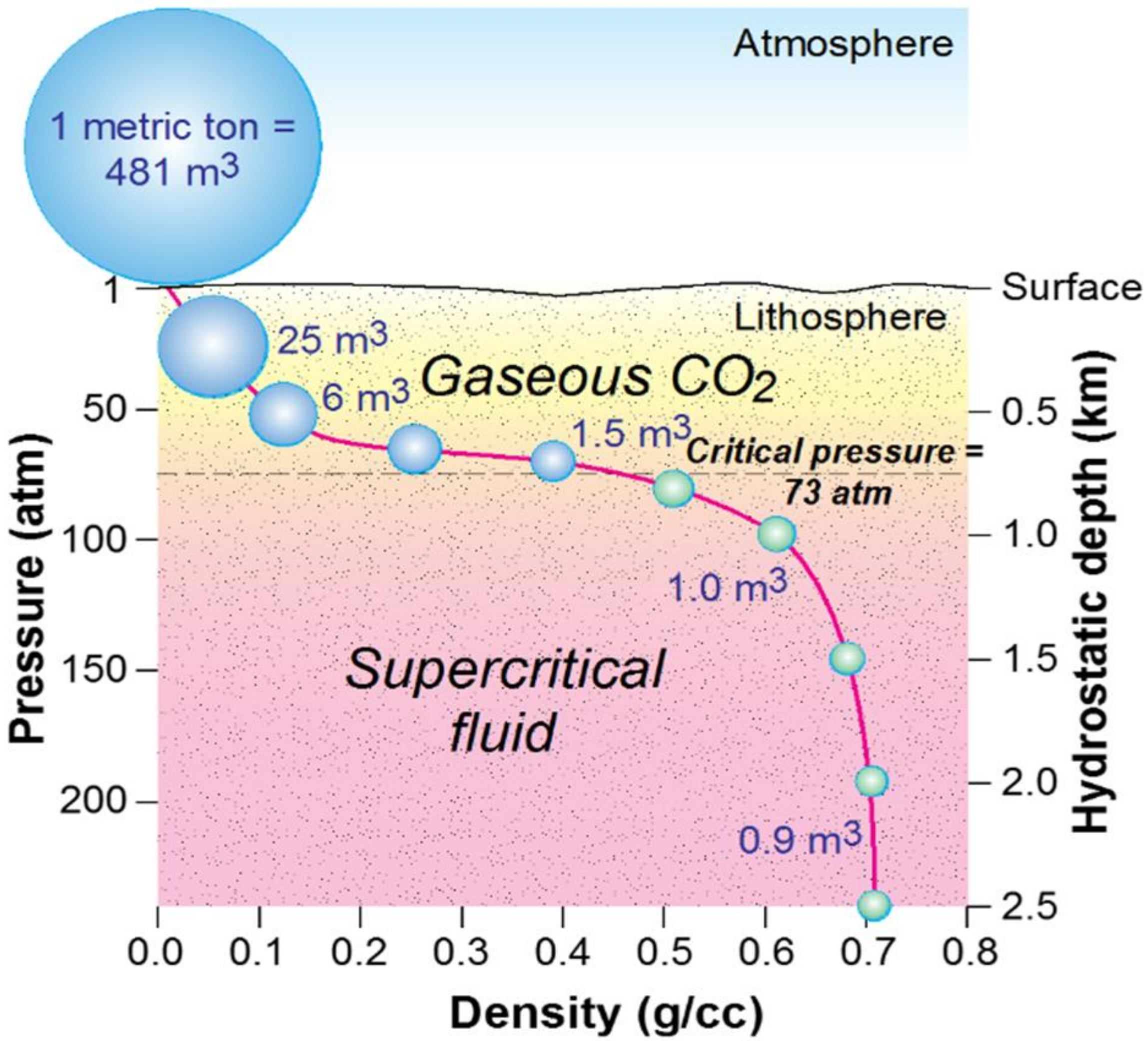

Figure 30. CO_2 density change with increasing depth (Pashin, 2016).

Cretaceous sandstone was determined by using bottom-hole temperatures (BHT). Furthermore, reservoir pressure was estimated by using geochemical data from the interior salt basins of Mississippi, Alabama, and Florida to constrain brine density (Pashin and Payton, 2005). These criteria are necessary components for calculating storage capacity and have been listed in Table 3. Furthermore, CO_2 density is another criteria used to calculate storage capacity and can be estimated using Bachu's (2003) PVT chart (Figure 31). Thus, approximate CO_2 density is about 710 kg/m^3 in the Paluxy Formation, 680 kg/m^3 in the Washita-Fredericksburg interval, and 650 kg/m^3 in the lower Tuscaloosa Group. Table 3 is a summary of the parameters used to calculate the storage capacity of the Paluxy Formation, Washita-Fredericksburg interval, and lower Tuscaloosa.

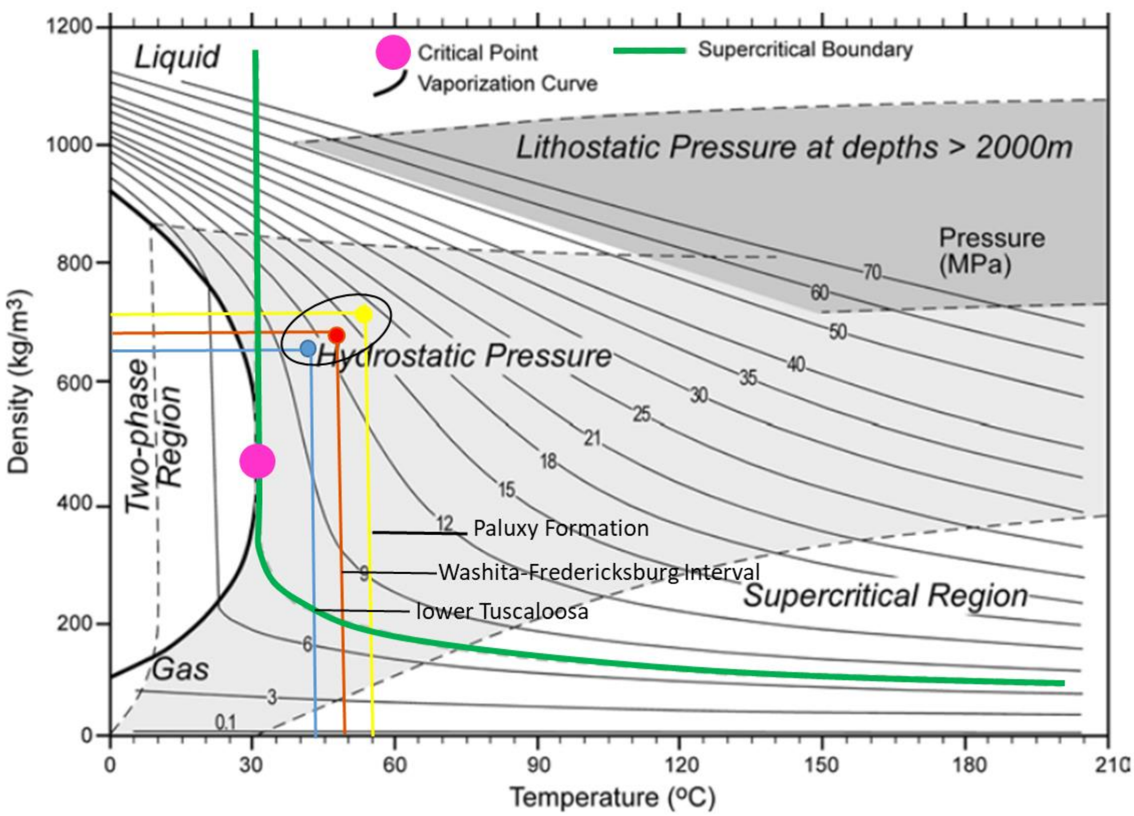

Figure 31. Variation of CO_2 density as a function of temperature and pressure (modified from Bachu, 2003).

Table 3. Reservoir properties in the Paluxy Formation, Washita-Fredericksburg interval, and the lower Tuscaloosa Group.

Reservoir Parameters	Paluxy	Washita-Fredericksburg	Lower Tuscaloosa
Reservoir Area (km^2)	137	137	137
Average Sandstone Thickness (ft)	392.8	692	166.9
Average Porosity (%)	26.3	27.4	28.8
Average Reservoir Depth (ft)	5222	4255	3564
Average Reservoir Temperature (°C)	55	48	43
Average Reservoir Pressure (Mpa)	17	13	11
CO_2 Density at Reservoir Depth (kg/m^3)	710	680	650
Reservoir Capacity at 100% Saturation (Mt)	3062	5383	1304

The CO_2 storage resource in the Paluxy Formation, Washita-Fredericksburg interval, and the lower Tuscaloosa Group was estimated using efficiency factors for well-defined saline reservoirs shown in Table 4. The total P_{50} CO_2 storage resource was estimated at 428 Megatonnes (Mt) in the Paluxy Formation, 753 Mt in the Washita-Fredericksburg interval, and 182 Mt in the lower Tuscaloosa Group. Table 5 shows the average storage capacity in Mt per unit area.

Table 4. Estimated storage resource in the Paluxy Formation, Washita-Fredericksburg interval, and lower Tuscaloosa Group using efficiency factors for displacement terms.

Categories	Paluxy	Washita-Fredericksburg	Lower Tuscaloosa	Total
Efficiency Factor (P_{10})%	7.4	7.4	7.4	
Efficiency Factor (P_{50})%	14	14	14	
Efficiency Factor (P_{90})%	24	24	24	
Reservoir CO_2 Storage Resource (P_{10}) (Mt)	226	398	96	720
Reservoir CO_2 Storage Resource (P_{50}) (Mt)	428	753	182	1363
Reservoir CO_2 Storage Resource (P_{90}) (Mt)	735	1292	313	2340
Reservoir Capacity at 100% Saturation (Mt)	3062	5383	1304	9749

Table 5. P_{50} storage resource per unit area for the Paluxy Formation, Washita-Fredericksburg interval, and the lower Tuscaloosa Group.

Categories	Paluxy	Washita-Fredericksburg	Lower Tuscaloosa
G (P_{50}/km^2) (Mt)	3.1	5.5	1.3
G (P_{50}/mi^2) (Mt)	8	14.2	3.4

In addition, maps were made to illustrate the P_{50} storage resource potential per unit area (Mt/mi^2) across the study area for the Paluxy Formation, Washita-Fredericksburg interval, and the lower Tuscaloosa (Figure 32). Figure 32 (A) shows the Paluxy Formation having a storage resource that exceeds 9.5 Mt/mi^2 in the northwest portion of the study area where the sandstone of reservoir quality is the thickest. The Washita-Fredericksburg interval (Figure 32 B) has a storage resource that exceeds 14.75 Mt/mi^2 in the western portion of the study area which is roughly a 1 Mt/mi^2 difference to that of the eastern part. Lastly, the lower Tuscaloosa (Figure 32 C) contains the highest storage resource in the southern part of the energy facilities acreage. The southern part has resource values over 4.0 Mt/mi^2 comparative to the north which sits at approximately 1.5 Mt/mi^2. Importantly, these storage resource distributions follow patterns observed in the net reservoir sandstone isolith maps. Given the exceptionally high porosity seen across control points the single most important variable that plays on these values is qualified reservoir sandstone volume.

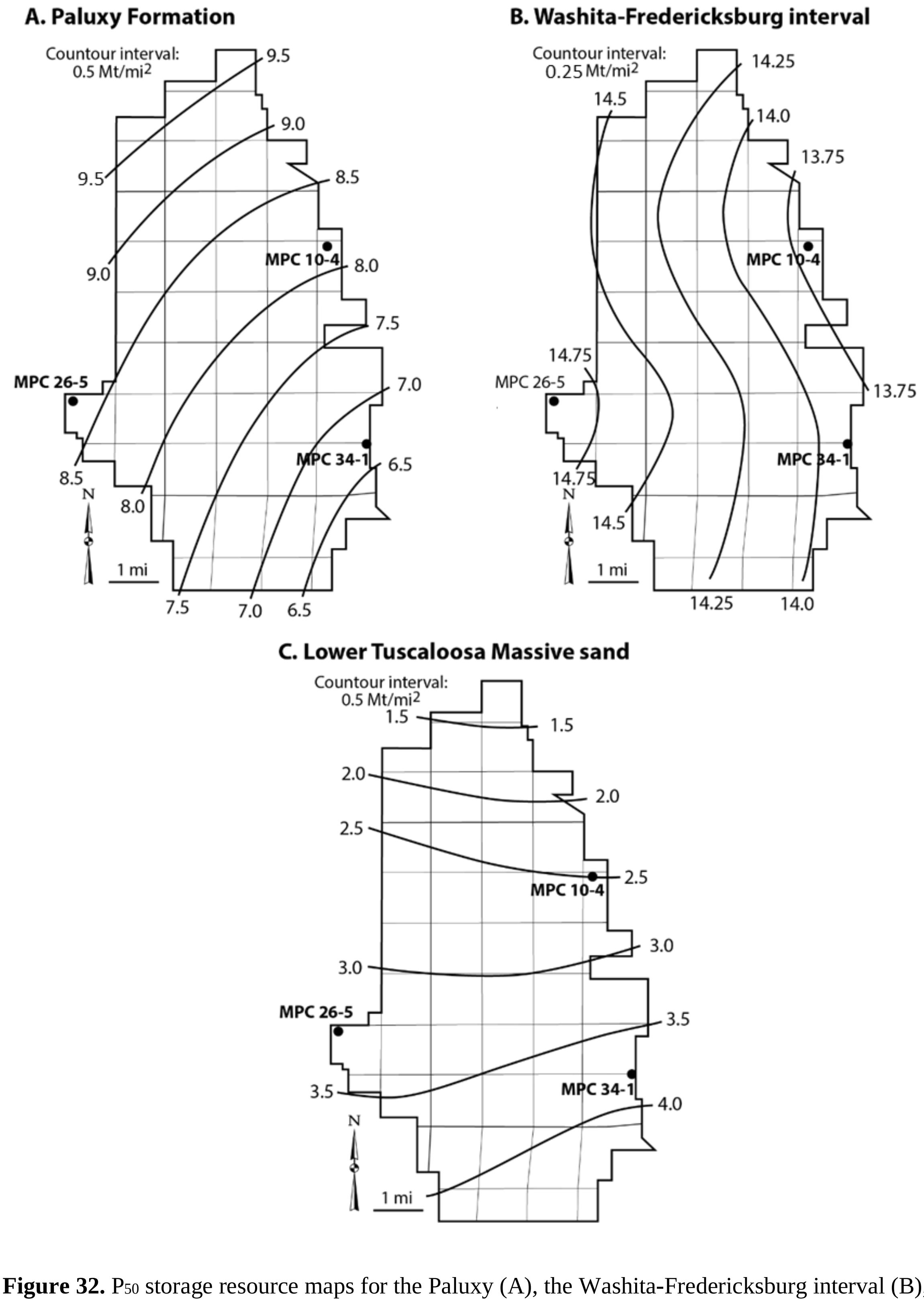

Figure 32. P_{50} storage resource maps for the Paluxy (A), the Washita-Fredericksburg interval (B), and the lower Tuscaloosa (C). Storage resource patterns fall closely in line with net reservoir sandstone isolith maps (Figures 27-29).

CHAPTER IV

DISCUSSION

Provenance

Framework grain composition and character such as angularity, roundness, and sphereicity are extremely similar among sandstone in the Paluxy Formation, Washita-Fredericksburg interval, and lower Tuscaloosa Group. Therefore, the sediment source for each unit bears some level of similarity. Due to many of the polycrystalline quartz grains having sutured grain boundaries and internal crystals elongated in one direction, polycrystalline quartz grains were plotted as lithic rock fragments for provenance determination. That said, when plotting sandstone composition on the ternary provenance diagrams of Dickinson and Suczek (1979) and Dickinson et al. (1983), Cretaceous sandstone is dominated by monocrystalline quartz but contains a significant amount of lithic rock fragments with polycrystalline quartz and schistose grains being common. Additionally, the common occurrence of grains exhibiting undualtory extinction, in conjunction with variable polycrystalline quartz grain boundaries, suggests sediment underwent significant stress alluding to regional metamorphism or plutonic origins. In the provenance ternary diagram, sandstone plots dominantly as recycled orogenic (Figure 33). However, this classification is only representative of the in-situ sandstone

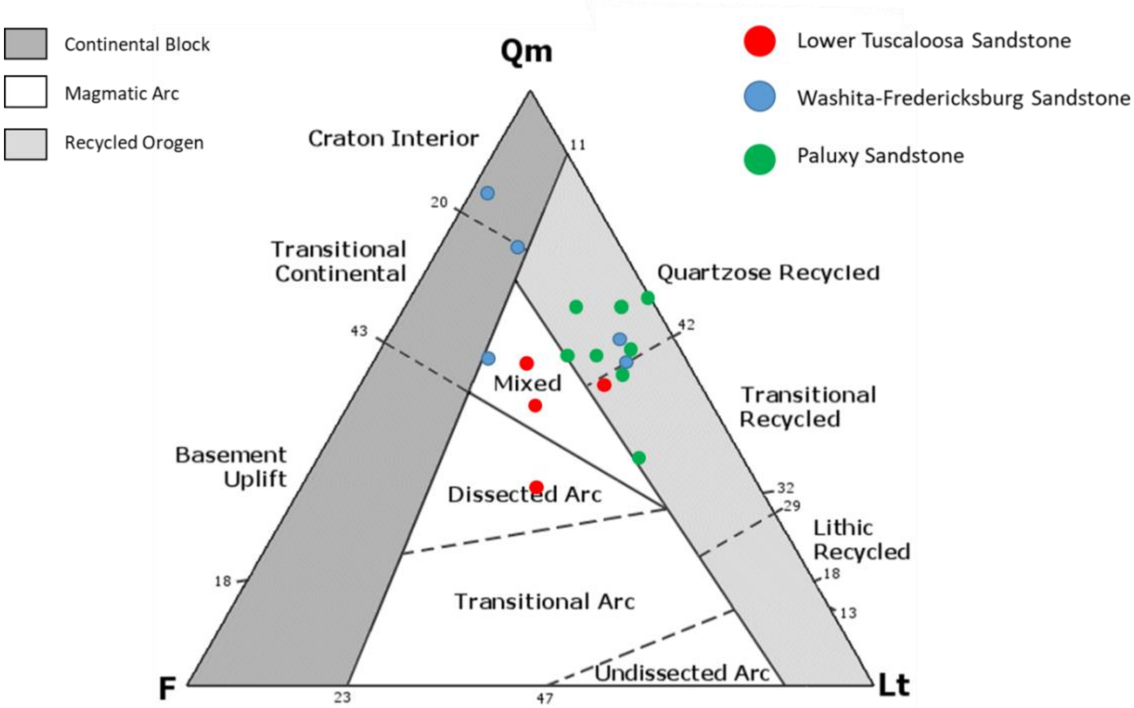

Figure 33. Provenance ternary diagram of the Paluxy Formation, the Washita-Fredericksburg interval, and the lower Tuscaloosa (modified from Dickinson et al., 1973, 1983).

composition. It was previously noted that Cretaceous sandstone has had a significant amount of feldspar that was dissolved, as suggested by grain-size voids with stranded clay coats. Therefore, in order to more accurately interpret provenance, an attempt to restore the original composition was made by assuming all moldic pores were originally feldspar grains. In doing so, Figure 34 shows a compositional ternary diagram revealing that the interpreted original sandstone composition would have been significantly more arkosic than what is observed today. Similarly, Figure 35 shows the potential source type from the interpreted original composition as being dominantly mixed origins.

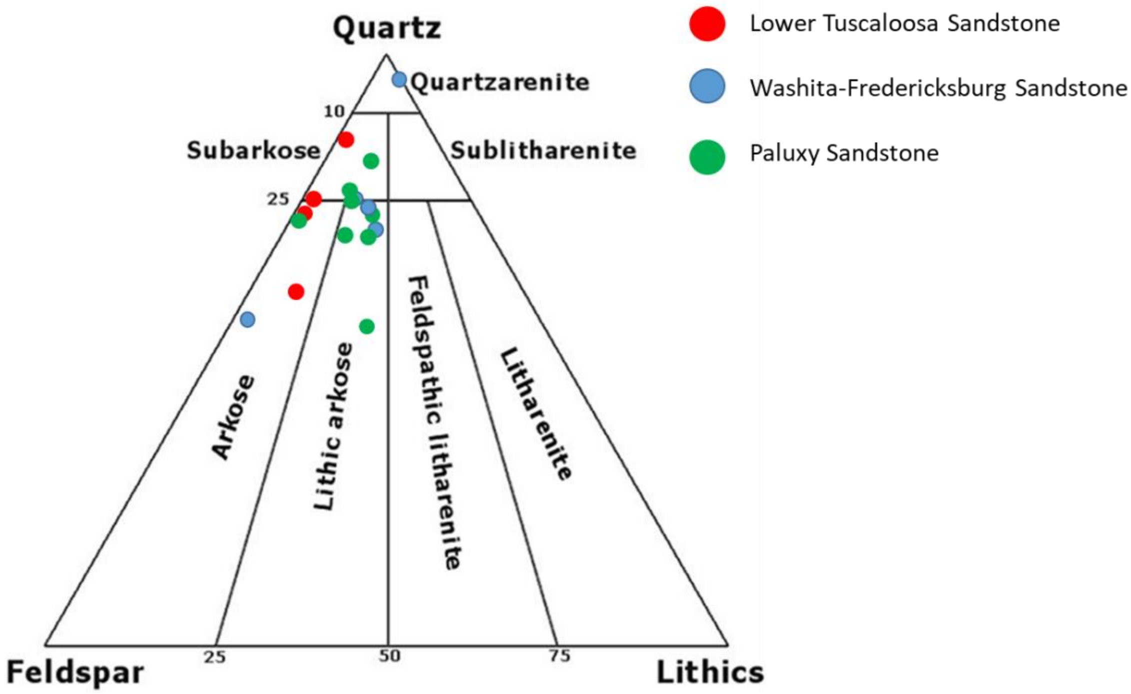

Figure 34. Interpreted original composition of the Paluxy, Washita-Fredericksburg, and lower Tuscaloosa sandstone (modified from Folk, 1980).

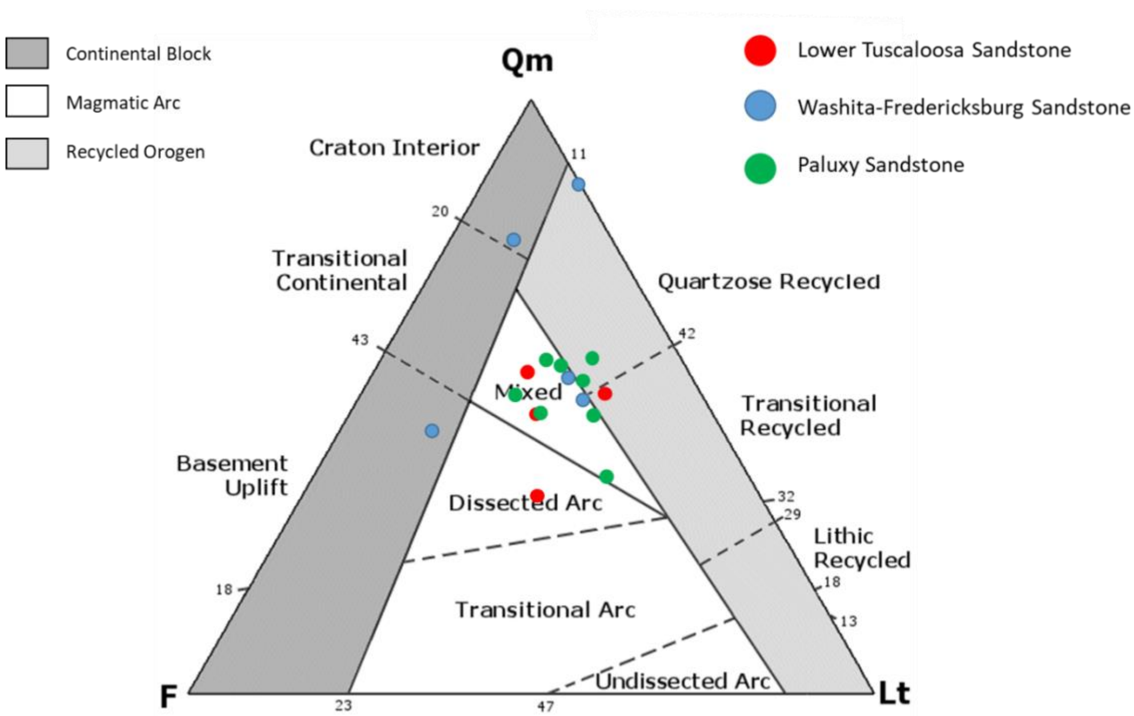

Figure 35. Provenance diagram using the corrected original composition of the Paluxy, Washita-Fredericksburg, and lower Tuscaloosa sandstone (modified from Dickinson et al., 1973, 1983).

The rectified composition of Cretaceous sandstone suggests that the study area is somewhat of a melting pot in terms of sediment sources with the dominant source code being mixed. The abundance of strained polycrystalline quartz and common occurrence of schistose rock fragments definitely implies that a significant amount of sediment can be attributed to the unroofing of the Appalachian Orogen. The observation of oolitic chert also implies sediment input from Paleozoic carbonates, which could have potentially been sourced from the adjacent Black Warrior Basin, as well as other sedimentary sources, such as the Appalachian thrust belt as well as other basins and arches. Lastly, the original composition of Cretaceous sandstone was significantly more arkosic than it is today. This suggests that some sediment could originate from stable, feldspar rich, basement provinces such as the Canadian Shield and thus have traveled very far. However, it must also be noted that formation micro-imaging (FMI) data reveals that the Paluxy exhibits a strong unidirectional flow to the north/northwest suggesting a tributary flow to the greater Mississippi Valley with the ultimate sources being in the Appalachian region (Pashin et al., 2020).

Depositional Environment

The Paluxy Formation, Washita-Fredericksburg interval, and lower Tuscaloosa Group are similar in that they are composed of numerous stacked sandstone and mudstone packages. Furthermore, sandstone units in the respective formations are similar in their composition, sedimentary structures, sedimentary accessories, and biogenic structures; with only minor differences. Dominant sedimentary structures are high-angle cross-beds, horizontal laminae, and current ripples. These sedimentary structures in conjunction with the dominantly upper medium to coarse grain size suggests deposition within a bedload dominated fluvial system (i.e., braided streams) (Galloway and Hobday, 2012). High-angle, planar cross-beds are by far the most prevalent sedimentary structure in Paluxy and Washita-Fredericksburg sandstones. These structures are commonly seen in transverse and linguoid bar deposits of low-sinuosity braided systems, as described by Miall (1977). Furthermore, Cant and Walker (1978) observed deposits with similar characteristics within transverse and linguoid bars of the modern South Saskatchewan River. The cross-bedded sandstone likely accreted via the down-stream migration of linguoid and transverse bars during high-energy flooding events, while the rippled and horizontally laminated sandstone was deposited during low flow events. A similar interpretation was made for Paluxy sandstone by Folaranmi (2015) in Citronelle Dome in southwest Alabama. The lower Tuscaloosa, due to coring issues, was not described in detail but has been interpreted by Mancini et al. (1996) as transgressive fluvial and shoreline deposits.

Biogenic structures are limited to meniscate burrows likely that of insects (Hasiotis, 2002), and sedimentary features such as root traces point to the development of vegetation and paleosols. Together these features suggest that channel and bar deposits were eventually stranded and subaerially exposed for long periods of time. Additionally, it is likely during these long periods of subaerial exposure that sediment underwent the majority of diagenetic alteration.

As it was mentioned in the petrologic analysis methods, many feldspar grains observed in the studied Cretaceous sandstone have been partially dissolved and/or vacuolized. While some of the void space is occupied by pore-filling kaolinite, the majority of it is free of debris likely due to active fluid transport moving altered and degraded feldspars out of the system. The delicate morphology of the kaolinite suggests authigenic origins and therefore could have been the result of feldspar alteration. Heald and Larese (1973) identified kaolinite in the Berea and Mt. Simon sandstone formations from the alteration of unstable feldspar grains. Of the framework grains observed, feldspars appear to be the least stable given no other grains displayed any degree of dissolution or degradation. Therefore, it is interpreted that the moldic and oversized pores (two types of secondary pores) occur from the complete dissolution of feldspars (Schmidt and McDonald, 1979). Schmidt and McDonald (1979) also noted that carbonic acid from CO_2 in meteoric water plays an important role in grain dissolution. Such water is a viable possibility in the proposed depositional environment of a bedload dominated braided system which would have been adequate to alter, leach, and transport degradation products out of the system. Work performed by Emery et al., (1990) concluded that subaerial exposure and freshwater played a major role in the leaching of feldspars in the Jurassic Magnus sandstone of the North Sea.

Potential Reservoirs

Stratigraphic analysis shows that the Paluxy Formation dips south-southwest and is thickest in the northwestern portion of the study area. The Paluxy is interpreted to be the result of bedload-dominated fluvial sedimentation, evident by characteristic sedimentary structures and gamma ray log characteristics that range from blocky to bell shaped. A high degree of lateral variability exists within the Paluxy as suggested by the lack correlation between wells. This reflects the complexity of the depositional system. Thickness of reservoir quality sandstone bodies throughout the Paluxy ranges from less than 5 feet to more than 100 feet with an average thickness of about 30 feet. Petrologic analysis shows that depositional and diagenetic processes are key contributors to reservoir architecture such as detrital clay coats, which inhibited authigenic cementation and feldspar dissolution, which increased porosity. Pittman et al. (1992) attributed the preservation of porosity in sandstones such as the Berea and the Tuscaloosa from the occurrence of clay coats.

The Washita-Fredericksburg is the thickest interval and as such contains the most qualified sandstone for sequestration. Log character of the Washita-Fredericksburg is dominantly blocky, which in conjunction with the core analysis, suggest deposition via bedload dominated fluvial systems. While the Washita-Fredericksburg displays lateral heterogeneity, the large accumulation of sandstone referred to as the Big Fred towards the middle of the interval are easily recognized throughout the study area. That said, the majority of the storage potential lies within the Big Fred; however, there are numerous single-storey sandstone bodies interbedded with mudstone in the upper and lower portion of the Washita-Fredericksburg interval that can provide significant storage.

The third potential reservoir in the study area is the Massive sand of the lower Tuscaloosa Group. The lower Tuscaloosa contains the Massive sand which displays a characteristically blocky log signature and has an average reservoir thickness of nearly 170 feet in the study area. The lower Tuscaloosa is interpreted to be deposited as part of a transgressive shore zone system (Mancini and others, 1987; Mancini and Puckett, 2005). The lower Tuscaloosa, like the Washita-Fredericksburg and Paluxy dips gently southwest, while the thickest succession of reservoir rock lies within the southeastern portion of the study area.

Storage Potential

Cretaceous strata in the area of the Kemper energy facility make up a structurally simple wedge of strata that dip homoclinally southwest and is capped by the Marine Tuscaloosa shale, which is regionally widespread. The repetitive sandstone and shale packages provide stacked potential for CO_2 injection with the shale layers acting as local baffles and barriers to flow, limiting upward and potentially lateral migration of the plume to the primary seal.

The size of the evaluated area is approximately 53 mi^2 (137 km^2) with an estimated P_{50} storage capacity of 428, 753, and 182 Mt for the Paluxy, Washita-Fredericksburg, and lower Tuscaloosa, respectively. Therefore, the combined storage capacity for the area is about 1.3 Gt. This supports the original hypothesis of Pashin et al. (2008) that the Kemper Energy Facility could provide gigatonne-class storage.

Volumetric analysis indicates that the Washita-Fredericksburg interval and the Paluxy Formation are the primary targets for injection, making up 86% of the storage potential. While the lower Tuscaloosa holds notable potential for CO_2 storage, caution must be taken as the interval is exposed at the surface in northwestern Alabama and contains fresh water updip (Pashin et al., 2008).

The Paluxy Formation and the Washita-Fredericksburg interval are restricted to the subsurface and display exceptionally low resistivity values and negative SP deflections. This suggests that they are completely saturated with saline water making them ideal for sequestration. When comparing the two, caution must be taken when considering the Paluxy, as significant differences in stacking patterns are observed among the three wells, making correlation of sand bodies nearly impossible and ultimately, making it difficult to predict plume migration. This can be attributed to complex depositional systems that contributed to a high degree of lateral variability.

CHAPTER V

CONCLUSION

Mesozoic-Cenozoic strata form a wedge of sediment that was deposited in the Gulf of Mexico Basin and thickens to the southwest in the area of the Kemper County energy facility. These strata disconformably overlie Paleozoic strata of the Appalachian-Ouachita Orogen in Kemper County, with the oldest Mesozoic strata being Early Cretaceous in age. Cretaceous strata onlap Paleozoic strata toward the northeast, and the Paluxy Formation and the Washita-Fredericksburg interval are completely restricted to the subsurface.

The area is a geologic crossroads marking the juncture among the late Paleozoic Appalachian and Ouachita orogenic belts and the prolific Black Warrior foreland basin; however the Cretaceous and younger deposits overlying the Appalachians are relatively understudied. Previous studies in the area have suggested a world-class potential for carbon sequestration.

The current study identified and evaluated the CO_2 storage potential for Cretaceous saline reservoirs in the area of the Kemper County energy facility, namely; the Paluxy Formation, the Washita-Fredericksburg interval, and the lower Tuscaloosa Group by delineating the stratigraphic framework, characterizing the depositional and diagenetic fabric, quantifying the storage capacity, and identifying optimal reservoirs. Such goals were achieved by employing an integrated geologic approach and using diverse analytical methods, including core analysis, thin section analysis, well log analysis, digital mapping, and volumetric assessment.

Stratigraphic analysis using well logs helped identify potential saline reservoirs that had exceptional reservoir characteristics (≥15% porosity and a gamma reading of ≤75 API units) within Cretaceous formations. Reservoirs identified are within the Paluxy Formation, the Washita-Fredericksburg interval, and the lower Tuscaloosa Group. All of these reservoirs are regionally extensive and contain thick porous zones, as well as interbedded shales that act as baffles and barriers to flow. The Paluxy and Washita-Fredericksburg contain saline water and are confined to the subsurface; however, the lower Tuscaloosa is exposed at the surface in northwestern Alabama and contains freshwater up-dip.

Cretaceous sandstone units within each formation all display some degree of lateral heterogeneity, which decreases moving upward in the section. The Paluxy Formation and Washita-Fredericksburg interval are interpreted to contain bedload dominated fluvial sandstone, while the lower Tuscaloosa is interpreted as a transgressive shoreline deposit.

Volumetric calculations show that the P_{50} storage capacity of Cretaceous saline reservoirs in the area of the Kemper Energy Facility is about 1.3 Gt. The Paluxy has the second largest volume with a P_{50} capacity of 428 Mt. The Washita-Fredericksburg interval has the most storage potential with a with a P_{50} capacity of 753 Mt. Finally, the lower Tuscaloosa has the smallest storage potential with a P_{50} storage capacity estimated at 182 Mt. CO_2 storage at the gigatonne scale over a relatively small acreage footprint is extremely encouraging and worthy of progressing to the next phase with the drilling of additional wells and an application for a Class VI Underground Injection Control permit.

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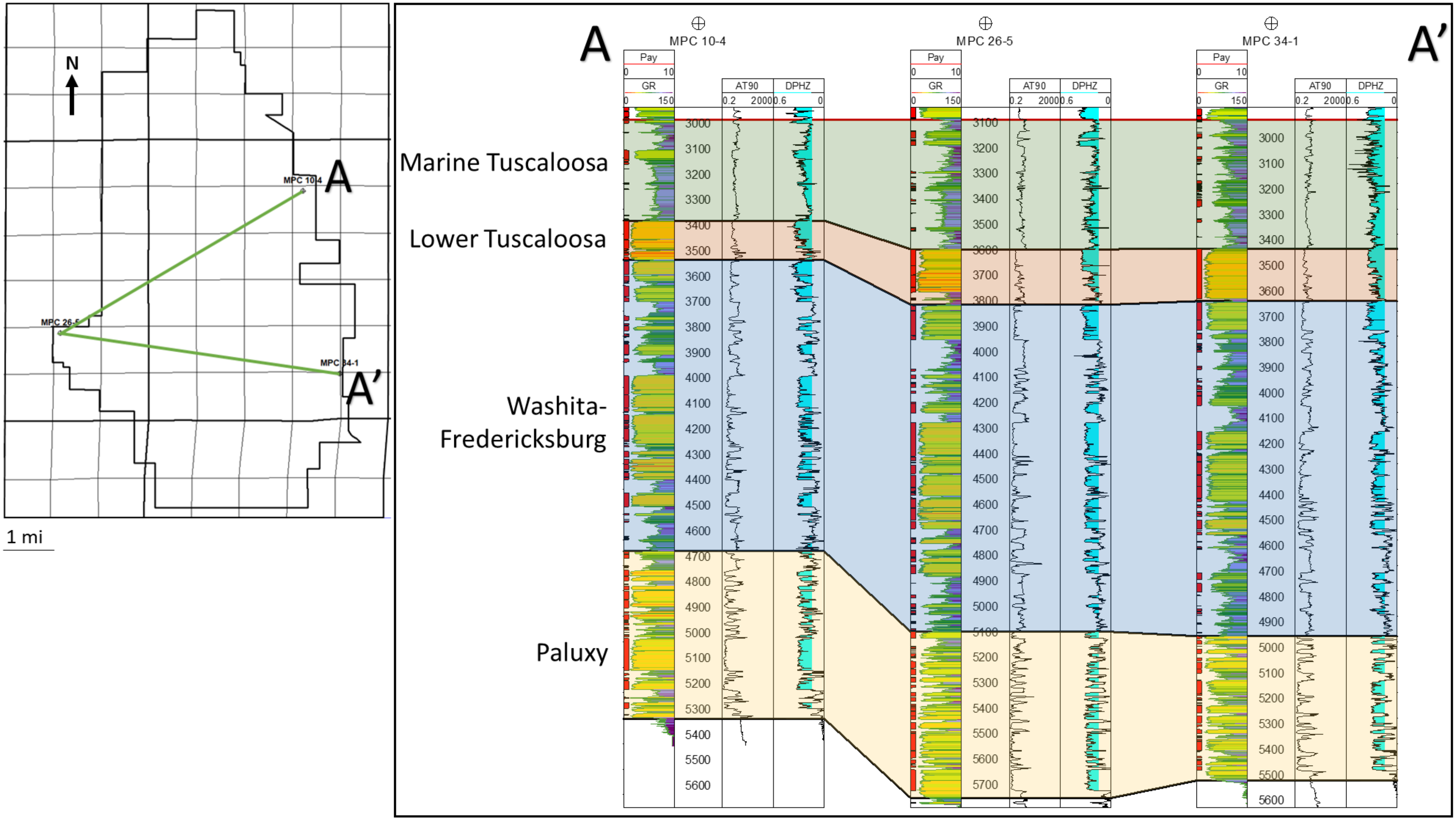

Plate 1. Map of Kemper Energy Facility acreage footprint with research well locations and cross-section from north to south showing stratigraphic framework of potential reservoirs and primary sealing unit (Marine Tuscaloosa). Red bars on the left side of each log represent sandstones that mean reservoir criteria (≥15% porosity and ≤75 API units). Datum=Marine Tuscaloosa.

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