DECIPHERING THE CLEVELAND SANDSTONE STRATIGRAPHIC FRAMEWORK: DIFFERENTIATING THE KIEFER AND OWASSO SANDSTONE COMPLEXES, NORTH-CENTRAL AND NORTHEASTERN OKLAHOMA

BY

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Abstract: The Cleveland sandstone interval contains a large Middle Pennsylvanian siliciclastic sediment dispersal system that covers a large portion of north-central Oklahoma including the Cherokee Platform, and host numerous oil and gas accumulations. The Cleveland sandstone interval, as used operationally by the petroleum industry, includes the stratigraphic section between the top of the Marmaton Group carbonates, frequently the Oologah Limestone (or "Big Lime") and the regionally extensive Checkerboard Limestone. Historically, most sandstones occurring in this interval were labeled "Cleveland" without considering their true age or stratigraphic position. Two primary Cleveland sandstone trends transect the study area: Kiefer and Owasso (Krumme, 1981). These sandstone complexes converge and intersect near the Cleveland Field Unit in Pawnee County, Oklahoma, which is operated by Mid-Con Energy. Mid-Con began a drilling program in 2011, followed by a secondary recovery (waterflood) program targeting the Cleveland sandstone. Discrepancies in production within the field prompted this study. One principal hypothesis was that the interaction between the Kiefer and Owasso sandstone complexes contributed to differences in rock properties that had an impact on production rates for wells in the Cleveland Field Unit, however, relating the production discrepancies to differentiated sandstones from the Kiefer or Owasso sandstone complex was not possible due to the complexities of these valleys. In order to test this hypothesis and evaluate the impact of the Kiefer and Owasso deposition on reservoir quality, detailed analyses of the stratigraphic framework, regional distribution, depositional lithotypes, and reservoir characteristics of the Kiefer, Owasso, and other Cleveland sandstones were completed. Findings of this study show that the Owasso sandstone complex occurs below the Nuyaka Creek Shale and is Marmaton aged, whereas the Kiefer sandstone complex is true Cleveland and in many cases fills a valley that eroded through the Nuyaka Creek Shale. Another key finding is that Marmaton carbonate paleotopography influenced Owasso complex distribution, but not the Kiefer, which is some cases appears to fill a deeply incised valley that eroded to the top and possibly removed Marmaton carbonate.

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CHAPTER I

INTRODUCTION

The Cleveland sandstone interval is part of a large siliciclastic sediment dispersal system, active during the Middle to Late Pennsylvanian, responsible for the formation of sandstone and interbedded siltstone and shale now present in parts of northeastern north-central Oklahoma including the Cherokee Platform. The Cleveland sandstone interval, as used operationally by the petroleum industry, includes the stratigraphic section between the top of the Marmaton Group carbonates, frequently the Oologah Limestone (or “Big Lime” by the oil and gas industry) and the regionally extensive Checkerboard Limestone.

The Cleveland sandstone is an operational term applied to sandstone bodies occurring at any position in the section between the “Big Lime” and the Checkerboard Limestone. The informal status of the Cleveland sandstone is acknowledged and will not be referred to with quotation marks.

The stratigraphy of the Cleveland sandstone interval is complicated due to the presence of multiple sandstone bodies that are almost exclusively labeled Cleveland by the oil and gas industry.

Sandstone within the Cleveland interval can be found over much of the Cherokee Platform, however, two primary east-west trending Cleveland sandstone complexes contain up to 200 ft (~61 m) of sandstone and are responsible for the majority of oil and gas production from the Cleveland sandstone in north-central Oklahoma. These two Cleveland sandstone trends were identified and named the Owasso and Kiefer “Channels” by Krumme (1981). For this study, the classification of “sandstone complex” will be applied to better describe the sandstone accumulations. Multiple depositional episodes are distinguished in the Kiefer and Owasso sandstone complexes, resulting in a stacked sandstone reservoir; therefore, the term “channel” could be misleading.

Both the Kiefer and Owasso sandstone complexes crop out at the approximate latitude of Tulsa, Oklahoma. The Owasso sandstone complex outcrops in northern Tulsa County, whereas the Kiefer sandstone complex outcrops in eastern Creek/western Tulsa County. Krumme (1981) observed that the two sandstone complexes interact near the location of Cleveland Field, directly south of the town of Cleveland, Oklahoma, where the sandstone was discovered and first named by oil and gas companies. The crossing of these two sandstone complexes contributes further to complicating the stratigraphy of the interval including reservoir properties and trapping mechanisms found within the field.

Cleveland sandstone production was discovered in 1904 south of the town of Cleveland, Indian Territory. The discovery well, the Uncle Bill #1, was spudded on May 27, 1904, and completed in June of the same year on the Lowery Family Farm. Original production from the Cleveland sandstone was approximately 10 barrels of oil a day. Two days later the Cleveland sandstone was shot with nitroglycerin and came in flowing 250 barrels of oil per day, which eventually declined to a steady 50 barrels per day. This well sparked the oil boom in Cleveland, which became one of the earliest in Oklahoma. By July of 1905, 220 wells had been drilled and completed near Cleveland, and the area was making approximately 11,000 barrels of oil per day (John D. May – Oklahoma Historical Society). In addition to the Cleveland sandstone, the Bartlesville Sandstone, an older Middle Pennsylvanian sandstone, is an important oil and gas producing reservoir in Cleveland Field. The Bartlesville Sandstone occurs approximately 600 feet below the Cleveland sandstone interval, and also produced in the early life of the field. The success of the Cleveland Field is attributed to its location on an anticlinal fold composed of two localized domes and multiple sandstone reservoirs. The Cleveland sandstone continues to produce several hundred barrels of oil a day, most of which comes from bypassed zones within the stacked sandstone interval that were not initially targeted or completed correctly, along with a successful secondary recovery waterflood.

Recent drilling in the Cleveland Field Unit was initiated in 2011 by Mid-Con Energy Operating, LLC, following successful recompletions in bypassed zones within the Cleveland sandstone reservoir. This renewed production and potential development sparked interest in the Cleveland sandstone reservoir and the factors that contributed to the bypassed pay. Previous studies in Cleveland Field, including Roddy (2014), addressed the petrophysical characteristics of the Cleveland sandstone reservoir, however, the implications of the interaction of the Owasso and Kiefer sandstone complexes on reservoir properties and oil and gas production have not been studied and are one of the key objectives of this study.

Purpose of the Research

The primary purpose of this study is to better understand the stratigraphy of the Cleveland sandstone interval in northeastern and north-central Oklahoma and investigate the interaction between the Kiefer and Owasso sandstone complexes in the Cleveland Field Unit, Pawnee County, Oklahoma. A primary goal of the study is to correlate the subsurface Cleveland sandstone to the biostratigraphically constrained outcrop section, with an emphasis on the radioactive core shales that act as regional stratigraphic marker beds. To accomplish this, subsurface data (wireline logs, core, and thin sections) and data from outcrop sections were examined to identify the defining features of the Cleveland sandstone, determine the major controls on deposition of the Kiefer and Owasso sandstone complexes, and correlate the Kiefer and Owasso sandstone complexes from outcrop into the subsurface and across the Cherokee Platform.

This study was initiated by Mid-Con Energy to better understand the controls on production of oil and gas within the Cleveland Field Unit. Production from the Cleveland sandstone is high volume in some areas of the field, however, other areas within the unit have very low production rates with similar sandstone thickness. This discrepancy in production is one of the primary reasons for the need to better understand the Cleveland sandstone in a local and regional sense.

The principal objectives for this study are to: 1) Use the biostratigraphically established stratigraphic framework to discriminate true Cleveland sandstone, Skiatook Group, from older Marmaton Group sandstone on the Cherokee Platform, 2) use this information to evaluate the stratigraphic relationship and interaction of the Kiefer and Owasso sandstone complexes on the platform and specifically investigate the implications this interaction has on oil and gas production in Cleveland Field, and 3) identify the depositional lithotypes from cores within the Cleveland Field in order to determine the primary reservoir lithotypes for the Cleveland sandstone.

Study Area

The primary area of study encompasses the area south of the town of Cleveland, Oklahoma, which is now unitized as the Cleveland Field Unit, T. 21 N., R. 08 E., Pawnee County, Oklahoma (Figure 1).

To interpret regional stratigraphic relationships, the study area was expanded to approximately 173 townships and covers an area of approximately 6228 square miles. The overall study area includes multiple counties on the Cherokee Platform in northeastern and north-central Oklahoma (Figure 2), including, Logan, Noble, Osage, Pawnee, Payne counties, and portions of Creek, Lincoln, Garfield, and Tulsa counties. The area to the west of the Nemaha Uplift was not included in this study. The study area was chosen due to the significant number of Cleveland sandstone producing wells (approx. 3000), multiple producing Cleveland sandstone fields/units and availability of subsurface data, including wireline logs and cores (IHS Enerdeq). There are approximately 3000 Cleveland sandstone producing wells within the study area, and it is estimated that the Cleveland sandstone has produced 100 MMBO from the reservoirs on the Cherokee Platform (well count and production estimated from IHS Enerdeq).

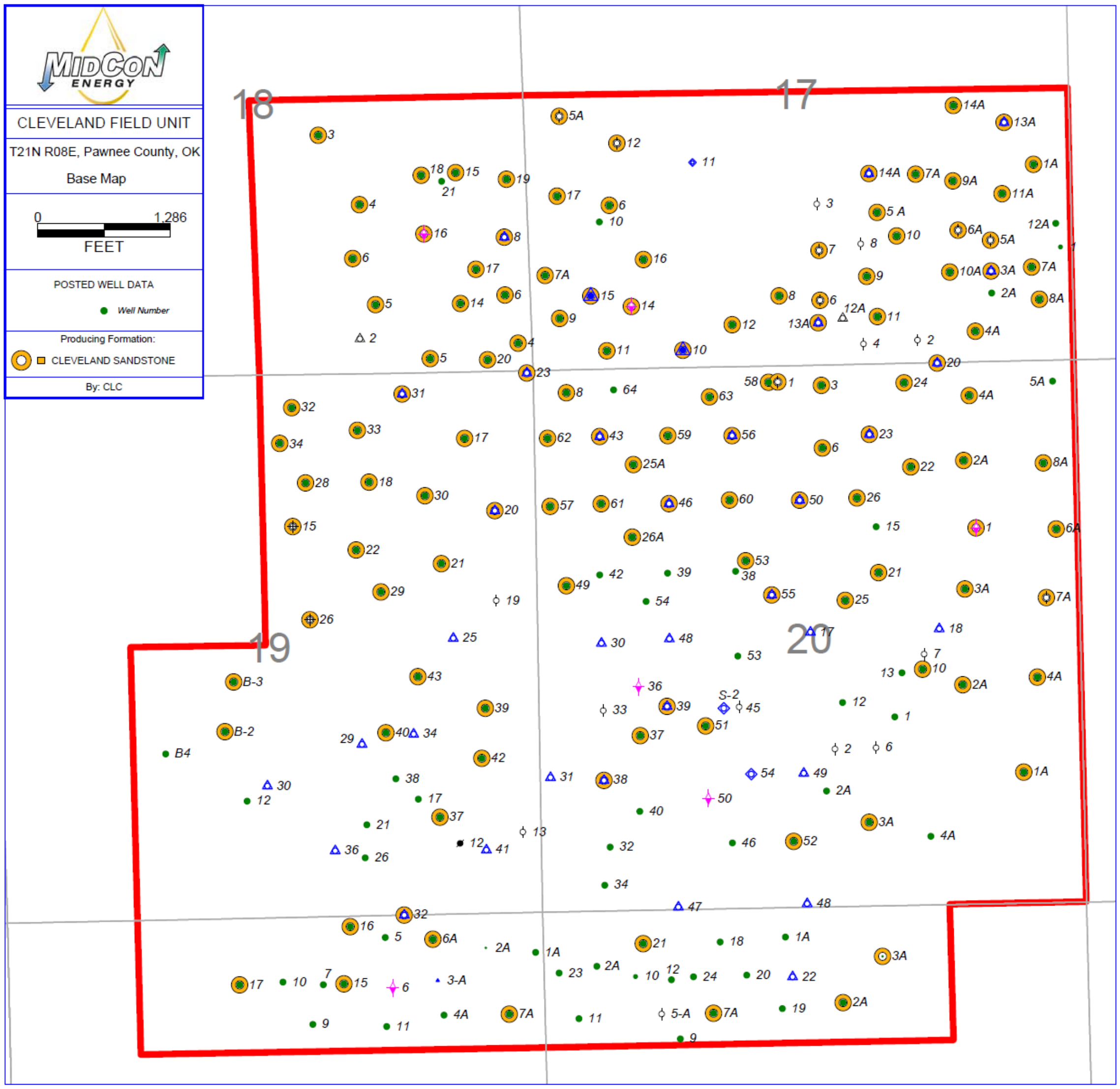


Figure 1. Base map of the Cleveland Field Unit, Pawnee County, Oklahoma. Wells displayed are the wells primarily used in the study due to presence of wireline log data and Cleveland sandstone production. Orange attribute denotes Cleveland sandstone producing wells.

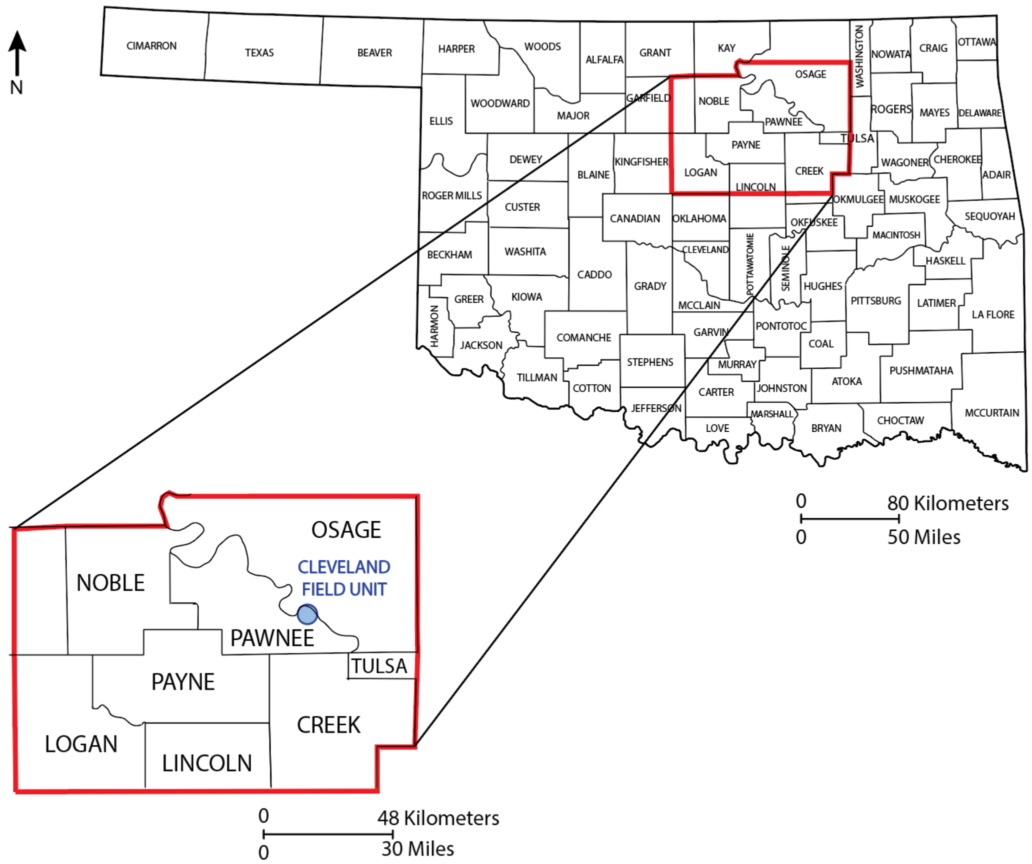


Figure 2. County map of Oklahoma with regional study area outlined in red. Location of the Cleveland Field Unit is denoted with a blue circle.

Methodology

Wireline Logs

Wireline logs were the primary source of data available for this study and were used in a variety of ways to interpret the Cleveland sandstone. Wireline logs were used to analyze and correlate stratigraphic tops, construct the regional stratigraphic framework, regional and local subsurface mapping, and field-scale lithotypes and electrofacies correlations. For the regional correlations, wells with gamma-ray and density-neutron curves were used in order to identify regional marker beds, which are primarily radioactive shales. The regional markers beds, defined by Heckel (1994) were identified using the “hot” gamma-ray values on wireline logs and hand-picked using Petra®. The stratigraphic tops were then correlated across the regional study area by constructing numerous cross sections in Petra®. In total, 6 cross sections were selected for inclusion in this document. These consist of 3 NW-SE trending sections and 3 SW-NE trending sections that illustrate the changes in the Cleveland sandstone interval and stratigraphic marker beds (Appendix). The orientation of these cross sections was based on the thickening trend of the Cleveland sandstone interval. The cross sections were flattened stratigraphically on a regional marker bed, typically the Checkerboard Limestone, in order to keep correlations consistent. On the cross sections, seven (7) stratigraphic tops were consistently picked. These included, in stratigraphically descending order, the Checkerboard Limestone, the Nuyaka Creek Shale, the top of the Marmaton Group carbonates (“Big Lime”), the Lake Neosho Shale, the Anna Shale, the Little Osage Shale, and the Excello Shale.

Interval thickness maps were constructed using the stratigraphic tops picked to decipher paleogeography and locate primary depocenters during the time of Cleveland deposition. Using Petra® mapping software, thicknesses between stratigraphic tops were calculated and plotted on the map. Petra’s mapping algorithms were used for the regional thickness maps; however, the local maps were hand-contoured.

In addition, the thickness of the Nuyaka Creek Shale was picked across the regional study area and mapped to display where the Nuyaka Creek is present/absent and interpret the overall distribution of the radioactive shale. The stratigraphic top for the Nuyaka Creek Shale was picked initially across the study area; however, it was necessary to know the overall thickness and distribution of the regional marker bed. The thicknesses were handpicked from wireline logs and mapped by hand. The thickness map for the Nuyaka Creek Shale did not provide any insight into the relationship with the Cleveland sandstone, so this map was not included in this document. Instead, the overall distribution was mapped and compared to the distribution of the Cleveland sandstone sandstone complexes.

The gross thickness of the Cleveland sandstone within the Kiefer and Owasso sandstone complexes was determined using basic sandstone cutoffs (>10% density porosity (ρ_m = 2.71 g/cc) and < 50 API gamma-ray values or >60 millivolt deflection on the SP curve). The values were plotted across the study area and mapped to show the geometry of the sandstone complexes. The sandstone thicknesses were hand-contoured using a 50-foot contour interval. Sandstones picked were differentiated into four intervals, the Kiefer sandstone complex, which includes sandstone with no distinguishable Nuyaka Creek Shale, the Owasso sandstone complex, which includes sandstone bodies below the Nuyaka Creek Shale and occupying the linear trend defined by the sandstone complex, the Marmaton aged sandstones, which are sandstones below the Nuyaka Creek Shale but do not belong to the Owasso sandstone complex, and the true Cleveland sandstone, which are sandstones above an observable Nuyaka Creek Shale. By definition, the Kiefer sandstone complex is a true Cleveland aged sandstone system and the Owasso sandstone complex is Marmaton aged. It was necessary to separate these during mapping to show the geometry of each sandstone complexes.

Structure maps referenced to sea level datum were constructed within the Cleveland Field Unit using multiple stratigraphic tops. The subsurface structure map included in this study was hand-contoured into Petra mapping software using the handpicked Checkerboard tops. The

Checkerboard structure map was used in conjunction with the gross sandstone thickness maps to better understand the relationship between the sandstone complexes at Cleveland Field Unit. Regional structure maps were constructed during the study but were not conclusive relative to Cleveland sandstone deposition.

During initial correlations and mapping, wells used in the stratigraphic correlations were selected based on two criteria: 1) wells drilled between 1980-2017, to construct a subset of wells that contained gamma-ray curves necessary to recognize regionally distributed radiogenic “hot shale” marker beds and 2) wells with raster images of wireline logs necessary for this study (primarily from IHS, MJ, and TGS). Approximately 1500 wells were used in the initial correlations. However, after evaluation of the initial correlations, it became evident that an increase in the number of wells was necessary to confidently map the distribution of the Nuyaka Creek Shale. The addition of a new set of wells to improve map accuracy increased the total number of wells used to approximately 3500. Petra® mapping software was used for all of the well-log analysis, cross section preparation, and correlations.

Detailed wireline log analysis was completed on many wells in the Cleveland Field Unit in order to better understand the petroleum geology and history of the production from the Cleveland sandstone during development of the field. Wireline log analysis included calculating water and oil saturations, determining cutoffs for net pay, and differentiating the gas, oil, and water zones within the stacked sandstone interval. Older wireline logs were compared to newly drilled wells to determine how fluid saturations in the reservoir have changed over the last fifty years of production and 7 years of waterflooding. An emphasis was placed on trying to differentiate the Kiefer and Owasso sandstone complexes within Cleveland Field; core analysis and wireline log correlations were used in attempts to identify the two sandstone complexes.

Core Data

Subsurface rock data was examined in order to evaluate biogenic and sedimentary structures, stratigraphic surfaces, and reservoir characteristics within the Cleveland sandstone interval to determine the depositional lithotypes present and identify any major stratigraphic surfaces that could distinguish the Cleveland sandstone complexes. Five cores were available from the Cleveland Field Unit in Pawnee County (Table 1) (Figure 3).

Well Name	Well Number	Feet of core	Operator	County
JA Jones	58	232	Mid-Con	Pawnee
Van Eman	16	181.3	Mid-Con	Pawnee
Frazee	22	183.8	Mid-Con	Pawnee
Lucinda Martin	13	212.4	Mid-Con	Pawnee
JL Miller	34	180	Mid-Con	Pawnee

Table 1. List of wells with core used in this study.

All five cores were cut by Mid-Con Energy from 2013-2017. Each core was examined and described in detail and graphically represented using petrologs (Appendix). Four of the cores were viewed in person for examination, however, high-resolution photographs were available for all five cores and were used extensively for detailed analysis and lithotype determination. The initial core examination included identifying large scale changes in lithology and sedimentary structures. It became evident that the depositional framework for the Cleveland sandstone was more complex and required detailed characterization to the inch scale to resolve the primary factors during deposition. This analysis was completed for each core and resulted in the identification of 8 depositional lithotypes. The lithotypes observed in each core were recorded on a petrolog and graphically represented in cross sections for comparison with the other cores in the field. Emphasis was placed on identifying major stratigraphic surfaces such as an unconformity that could mark a distinct boundary between the Kiefer and Owasso sandstone complexes. Core plugs were taken from the first 3 cores cut by Mid-Con (JA Jones #58, Frazee #22, and Van Eman #16). Standard and detailed core analysis was done which included core porosity, core permeability, and others that were the basis for Roddy's study (2014). The remaining 2 cores (Lucinda Martin #13 and Miller #34) did not have core plugs cut, but instead had minipermeameter values recorded that documented relative changes in permeability over the entire cored interval. This data was available for all 5 cores included in the study. The primary use of the core was to identify the lithotypes present in the Cleveland sandstone to understand the framework of the sandstone complex and help determine the factors controlling the production of oil and gas from the Cleveland Field Unit.

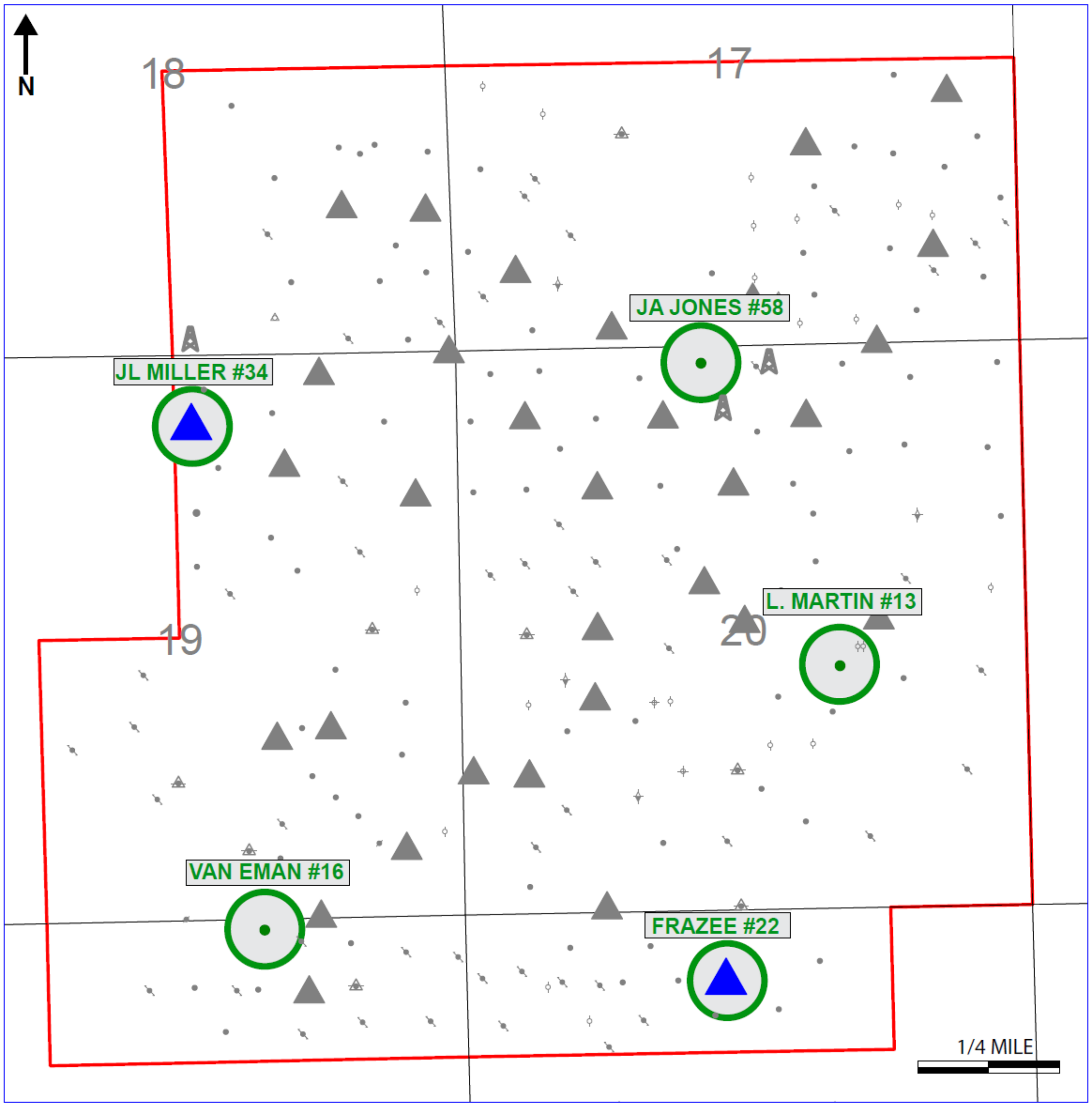


Figure 3. Map of Cleveland Field Unit with cored wells highlighted with green circles

Thin Section Microscopy

Thin sections were available for three of the cored wells in Cleveland Field (JA Jones #58, Van Eman #16, and Frazee #22), and samples collected from the three outcrops included in this study (Collinsville Lake, Jenks, and Kiefer/Glenpool). In total, 75 thin sections were available for this study. The majority were examined with a petrographic microscope to determine the types of detrital framework grains, authigenic constituents, and abundance and types of porosity. In addition, particular emphasis was placed on the grain size, grain shape, and unique mineralogy that could aid in determining the potential source for the Cleveland sandstone. Comparison of the different thin sections was important in determining if the Kiefer and Owasso sandstone complexes have distinct mineralogy or grain size/shape that could distinguish the two sandstone complexes in Cleveland Field. The outcrop thin sections were examined and then compared to those from Cleveland Field. Photographs were taken from multiple depths that display the overall framework of the Cleveland sandstone and identify important grains for provenance of the sediment. Roddy (2014) completed detailed thin section analysis in which the relative percentages of detrital and authigenic grains were recorded. In addition, Roddy (2014) completed x-ray diffraction on multiple samples from the Cleveland sandstone. This analysis was not repeated due to more emphasis on the regional stratigraphic framework and petroleum geology in the Cleveland Field Unit.

Outcrop Data

Three Cleveland sandstone outcrops were examined in Tulsa County, Oklahoma (Figure 4). The objective for including outcrop data in this study was to compare the outcrop depositional features and lithotypes with those observed in cores from Cleveland Field. The Owasso and Kiefer sandstone complexes were correlated from the subsurface to the outcrop using wireline logs and the specific outcrops were discovered using suggestions from local geologists (Bennison, 1972; Dr. John Shelton - Personal Communication). Each outcrop was analyzed for sedimentary structures, lithotypes, and unconformable surfaces. Particular emphasis was placed on identifying sedimentary structures that could help determine the paleocurrent direction of the primary Cleveland sediment dispersal systems. The lithotypes, sedimentary structures, and erosional surfaces were recorded in petrologs (Appendix). The primary structures and lithotypes observed in outctop were compared, and attempts to match the lithotypes observed in core were made. The three outcrop locations were chosen due to their position within the suspected sandstone complexes. The Collinsville Lake outcrop was located within the Owasso sandstone complex, the Jenks outcrop was initially thought to be within true Cleveland sandstone channels (Upper Cleveland), and the Kiefer/Glenpool outcrop was initially regarded to be within the Kiefer sandstone complex. Samples were collected from each outcrop and thin sections prepared for comparison to the Cleveland Field thin sections.

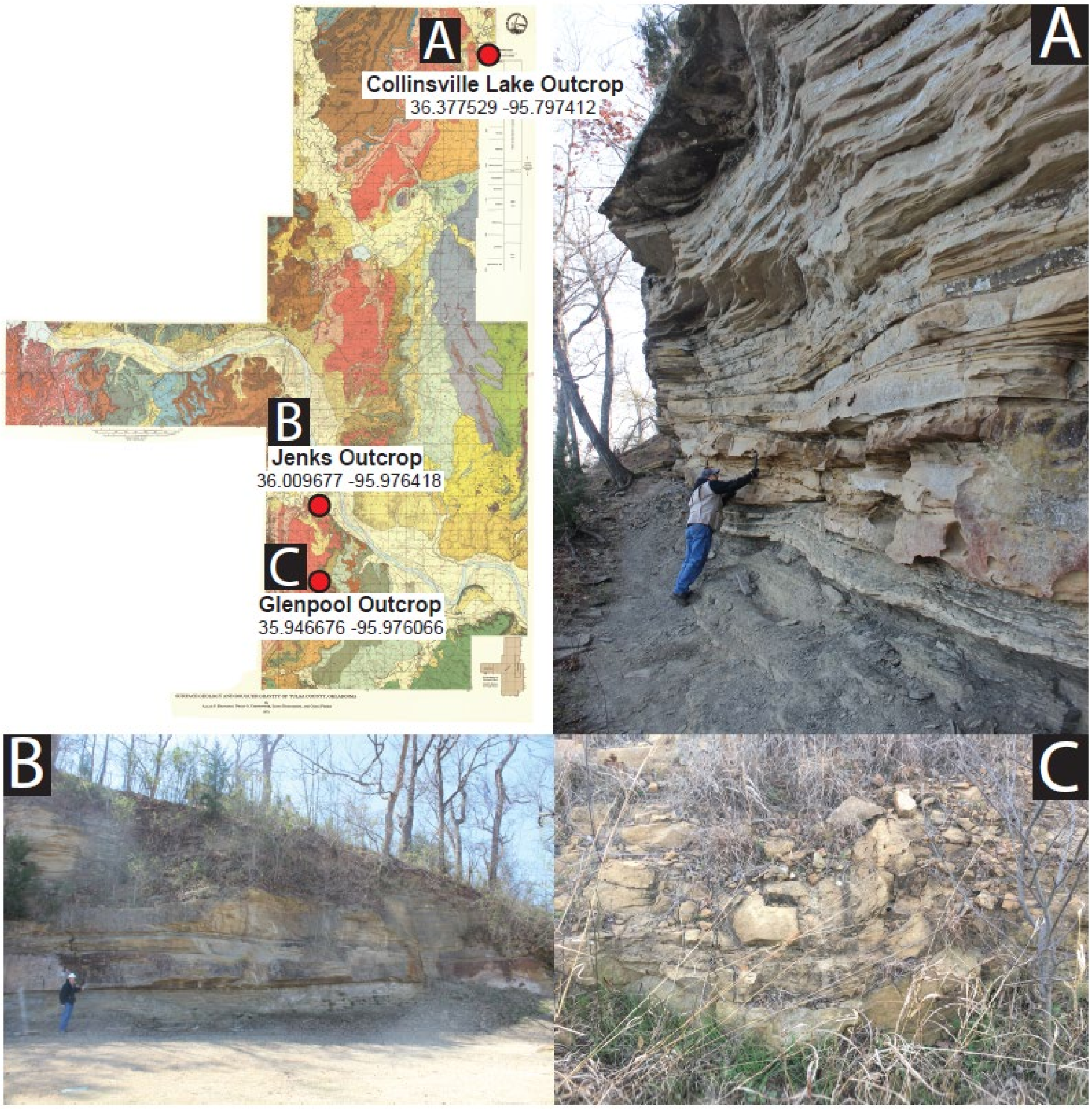


Figure 4. Top left: Tulsa County surface geology with outcrop locations labeled (Modified from Bennison et al., 1972) A) Cleveland sandstone outcrop at Collinsville Lake. B) Jenks outcrop, C) Kiefer/Glenpool outcrop

Data Limitations

The primary limitations to the dataset examined in this study are the lack of core data from other locations within the Kiefer and Owasso sandstone complexes. Multiple cores have been cut in the Cleveland sandstone over the Cherokee Platform, but few were available for this study. To further understand the relationship and distribution of the Kiefer and Owasso sandstone complexes, additional core needs to be examined and compared, specifically farther to the west where the sandstone complexes become undifferentiated. Additional core work would also lead to more thin section analysis that could aid in understanding the Cleveland sandstone; specifically, detailed analysis of the grain size, percentages of detrital grains, and geochronology would give a better idea of the provenance of the Cleveland sediments.

The outcrops examined and sampled in this study represents a rather small sample of outcrop locations in the general area of Tulsa, Oklahoma. However, many are poorly exposed, and they are generally regarded as part of the true Cleveland or upper Cleveland sandstone.

CHAPTER II

GEOLOGIC SETTING AND STRATIGRAPHY

Structural and Tectonic History

The study is located on the Cherokee Platform, an extensive area that includes the majority of north-central and northeastern Oklahoma and extends into Kansas. The Cherokee Platform is bounded to the west by the Nemaha Uplift, to the south by the Arkoma Basin and Seminole Uplift, and to the east by the Ozark Uplift (Figure 5). The Nemaha Uplift was not a strong positive feature during Cleveland sandstone interval deposition; however, the effect of the uplift is evident in the thinning of the overall Cleveland interval across the uplift and thickening of the interval both to the east and west.

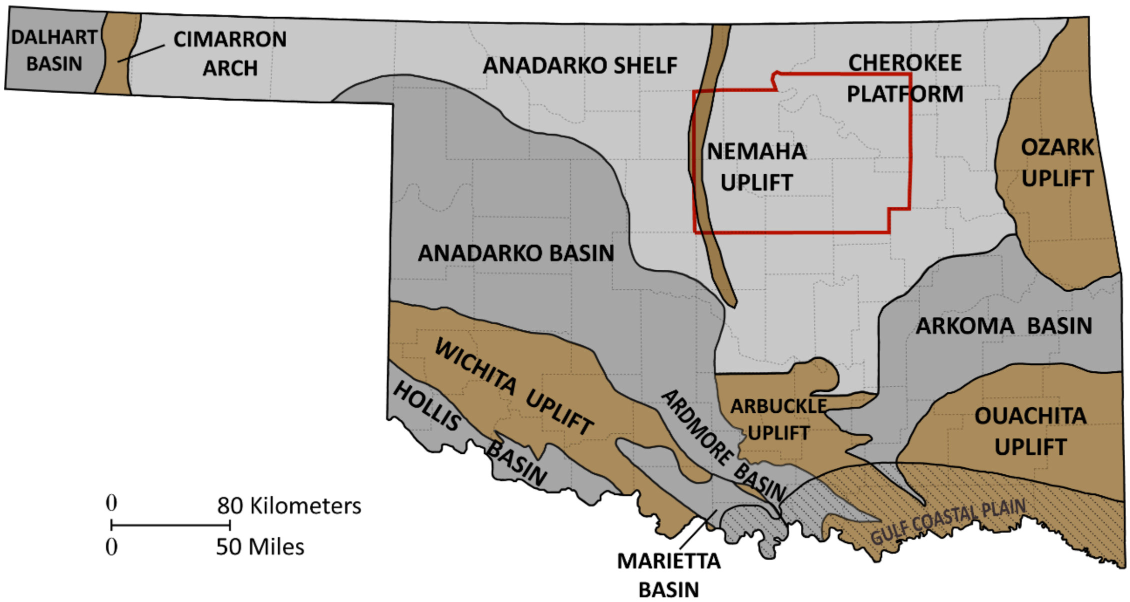


Figure 5. Geologic provinces of Oklahoma with regional study area outlined in red. Modified from Northcutt and Campbell (1996).

During the Early to Middle Pennsylvanian, the Ouachita foldbelt formed and the Arkoma Basin was undergoing significant subsidence due to the collision between the North American and South American Plates (Rascoe and Adler, 1983). The Arkoma Basin was subsequently filled with Morrowan, Atokan, and Desmoinesian sediment (Sutherland, 1988; Rascoe and Adler, 1983). By the late Desmoinesian/early Missourian, the Arkoma Basin still contained accommodation for sediment, but subsidence had slowed and the basin was not a prominent feature (Branson, 1961). As a result, a marginally stable platform dominated the majority of the southern Midcontinent. The early to middle Desmoinesian (Krebs and Cabaniss Groups) was dominated by southerly flowing siliciclastic sediment dispersal systems that formed the large fluvial deltaic complexes containing the "Cherokee sands," which are prolific hydrocarbon reservoirs in the Midcontinent. During the late Desmoinesian, deltaic deposition into the area from northern sandstone complexes was concluding, and the Cherokee Platform was dominated by a large carbonate shelf, on which formed the Marmaton Group carbonates (Krumme, 1981; Moore, 1979). Simultaneously, the Ouachita foldbelt began contributing sediment from the south to the area that was once the Arkoma Basin, resulting in the deposition of the Wewoka Formation and Cleveland sandstone bodies identified in Creek County that are not related to the prominent east to west trending Kiefer and Owasso sandstone complexes identified by Krumme (1981).

<u>Paleogeography and Climate</u>

During the Late Pennsylvanian, a broad epicontinental sea inundated the majority of the Midcontinent and deposition within the Cleveland sandstone interval was largely controlled by fluctuations in sea-level (Figure 6) (Algeo and Heckel, 2008). The study area was located on a relatively stable shelf/platform environment that gently dipped into the greater Arkoma Basin area to the south that allowed for significant change in the relative position of the shoreline with relatively minor changes in sea level (Figure 7). The late Desmoinesian/early Missourian was near the paleo equator and as a result experienced tropical, humid conditions (Algeo and Heckel, 2008). The Late Pennsylvanian was a time of icehouse conditions, therefore the cyclicity and major changes in sea level were controlled by Southern Hemisphere glaciation (Figure 8) (Schutter and Heckel, 1985). The third order sequences responsible for deposition of the major sandstone complexes in the Late Pennsylvanian have a periodicity of 400,000 years, which correlate to those observed in the Pleistocene (Heckel, 1980).

Coal beds are common in Pennsylvanian strata in the study area, including the Dawson Coal, which occurs in the same stratigraphic position as the Nuyaka Creek Shale in the area surrounding the Cleveland sandstone outcrop. The Dawson Coal is difficult to recognize wireline logs, but has been observed in core (Krumme, 1981).

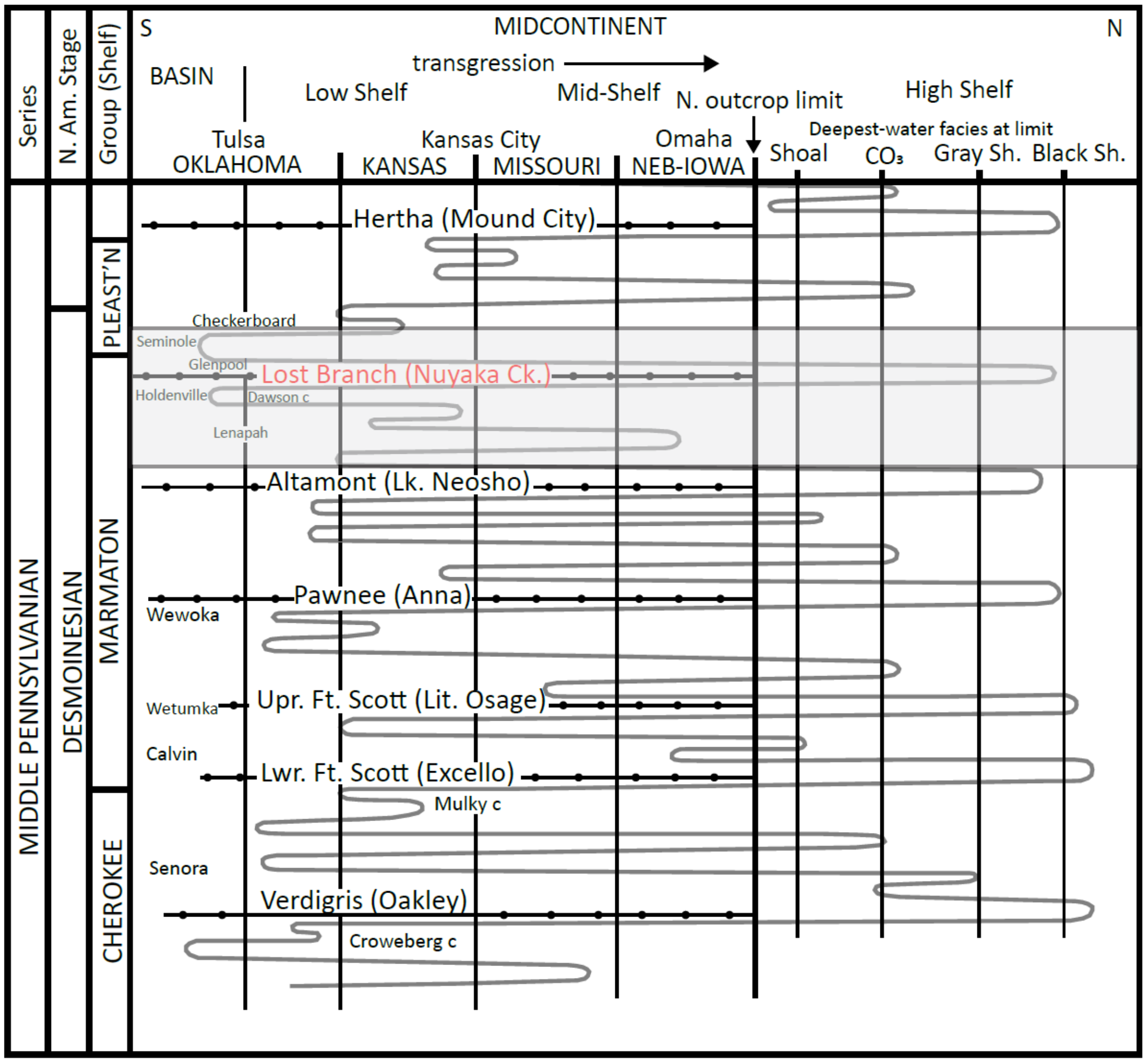


Figure 6. Relative sea-level curves showing the major transgressive and regressive cycles in the Midcontinent. Modified from Heckel (1994).

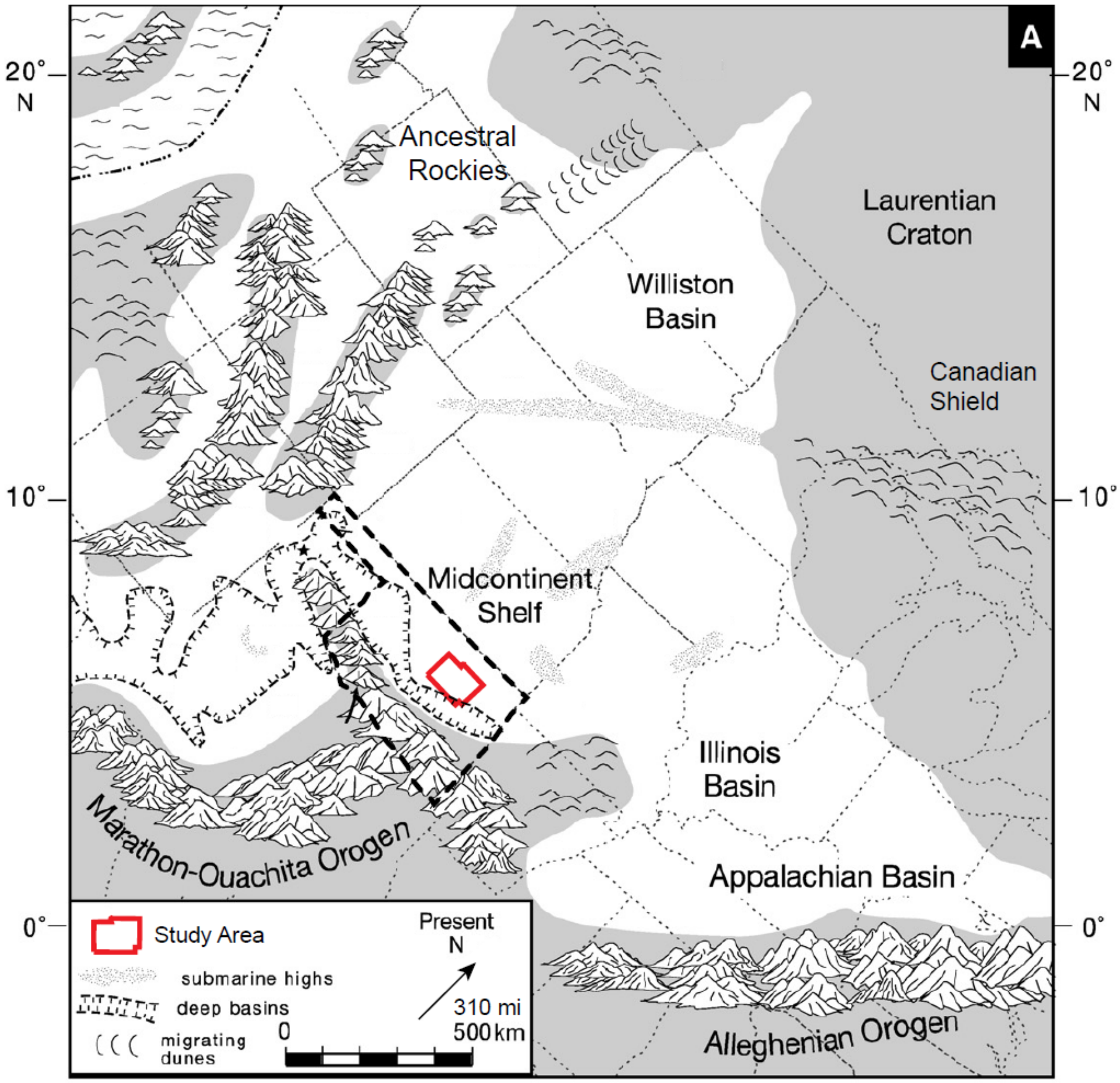


Figure 7. Paleogeography of the Late Pennsylvanian showing the major features during the time of Cleveland sandstone deposition. Oklahoma is outlined in black and the study area is outlined in red. Modified from Algeo and Heckel (2008).

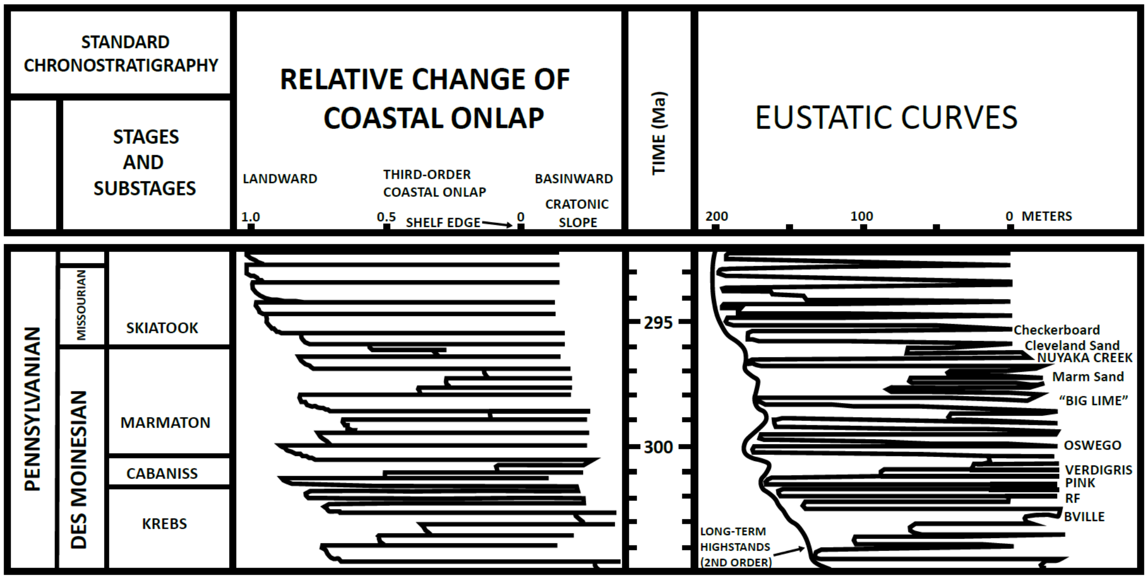


Figure 8. Sea-level curves. Modified from Ross and Ross, 1988.

General Stratigraphy

The stratigraphic nomenclature used in this study is based on the terminology commonly used on the Cherokee Platform in northeastern and north-central Oklahoma and the Arkoma Basin in southeast Oklahoma. The stratigraphic framework used for the basis of this study was defined biostratigrahically by Heckel (1991). Figure 9 displays the stratigraphic column of the Desmoinesian and Missourian section used in this study and includes the gamma-ray signature of a typical wireline log for the Cleveland sandstone interval on the Cherokee Platform where the Kiefer and Owasso sandstone complexes intersect at Cleveland Field.

As previously stated, the industry accepted Cleveland sandstone interval is defined as the stratigraphic section between the top of the Marmaton Group carbonates and the base of the Checkerboard Limestone. The Cleveland sandstone interval is primarily shale, sandstone, and occasional thin limestones.

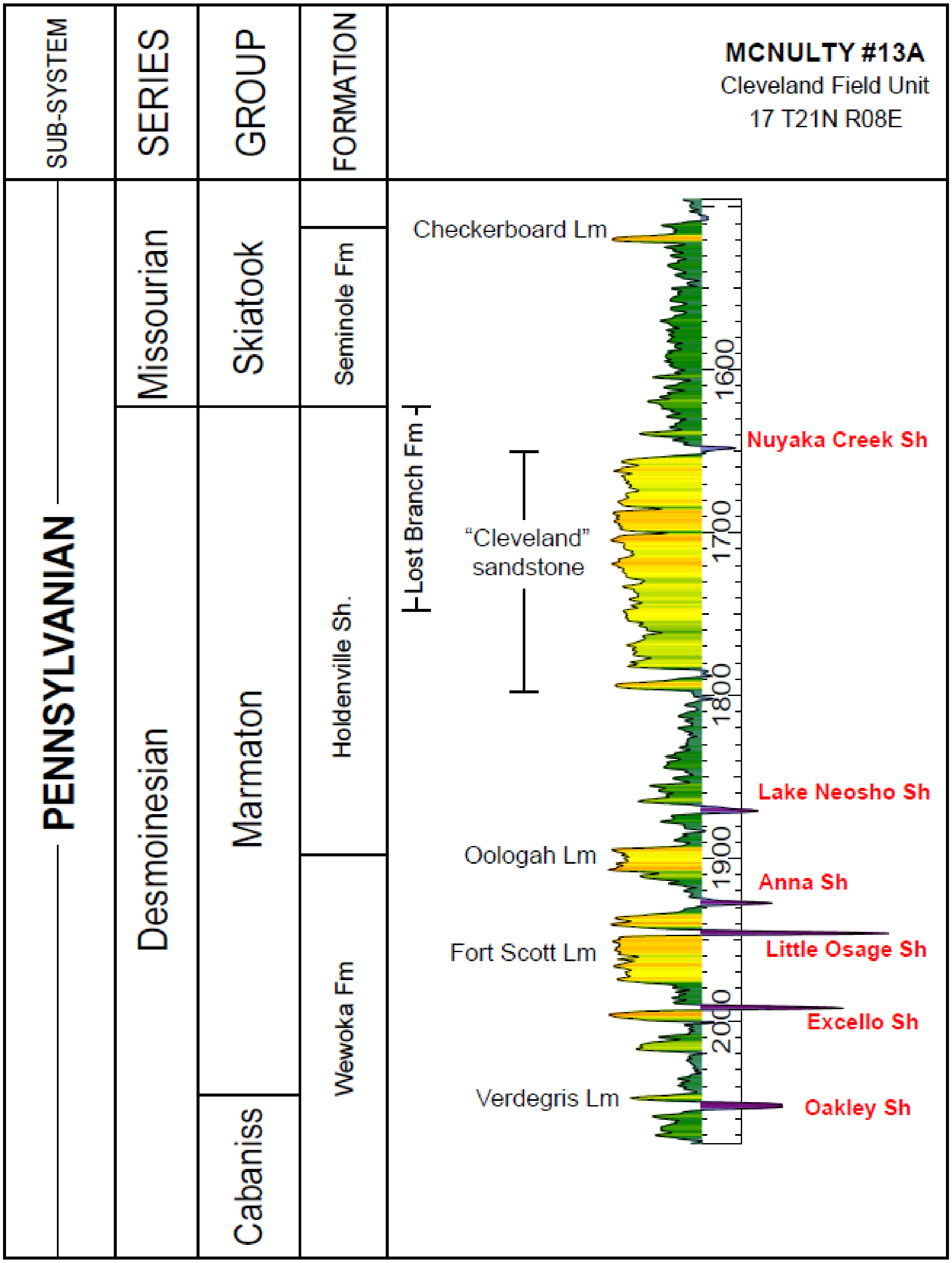


Figure 9. Stratigraphic column and typical log of the Cleveland sandstone interval and underlying marker beds from the Cleveland Field Unit, Pawnee County, Oklahoma

The interval contains key stratigraphic marker beds, including the Nuyaka Creek Shale, a marine “hot” shale, and the Dawson Coal that is subjacent to the Nuyaka Creek Shale. The distribution of the Dawson Coal is not well defined because of the difficulty in recognizing it in logs of the subsurface section. A thin interval of increased density porosity in the stratigraphic position of the Dawson Coal is apparent in some parts of the study area, but without core identifying the Dawson Coal with confidence is difficult. Krumme (1981) suggested that the Dawson Coal does not extend far into the subsurface from the outcrop.

In the study area, the Lost Branch Formation is positioned in the Cleveland sandstone interval and is defined as the interval between the top of the Dawson Coal and the base of the Tulsa or Hepler Sandstones, which is also the top of the Glenpool Limestone (Heckel, 1991). The top of the Lost Branch Formation is recognized as the top of the Marmaton Group and the boundary between the Desmoinesian and Missourian Series based on conodont, ammonoid, palynomorphs, and fusulinid data collected by several geologists and combined in Heckel (1991; Hentz, 1994; Bacon, 2012). The Nuyaka Creek Shale lies within the Lost Branch Formation. Identifying the top of the Lost Branch Formation and the Nuyaka Creek Shale in the subsurface is extremely important for understanding the stratigraphic framework of the Cleveland sandstone interval. Due to the difficulty in identifying the Dawson Coal on wireline logs and the variability in the stratigraphic position of the limestone beds used for the top of the Lost Branch Formation, the Nuyaka Creek Shale was used as the marker bed for the operational boundary between the Desmoinesian and Missourian series. Sandstone bodies occurring below the Nuyaka Creek Shale are assigned to the Marmaton Group and specifically the Holdenville Formation, whereas sandstones stratigraphically above the Nuyaka Creek Shale are considered to be in the Seminole Formation (Lost Branch Formation) of the Skiatook Group (Heckel, 1991). The Nuyaka Creek Shale is prevalent across the study area and is recognized by its radiogenic wireline log signature, which has resulted in it being classified as a "hot shale" by the petroleum industry.

In order to better understand basin configuration during Cleveland sand deposition and how accommodation influenced sand distribution, the overall interval included in the stratigraphic framework study extends from the Excello Shale and Breezy Hill Limestone at the base of the Marmaton Group through the Checkerboard Limestone. The Marmaton Group and Cleveland sandstone interval together contain four radioactive shales that are mappable across the study area. These radioactive shales (core shales of Heckel, 1994) are considered key stratigraphic units essential to mapping intervals within the study section and constructing the stratigraphic framework of the Cleveland sandstone. The more widely distributed and easily recognized shales are the Excello Shale and Little Osage Shale that occur across the majority of the study area and much of the Midcontinent region. Moving up the section, the Anna and Lake Neosho radioactive shales are easily recognized in some areas, but are not as widely distributed as the Excello and Little Osage shales. The Nuyaka Creek Shale is the only prominent stratigraphic marker bed within the upper part of the Cleveland sandstone interval. The Nuyaka Creek is mappable over much of the study area and is recognized in outcrop (Heckel, 1991) and subsurface (Bacon, 2013; Bennison, 1984; Morris, 2014).

CHAPTER III

RESULTS

Stratigraphic Framework

The importance of deciphering the stratigraphic framework for the Cleveland sandstone interval lies in understanding the factors controlling deposition of the Kiefer and Owasso sandstone complexes and determining the timing relationship between the two sandstone complexes. As the result of detailed cross section analysis, correlation, and mapping, the following observations were made for the Cleveland sandstone interval.

The Cleveland sandstone interval thickens to the south and southeast with thicknesses increasing from approximately 100 feet in the north and northwest portion of the study area (Noble County) to greater than 750 feet in the southeast (southern Creek County) (Figure 10).

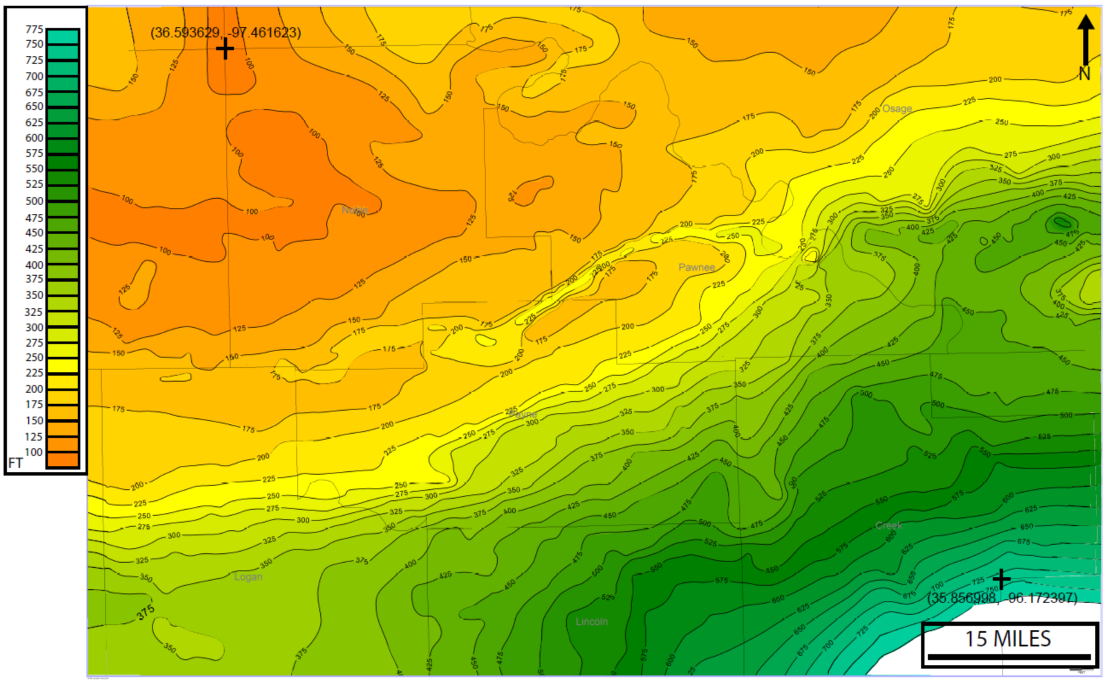


Figure 10. Cleveland sandstone interval thickness map (Checkerboard to top Marmaton Group carbonates). Contour interval = 25 ft.

Figure 11 is a northwest-southeast trending section that illustrates this thickening of the Cleveland sandstone interval (Figure 11). The northwest portion of the study area (Noble County and parts of Osage, Payne, Logan, and Garfield Counties) was part of a large stable shelf during the time after Marmaton Group carbonate deposition (Bennison, 1984). This area was predominately flat during the time preceding the Cleveland sandstone deposition, which created an optimal environment for carbonate generation and deposition, which is evident in the thick Marmaton Group carbonate section that is widely distributed across the southern Midcontinent.

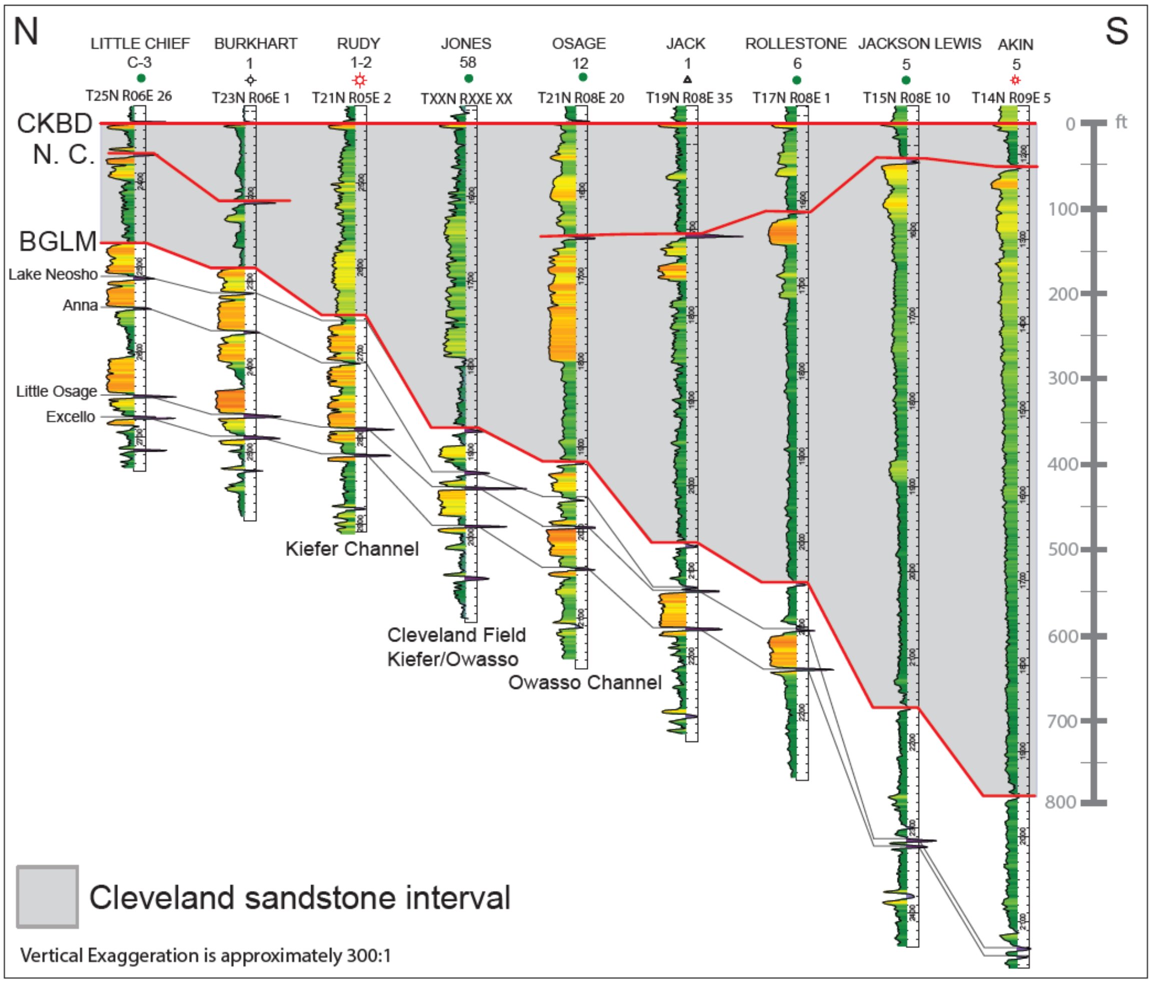


Figure 11. Cleveland sandstone interval cross section showing the increase in the overall thickness of the interval toward the southeast. Cross section length is approximately 63 miles. CKBD = Checkerboard Limestone; NC = Nuyaka Creek Shale; BGLM = "Big Lime."

Based on wireline log correlations and thickness mapping, there was a northward shift in the generation and deposition of the Marmaton Group carbonates (Bennison, 1984). The cumulative thickness of Marmaton Group carbonates decreases to the south, and they are absent in areas of southern Creek and Payne counties. The thickness map of Marmaton Group carbonates demonstrates that the thickness of that interval coincides with the increased thickness of the Cleveland sandstone interval (Figure 12). In addition to the thinning of the Marmaton Group carbonates, there is also evidence of basin subsidence causing an increase in the interval thickness between the Checkerboard Limestone and the base of the Marmaton Group (Excello Shale). As a result of the basin subsidence and loss of the Marmaton Group carbonate members, an area of accommodation was present during the initiation of Cleveland sandstone deposition. The majority of this accommodation was filled with mud and silty material coming off the shelf, with scattered localized sand accumulation.

On the map of the Cleveland sandstone interval (Figure 12), there is a sharp increase in the rate of thickening for the Cleveland sandstone interval that trends southwest to northeast. This same feature is observed on the Marmaton Group carbonate thickness map as an increase in the rate of thinning of the carbonate interval. This feature is defined as the Marmaton carbonate front and marks the boundary of the stable shelf (Krumme, 1981).

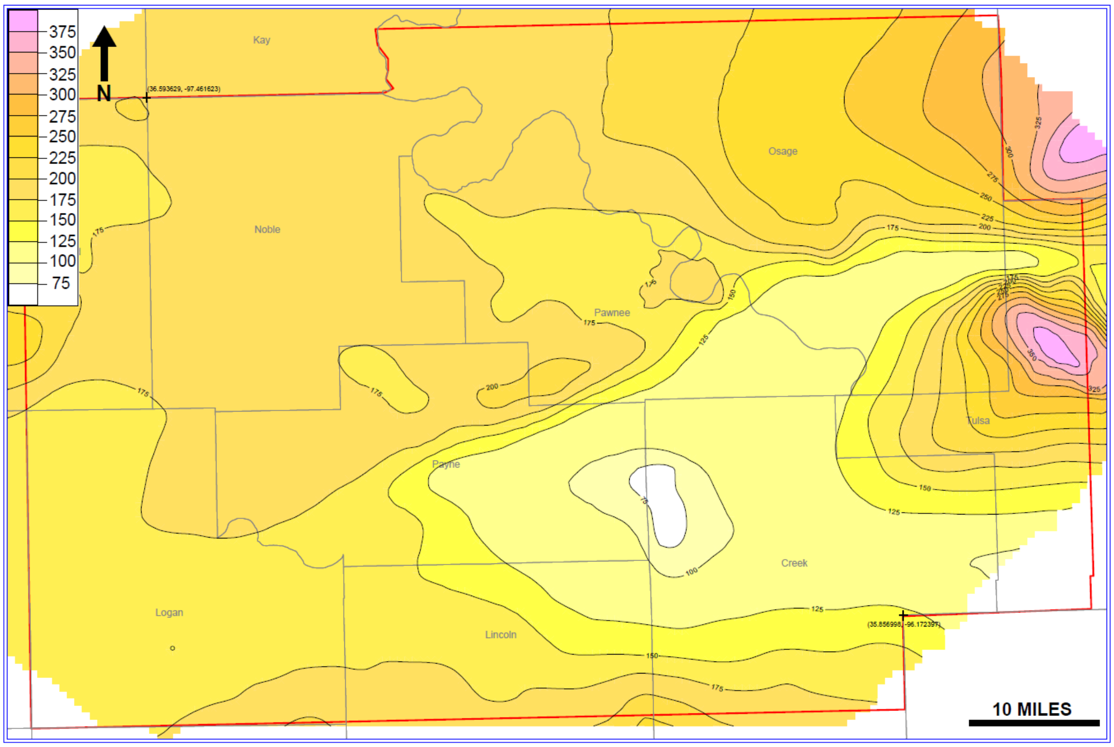


Figure 12. Thickness map of the Marmaton Group carbonates defined as the interval between the “Big Lime”/Lake Neosho Shale and the Excello Shale. Study area is outlined in red. Contour interval = 25 ft.

Due to the relatively rapid change in the thickness of the carbonate bodies that make up the Marmaton Group carbonate section, using the top of the carbonate section as the base of the Cleveland interval was not practical. As a result, the base was defined using either the Lake Neosho Shale, a radioactive shale associated with the Altamont Limestone or the Altamont Limestone. It is common over the study area, specifically in the Cleveland Field Unit, for the Altamont Limestone to be missing. In the carbonate dominated section of the Marmaton Group, the radioactive shales in ascending order are: Excello, Little Osage, Anna, and Lake Neosho. The Excello and Little Osage shales are regionally extensive marker beds that extend from the

Anadarko Basin in Oklahoma to outcrops in Iowa (Morris, 2014). Both the Excello and Little Osage Shales are present across the entire study area and are separated by a carbonate unit of the Oswego Limestone named the Blackjack Creek Limestone Member of the Fort Scott Limestone. The Anna and Lake Neosho Shales are recognized in wireline logs across the study area, however, they are not as consistently identifiable as the Excello or Little Osage.

In Osage County, the thickness between the “Big Lime” and the Oswego Limestone, which is typically 10-15 feet, increases to over 100 feet. This interval is the Labette Shale (Bennison, 1984). In some areas, a sandstone body develops within this interval called the Peru Sandstone (Bennison, 1984). The Peru Sandstone and Labette Shale interval are not a primary focus of the study and were not studied in detail.

Nuyaka Creek Shale

Previous studies, including Heckel (1991), Watney (1995), and Bacon (2013) established that the Nuyaka Creek Shale is a regionally extensive radioactive shale that is present in central Oklahoma and extends southward into both the Anadarko and Arkoma basins and northward into Kansas (Bennison, 1984; Heckel, 1991, Watney, 1995; Morris, 2014). In outcrop, the Nuyaka Creek Shale is a dark gray to black phosphatic shale that yields abundant conodonts that were used to help establish the Desmoinesian/Missourian boundary (Heckel, 1991).

The Nuyaka Creek Shale is the only post-Marmaton Group carbonate stratigraphic marker bed consistently recognized on wireline logs across the study area. In the northern portion of the study area (northern Noble, Pawnee, and Osage counties), the Nuyaka Creek Shale occurs some 30-40 feet below the Checkerboard Limestone. The interval between the Nuyaka Creek Shale and the Checkerboard Limestone increases over the central part of the study area and then gradually thins in the southern portion of the study area (Lincoln and Creek counties).

The Nuyaka Creek Shale extends south from Creek County and continues into the Arkoma Basin; likewise, correlations indicate that the Nuyaka Creek Shale is present to the north and west of the study area. However, in southern Payne County, much of Lincoln County, and southern Logan County, the Nuyaka Creek Shale cannot be identified on wireline logs. A map of the distribution of the Nuyaka Creek Shale, as identified by wireline logs, is shown in Figure 13.

The Nuyaka Creek Shale is missing or unidentifiable in many wells located on the stable shelf in Noble County and northern Payne County (Figure 13). The area with the highest concentration of wells without identifiable Nuyaka Creek Shale coincides with thin Cleveland sandstone intervals. In this area, identifying the Nuyaka Creek Shale on wireline logs is inconsistent and wells without the shale are in very close proximity to wells with the shale. The absence of shale in close proximity to wells with the Nuyaka Creek Shale is displayed in cross section C-C' (Figure 14). An additional thin, higher resistivity interval thought to represent a limestone occurs in the Cleveland sandstone interval above the Nuyaka Creek Shale and is used as a marker bed to interpret the position of the Nuyaka Creek Shale where the radioactive shale is not recognized. In areas of missing Nuyaka Creek Shale, this limestone allows for the recognition of the stratigraphic position of the Nuyaka Creek "hot" shale.

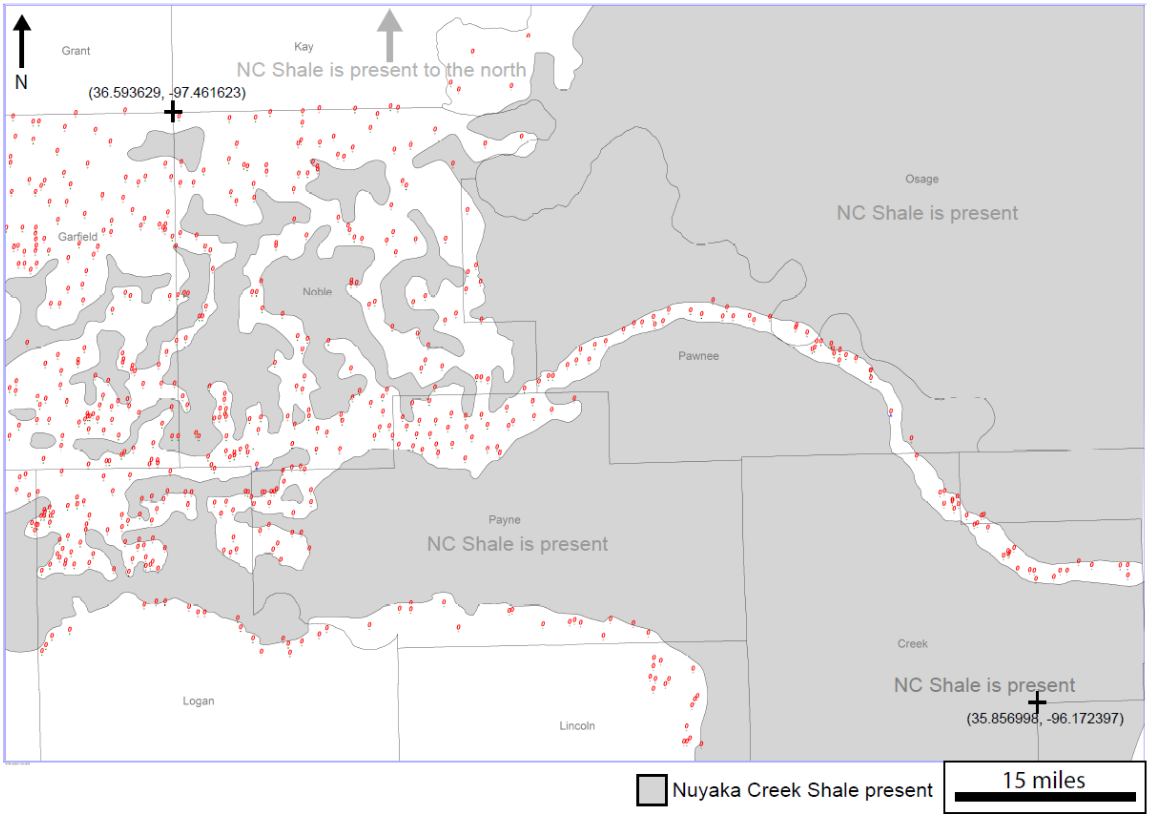
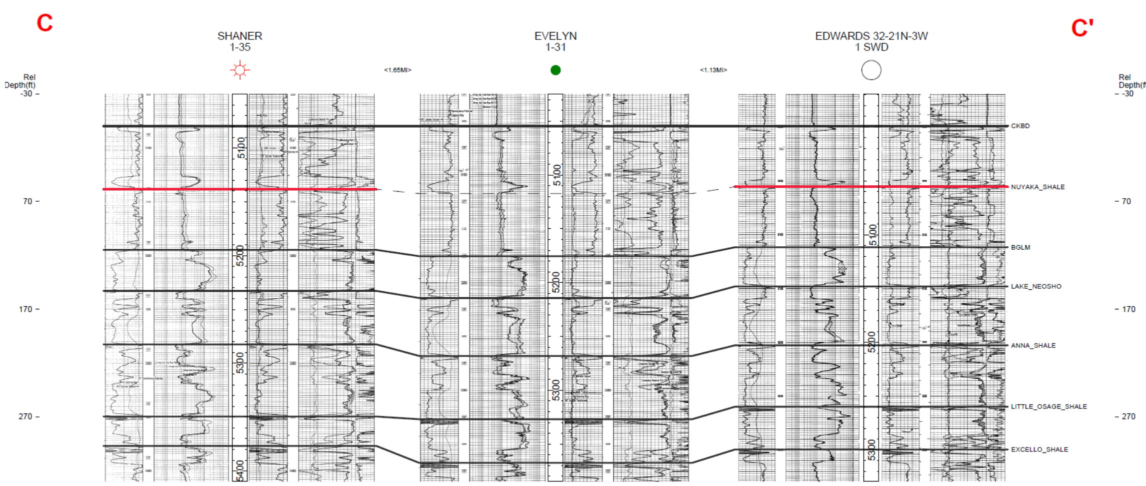


Figure 13. Map of the areal distribution and presence of the Nuyaka Creek Shale. Areas shaded in gray indicate Nuyaka Creek Shale was observed on wireline logs. Individual postings (red symbols) are zeroes where the shale is absent. The Nuyaka Creek Shale is present to the north of Osage and Kay Counties and extends south into the Arkoma Basin.



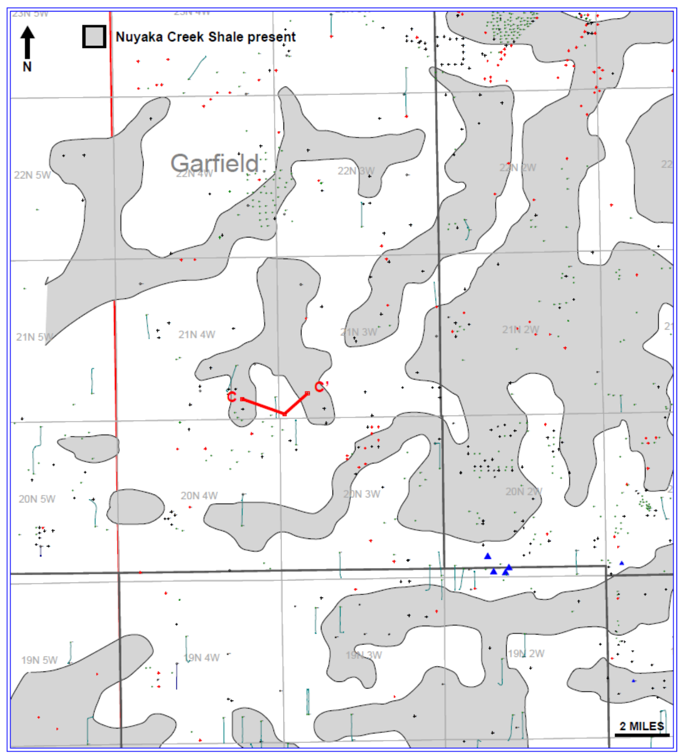


Figure 14. Top: Cross section demonstrating how quickly the Nuyaka Creek Shale is absent over parts of the stable shelf. Below: Locator map for the cross section.

In addition to wells in the northern part of the study area, wells drilled along the trend of the Kiefer sandstone complex that contain thick Cleveland sandstone do not have Nuyaka Creek Shale (Figure 13). The Nuyaka Creek Shale is not identified on wireline logs in any wells within the Kiefer sandstone complex trend, which runs from the eastern edge of Creek County to Kingfisher County. This relationship between the absence of Nuyaka Creek Shale and associated thick Cleveland sandstone is displayed in the NW-SE trending cross section from the Glencoe Field area in northern Payne County (Figure 15)

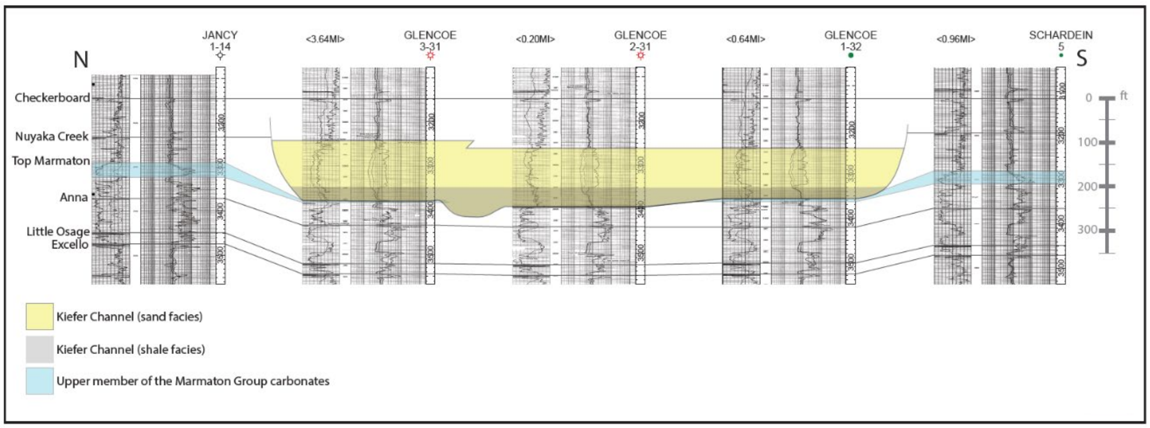


Figure 15. Cross section showing the Kiefer sandstone complex on the stable shelf and the downcutting into the upper member of the Marmaton Group carbonates and the Lake Neosho Shale. Cross section distance is approximately 4.5 miles.

Regional Cleveland Sandstone Trends

A primary objective of this study was to gain a better understanding of the depositional processes responsible for the Owasso and Kiefer sandstone complexes. In order to gain a better understanding of the spatial relationship of these sandstones to each other, the Nuyaka Creek Shale and the older section of the Marmaton Group cross sections were constructed, both parallel and perpendicular to the trends. Special attention was given to determining whether marker beds, primarily the Nuyaka Creek Shale, were present along with the sandstone bodies.

Owasso Sandstone Complex

The Owasso sandstone complex extends approximately due west from an outcrop in northern Tulsa County, near the communities of Collinsville and Owasso, through the southern portion of Osage County, through the middle of Pawnee County, and into Payne County (Figure 16).

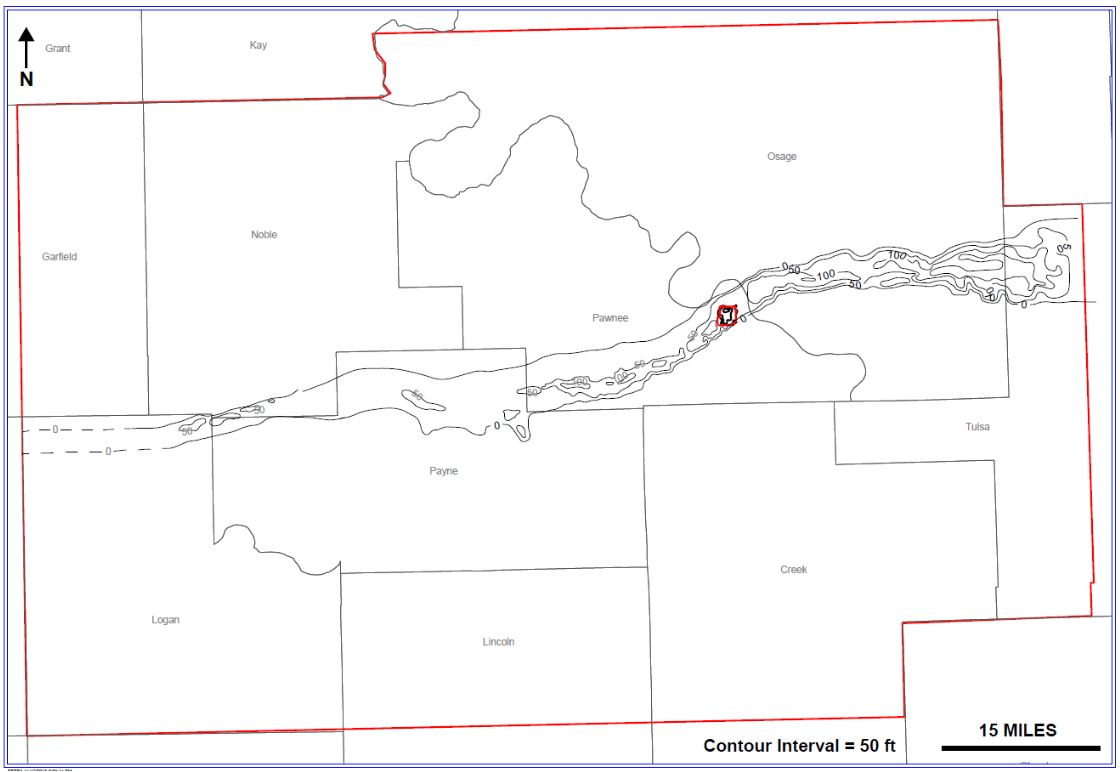


Figure 16: Gross thickness map of the Owasso sandstone complex.

The Owasso sandstone complex becomes less apparent in the western part of Payne County; however, there is evidence that the sandstone complex turns slightly north of Stillwater, Oklahoma (T20N, R02E). The average sandstone thickness in the Owasso sandstone complex is approximately 100 feet (30.5 m) with the thickest sandstone occurring northeast of Cleveland Field in Osage County. The sandstone thickness within the Owasso sandstone complex thins west of Cleveland Field (average 90 feet) near the boundary of Pawnee and Payne counties. However, it is evident the sandstone complex continues farther westward.

Extensive wireline log correlations and mapping indicate that the trend of the Owasso sandstone complex subparallels the trend of the Marmaton Group carbonate front for approximately 42 miles (67.6 km) from the outcrop in Tulsa County and extending into Payne County (Figure 17).

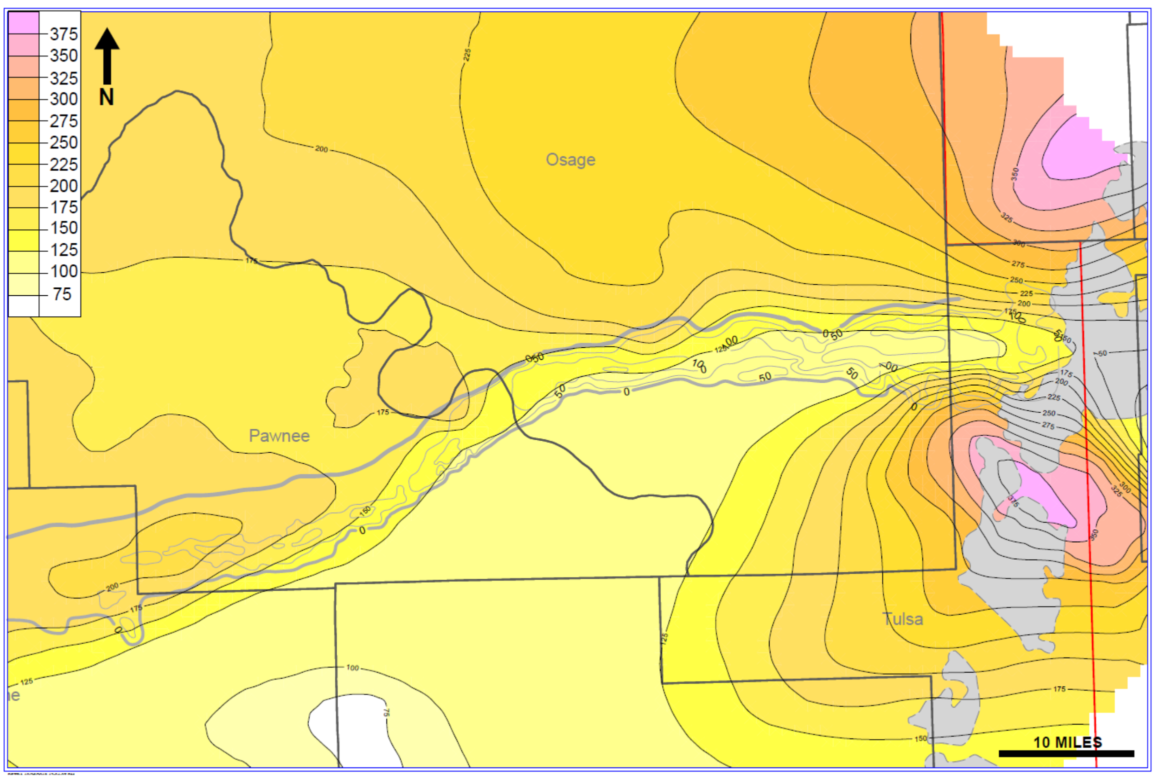


Figure 17. Thickness map of the Marmaton Group carbonates with contoured thickness of the Owasso sandstone complex to display how the sandstone complex follows the Marmaton carbonate front from northern Tulsa County to the center of Pawnee County. Gray polygons display where the Cleveland sandstone crops out (modified from Campbell, 1997). Owasso sandstone complex map contour interval = 50 ft. Marmaton Group carbonates interval thickness map contour interval = 25 ft.

A distinguishing feature of the Owasso sandstone complex is the presence of the Nuyaka Creek Shale overlying the sandstone. The Nuyaka Creek Shale was correlated along with the Owasso sandstone complex from the outcrop in Tulsa County to near Stillwater, Oklahoma in Payne County. This relationship of the Cleveland sandstone within the Owasso sandstone complex and the overlying Nuyaka Creek shale is illustrated in Figure 18.

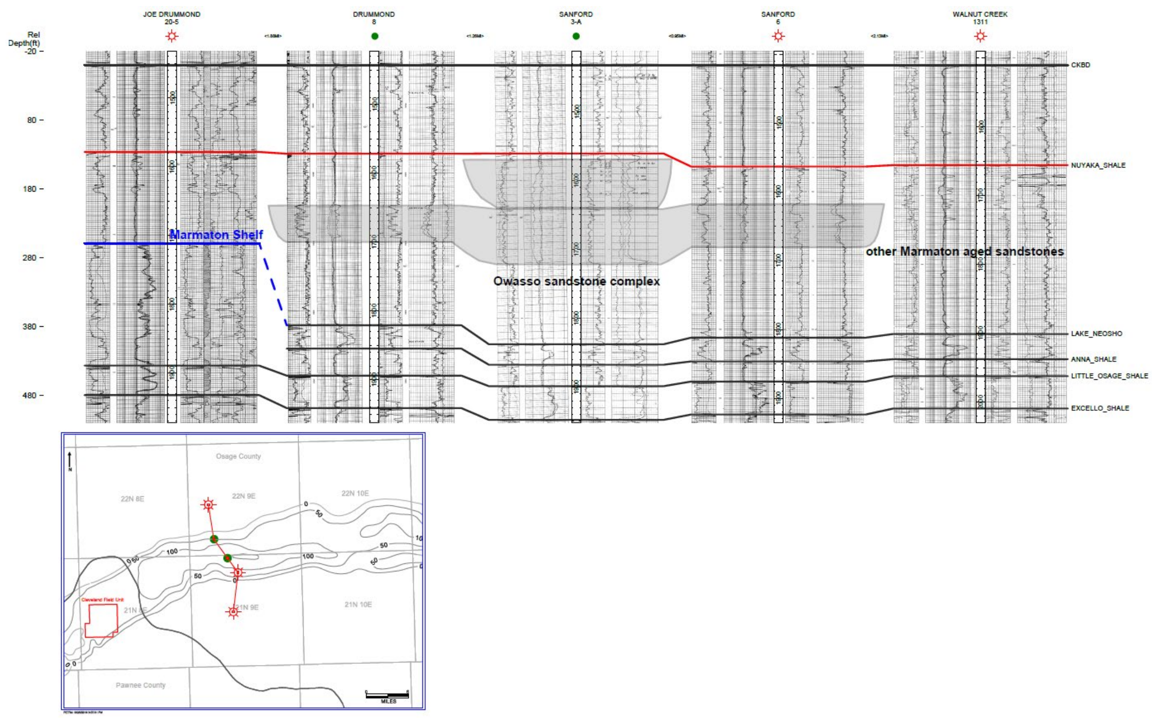


Figure 18. Owasso sandstone complex cross section showing the Nuyaka Creek Shale overlying Cleveland sandstone. This is typical for the Owasso sandstone complex. The distance covered in the cross section is approximately 6 miles.

An outcrop of the sandstone in the Owasso sandstone complex was examined at Collinsville Lake, north of Tulsa, Oklahoma near the communities of Owasso and Collinsville. The outcrop along the south side of Collinsville Lake forms an east-west trending bluff, that is approximately 40 feet high. The lower part of the outcrop is 16 feet of shale that grades upward into a silty interbedded shale, siltstone, very fined-grained sandstone (Figure 19).

Figure 19. Silty shale interval from the lowermost part of the Collinsville Lake outcrop in sharp contact with overlying sandstone (Owasso sandstone complex). Rock hammer for scale = 13 inches).

Directly above and in sharp contact with the silty shale interval is a sandstone dominated section (Figure 19) that includes massive sandstone beds approximately 2 feet thick with a basal shale clast conglomerate containing sideritized clay clasts. This sandstone body forms an uneven (erosional) contact with the underlying silty shale interval (Figure 20).

Figure 20. Sandstone interval containing sideritized clay pebble and shale clast conglomerate that cuts downward into the silty shale interval below (Collinsville Lake outcrop, Owasso sandstone complex).

A thin coal bed (~4 inches thick) occurs at the top of the silty shale zone, but is not continuous across the outcrop. The middle section of the sandstone is dominated by relatively thin stacked sandstone bodies that average 4-5 inches in thickness with low angle dip. The base of this interval is marked by a shale clast conglomerate with sideritized clay clasts (Figure 21).

Figure 21. Sandstone interval containing sideritized clay clasts and shale fragments that are consistent with Lithotype 11 in Cleveland Field cores (Collinsville Lake outcrop, Owasso sandstone complex).

The uppermost section of the outcrop contains massive sandstone bodies that are approximately 4-5 feet thick and form ledges. Observed sedimentary structures include ripple marks, trough-cross bedding, low angle cross-stratification, and shale clast conglomerates (see detailed outcrop description – Figure 23 description).

Paleocurrent indicators include small ripple-laminations and planar cross-lamination in the thinly-bedded, stacked sandstone interval (Figure 22). Measurements taken from photos A and B with a Brunton compass indicate the paleocurrent direction was westward to southwestward (Photo A: S 40° W, 220°; Photo B: S 60° W, 240°) (Figure 22).

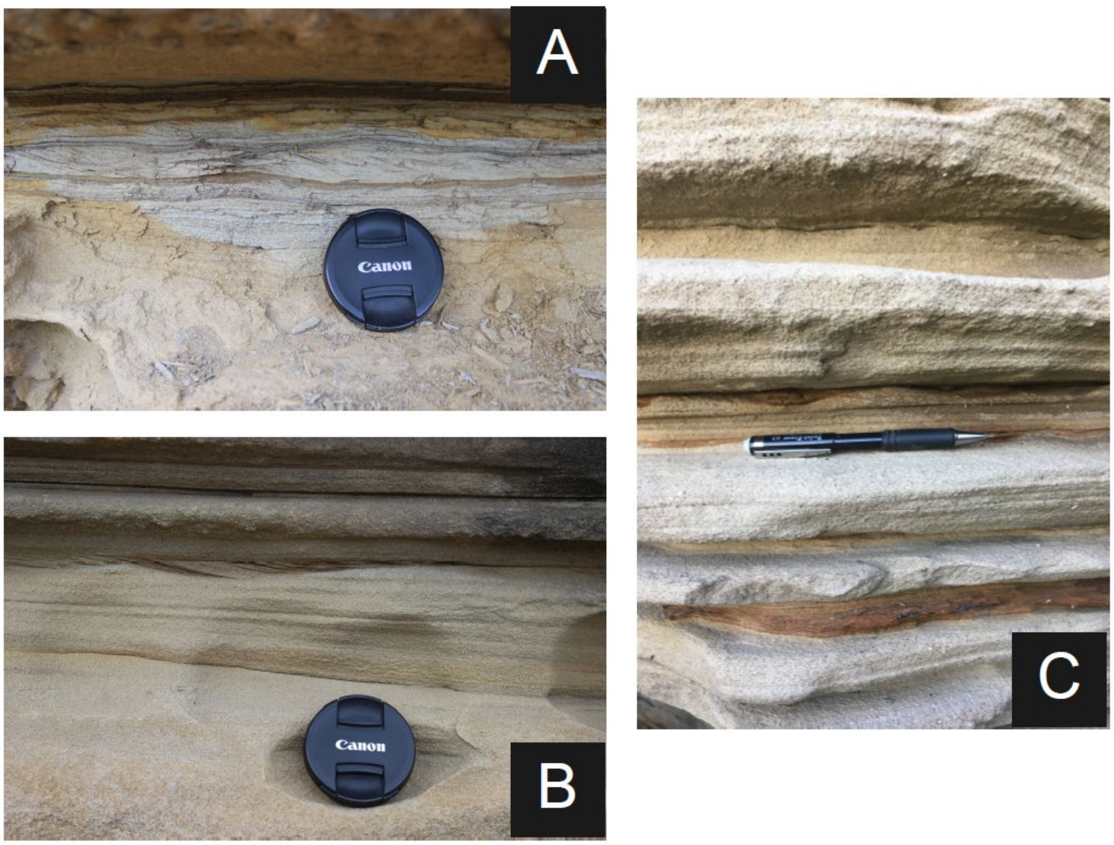


Figure 22. Multiple photos from the Collinsville Lake outcrop. Photo A – ripple-laminated sandstone. Photo B – Ripple-laminated sandstone, planar cross-laminated sandstone, and horizontally-laminated sandstone. Photo C – planar cross-laminated sandstone and wavy-laminated sandstone. Paleocurrent direction measurements were recorded from Photo A and Photo B using a Brunton Compass.

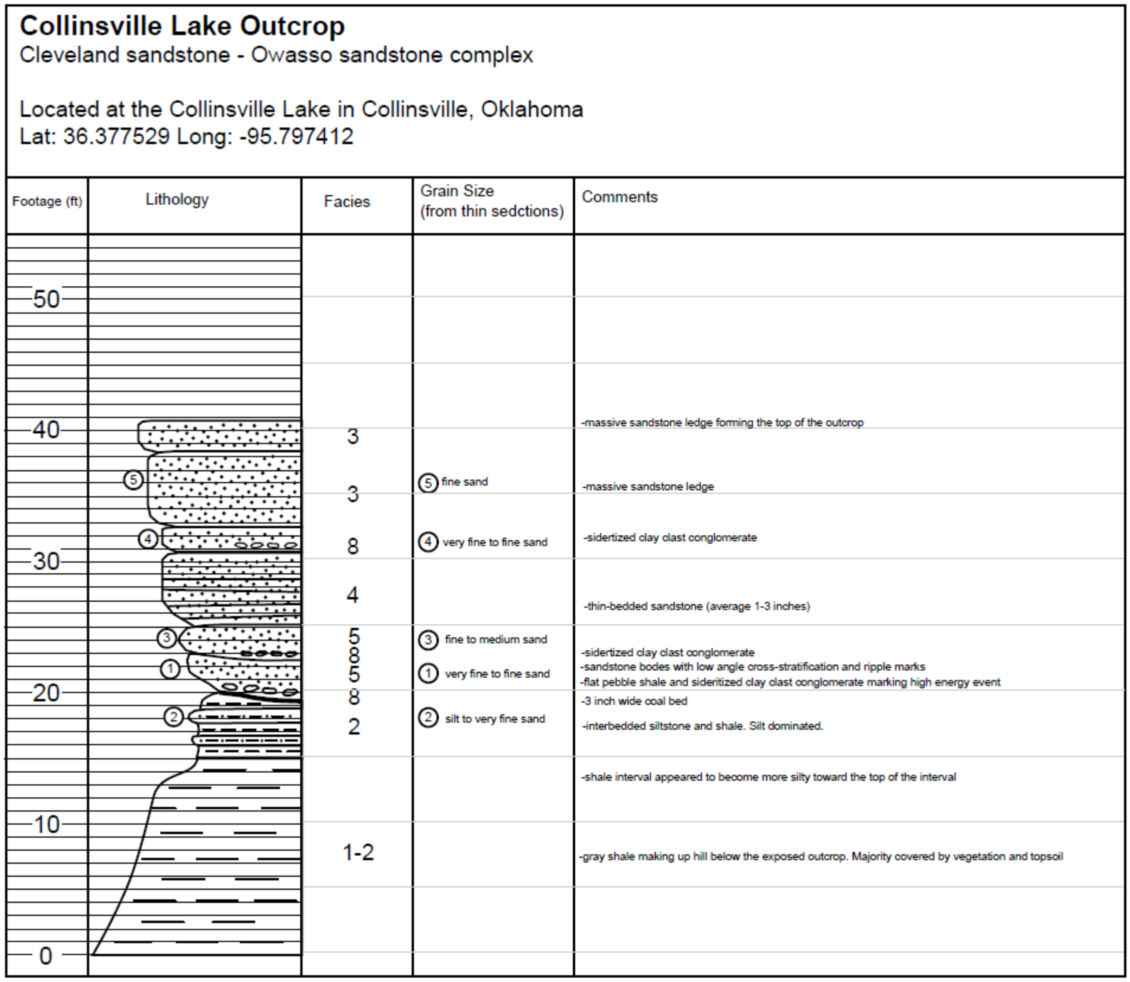


Figure 29. Kiefer/Glenpool outcrop. Uneven contact between the sideritized clay clast conglomerate and the underlying massive sandstone. (Hammer for scale = 8 inches)

Kiefer Sandstone Complex

The Kiefer sandstone complex is the second major Cleveland sandstone complex and extends northwestward from the outcrop in western Tulsa County (T18N, R13E), near the town of Jenks, Oklahoma (Figure 24).

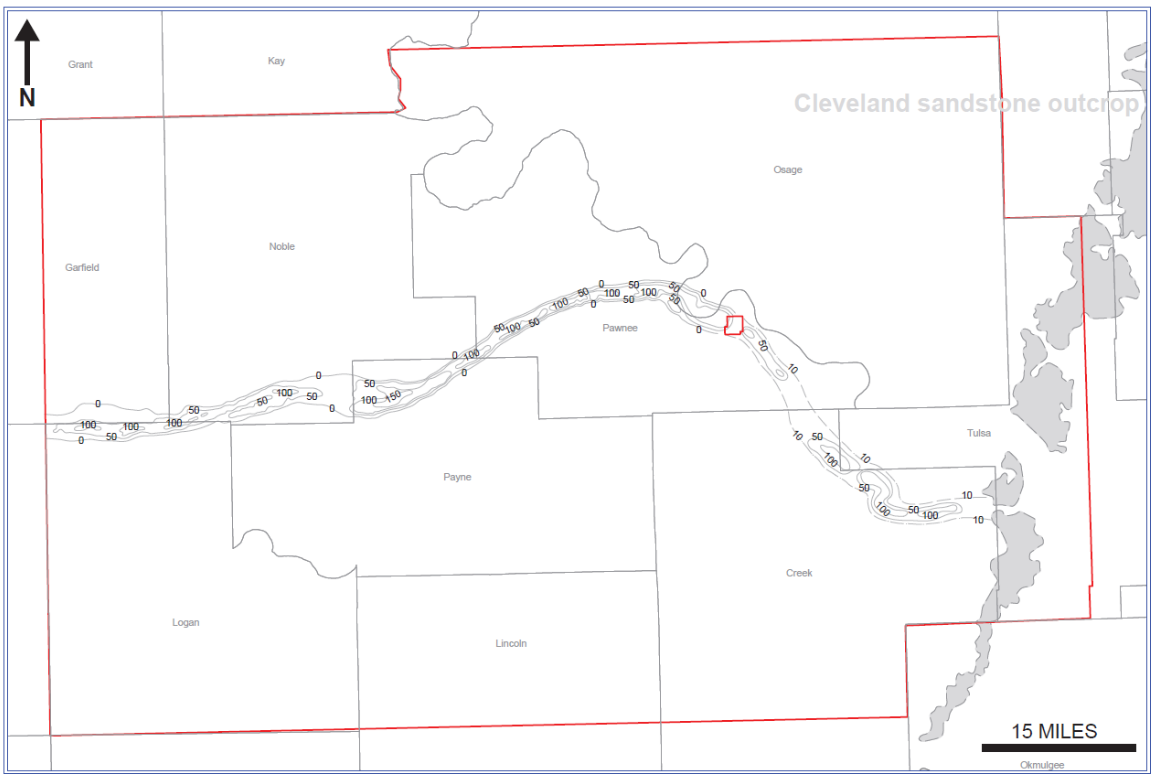


Figure 24. Kiefer sandstone complex gross sand map. Contour interval = 50 feet. Study area outlined in red. Cleveland sandstone outcrop denoted in gray fill (modified from Andrews, 1997). Contour interval = 50 ft.

The Kiefer sandstone complex is over 250’ thick directly west of the Tulsa and Creek County boundary. This is the thickest observed Cleveland sandstone over the entire study area. As the sandstone complex trends northwest towards Cleveland Field, the gross thickness decreases to a consistent value of 100’. As the sandstone complex trends northwest toward Cleveland Field, the correlation of the Kiefer sandstone complex becomes more difficult due to a lack of useful wireline logs. The majority of the vintage wells to the southeast of Cleveland Field only have strip logs or SP-resistivity logs; this makes detailed correlations difficult. The Kiefer sandstone complex passes through the Cleveland Field area and continues northwestward for approximately 20 miles until turning west and continuing through Pawnee County. West of Cleveland Field, the sandstone complex continues through Pawnee, Payne, and into Noble County, where the thicknesses maintain a gross interval of approximately 100 feet. In central Pawnee and northern Payne counties, the sandstone complex is expressed in the Cleveland sandstone interval thickness map as an east-west trending area of thickness greater than 175 feet (Figure 25).

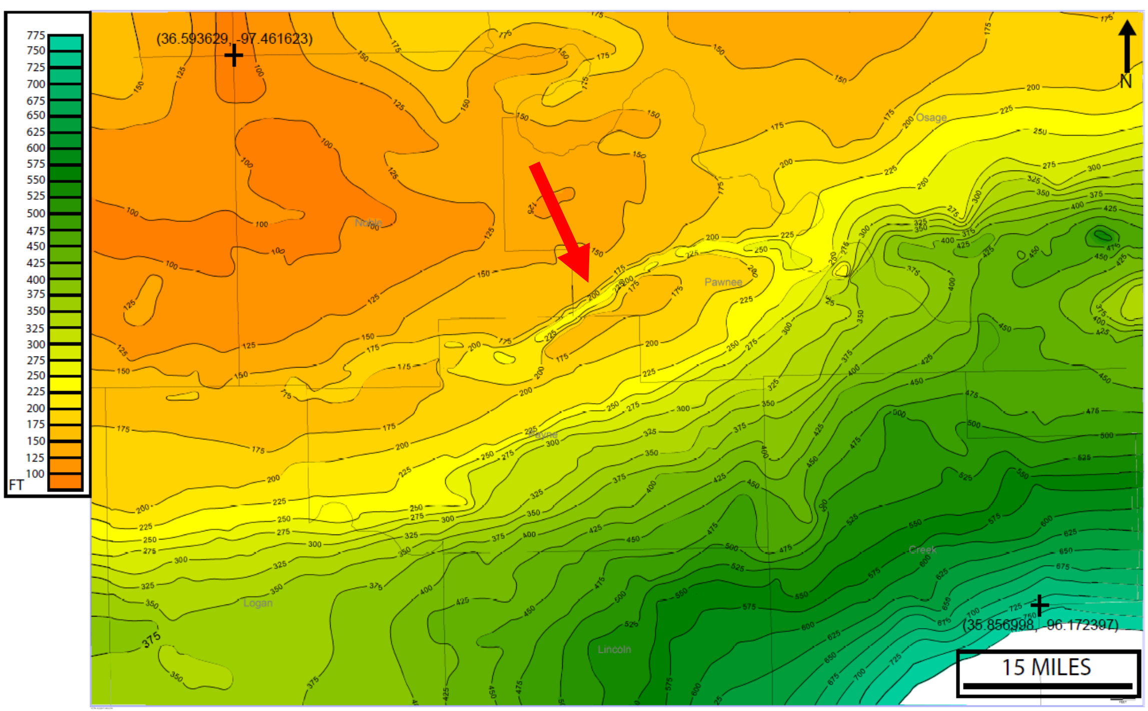


Figure 25. Cleveland sandstone interval thickness map (Checkerboard to top Marmaton Group carbonates). Red arrow indicates Kiefer sandstone complex. Contour interval = 25 ft.

Two distinct observations concerning the Kiefer sandstone complex contribute to a better understanding of the depositional relationship between the Kiefer and Owasso sandstone complexes. The first observation is that within the mapped area, the Nuyaka Creek Shale is absent on wireline logs where the Kiefer sandstone complex is present. The second observation is that the upper member of the Oologah Formation, which is the top of the Marmaton Group carbonates over much of the study area on the stable shelf, thins beneath the trend of the Kiefer sandstone complex in Pawnee, Payne, and Noble counties. The localized thinning of the uppermost Marmaton carbonate in northern Payne and southern Pawnee counties is shown in cross sections and expressed as an area of thinning on the thickness map of the upper carbonate member (Figures 26 and 27).

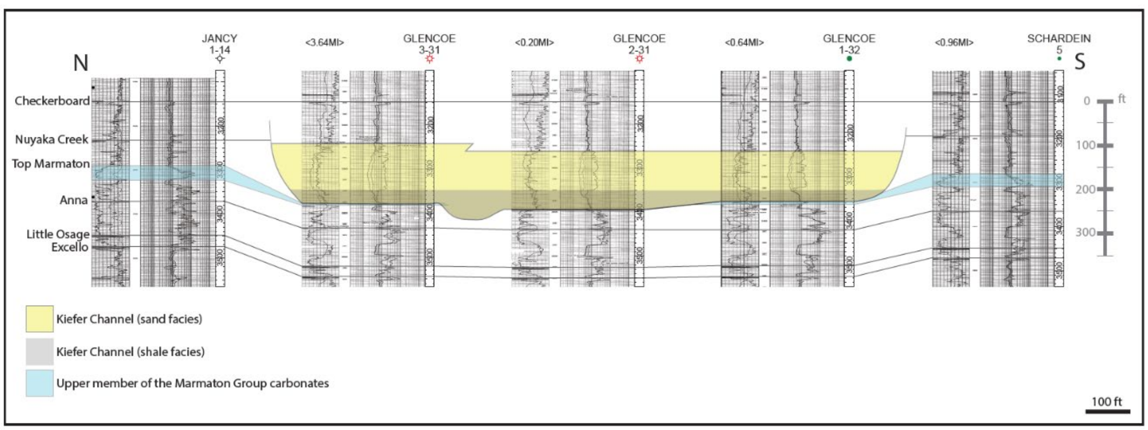


Figure 26. Cross section showing the relationship between the Kiefer sandstone complex and the Marmaton Group carbonates, specifically the absence of the upper member of the Marmaton Group carbonates where the sandstone is present.

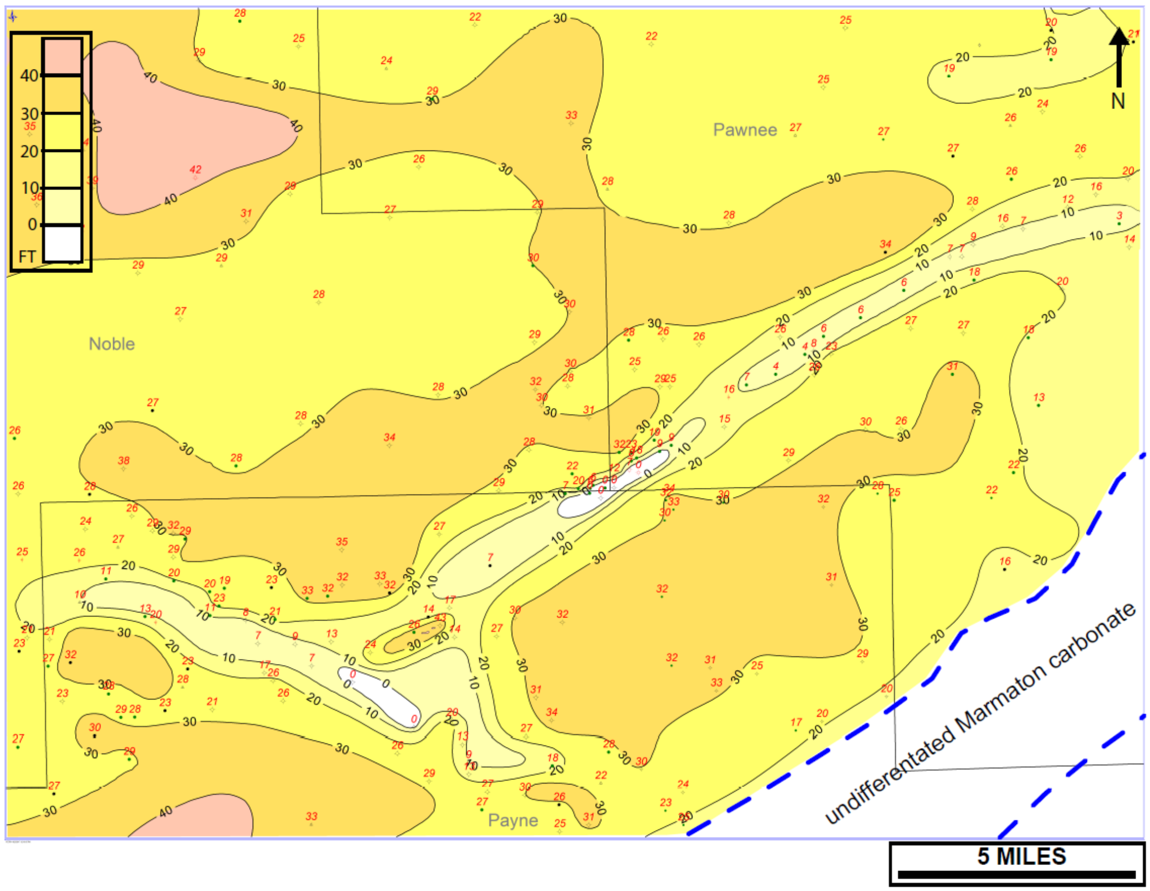


Figure 27. Isopach map of the Oologah limestone, Marmaton Group (upper unit of the Marmaton Group carbonate section, “Big Lime” of industry). Contour interval = 10 ft.

Krumme and Visher (1972), described outcrops of sandstone in the Kiefer sandstone complex near the towns of Glenpool (eastern Creek County, OK) and Kiefer (western Tulsa County, OK). Based on wireline log correlations, there are a number of outcrops in eastern Creek County and western Tulsa County that could correlate to the Kiefer sandstone complex. Two Cleveland sandstone outcrops that are approximately 4.5 miles apart were visited and analyzed for this study. The first outcrop is approximately 1-mile south of the community of Jenks, Oklahoma, at the intersection of Peoria and 106th Street, just south of the Creek Turnpike. This outcrop was described by Bennison (1972) as a Seminole Sandstone member that filled a channel eroded into the Holdenville Shale (Bennison, 1972) and not part of the Kiefer sandstone complex. The second outcrop is at the intersection of Peoria and Highway 67 (151st Street), 2 miles east of Glenpool. This outcrop was identified as part of the Kiefer sandstone complex (Krumme and Visher, 1972).

The outcrop near Glenpool is located on the east and the west side of Peoria Avenue and is approximately 10 feet of exposed rock (Figure 28). The majority of the outcrop is covered in vegetation and highly weathered; therefore, it was difficult to observe any detailed sedimentary structures or paleocurrent indicators.

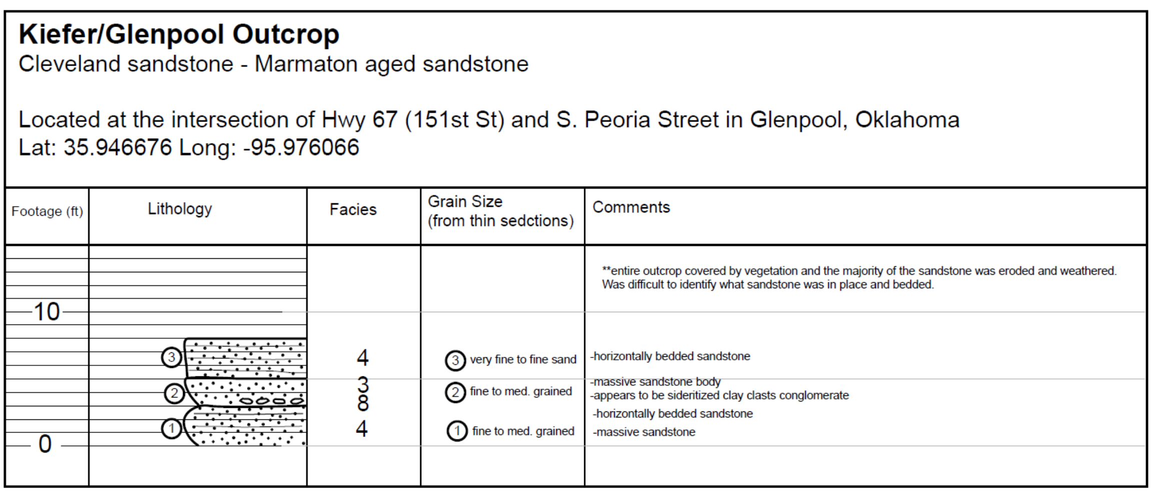


Figure 28: Description of the Kiefer/Glenpool outcrop located directly north of the intersection of S. Peoria and Highway 67, Glenpool, Oklahoma.

The lowest exposed sandstone is a massive sandstone that was approximately 1-2 feet thick and formed the lowest part of the outcrop. Above this sandstone is a sandstone body containing horizontal lamination and a sideritized clay clast layer at the base. The contact between the lowermost sandstone and the sideritized clay clast conglomerate is uneven (Figure 29).

Figure 29. Kiefer/Glenpool outcrop. Uneven contact between the sideritized clay clast conglomerate and the underlying massive sandstone. (Hammer for scale = 8 inches)

Above the massive sandstone is another massive sandstone that forms a ledge near the top of the outcrop. This interval is unlike the other Cleveland sandstone outctops examined in that the uppermost sandstone ledge appears to be much more resistant to weathering (Figure 30).

Figure 30. Uppermost massive sandstone ledge at the Kiefer/Glenpool outcrop. (Hammer for scale = 14 inches)

Above the massive sandstone ledge is a thin interval of thinly bedded sandstone. This zone was not uniform across the outcrop and is highly weathered (Figure 31).

The lowest massive sandstone, middle laminated sandstone, and upper massive sandstone were sampled for thin sections.

Figure 31. Thinly bedded sandstone interval, Kiefer/Glenpool outcrop. (Hammer for scale = 14 inches)

The Jenks outcrop is a naturally exposed sandstone bluff that trends southeast to northwest along the south side of the Arkansas River valley. The exposed outcrop is approximately 40 feet high and 250 feet long. The outcrop is dominantly sandstone with intervals of interbedded sandstone and shale. The base of the outcrop is an interlaminated to interbedded sandstone/siltstone and shale interval that is approximately four to five feet thick. The interval contains well defined ripple marks (Figure 32). This lowest interval is dominated by siltstone and shale.

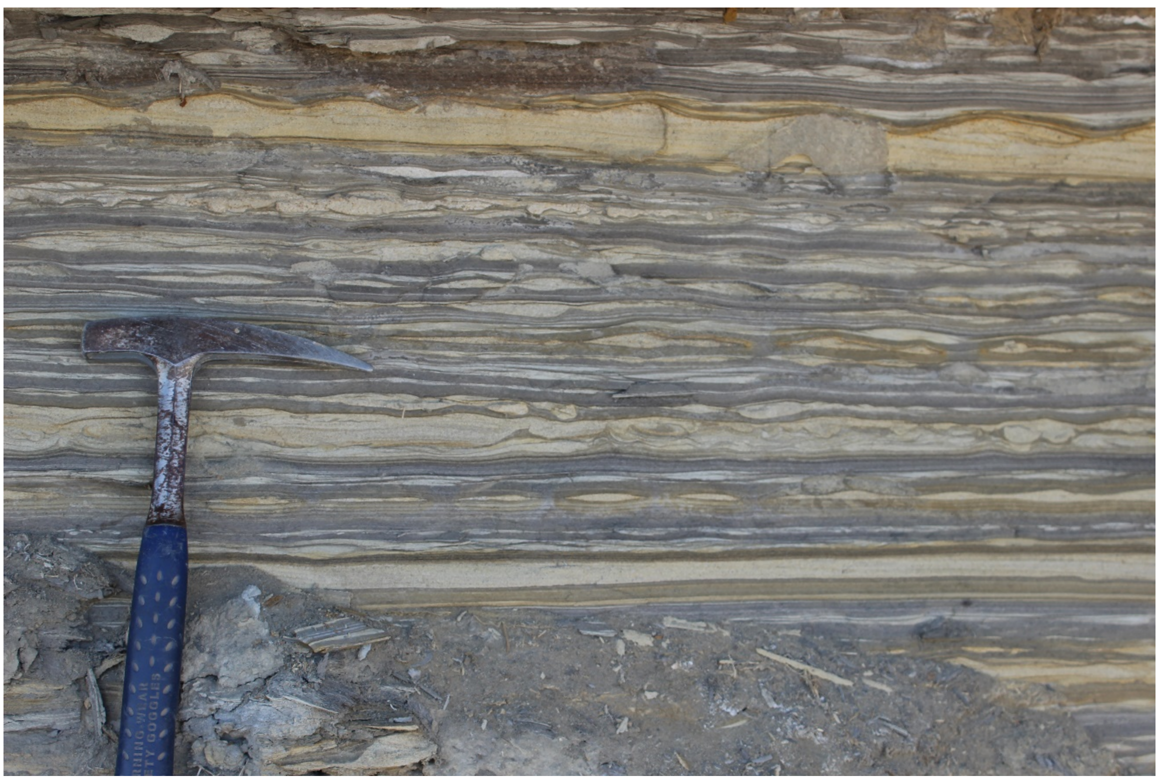


Figure 32. Interlaminated and interbedded sandstone and shale observed at the Jenks outcrop near Jenks, Oklahoma. (Rock hammer for scale = 13 inches)

Above the interlaminated to interbedded sandstone, a distinct coal bed is present that is four to five inches thick (Figure 33). This coal is present at the NW and SE edges of the outcrop, but terminates laterally against sandstone toward the middle of the outcrop.

Figure 33. Coal bed present on the southeast end of the Jenks outcrop. (Rock hammer for scale = 13 inches)

The overlying sandstone is a horizontally-laminated sandstone that appears to cut down through the coal bed and lies uncomformably on the laminated and interbedded sandstone and shale at the base of the outcrop. This sandstone interval is composed of thin sandstones that appear to be horizontally stacked forming a thick sandstone interval. Above this interval is another sandstone that is thinly laminated with silt and shale laminae, with a total thickness of approximately six feet.

The next interval is a massive sandstone body some three to four feet thick that forms a ledge in the upper section of the outcrop. Due to the height and vertical nature of the outcrop, detailed examination of sedimentary structures was not possible; however, some faint directional features were seen.

The top of the outcrop is composed of another interval of thinly bedded stacked sandstone bodies. They appear to be two to five inches in thickness and form an overall interval of approximately 12 feet. The majority of this upper interval is covered by vegetation and is unreachable for detailed analysis of sedimentary structures. Figure 34 is a photograph of the Jenks outcrop from the north and Figure 35 displays the detailed description of the Jenks outcrop.

Figure 34. Jenks outcrop from north. (Dr. Jim Puckette for scale)

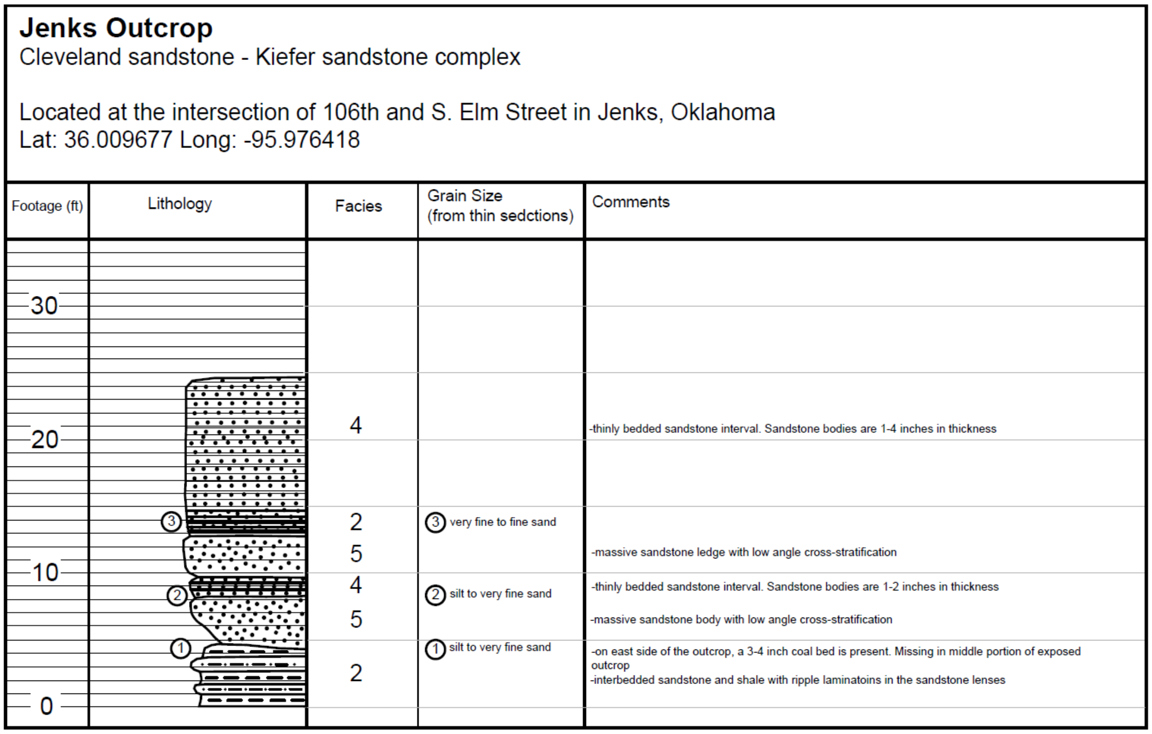


Figure 35. Description for the Jenks outcrop.

Cleveland Sandstone Lithotypes

Eight distinct lithotypes were identified within the Cleveland sandstone section represented in cores available from the Cleveland Field Unit. Lithotypes were defined primarily using grain size and unique sedimentary structures. Lithotypes observed in core were compared to those in outcrop in order to verify that similar depositional events and processes affected deposition of sediments represented in both core and outcrop. Lithotypes and their stacking patterns were another line of evidence used to determine if the boundary between the Owasso and Kiefer sandstone complexes was observable in core.

	Frazee 22	JA 58	L Martin 13	Miller 34	Van Eman 16
Lithotype 1	41.8	9.2	24.6	3.1	15.4
Lithotype 2	19.1	28.2	67.1	18.4	14
Lithotype 3	29.4	24.2	4.4	29.5	37.6
Lithotype 4	52.6	19.6	5.7	11.1	18.5
Lithotype 5	27	10.3	34.5	19.2	42.9
Lithotype 6	12.8	88.9	67.3	65.3	41.9
Lithotype 7	1.6	19.6	6.7	10.5	2
Lithotype 8	1.5	23	2.1	22.9	7.2
totals:	185.8	223	212.4	180	179.5

Table 2. Breakdown of each lithotype thickness per core (in feet).

Lithotype 1: Shale

The shale lithotype (Figure 36) is dark gray to black and occurs primarily at the base of the Cleveland sandstone interval. The shale lithotype is present at the base of the cored interval in four of the five cores (Lucinda Martin #13, Van Eman #16, JA Jones #58, and Frazee #22). The thickest interval of the shale lithotype cored was 41.8 feet in the Frazee #22. The majority of the shale lithotype found below the Cleveland sandstone is macroscopically featureless, but can contain occasional burrows filled with silty material and sporadic marine fossils. Thin shale intervals are observed within the Cleveland sandstone; however, none is greater than 5 inches in thickness. The shale lithotype is easily identified on wireline logs with average gamma-ray values of 120-130 API units. No core plugs were cut in the shale, so no thin sections were available for shale lithotype.

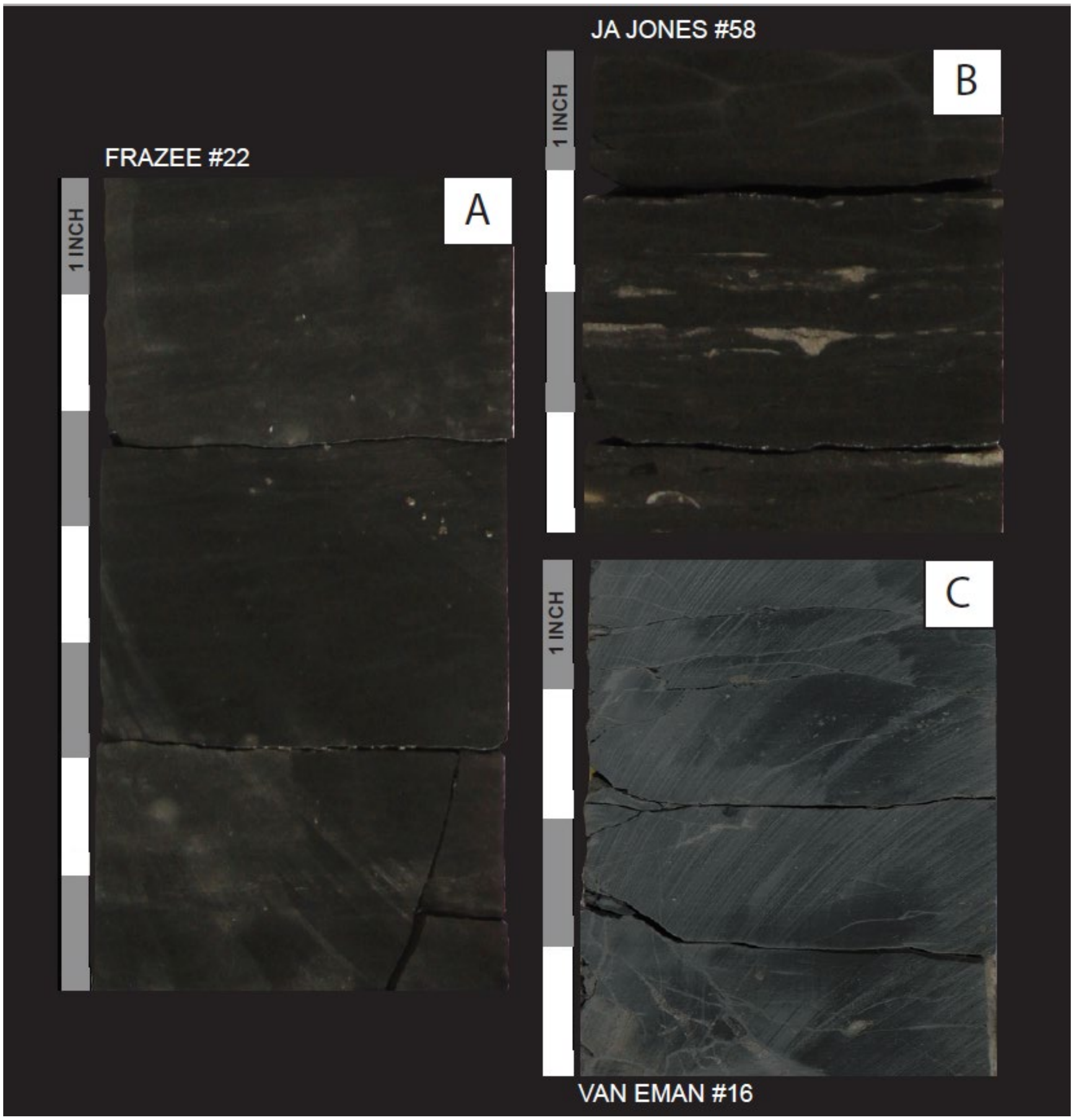


Figure 36. Lithotype #1 – Shale. A) Core photograph of the Frazee #22 in normal light showing a dark gray shale interval with some silty material at the base of the Cleveland sandstone interval. B) Core photograph of the JA Jones #58 in normal light showing a dark gray, faintly laminated shale with load features filled with silty material. C) Core photograph of the Van Eman #16 in normal light showing a featureless gray shale.

Lithotype 2: Interlaminated to Interbedded Siltstone and Shale

The interlaminated to interbedded siltstone and shale lithotype (Figure 37) is composed of varying intervals of thinly laminated silt and shaly material to interbedded siltstone and shale beds that are greater than 1 cm thick. Ripple-laminations and planar bedding are common in this lithotype. Other sedimentary features observed are flaser bedding, load features, and soft sediment deformation. The planar cross-laminated layers occasionally display a rhythmic pattern of deposition. The interlaminated and interbedded siltstone and shale lithotype is present in all 5 cores from Cleveland Field (Miller #34, Van Eman #16, JA Jones #58, Lucinda Martin #13, and Frazee #22). Lithotype #2 is commonly observed at the base of the cored intervals above the marine shale lithotype or at the top of the cored interval above the clean sandstone lithotypes. In wells from the southern half of Cleveland Field (Frazee #22 and Lucinda Martin #13), lithotype 2 is found at the base of the Cleveland sandstone directly above the marine shale and underlying the cleaner sandstone. In northern wells (JA Jones #58 and Miller #34), the interlaminated and interbedded sandstones are found at the top of the section but not near the base. Instead, the marine shale is directly overlain by clean sandstone. Lithotype #2 is thickest in the Lucinda Martin #13 core, with 24.5 feet in the lowermost part of the cored interval and 67.1 feet total; in the Frazee #22 there is 10 feet of lithotype #2 between the lowermost sandstone and the rest of the sandstone bodies. In the other 3 cores from the field, lithotype #2 occurs as thin intervals marking boundaries between sandstone bodies. Multiple thin sections from the JA Jones #58, Frazee #22, and Van Eman #16 display the grain size and texture of lithotype #2. The dominant grain size for lithotype #2 is silt with one thin section displaying predominantly very fine sand (Van Eman #16).

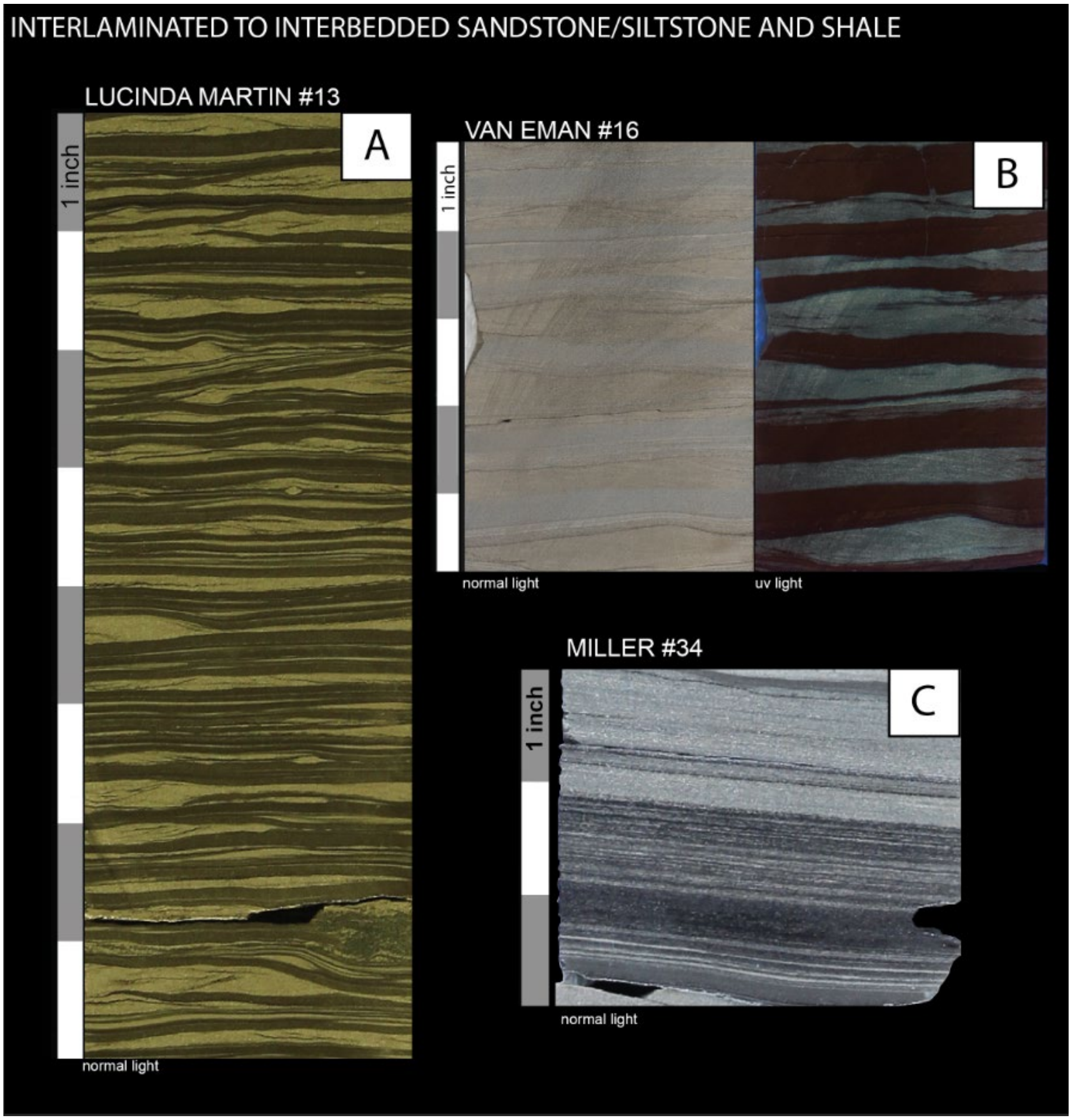


Figure 37. Lithotype #2 – Interlaminated to interbedded sandstone/siltstone and shale A) Core photograph of the Lucinda Martin #13 in normal light displaying interlaminated and interbedded sandstone and shale with ripple-laminations. B) Core photograph of the Van Eman #16 in both normal and UV light displaying interbedded sandstone and shale with faint ripple-laminations within the sandstones. C) Core photograph of the Miller #34 in normal light showing interlaminated siltstone and shale that have planar cross-laminations (with initial dip).

Lithotype 3: Ripple-Laminated to Ripple-Bedded Sandstone

The ripple-laminated to ripple-bedded sandstone lithotype (Figure 38) is characterized by silty fine-grained sandstones that are light gray, tan, and brown in color. The distinguishing sedimentary structures observed in lithotype #3 are ripple-laminations that are commonly two to six mm thick and ripple beds that are greater than one cm in thickness. The thickness of the ripple-laminations and beds varies significantly in the cored intervals from Cleveland Field. In certain intervals, the ripple beds are composed of visible shale beds greater than one cm in thickness, and in other intervals, the shale and ripple laminae are so thin they are hard to see in normal light and become evident in the UV light photographs. In some cases, the ripple-laminations are closely spaced with only centimeters of sand between ripples, however, in other cores, there is upward of 1 to 1 ½ inches of sand between ripple-laminations (Figure 38). Lithotype #3 is the finest grained sandstone out of the main four sandstone lithotypes, with an average grain size of silt to very fine (based on thin section examination and visual inspection). Primary detrital grains are quartz and feldspar along with metamorphic rock fragments. Detrital quartz is moderately-sorted and subround to round with frequent quartz overgrowth. The ripple-laminated and ripple bedded sandstones are found throughout the cored intervals with no obvious preferred position with respect to the sandstone bodies. In the Frazee #22 core, lithotype #3 is the most prevalent in the lower portions of the interval. In contrast, in the JA Jones #58, Van Eman #16, and Miller #34, the ripple-laminated to bedded sandstones are common at the top of the Cleveland sandstone interval above the cleaner sandstone bodies.

The Van Eman #16 contains the greatest thickness of lithotype #3 with 37.6 feet.

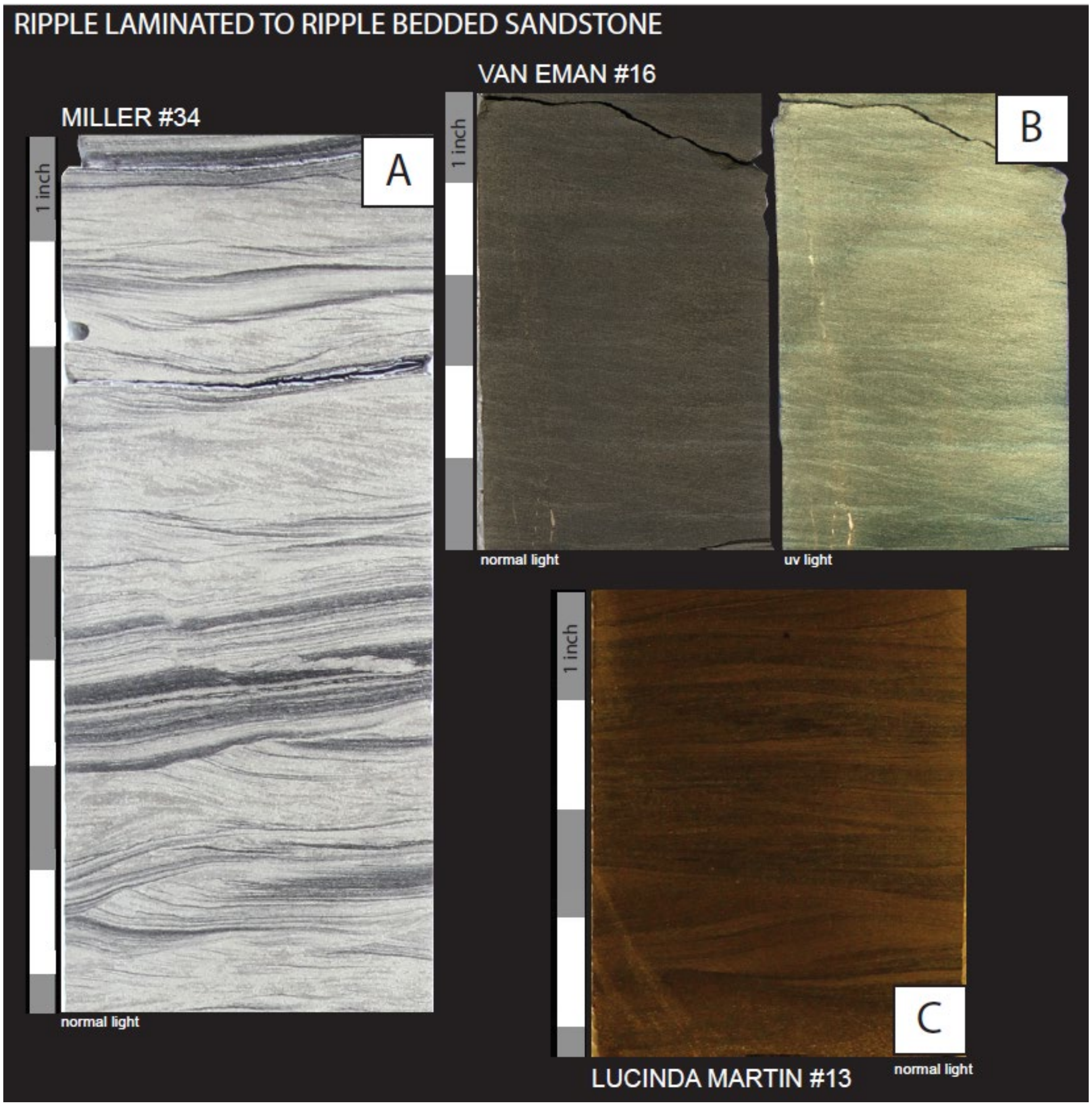


Figure 38. Lithotype #3 – Ripple-laminated and bedded sandstones. A) Core photo of lithotype #3 from the Miller #34 under normal light. Abundant ripple-laminations are present along with very small-scale slump-flow features. The sandstone is light gray in color with dark gray shale and carbonaceous material. B) Core photograph from the Van Eman #16 under both normal and UV light showing very thin ripple-laminations in the brown sandstone. C) Core Photograph from the Lucinda Martin #13 under normal light showing ripple-laminations that are less than 1 cm thick. Sandstone is tan in color due to oil staining.

Lithotype 4: Horizontally-Laminated Sandstone

The horizontally-laminated sandstone (Figure 39) is composed of very fine- to fine-grained sandstones that contain horizontal-laminations that range in thickness from 2 to 5 mm. The dominant grain size is fine sand and the grains are well-sorted. The sandstone bodies in lithotype #4 are light gray to tan in color. The horizontal-laminations are commonly due to of carbonized material or shale. The laminated sandstone bodies range in thickness from 1-12 feet. Sandstone bodies within lithotype #4 commonly do not have sharp contacts at the boundaries, but instead the sandstone changes subtly from horizontally-laminated to ripple- or planar-laminated. Lithotype #4 comprises small portions of 4 of the 5 cores, except for the Frazee #22, where the horizontally-laminated sandstones total 52.6 feet of the core. Nine thin sections were examined from the horizontally-laminated intervals (5 from the Frazee #22 and 4 from the Van Eman #16). Quartz grain sizes range from silt to medium-grained sand, whereas the average and most abundant grain size is fined-grained.

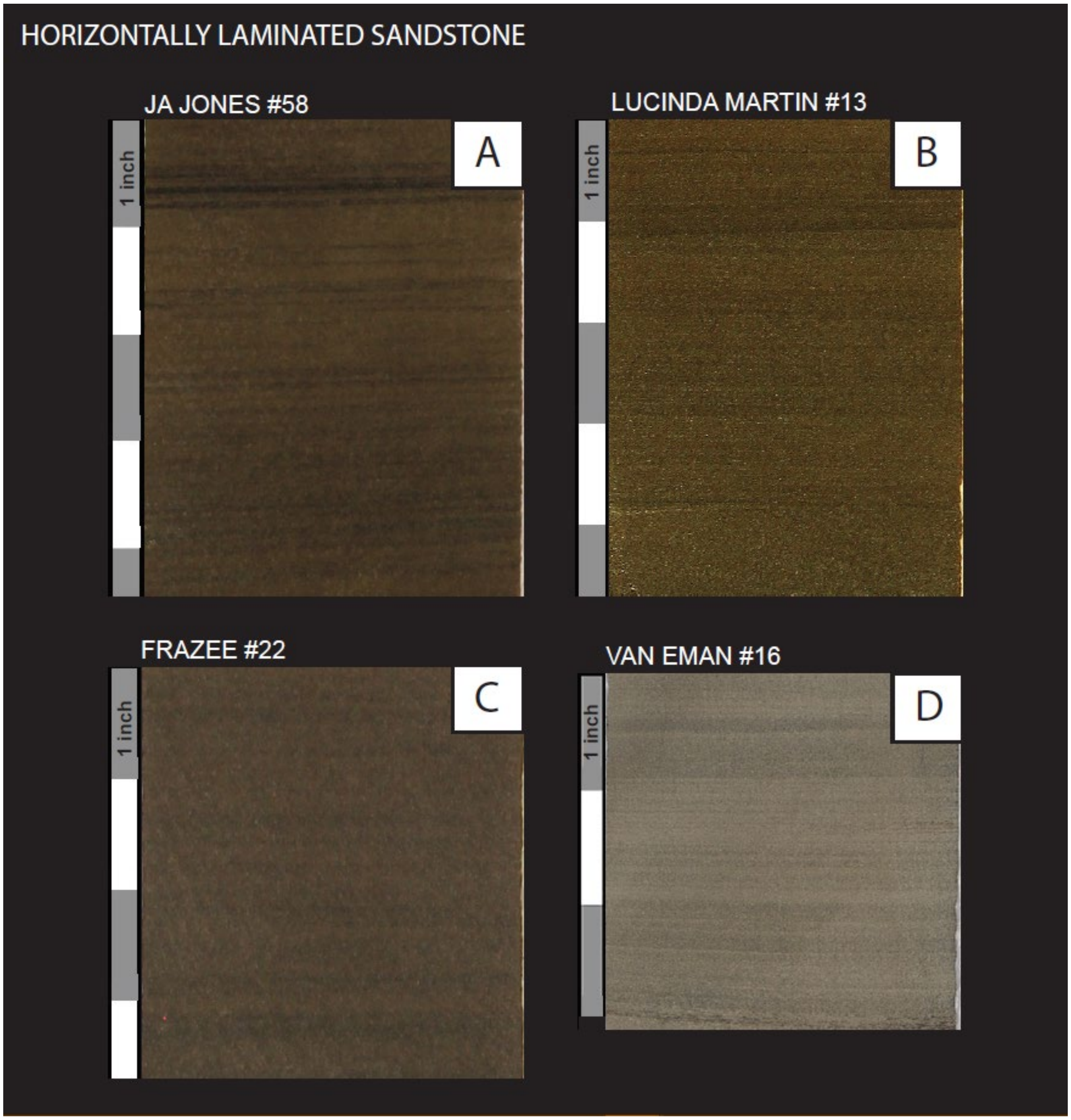


Figure 39. Lithotype #4 – Horizontally-laminated sandstone. A) Core photograph of the JA Jones #58 in normal light showing horizontal shale laminations within brown sandstone. B) Core photograph of the Lucinda Martin #13 under normal light showing horizontal-laminations. C) Core photograph of the Frazee #22 under normal light showing horizontal-laminations in brown sandstone. D) Core photograph of the Van Eman #16 under normal light showing faint horizontal-laminations in tan sandstone. Brown color is a result of oil staining.

Lithotype 5: Planar Cross-Laminated Sandstone

Lithotype #5, planar cross-laminated sandstone, is characterized by fine- to medium-grained sandstone that is light gray, tan, and brown in color. The distinguishing feature of this lithotype is inclined planar cross-laminations highlighted by carbonized material and shale (Figure 40). Overall, this lithotype has the coarsest sandstone grains observed in Cleveland Field, with an average grain size of fine-grained, but also contains medium-grained sand. The planar cross-laminations are typically 1-2 mm in thickness and are faint within the sandstone. These intervals with cross-laminations range from a few inches to over 10 feet. Lithotype #5 commonly has sharp contacts with the underlying strata, however, most of the contacts are sandstone to sandstone. Nine thin sections were examined from this lithotype and the dominant grain size is fine sand. The dominant grain shape is subround with abundant quartz overgrowths. The overall texture is moderate to well sorted. Sandstones from this lithotype are composed of predominantly detrital quartz with lesser amounts of feldspar, chert, and metamorphic rock fragments. Besides quartz cement, ferroan dolomite is common. The dominant porosity type is secondary developed presumably from dissolved feldspar grains, however, some primary porosity is observed between quartz overgrowths. The planar cross-laminated sandstone lithotype composes a relatively small portion of the cored interval from the Miller #34 and the JA Jones #58 (19.2 ft and 10.3 ft, respectively). This lithotype is a larger percentage of the core in the Lucinda Martin #13, Frazee #22, and Van Eman #16 (34.5 ft, 27 ft, 42.9 ft respectively).

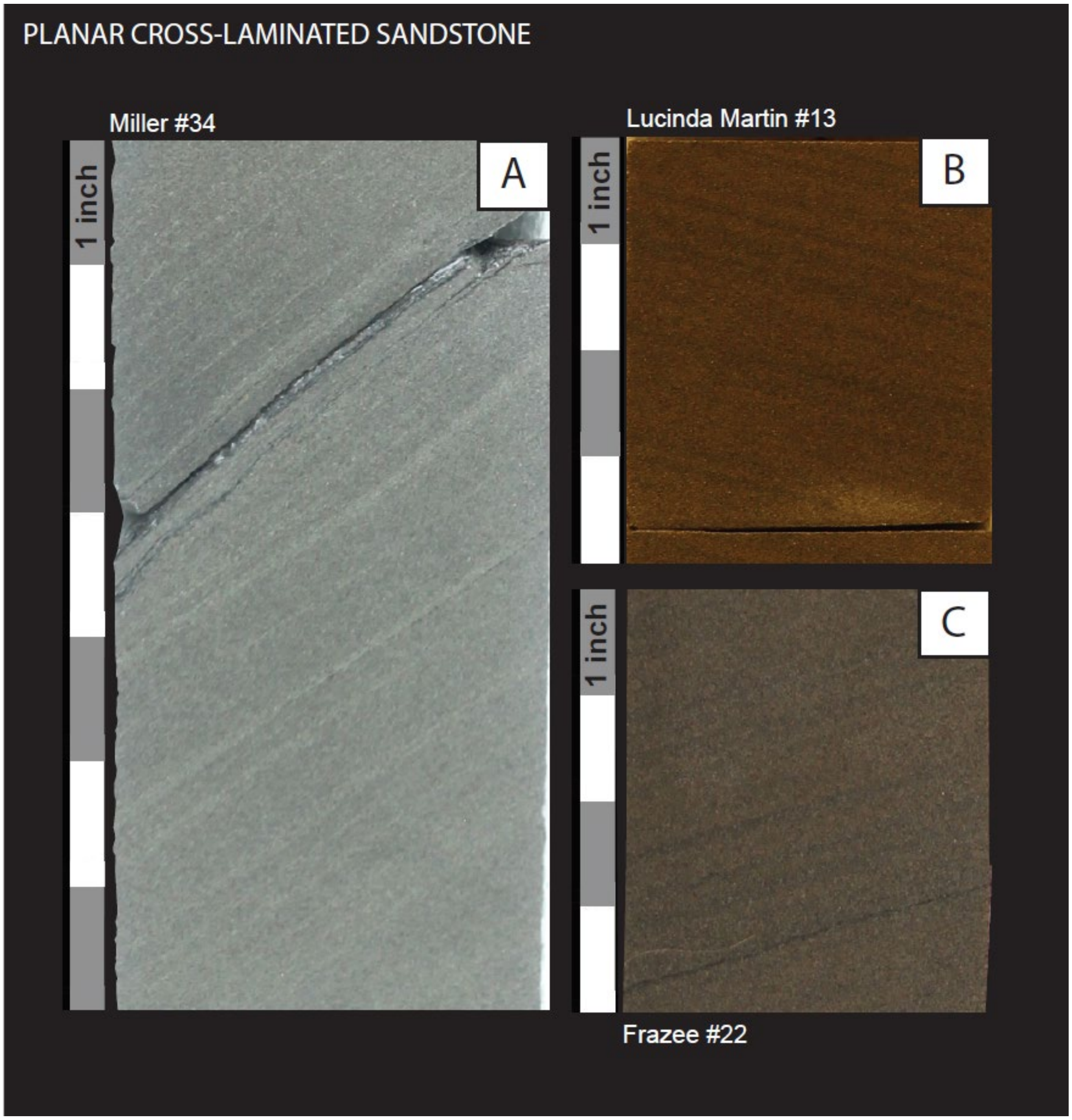


Figure 40. Lithotype #5 – Planar cross-laminated sandstone. A) Core photograph from the Miller #34 under normal light displaying common planar cross-laminations. The angle of the planar cross-laminations is approximately the angle of repose, suggesting this interval could be a rotated block. B) Core photograph of the Lucinda Martin #13 under normal light showing planar cross-laminations in a tan sandstone. C) Core photograph of the Frazee #22 under normal light showing planar cross-laminations in a brown sandstone.

Lithotype 6: Massive Sandstone

The massive sandstone lithotype (Figure 41) is characterized by very fine- to medium-grained sandstones without any defining sedimentary structures. The massive sandstone lithotype is tan to light brown in color with isolated intervals with dark brown oil staining. Lithotype #6 contains no visible bedding or other sedimentary structures. One defining feature of the massive sandstone lithotype is the presence of carbonaceous wisps that are randomly oriented within the sandstone. The massive sandstone lithotype comprises the majority of 4 of the 5 cores from the Cleveland Field, excluding the Frazee #22 (88.9 ft in the JA Jones #58, 67.3 ft in the L. Martin #13, 65.3 ft in the Miller #34, 41.9 ft in the Van Eman #16, and 12.8 ft in the Frazee #22). Lithotype #6 has sharp contacts with underlying strata in multiple cores. Eight thin sections were examined from the massive sandstone lithotype (3 from the Frazee #22, 2 from the JA Jones #58, and 3 from the Van Eman #16). The dominant detrital grains in lithotype #6 are quartz (subround to round) and metamorphic rock fragments. Primary and secondary porosity are both observed in thin sections from lithotype #6, with the dominant type being secondary presumably due to dissolution of feldspar grains.

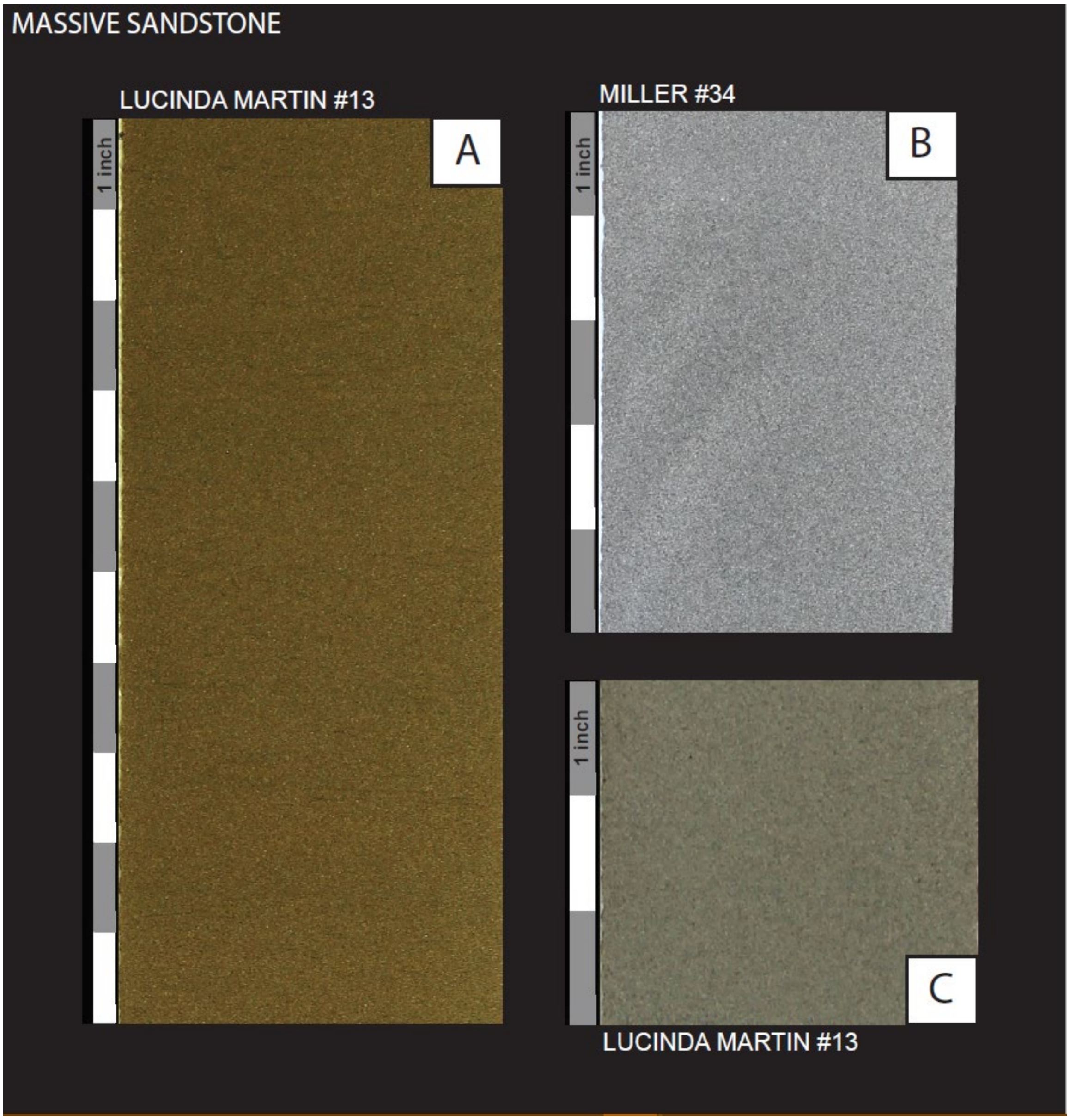


Figure 41. Lithotype #6 – Massive sandstone. A) Core photograph from Lucinda Martin #13 in normal light showing a typical massive sandstone with very faint randomly oriented carbonaceous wisps. B) Core photograph from the Miller #34 in normal light showing a massive light gray sandstone with no obvious sedimentary structures. C) Core photograph from the Lucinda Martin #13 in normal light showing a featureless massive sandstone.

Lithotype 7: Rounded Clay Clast Conglomeratic Sandstone

The rounded clay pebble conglomeratic sandstone lithotype (Figure 42) consist of tan to brown fine-grained sandstone matrix and rounded mudstone clasts. The distinguishing feature of this lithotype is the presence of rounded clay pebbles without apparent bedding and subrounded shale clasts. This interval is defined as a transitional zone above the deposition of the more angular clay clasts and shale clasts found in lithotype #8. Clay pebbles are predominantly sideritized and range from 1 cm to 1.5 inches in length. Generally, the clay pebbles are elongated and have rounded edges. The clay pebbles are much more common in this lithotype than the shale clasts; this is in contrast to the abundant shale clasts in the true conglomerate intervals found below. The shale clasts and clay pebbles are randomly oriented in the sandstone matrix, but are isolated to thin intervals within cores. Two thin sections were examined from the JA Jones #58 in the rounded clay pebble and shale clast conglomerate lithotype; sandstone in both thin sections is fine-grained with subround to rounded quartz grains.

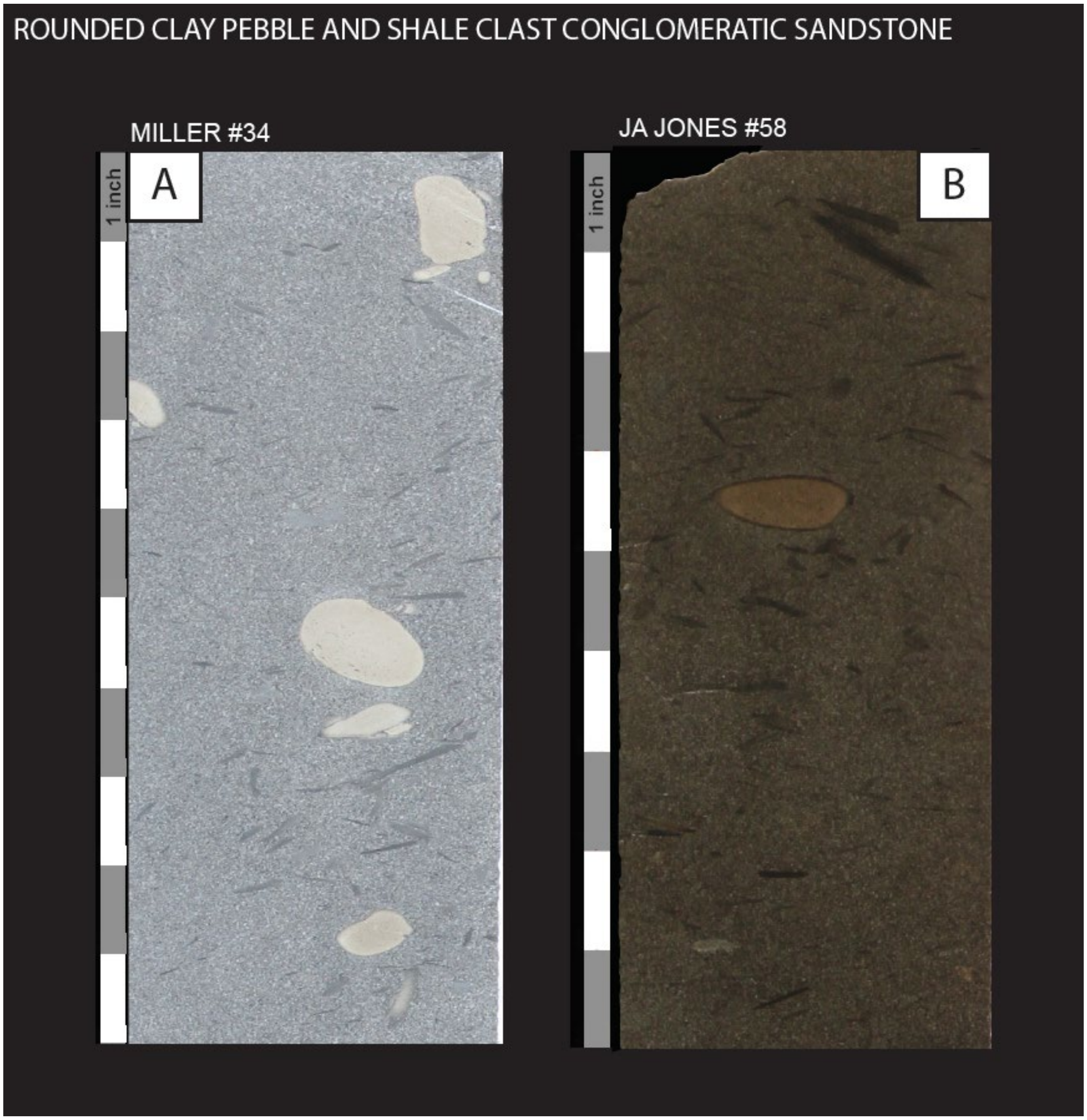


Figure 42. Lithotype #7 - Rounded clay pebble and shale clast conglomeratic sandstone. A) Core photograph of the Miller #34 in normal light displaying the rounded sideritized clay pebble and small angular shale clasts in a light gray sandstone matrix. B) Core photograph from the JA Jones #58 in normal light displaying a rounded sideritized clay clasts with sporadic shale clasts.

Lithotype 8: Shale Clast and Clay Pebble Conglomerate

The shale clast and clay pebble conglomerate lithotype (Figure 43) is characterized as clast-supported with silt to medium-grained matrix. These conglomeratic intervals form very sharp contacts with the underlying rock and are commonly several feet thick. The shale clast and clay pebble conglomerate lithotype transitions into the matrix supported, rounded clay pebble conglomeratic sandstone lithotype mentioned previously. Shale clasts observed in this lithotype are angular and some show bedding and laminations (Figure 43). The clay pebbles are commonly sideritized. Shale clasts are more common in this lithotype than clay pebbles; however, in a few instances, this conglomeratic zone is dominated by clay pebbles (Lucinda Martin #13 and JA Jones #58). Associated with this lithotype are significant fluctuations in the grain size of the sandstones that comprise the matrix. Five thin sections are available from this lithotype and the dominant grain size of the matrix ranges from silt to medium-grained sand with a dominant grain size of fine-grained sand.

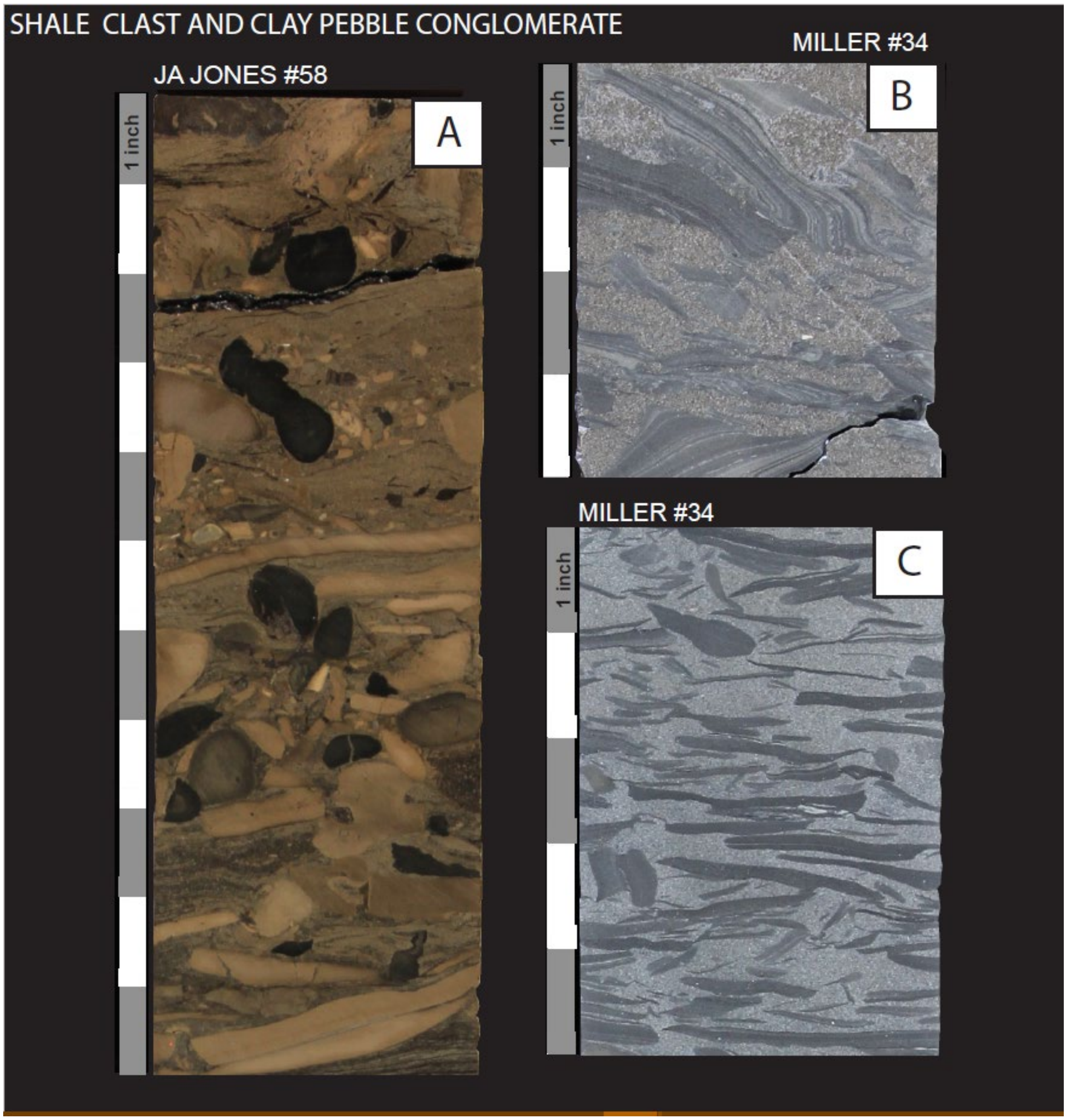


Figure 43. Lithotype #8 - Shale clast and clay pebble conglomerate. A) Core photograph of the JA Jones #58 in normal light displaying the sideritized clay clast-dominated interval (above a sharp contact with the underlying strata). B) Core photograph from the Miller #34 in normal light showing angular shale clasts with laminations intact. C) Core photograph from the Miller #34 in normal light showing an angular shale clast conglomerate interval.

Cleveland Field Unit Petroleum Geology

The Cleveland Field Unit covers 1,760 acres in T21N, R08E, Pawnee County, Oklahoma. This area was unitized in 2011 by RDT Properties (now Mid-Con Energy) of Tulsa, Oklahoma. In the same year, an infill drilling program was initiated by Mid-Con, which resulted in 52 wells drilled to date. The Cleveland Field Unit primarily produces from the Cleveland sandstone (76 active Cleveland sandstone wells); however, oil is produced from the Osage Layton sandstone, Layton Sandstone, Lower Skinner Sandstone, and Bartlesville Sandstone in co-mingled wells.

The Cleveland Field Unit is located on a structural high, well defined by a structural contour map of the Checkerboard Limestone. The structural dome has two prominent high points located within the field, one in the northwest and one in the southeast (Figure 44). The field contains multiple faults that are inferred from missing sections on wireline logs. These fault cuts occur at various depths within the field, with the most prominent fault cutting through the Cleveland sandstone on the western edge of the unit boundary. This fault is located on the western flank of the structural high in the northwest portion of the field.

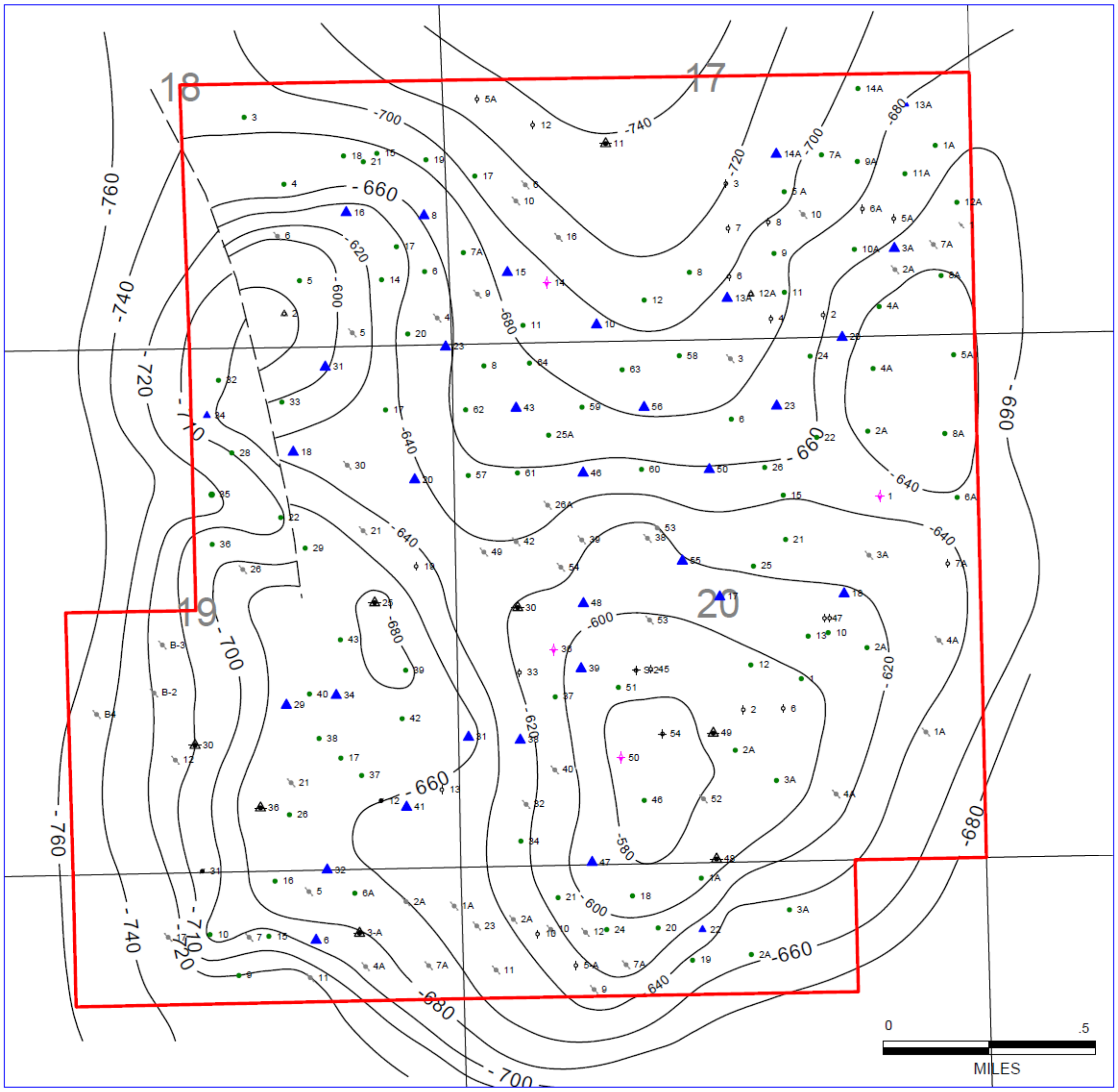


Figure 44. Checkerboard structure map in Cleveland Field Unit. Unit is outlined in red. Contour interval = 20 feet.

Other significant features in Cleveland Field include a significant change in the thickness of the Marmaton Group carbonates in the western half of the field. Wireline logs from the JL Miller Lease show a significant thickening of the upper carbonate unit (“Big Lime”). The “Big Lime” is not present in other portions of the field or to the south, southeast, or east; however, in the western half of Cleveland Field, the limestone reaches thicknesses of 80 feet. This thick limestone interval results in the Cleveland sandstone lying directly above it without the normal marine shale found in the rest of the field.

The Nuyaka Creek Shale is only observed in the far northeast and southwest corners of the Cleveland Field Unit. The field contains over 100 wells with gamma-ray and porosity logs surveys over the Cleveland sandstone interval and the Nuyaka Creek Shale is not present in any of these wells. In the majority of the field and surrounding area, Cleveland sandstone accumulations are undifferentiated with none of the stratigraphic markers recorded in wireline logs or present in cores.

Based on cross section correlations and mapping, the Kiefer and Owasso sandstone complexes converge near the Cleveland Field Unit; this results in sandstone thicknesses averaging 200 feet across the unit. Based on wireline log correlations, the Owasso sandstone complex enters the Cleveland Field Unit from the northeast and trends diagonally across the field toward the southwest. Additionally, the Kiefer sandstone complex extends across Cleveland Field from the southeast and continues to the northwest (Figure 45). In previous investigations of the Cleveland sandstone in Cleveland Field Unit, the sandstone interval was not divided into Kiefer and Owasso sandstone complex; however, petrophysical analysis was performed, and the Cleveland sandstone was divided into four depositional events (Roddy, 2014; Roddy et al., 2018).

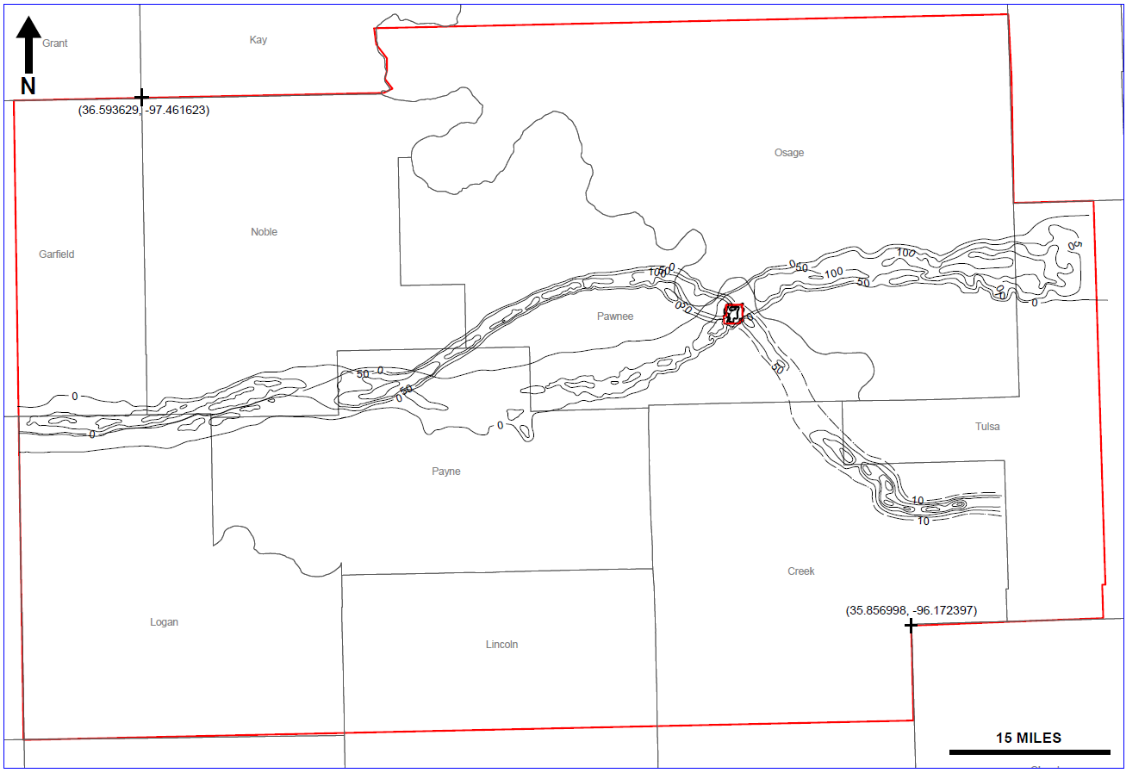


Figure 45. Regional map of the gross sandstone for the Kiefer and Owasso sandstone complexes. Contour interval = 50 ft.

Sandstone thickness across the field is fairly consistent with the majority of the wells in the field containing over 100 feet of greater than 10% porosity sandstone. The area with the thinnest gross sandstone is the west-southwest corner, where some wells contain only 50-60 feet. Given the consistent thickness across the field, there are considerable changes in the nature of the sandstone bodies. The majority of the wells in the northern half and southwestern corner of the field contain more sandstone in the lower portion of the interval. There are defined sandstone bodies that make up the basal part of the Cleveland sandstone and are in contact with the underlying marine shale. In contrast, the southern half minus the southeast contains less developed sandstone bodies and instead has intervals of interlaminated to interbedded sandstone and shale (Figure 46). The underlying marine shales are overlain unconformably by the interbedded sandstone and shale intervals. The position of the Cleveland sandstone is consistent across the field. In areas with less developed “lower” Cleveland sandstone, the interbedded sandstones and shales display lower porosity and higher gamma-ray

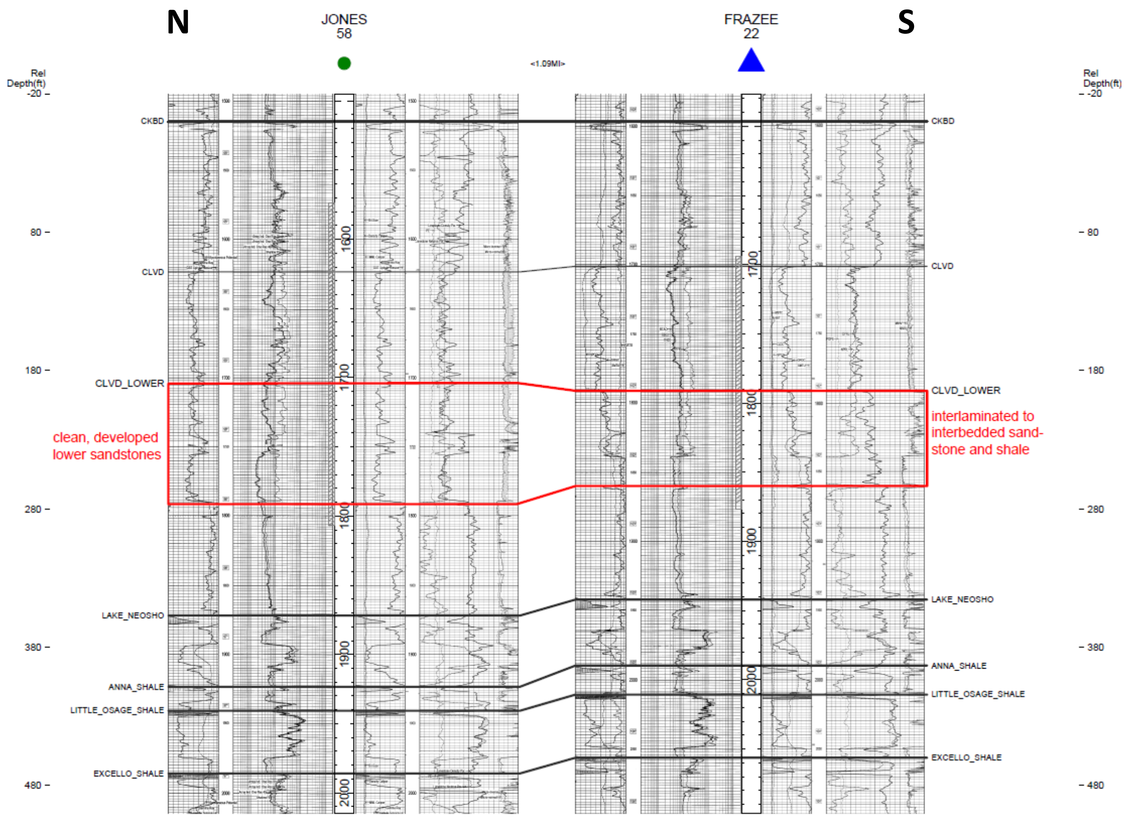


Figure 46. Stratigraphic cross section from Cleveland Field showing the change in the lower sandstone bodies from the north to the south of the field. Both of these wells are cored. Area of interest on the logs outlined in red.

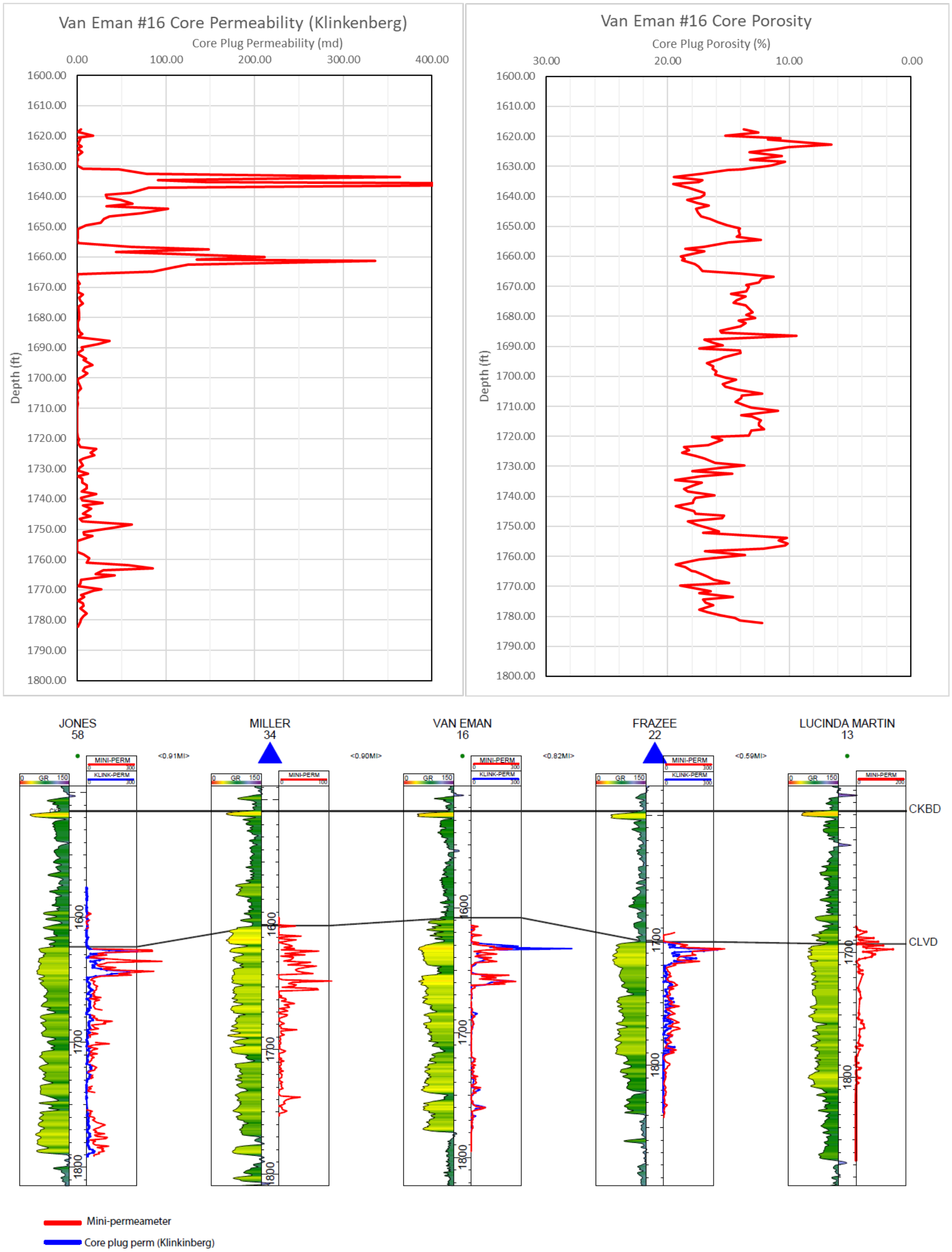


Figure 47. Above: Permeability and porosity data graphed from the Van Eman #16 showing the change in relative permeability over the sandstone interval. Below: Cross section of the cored wells in Cleveland Field with gamma-ray and permeability curves plotted. Blue lines represent core plug derived permeability, and red lines indicate permeability from minipermeameter.

The upper 50-75 feet of the Cleveland sandstone displays the highest permeability and cleanest sandstone on the gamma-ray log (Figure 47). Based on the earliest well completion records, this interval was the primary interval produced when the field was discovered. In the earliest wells drilled in the field (1904-1915), completion reports claim the upper interval produced significant volumes of gas (the highest being initial potential test of 5 million cubic feet in the Miller #1) and also produced large volumes of oil. The discovery well for the field, the Uncle Bill #1, flowed 250 barrels of oil a day after being stimulated (“shot”) with nitroglycerin. Cleveland sandstone core reports are available from 4 wells cored during the 1960s (Mullendore & Berry #31, Mullendore & Berry #34, Booher #29, and LM Jones #46). The reports from the Mullendore & Berry #31 and #34 indicate only slight odor in the upper 50 feet with low oil saturations (4-5%). Underlying this zone, both cores reported strong odor-bearing sandstones with notes of bleeding oil and greater oil saturations. In both wells, the upper sandstone contains higher porosities and permeabilities (14-20% porosity and 3-100 millidarcies), compared to the lower sandstone with 10-14% porosity and <1 to 5 millidarcies (from core reports). Another interesting observation from the M&B #31 and #34 is the change is the resistivity curve from the wireline logs. The upper interval has resistivity values that average 25 ohm∗m. The lower sandstone decreases to 5-10 ohm∗m. This is in contrast to the Booher #29 wireline log that has less than 5 ohm∗m over the upper sandstone interval and increases in the lower zone. Core reports from the Booher #29 indicate no shows in the upper sandstone and bleeding oil in the lower sandstone.

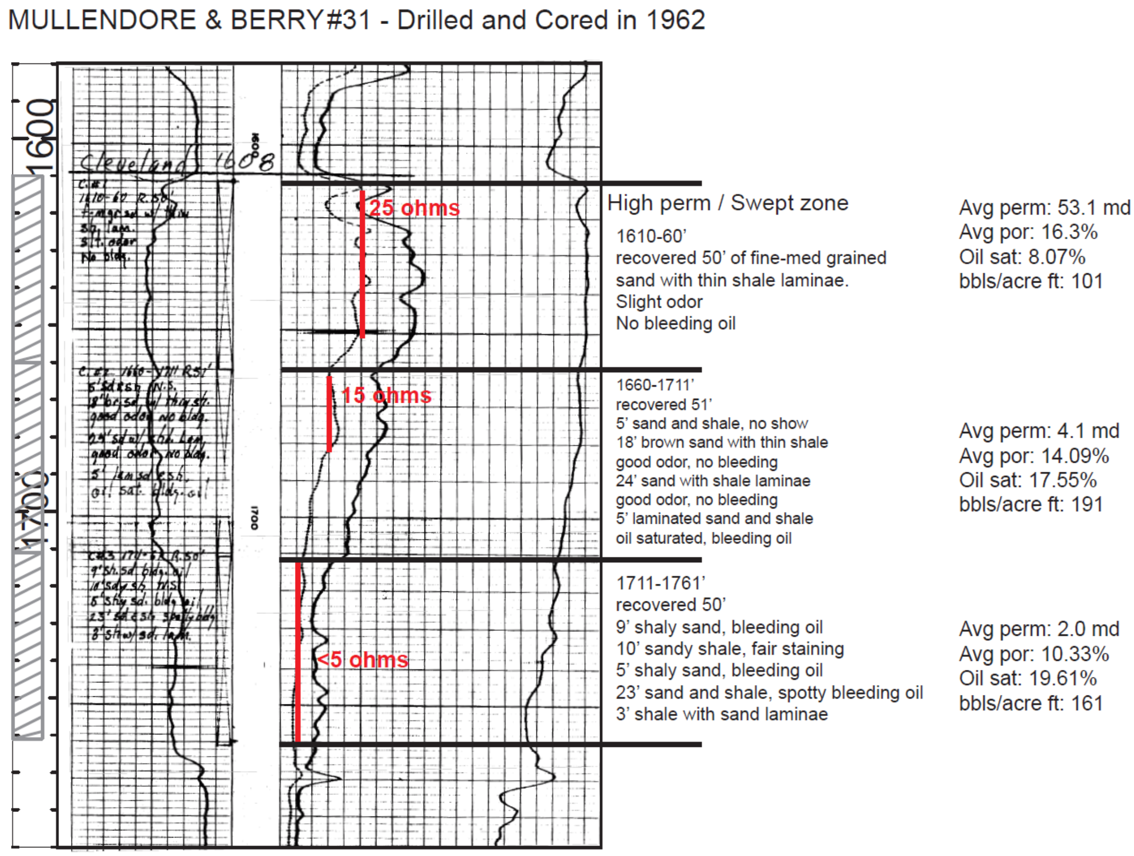


Figure 48. Wireline log of the Mullendore & Berry #31 with annotations from the core reports. Well was drilled and cored in 1962. Notes from the core report indicate a depleted or flushed upper interval with lower oil saturations and no shows, and a more saturated lower interval with higher oil saturations, but significantly lower porosity and permeability.

Data for the older cored wells (1960s) are from wells in the southern half of the field and show a consistent trend of higher permeability and swept sandstone at the top of the core and higher oil saturations in the lower quality rock toward the base of the overall interval. Recent core analyses from 2 wells in the southern portion of the field indicate similar results to the cores cut in the 1960s. The highest porosities and permeabilities are located in the upper sandstone bodies and contain a lower oil saturation than the lower permeability sandstones found near the base of the interval. These lower intervals are highly laminated sandstones and shales. The wells from the northern half of the field still show higher permeabilities in the upper 40-50 feet; however, multiple sandstone bodies are present in the middle to lower interval that contain good oil saturation and have not been swept by early development. These sandstone bodies are the primary target for the recent development of the Cleveland Field Unit.

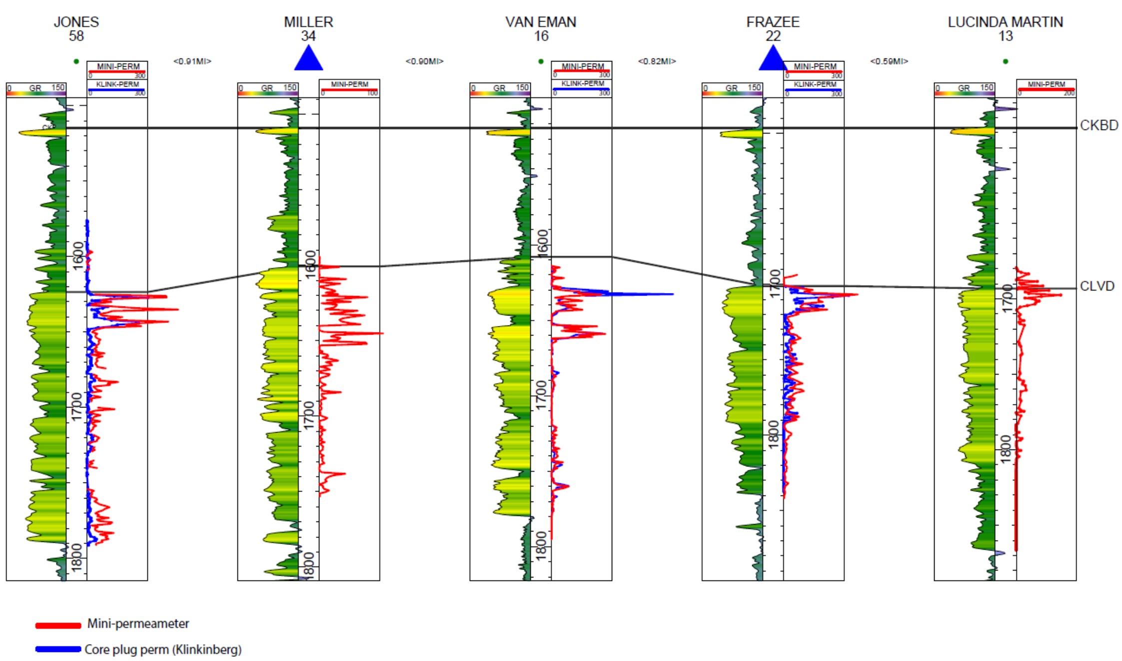


Figure 49. Cross section of the newer cored wells in Cleveland Field that display the location of higher permeability in the upper portion of the sandstone interval.

Oil and gas production from the Cleveland sandstone within the field is inconsistent. The north half of the field produces approximately 90% of the oil for the entire field (Figure 50). The sandstone quality and thickness do not change significantly from the north to the south, however, the southern portion of the field exhibits lower resistivity values on average. Multiple recompletions were attempted in the southern half of the field, and none has resulted in the oil production rates that wells in the north are achieving. Wells in the northern half of the Cleveland Field Unit average 30 BOPD with the best wells making over 100 BOPD. In contrast, wells from the southern half of the field average 5 BOPD or less with the highest volumes coming from other reservoirs in the field. Initial hypotheses for this discrepancy included structural changes in the Cleveland sandstone that resulted in a more significant gas cap in the south, a more homogeneous sandstone interval overall that resulted in fewer stratigraphic traps and allowed for better vertical permeability and migration of oil, and production that is tied to the sandstone complex being produced (Owasso in the north and Kiefer in the south).

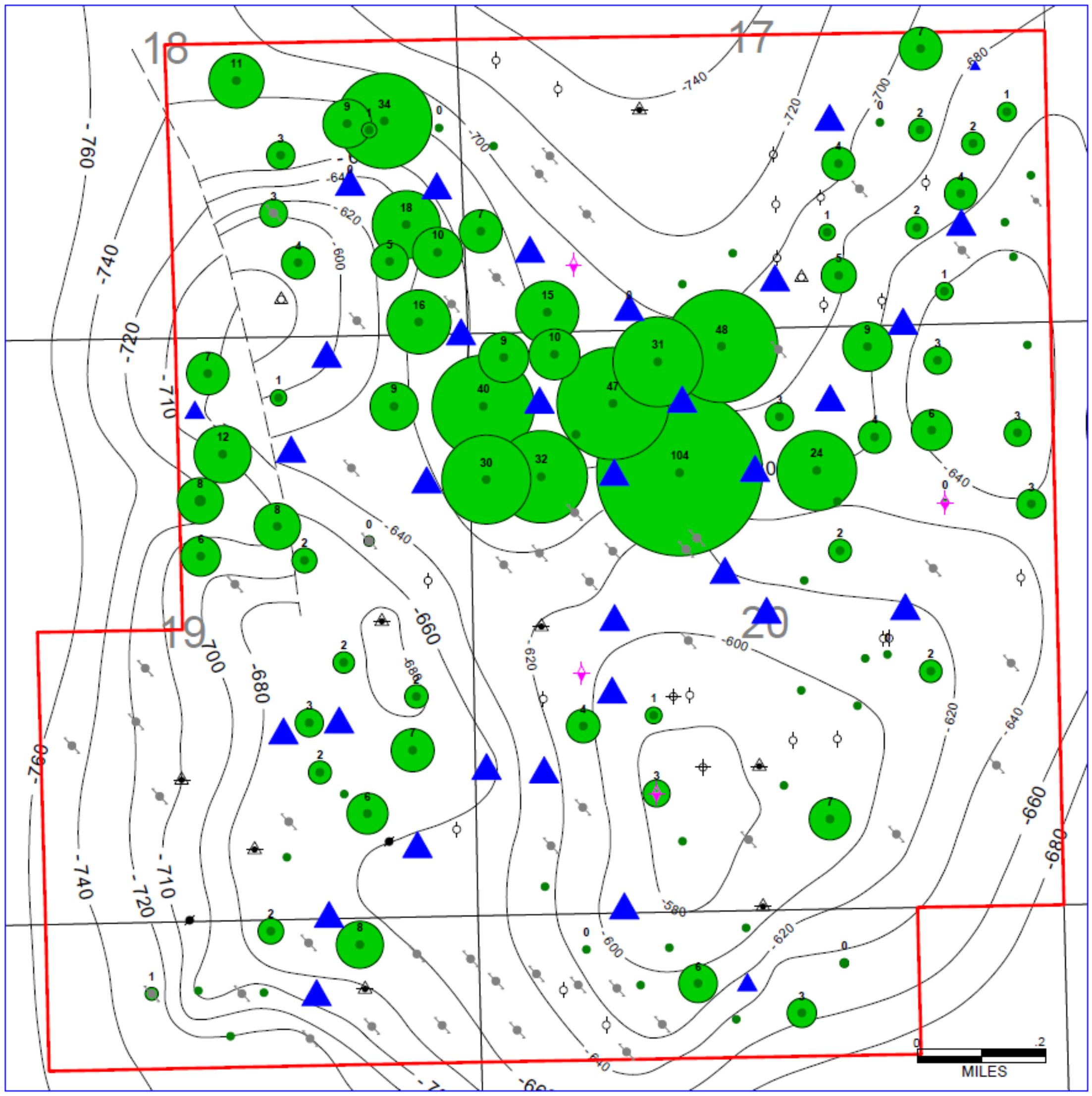


Figure 50. Production bubble map of daily Cleveland sandstone production overlying the Checkerboard Limestone structure map. Larger bubbles indicate higher production. Contour interval for Checkerboard Limestone = 20 ft.

CHAPTER IV

DISCUSSION

Stratigraphy and Stratigraphic Framework

Detailed cross section work and wireline log correlations indicate that both the Owasso and Kiefer sandstone complexes are incised valley complexes formed by fluvial processes that cut down into the existing strata and formed the linear trends observed across the study area. Paleocurrent indicators from the Collinsville Lake outcrop and image logs ran in Cleveland Field Unit indicate dominate flow direction of west-southwest (Table 3).

Well Name	Surface Type	Depth	Measurement	Remarks
JA JONES #58	distributary front	1637-1677'	N 20 W - S 20 E	tidal reworking
JA JONES #58	channel	1665-1677'	N 8 E - S 8 W	current flow to 199
JA JONES #58	channel	1677-1689'	N 10 E - S 10 W	
JA JONES #58	channel edge	1689-1697'	N 36 E - S 36 W	
JA JONES #58	channel	1706-1718'	N 4 E - S 4 W	
JA JONES #58	channel	1718-1732'	N 37 E - S 37 W	
JA JONES #58	channel	1732-1745'	N 13 E - S 13 W	
JA JONES #58	channel	1754-1774'	N 13 E - S 13 W	
JA JONES #58	channel	1774-1789'	N 35 E - S 35 W	
FRAZEE #22	distributary channel	1702-1705'	N 62 E - S 62 W	current flow is SW
FRAZEE #22	distributary channels	1705-1770'	N 19 E - S 19 W	current flow is SSW
FRAZEE #22	distributary channels	1770-1810'	N 10 E - S 10 W	current flow is S
FRAZEE #22	channel margin	1810-1837'	N 44 E - S 44 W	NE - SW trend

Table 3. Image log interpretation from two wells in the Cleveland Field Unit showing dominate flow direction of the fluvial channels. Interpretation by Mike Grace (2014).

The incised valley systems were subsequently filled with sediment as sea level fluctuated with transgressive and regressive cycles over the Cherokee Platform. Downcutting into the underlying Marmaton Group carbonates was achieved by both the Kiefer and Owasso sandstone complexes on the stable shelf. Evidence for fluvial processes was observed in both outcrop and core data. However, the overall Cleveland sandstone interval is heterogeneous and is composed of multiple depositional events and environments as is typical of a backfilling system including rhythmic tidal deposits at various positions within the cores, multiple episodes of scouring, and an overall lack of correlation between Cleveland intervals in the cores from Cleveland Field Unit.

The Nuyaka Creek Shale is the most important stratigraphic marker bed in the Cleveland sandstone interval, as it is crucial to determining whether sandstone bodies are true Cleveland or Marmaton aged. It is well documented that sandstones across the Cherokee Platform have long been classified “Cleveland” without any indication of whether they are above or below the Nuyaka Creek Shale. In this study, emphasis was placed on correlating the Nuyaka Creek Shale across several counties in order to better understand the distribution of true Cleveland and Marmaton sandstones. One of the primary questions for this study was whether or not the interaction between the Kiefer and Owasso sandstone complexes could explain the discrepancy in oil production from the Cleveland Field Unit. Part of answering this question included deciphering which sandstone complex was younger/older. After detailed correlations, it became evident that the Nuyaka Creek Shale was the key in aging the two sandstone complexes. The Nuyaka Creek Shale is consistently observed directly above the thick Cleveland sandstone in the Owasso sandstone complex and other Marmaton aged sandstones. This observation is consistent over the entire length of the Owasso sandstone complex. In contrast, the Nuyaka Creek Shale is not present in any wells containing the thick Kiefer sandstone complex. Along the length of the Kiefer sandstone complex, the Nuyaka Creek Shale is observed in wells only on the edges of the trend, however, where the sandstone is thick, the shale marker is missing. Based on these observations, the Owasso sandstone complex is the older sandstone complex and was deposited following the Marmaton Group carbonate deposition, but before the widespread flooding associated with the Nuyaka Creek Shale. The Kiefer sandstone complex, on the other hand, was deposited later after the major transgressive event that resulted in the deposition of the Nuyaka Creek Shale. The Kiefer incised valley cut through the Nuyaka Creek Shale, into the Owasso sandstone in Cleveland Field, and into the Marmaton Group carbonates in parts of the stable shelf.

The Nuyaka Creek Shale is a regionally distributed shale; however, the shale is inconsistently developed over much of the stable shelf including the majority of Noble, Garfield, and northern Logan Counties. Due to the scope of this study, this area was not studied extensively and time was not dedicated to determining why the shale is missing in this area. However, absence of the Nuyaka Creek Shale does not appear to be due to incision by fluvial systems. A preferred hypothesis is that the area was experiencing shallower water with higher energy that resulted in less clay availability, less water stratification, and more oxygenation. This resulted in lower concentrations of radioactive minerals due to dilution by sediment and/or oxidation of uranium in oxygenated waters. Schaffer and Heckel (1985) state that core shales in the Midcontinent are commonly missing over paleogeographic highs, adding evidence for the missing Nuyaka Creek Shale over areas on the stable shelf.

The paleogeography of the Marmaton Group carbonates greatly influenced the deposition and geometry of the Owasso sandstone complex and other Marmaton aged sandstone bodies. Interval isopach maps of the Marmaton Group show a linear thicker carbonate section interpreted as a buildup along a shelf boundary that runs approximately south-southwest to north-northeast across the study area and significant carbonate banks on the eastern edge of the study area (Figure 51). The southwest to northeast shelf break not only marks a significant increase in the overall thickness of the Cleveland sandstone interval, but also correlates to the geometry of the Owasso sandstone complex. The Owasso sandstone complex follows the shelf break from the county line between northern Tulsa and Osage counties and continues west along the trend for approximately 40 miles, where the sandstone complex overcomes the shelf and continues west in middle Pawnee County, indicating that the

Marmaton Group carbonate shelf was a prominent feature during the deposition of the Owasso sandstone complex and similarly aged Marmaton sandstones.

In addition to the Marmaton carbonate shelf, it is also evident that the Marmaton aged sandstones (Owasso sandstone complex and other Marmaton aged sandstones in southern Creek County) are deposited in areas of thin Marmaton Group carbonate. A noticeable thin is present along the trend of the Marmaton carbonate shelf and extends to northern Tulsa County where the Owasso sandstone complex is observed in outcrop. In southeastern Creek County, a major thinning of the Marmaton Group carbonates occurs and the area contains several sandstone trends that are interpreted to be Marmaton aged sandstones that were sourced from a southeastern or southern source (these are stratigraphically below the Nuyaka Creek Shale unlike the Kiefer sandstone complex). In summary, the mapped Marmaton sandstone bodies took advantage of the accommodation allowed by the thinning Marmaton Group carbonates and in most of the study area are not thought to have incised the Marmaton carbonate intervals. In contrast, the Owasso sandstone complex does however display downcutting into the Marmaton Group carbonates on the edge of the stable shelf in Payne County.

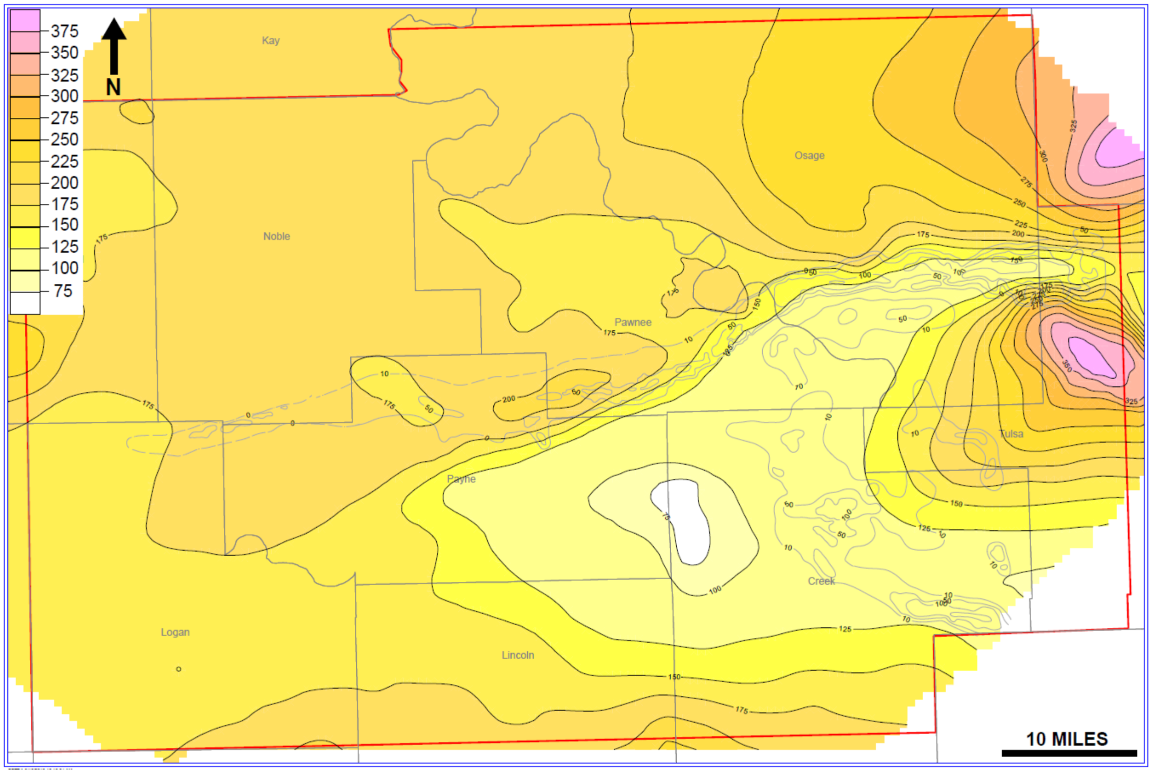


Figure 51. Thickness map of the Marmaton Group carbonates with contoured thickness of the Marmaton aged sandstones including the Owasso sandstone complex and other sandstone bodies in Creek County. Study area outlined in red. Contour interval for Owasso sandstone complex and Marmaton sandstones = 50 ft. Contour interval for Marmaton Group carbonates interval thickness map = 25 ft.

As a result of its deposition long after accommodation was filled with Marmaton sediment, the Kiefer sandstone complex distribution does not appear to be influenced by underlying Marmaton Group carbonates. The Kiefer sandstone complex trends northwest from southern Creek County and intersects the trend of the Marmaton shelf at a high angle before turning slightly west and continuing across Pawnee and Payne counties. The Kiefer sandstone complex trend does not show any change in depositional direction related to the carbonate shelf trend, indicating the Marmaton Group carbonate paleo-features were no longer prominent. Additionally, it does not appear that the presence of the Owasso sandstone complex influenced the deposition of the Kiefer sandstone complex. The overall flow direction of the sandstone complexes is west towards the prominent depocenter, the Anadarko Basin. The westward turn of the Kiefer sandstone complex is attributed to a flat stable shelf that still existed over much of the Cherokee Platform. The Kiefer sandstone complex shows clear incision on the stable shelf (Figure 52). On the interval isopach map of the Cleveland sandstone interval, the Kiefer sandstone complex is clearly observable due to differential compaction of the sandstone verses the surrounding shale and the downcutting of the sandstone complex into the Marmaton Group carbonates (Figure 53).

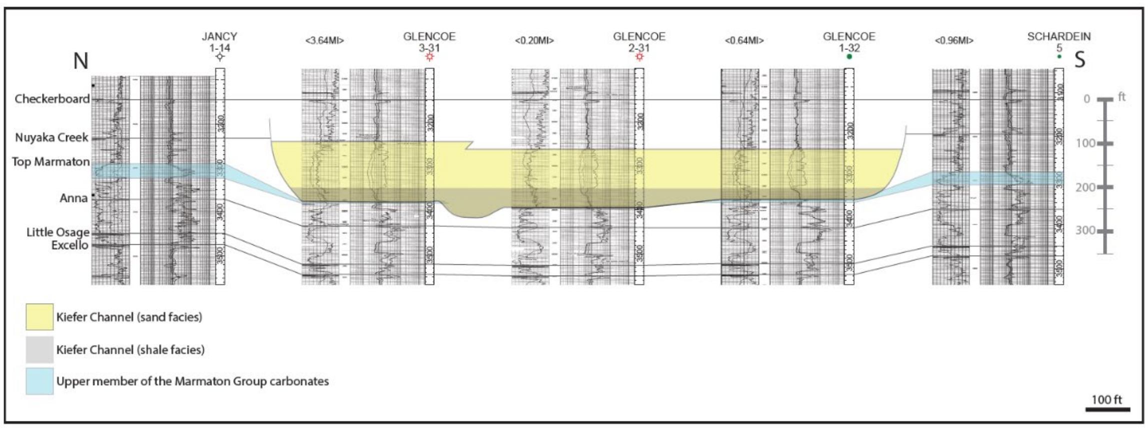


Figure 52. Cross section through the Kiefer sandstone complex showing possible incision into the upper unit of the Marmaton Group carbonates.

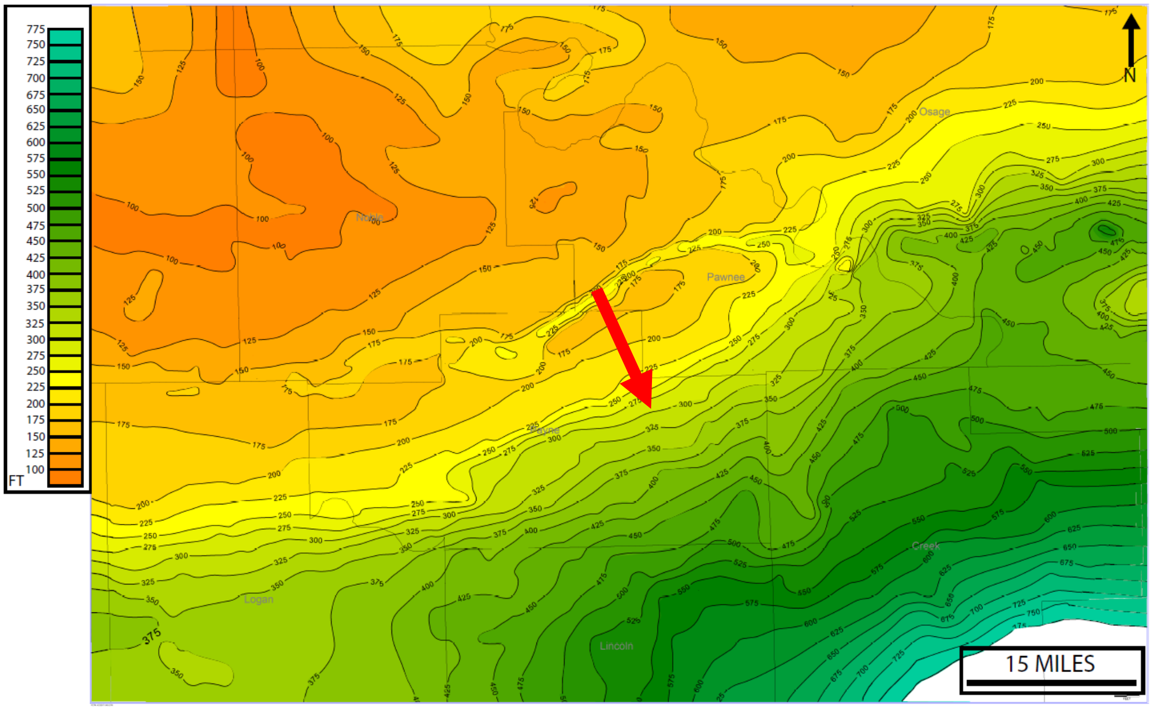


Figure 53. Interval isopach map of the Cleveland sandstone interval. The Marmaton Group carbonate shelf has a SW - NE trend diagonally across the middle of the study area. Additionally, the Kiefer sandstone complex is seen as a thickening trend on the stable shelf (red arrow). Contour interval = 25 ft.

Cleveland Field Unit

The Cleveland sandstone in the Cleveland Field Unit has an average thickness of 150 feet, which is consistent over the majority of the field. The multi-storied sandstone is composed of both the Owasso and Kiefer sandstones complexes, which converge and intersect at or near the Cleveland Field Unit (Figure 54). Considerable time was dedicated to wireline log correlations, core analysis, and thin section analysis to determine if the Kiefer sandstone complex could be distinguished from the Owasso sandstone complex. An expected erosional contact between the two complexes was not identified using the available data. As a result, the sandstone within the Cleveland Field Unit will remain undifferentiated, given the missing

Nuyaka Creek Shale and the difficulty in identifying how deeply the Kiefer sandstone complex eroded into the existing Owasso sandstone complex (Figure 55).

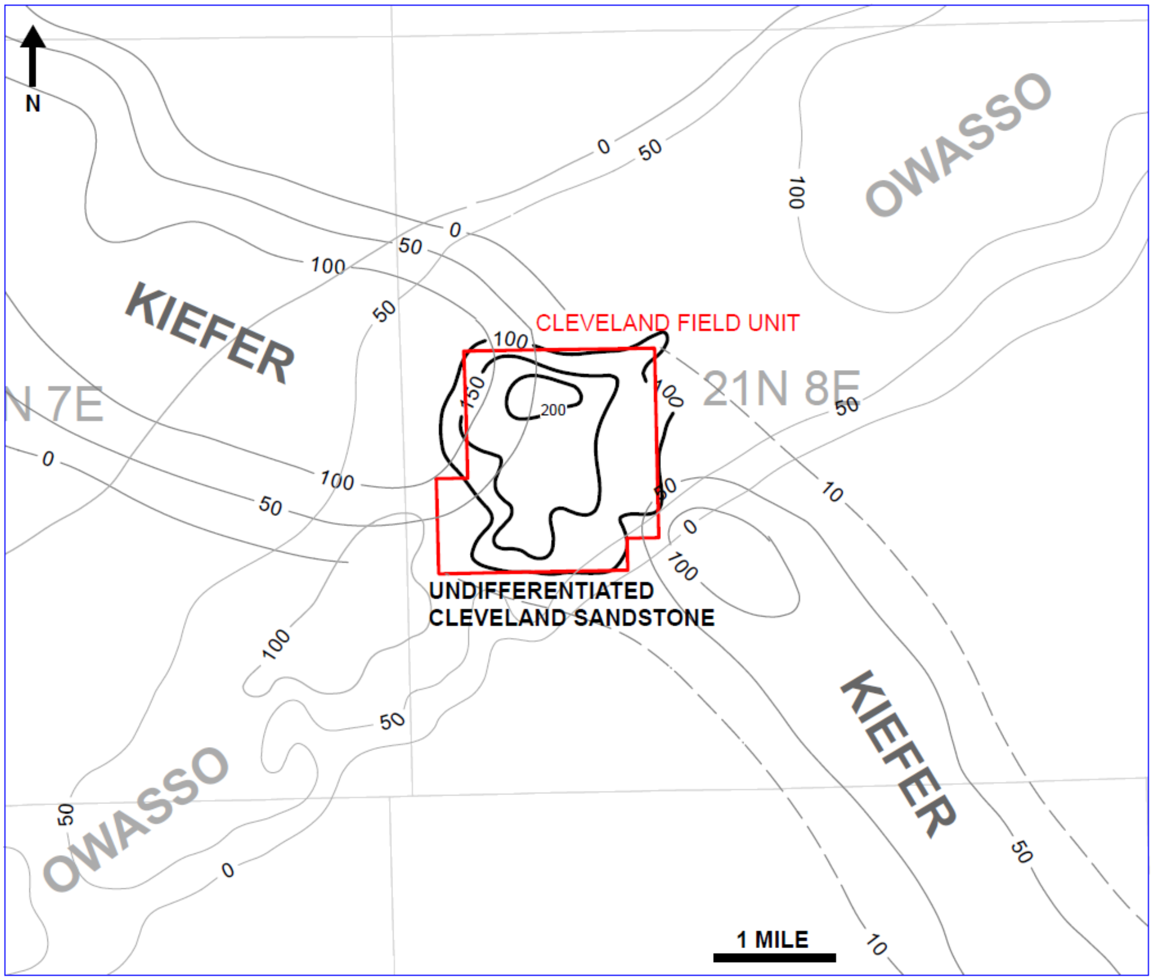


Figure 54. Map of the Kiefer and Owasso sandstone complexes intersecting at the Cleveland Field Unit, including the undifferentitated sandstone thickness within the Cleveland Field Unit. Contour interval = 50 ft.

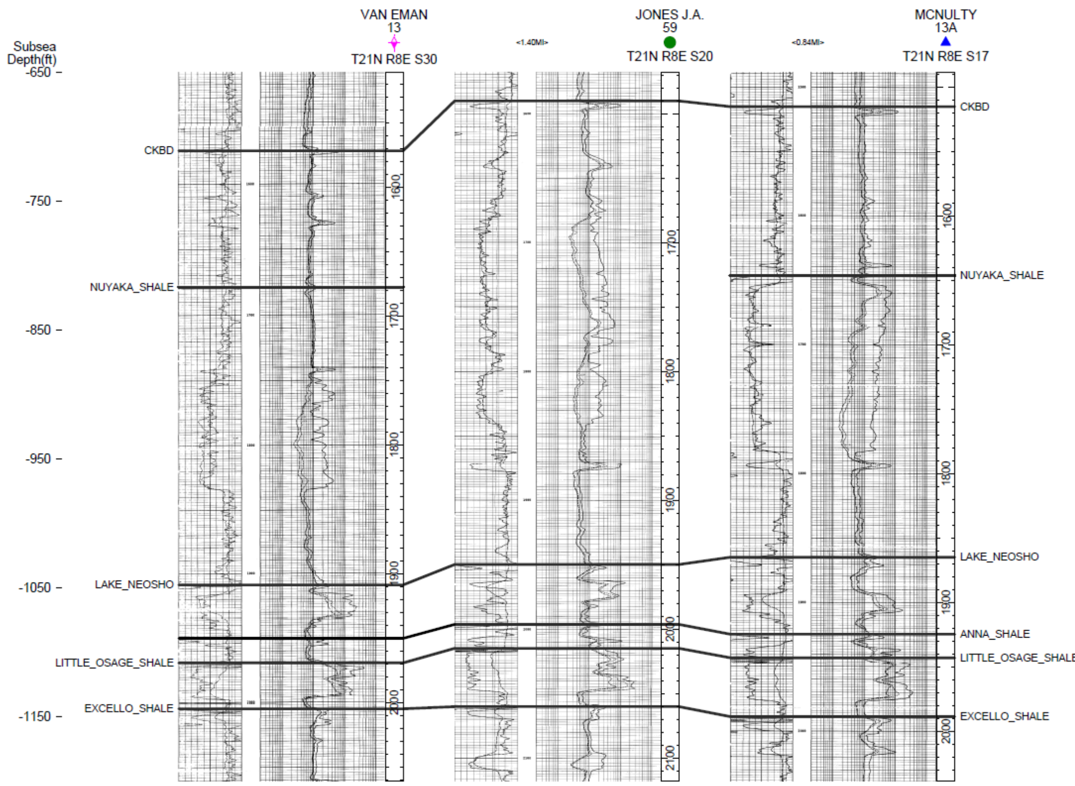


Figure 55. Cross section from the Cleveland Field Unit showing undifferentiated sandstone due to the absence of the Nuyaka Creek Shale marker bed.

The cores examined contained multiple erosional surfaces, representing high energy events at different depths, however, these surfaces cannot be correlated between the different cores from the Cleveland Field Unit, and none could be attributed to the major incision of the Kiefer sandstone complex. Adding to the difficulty of differentiating the two sandstone complexes in Cleveland Field, the mineralogy of the two sandstone complexes is very similar, which was verified by comparing outcrop thin sections first, and then to thin sections from Cleveland Field. Grain size, texture, and constituent grains are all comparable between the two sandstone complexes.

The discrepancy in production from the northern to southern portions of the field cannot be confidently attributed to the interaction of the Kiefer and Owasso sandstone complexes. As mentioned previously, the upper 50 feet of the Cleveland sandstone within the field contains the highest permeability and porosity and was the reservoir that was initially depleted by early development. This is evident through early completion reports and core cut in the 1960s. The Cleveland Field Unit is still producing several hundred barrels of oil per day because of bypassed zones within the sandstone interval that were stratigraphically trapped. As a result of large hydraulic fracture treatments, the less permeable zones produce at acceptable rates. In conjunction, a waterflood was initiated to aid in flushing movable oil through the bypassed intervals. Comparing the north wells to the south wells, it is clear that these bypassed zones are not present in the south due to the missing stratigraphic traps. The southern wells contain a transitional zone from interbedded sandstone and shale to cleaner sandstones near the top of the interval. The lower to middle sandstones are not apparent in the south. Based on core analysis from the Lucinda Martin #13, the upper sandstones are significantly more homogeneous and do not contain the same vertical permeability baffles that would result in trapped oil. During initial completions in the south, the permeable rock was efficiently depleted. An additional hypothesis is that the structure resulted in buoyancy separation of associated gas, and had an effect on oil production. The highest structural closure is located in the southeast portion of the unit study area, and production and completion data indicate that this structure contained a gas cap of unknown size. Due to early development, this gas cap was not maintained; this allowed for oil migration into the gas cap and water influx into the highest permeability rock.

Based on the core data from older and recent cores, the lower sandstone intervals in the south maintained oil saturation due to lower quality reservoir rock (low permeability); however, the upper zones were swept and depleted and in some cases filled with water from cross-flow or other injection.

Cleveland Field Lithotypes:

Based on the stratigraphic correlations, distribution patterns, and identification of lithotypes within the Cleveland sandstone, it is evident that the Owasso and Kiefer sandstone complexes were both incised valley systems that are interpreted to have formed by eroding previously deposited sediments during drops in sea level and filled during subsequent transgression or highstands. As a result, the complexes contain several depositional environments and changes in lithotype. The majority of the lithotype intervals are less than 5 feet thick (many being less than 1-foot-thick) and most changes between lithotype are abrupt. In many cases there are several lithotypes in 1 foot of core. The differentiation of each core into lithotypes is displayed in Figure 57. A cross section of the lithotypes was constructed to show the variation in lithotypes of each well (Figure 56). Establishing lithotypes in core aided in understanding the depositional environments that contributed to the complex sediment suites that comprise the Cleveland sandstone within these incised valleys.

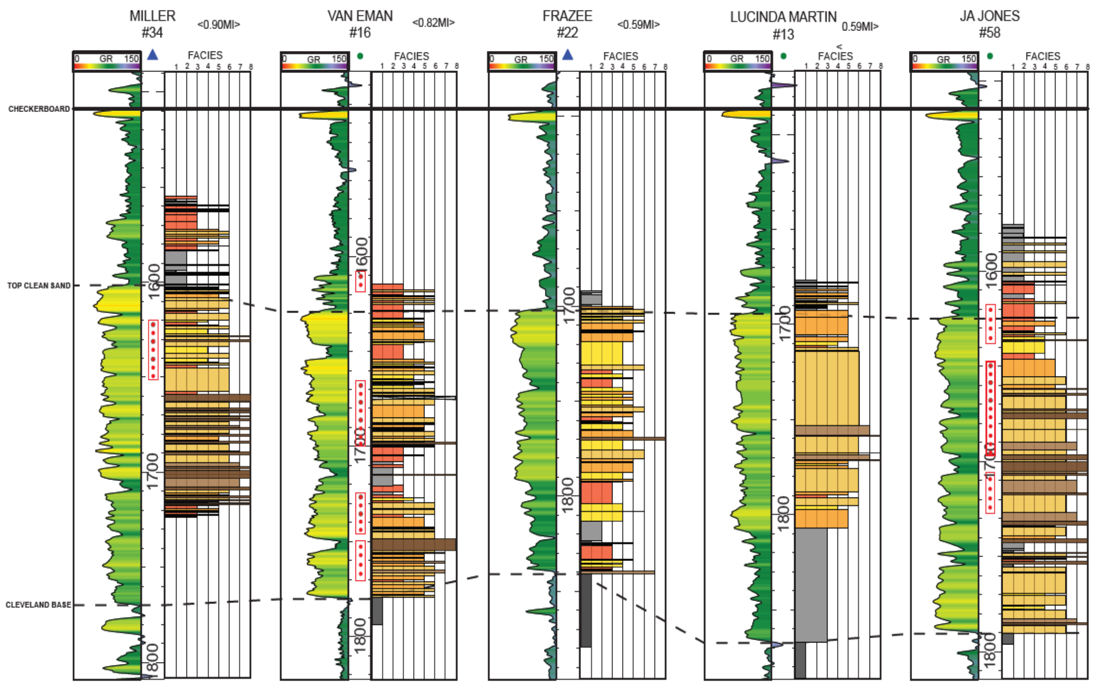


Figure 56. Cross section of the cored wells in Cleveland Field that show the lithotype in each core. Datum for the cross section is the Checkerboard Limestone and shows the significant variability in lithotypes over the cored interval. Perforations are shown in red.

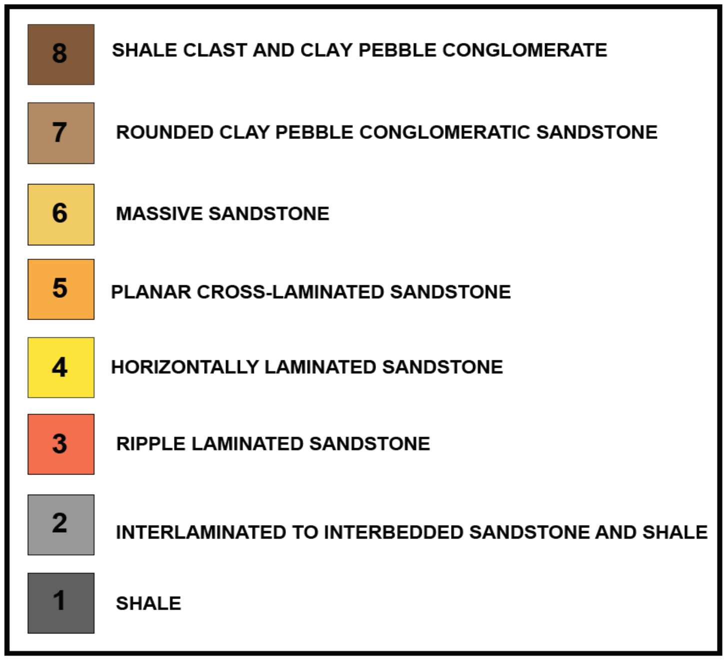


Figure 57. Lithotypes and color guide.

Lithotype #1 (shale), which is mainly subjacent to the base of the sandstone interval as a marine shale that most likely predates the incision of the sandstone complexes. Based on the observed intervals, this marine shale signifies that the area was inundated by a significant body of water before major progradation and after deposition of the Marmaton Group carbonates. The thin shale intervals present within the sandstone intervals could indicate short-term increases in sea level, temporary abandonment of channels, or other low-energy environments. Without obvious environmental indicators, such as marine fossils, detailed environment of the shale remains unresolved.

Lithotype #2 (interbedded to interlaminated sandstone and shale) is more common at the base of the cored intervals in the southern Cleveland Field wells (Frazee #22 and Lucinda Martin #13) as an intermediate zone from the underlying marine shale to the cleaner fluvial sandstones in the upper interval. It is unclear if the boundary between the marine shale and the interbedded and interlaminated sandstone and shale is a conformable surface or the interbedded to interlaminated intervals are the first preserved strata that filled the valley. The interbedded and interlaminated sandstone and shales are believed to be the result of estuarine and tidal influences that occurred during backfilling of these valleys.

Lithotypes 4-6 (sandstone lithotypes with varying sedimentary features) are the more common lithotypes observed in the Cleveland sandstone cores and outcrops. They are fluvial and were deposited in channels. Varying levels of energy are represented.

Lithotypes 7 and 8 (shale clast and clay pebble conglomerates) are sporadic throughout the cored intervals. There is not a recognizable pattern of erosional surfaces and high energy events that resulted in the conglomerate intervals. These lithotypes indicate high energy events that deposited shale fragments eroded from the channel walls or floor. These intervals were likely deposited following storms or other high energy events, but are generally less than 1 foot thick. Based on the angularity of shale clasts and preserved laminations in shale fragments, clasts were not transported far, suggesting these are the product of short-lived events.

Due to the significant variations in lithotypes across the cored intervals, stacking patterns of lithotypes were difficult to establish and when attempted, did not result in any meaningful interpretation of field wide patterns that could be used to interpret trends in production from the Cleveland Field Unit. Instead, emphasis was placed on identifying lithotypes that are targets for producing the Cleveland sandstone. Out of the five cored wells, only three are perforated and completed in the Cleveland sandstone (JA Jones #58, Van Eman #16, and Miller #34). Out of these, the Miller #34 is an injection well for the Cleveland sandstone waterflood. Therefore, the JA Jones #58 and Van Eman #16 were studied for the primary reservoir lithotypes. In the JA Jones #58, which produces approximately 50 barrels of oil per day, the completion interval primarily covers the massive sandstone, planar cross-laminated sandstone, and shale clasts conglomerate lithotypes. The shale and clay clast conglomerate intervals are commonly found adjacent to the massive sandstone facies so this relationship is expected. In the Van Eman #16, which produces less than 5 barrels of oil per day, the primary reservoir lithotypes are the massive sandstone, planar cross-laminated sandstone, and thin intervals of ripple-laminated sandstones. The Miller #34 injection well was never produced, but the perforated interval (waterflood target) is composed of massive sandstone, horizontally-laminated sandstone, and thin ripple-laminated sandstone lithotypes.

CHAPTER V

CONCLUSIONS

This study incorporated multiple forms of subsurface and surface data in order to better understand the Cleveland sandstone interval in terms of stratigraphic framework and deposition. The ultimate goal of this study was to answer key questions about the production in the Cleveland Field Unit and whether certain discrepancies in production could be attributed to the two major sandstone complexes that cross the field. In the process of correlating and mapping the Kiefer and Owasso sandstone complexes, emphasis was placed on determining their respective ages in order to determine how they might interact in Cleveland Field. The key to determining which sandstone complex was older was recognizing the presence of the Nuyaka Creek Shale, which occurs above and is therefore younger than the Owasso sandstone complex. In contrast, the Nuyaka Creek Shale is eroded by the valley filled with the Kiefer sandstone complex, indicating the shale must be older based on cross-cutting relationships. The key findings of this study are:

1. The Kiefer and Owasso sandstone complexes filled incised valleys formed during times of regression and lowstand. The sandstone complexes backfilled with fluctuation in sea-level resulting in stacked sandstone complexes containing a number of depositional events related to fluvial to tidal processes.
2. The Owasso sandstone complex was deposited as part of the Marmaton Group and should not be classified as a Cleveland sandstone.
3. The Kiefer sandstone complex was deposited as part of the Skiatook Group (Missourian Series) and is considered to be true Cleveland sandstone.
4. The Nuyaka Creek Shale is a regionally extensive, stratigraphic marker bed that was crucial in determining that the Owasso sandstone complex is the older complex deposited during Marmaton time and that Kiefer sandstone complex incised through it.
5. Marmaton Group carbonate paleogeography greatly influenced the deposition of the Marmaton aged sandstones, including the Owasso sandstone complex.
6. The contact of the Kiefer sandstone complex with the Owasso sandstone complex was unidentifiable in the Cleveland Field Unit, even with multiple cored wells and modern wireline logs.
7. The production discrepancies in the Cleveland Field Unit cannot be confidently attributed to the interaction between the Kiefer and Owasso sandstone complexes due to the difficulty in differentiating the two complexes in core data.
8. The primary factor in better production in the north half of the Cleveland Field Unit is the presence of lower interval sandstone bodies that were bypassed by early development and exploitation due to stratigraphic trapping. These sandstone bodies are not present in the same position in the south and southeastern portions of the field.

9. The structural high present in the southeastern portion of the Cleveland Field Unit resulted in a gas cap that was “blown down” (depleted) by early development. This gas cap was then filled with injected water resulting in water-filled high permeability sandstones near the top of the interval.
10. Eight lithotypes were identified within cores from the Cleveland Field Unit wells. The lithotypes range from shales and interlaminated sandstone and shales to massive sandstones. The majority of the lithotypes observed in core were also observed in the Collinsville Lake and Jenks outcrops.
11. The primary reservoir lithotypes for the Cleveland sandstone include the massive sandstone, planar cross-laminated sandstone, horizontally-laminated sandstone, and ripple-laminated sandstone.

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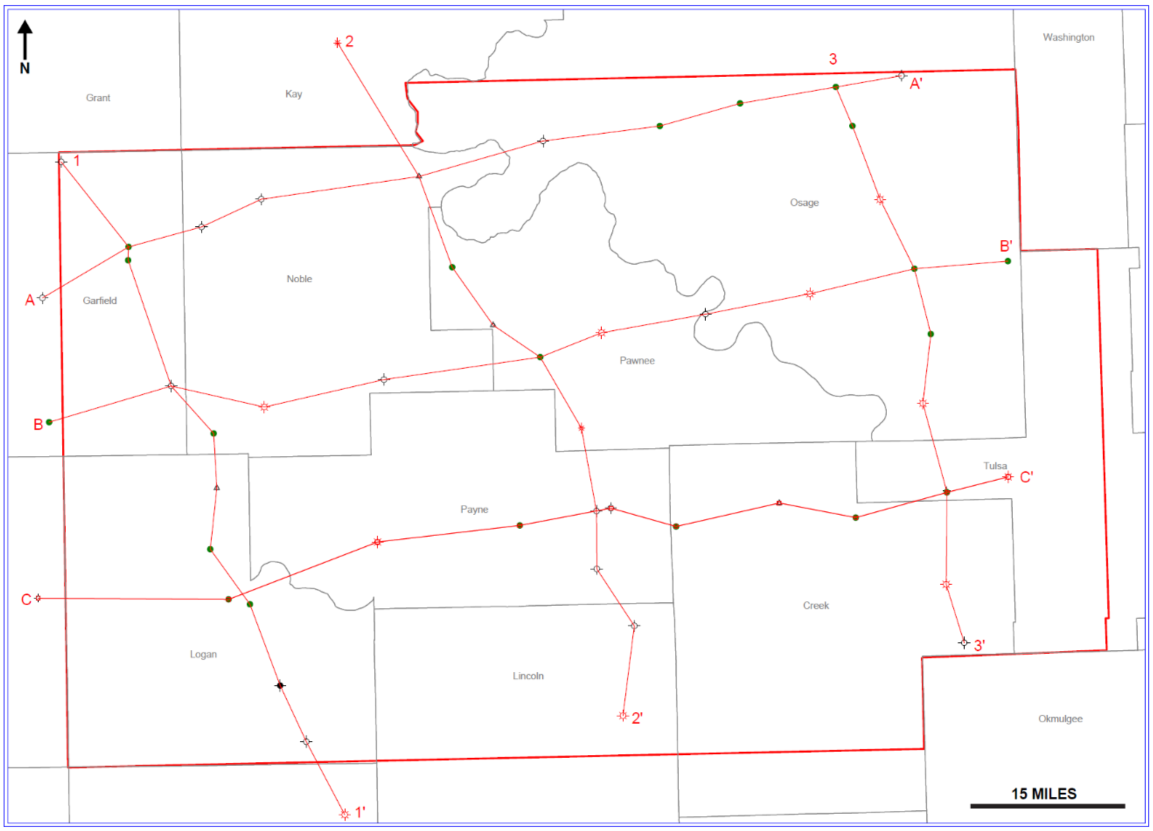
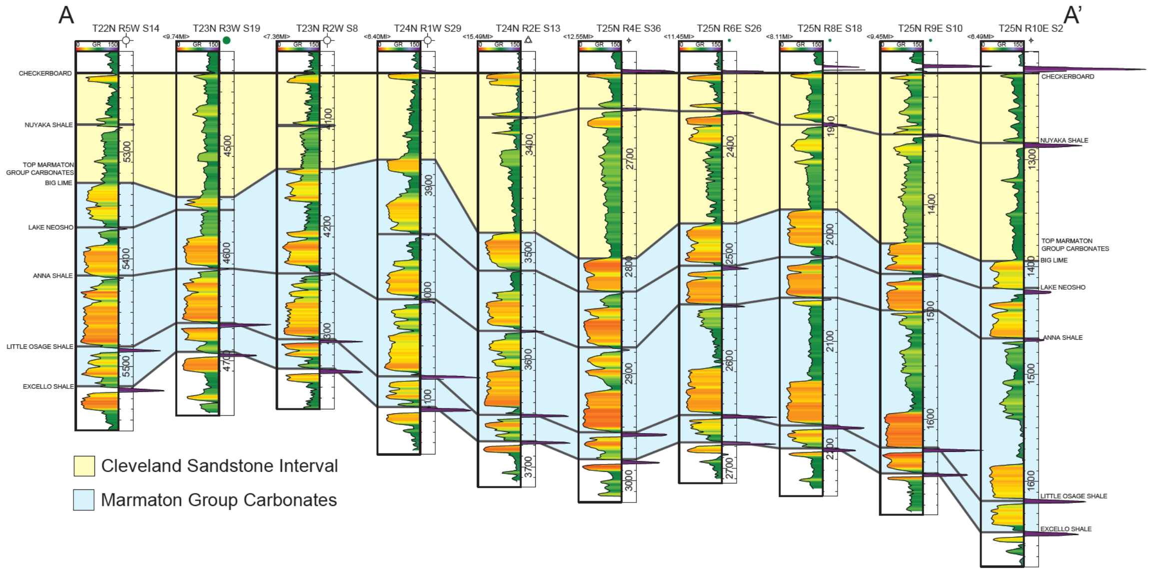
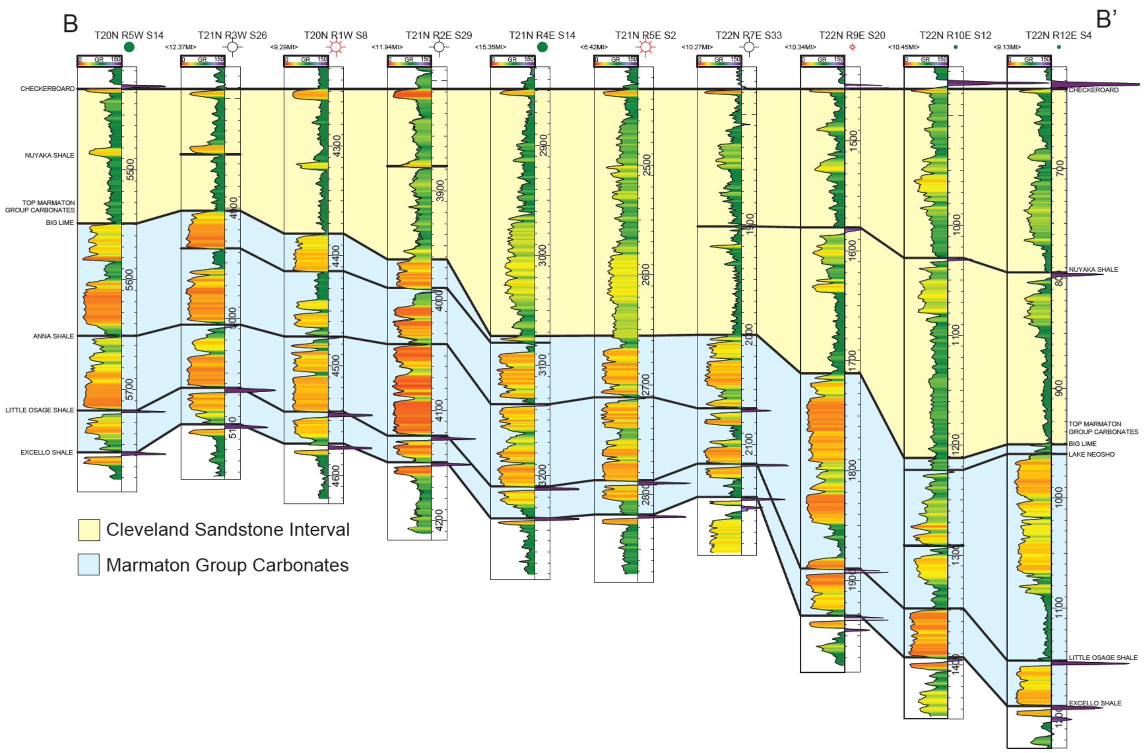
APPENDIX



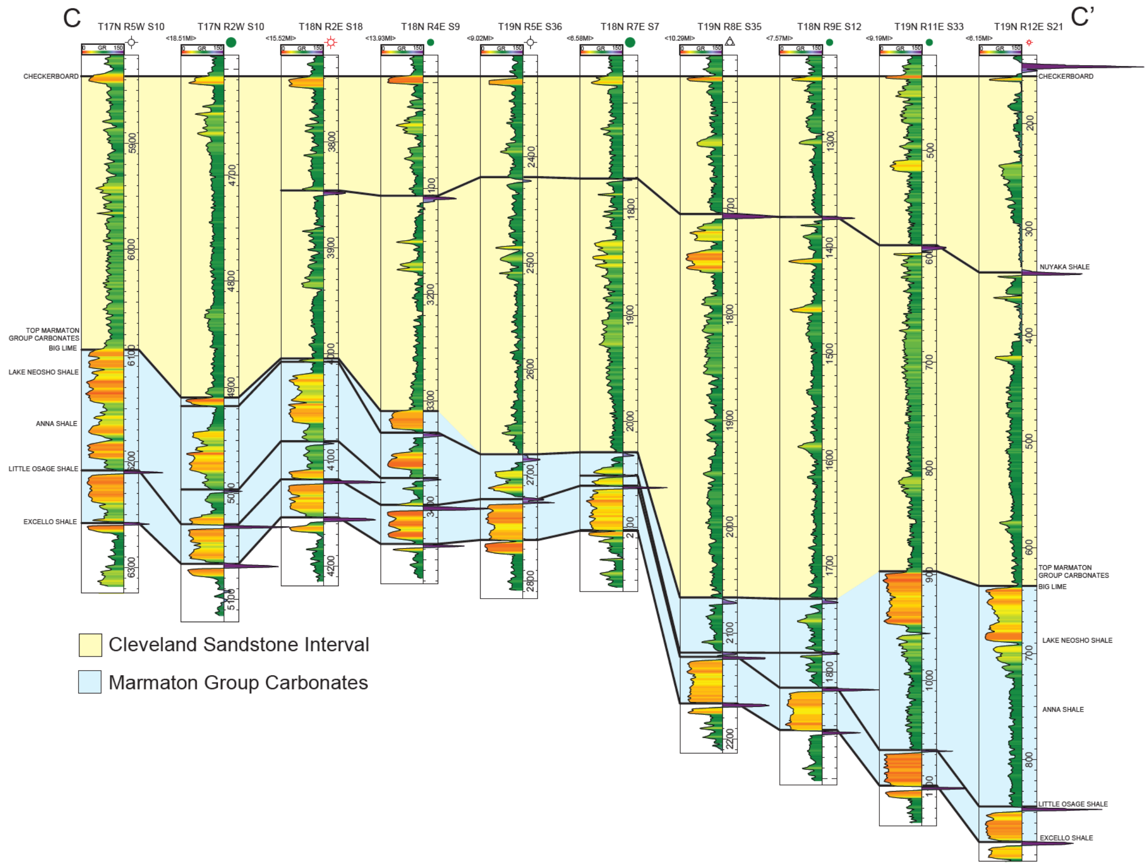
Regional map showing the official regional cross sections for this study. Study area outlined in red.



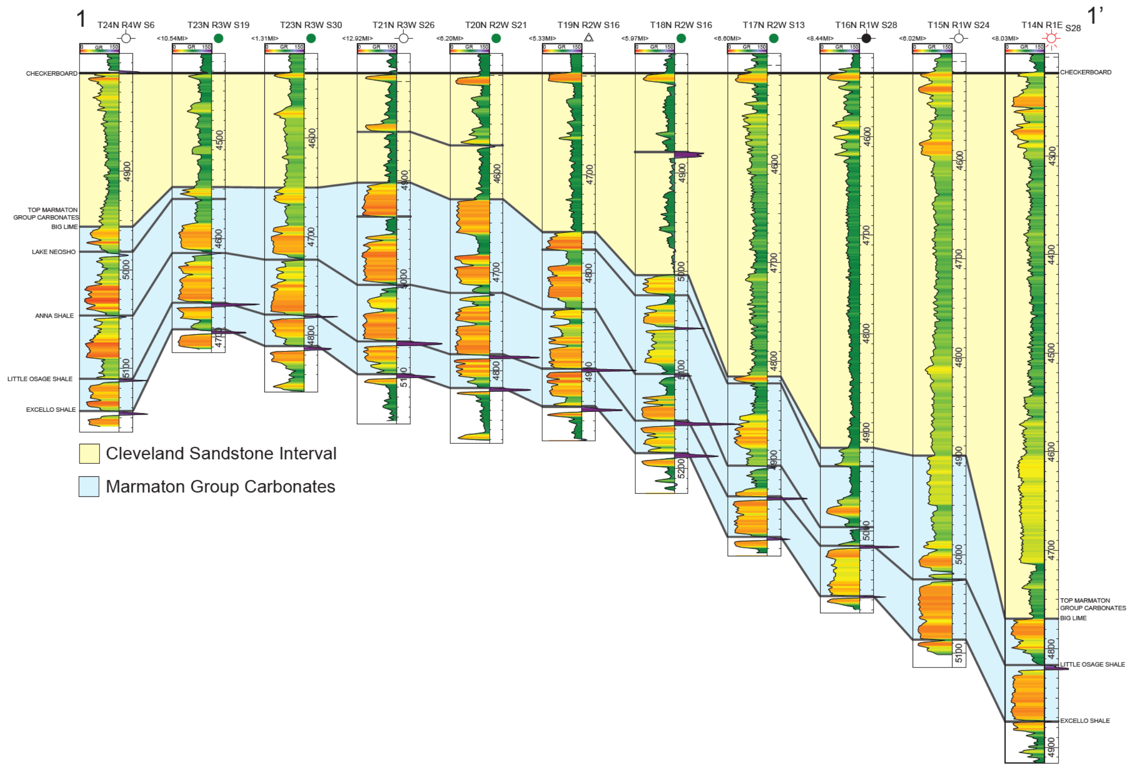
Regional cross section A-A' (west to east)



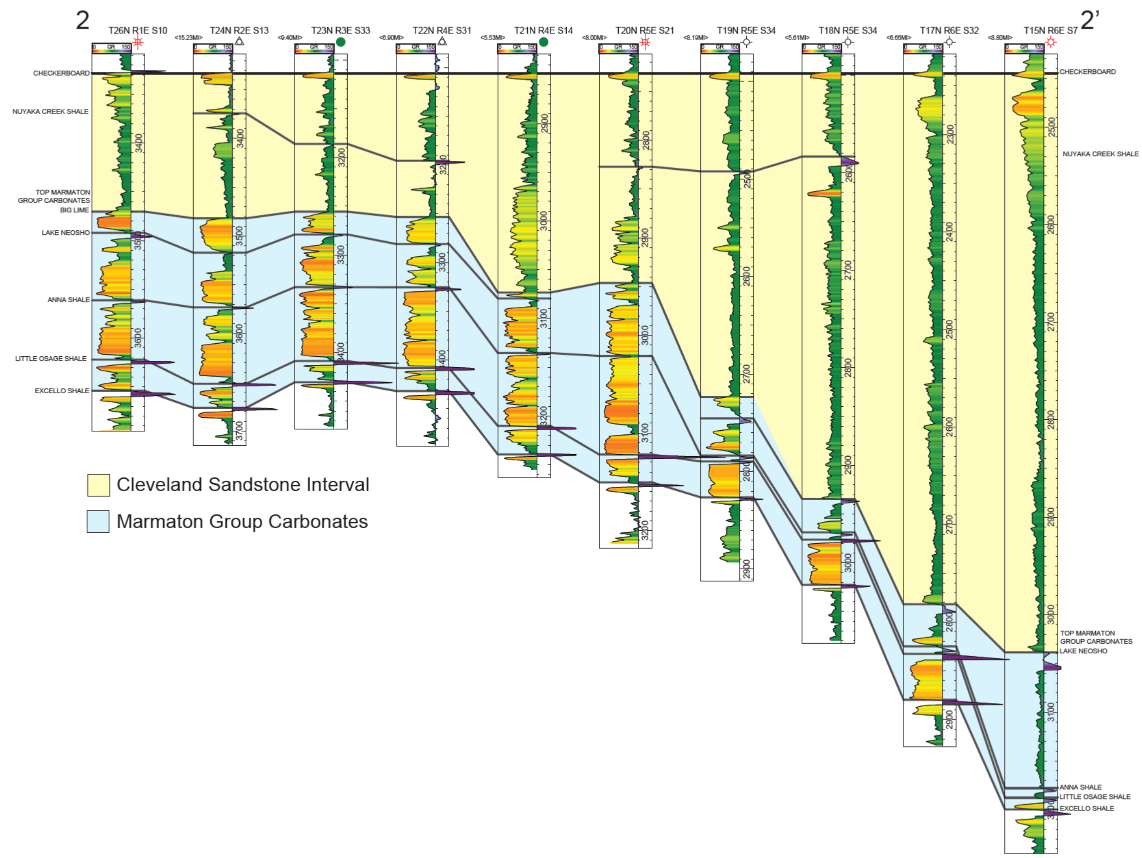
Regional cross section B-B' (west to east)



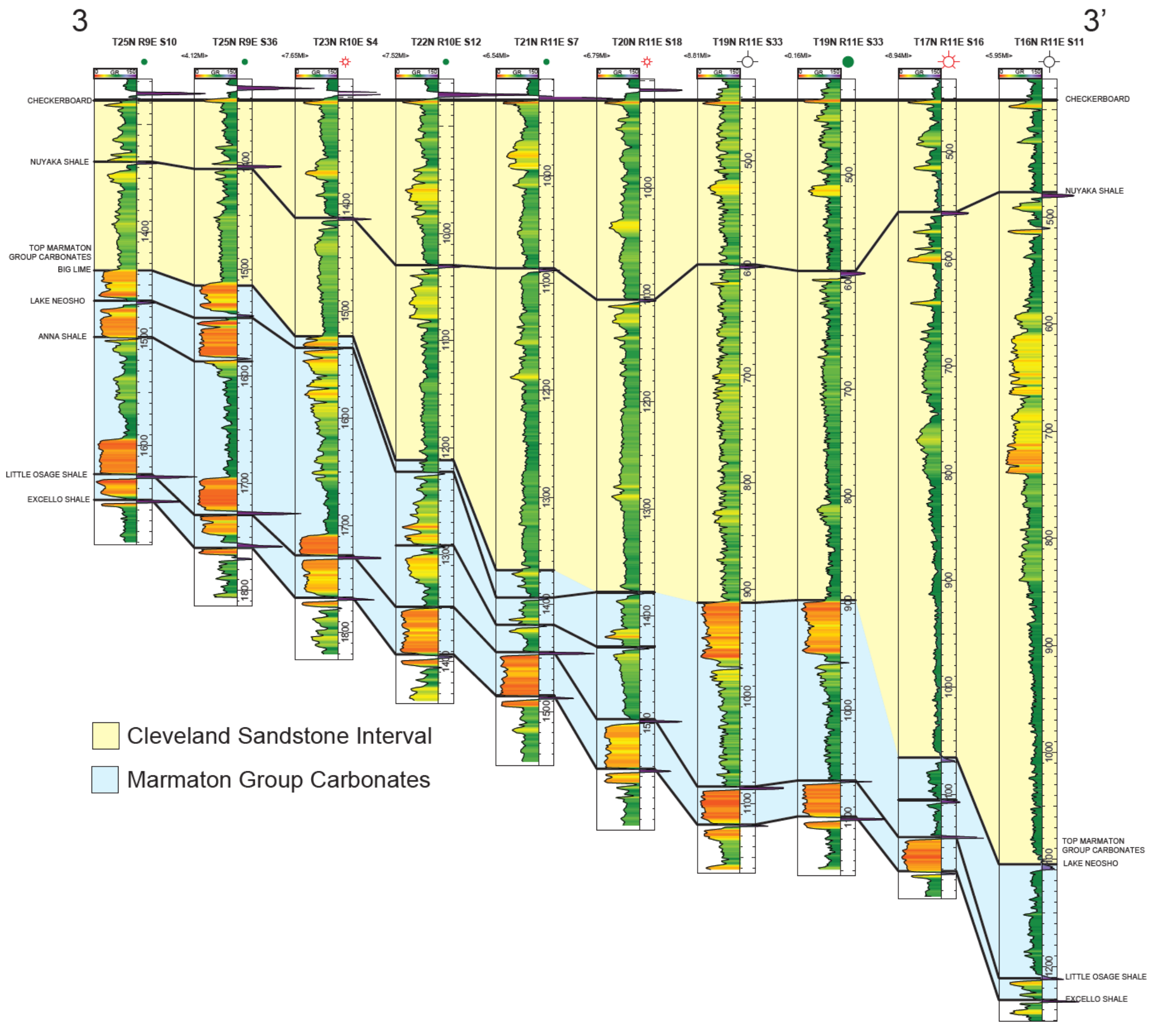
Regional cross section C-C' (west to east)



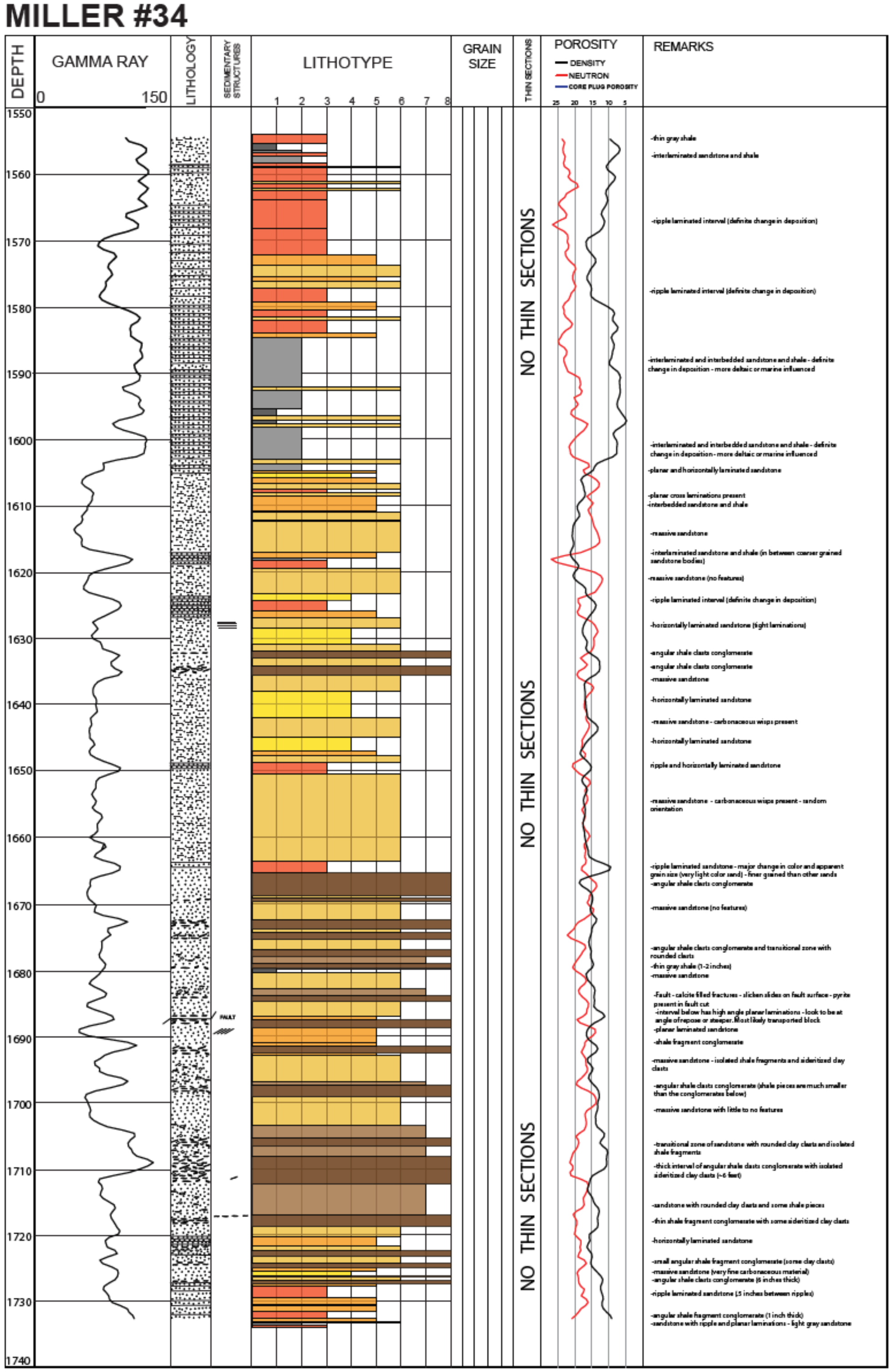
Regional cross section 1-1' (north to south)



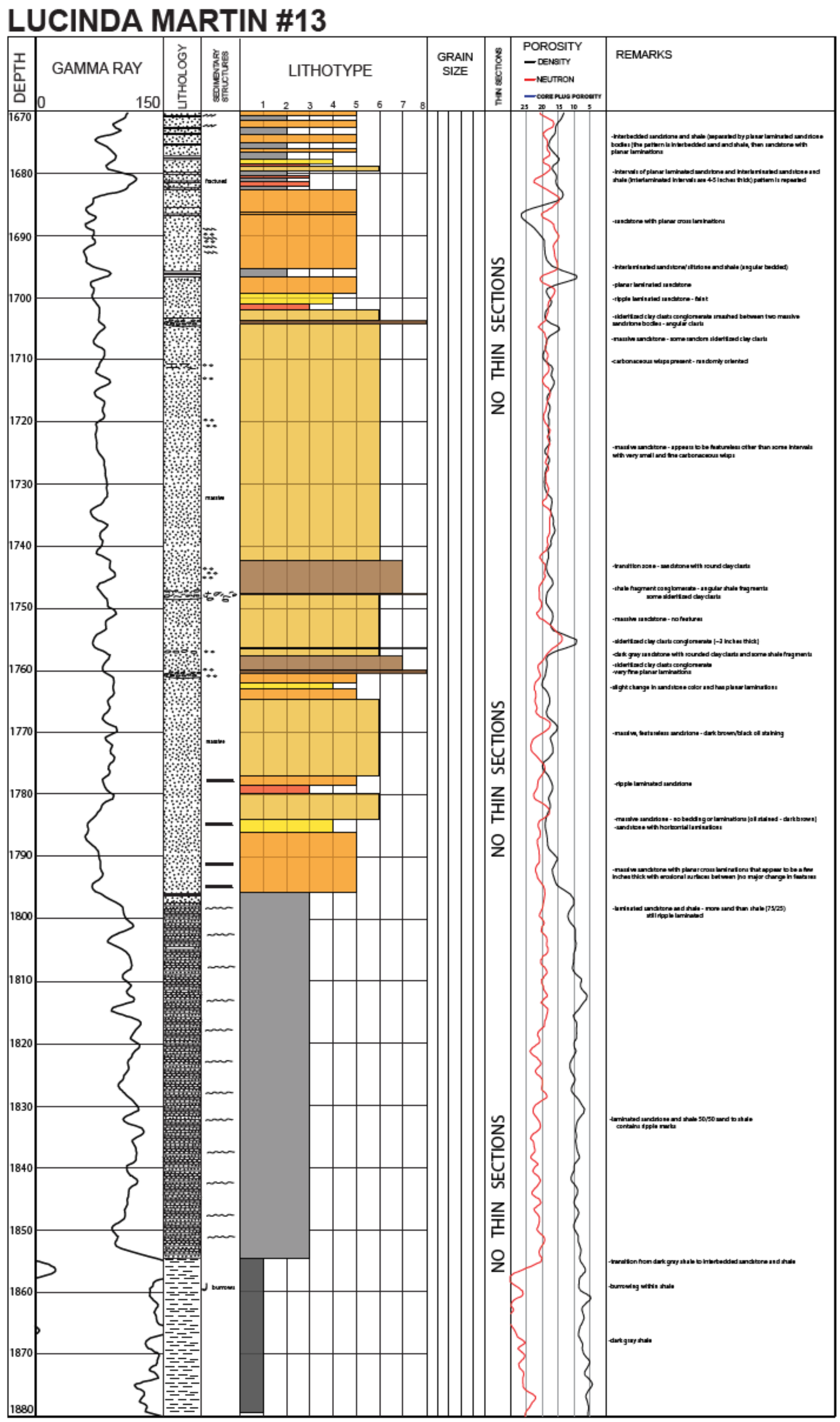
Regional cross section 2-2' (north to south)



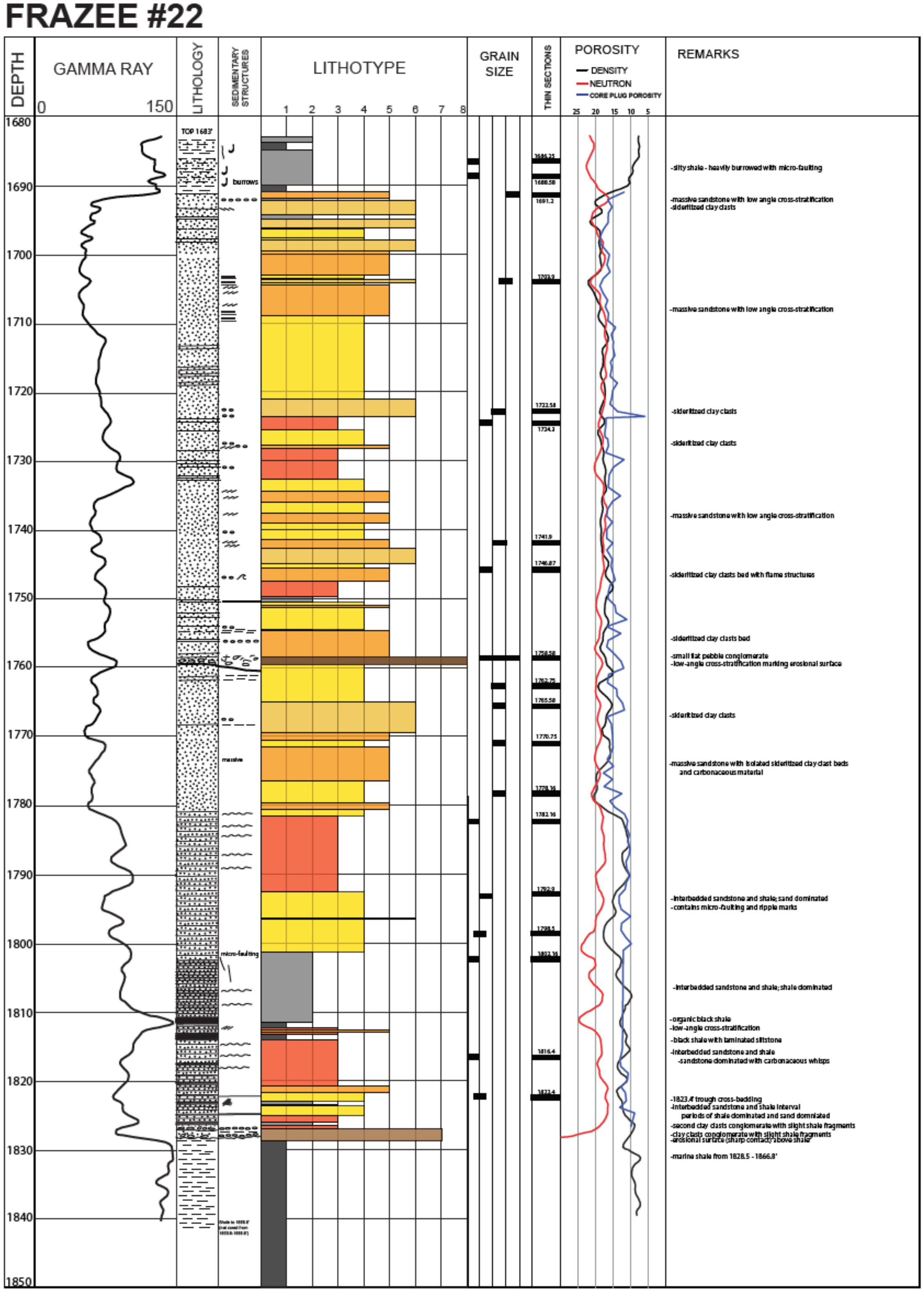
Regional cross section 3-3’ (north to south)



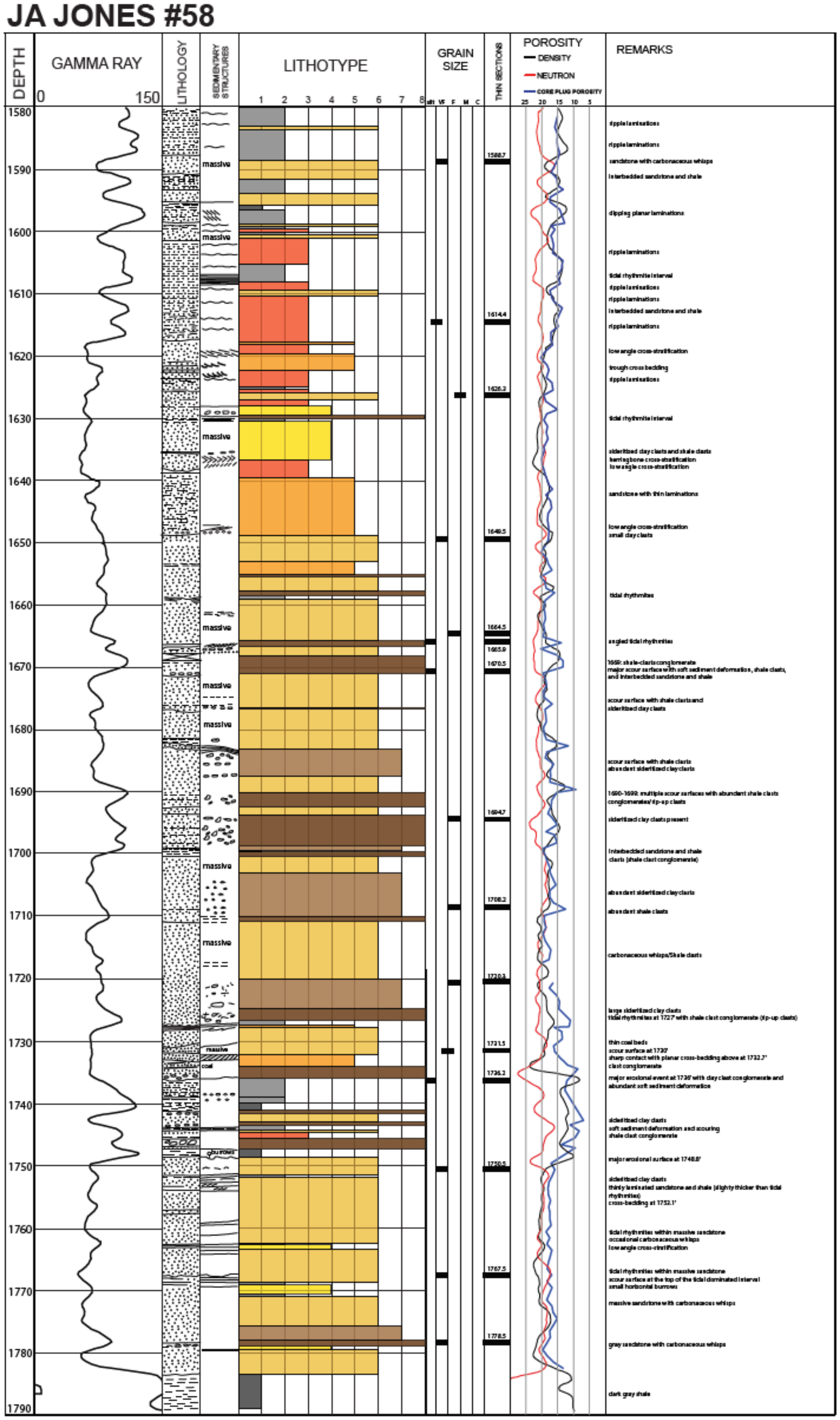
Core petrolog for Miller #34. Located in T21N, R08E Section 19, Pawnee County, OK.



Core petrolog for Lucinda Martin #13. Located in T21N, R08E Section 20, Pawnee County, OK.

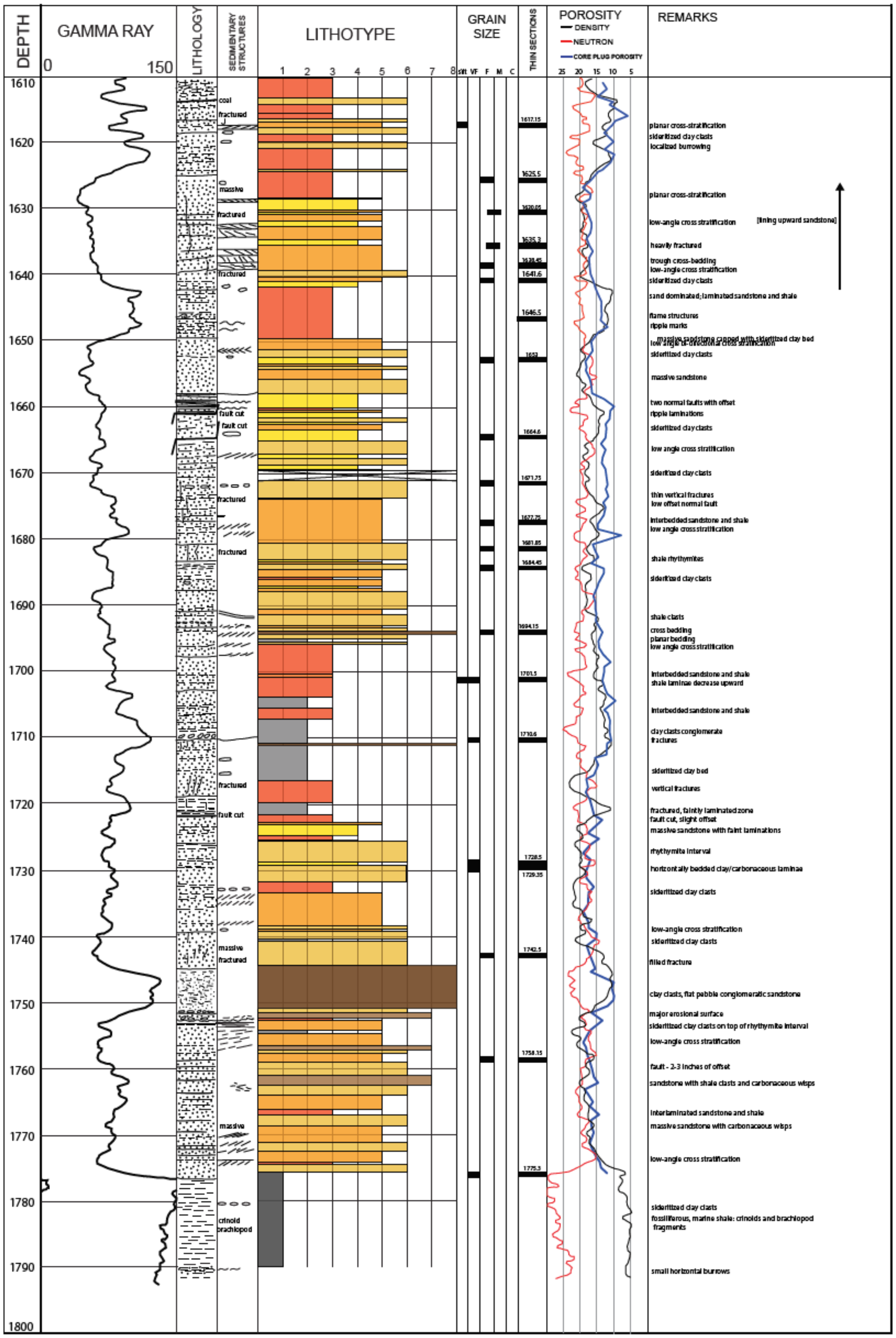


Core petrolog for Frazee #22. Located in T21N, R08E Section 29, Pawnee County, OK.



Core petrolog for JA Jones #58. Located in T21N, R08E Section 20, Pawnee County, OK.

VAN EMAN #16



Core petrolog for Van Eman #16. Located in T21N, R08E Section 30, Pawnee County, OK.

VITA

Connor Leland Cain

Candidate for the Degree of

Master of Science

Thesis: DECIPHERING THE CLEVLEAND SANDSTONE STRATIGRAPHIC FRAMEWORK: DIFFERENTIATING THE KIEFER AND OWASSO SANDSTONE COMPLEXES, NORTH-CENTRAL AND NORTHEASTERN OKLAHOMA

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Master of Science Degree in Geology at Oklahoma State University, Stillwater, Oklahoma in December, 2018

Completed the requirements for the Bachelor of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in 2014

Work Experience:

Interned at Post Rock Energy Corporation in Oklahoma City, OK in 2014

Interned at Mid-Con Energy Operating, LLC in Tulsa, OK in 2014

Began full-time job as a geologist at Mid-Con Energy Operating, LLC in Tulsa, OK in 2015

Professional Memberships: American Association of Petroleum Geology

Geological Society of America

Tulsa Geological Society

Oklahoma City Geological Society