STRATIGRAPHIC FRAMEWORK AND RESERVOIR PROPERTIES, MARMATON/“CLEVELAND” INTERVAL, NORTH CENTRAL OKLAHOMA

By

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STRATIGRAPHIC FRAMEWORK AND RESERVOIR

PROPERTIES, MARMATON/"CLEVELAND"

INTERVAL, NORTH CENTRAL OKLAHOMA

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CHAPTER I

INTRODUCTION

The “Cleveland sandstone” interval in central Oklahoma has not been intensely studied or interpreted in a sequence-stratigraphic framework. While the Cleveland sandstone is an important oil- and gas-producing reservoir in the Anadarko Basin and on the Cherokee Platform of northeastern Oklahoma, the spatial distribution of Cleveland sandstone bodies is not well defined in central Oklahoma. The petroleum industry has almost uniformly labeled the producing reservoirs beneath the Checkerboard Limestone and above any Marmaton carbonate as the Cleveland sandstone. In this study, (Figure 1) these sandstones will be placed within a sequence stratigraphic framework that will improve the understanding of their origin and distribution.

In the study area in central Oklahoma, sandstone bodies occuring above the Big Lime/Oswego carbonate and below the Checkerboard subsurface markers are typically called “Cleveland.” To establish the position of the true Cleveland Sandstone, the stratigraphy of the outcrop section is extended into the subsurface to establish a proper stratigraphic framework.

The Nuyaka Creek Shale, which marks the base of the true Cleveland interval, was named by Bennison from the type locality at the center of the west line of the NE/4 of Sec. 32-T.12N.-R.10E which lies in the “Nuyaka Creek”. This shale exhibits a highly radioactive signature on wireline logs and contains phosphate nodules as well as small limestone concretions (Bennison 1981).

The Cleveland Sandstone was named for the location where it first produced oil in Sec. 17-T.21N.-R.8E., Indian Territory, (present-day Pawnee County) in 1904 near the town of Cleveland, Oklahoma (Campbell 1997). This discovery marked one of the first important oil finds in Oklahoma's history (Bennison 1981).

The name "Checkerboard Limestone" has been applied to limestone both in the subsurface and on the surface as early as (Hutchison 1911). The limestone derives its name from its appearance at the surface where it is separated into blocks by two sets of perpendicular joints enhanced by solution channels giving it a checkered pattern (Oakes 1963). The type locality for the Checkerboard Limestone is in Sec. 22-T.15N.-R.11E in Checkerboard Creek (Gould 1925). This limestone marks the top of the true Cleveland interval.

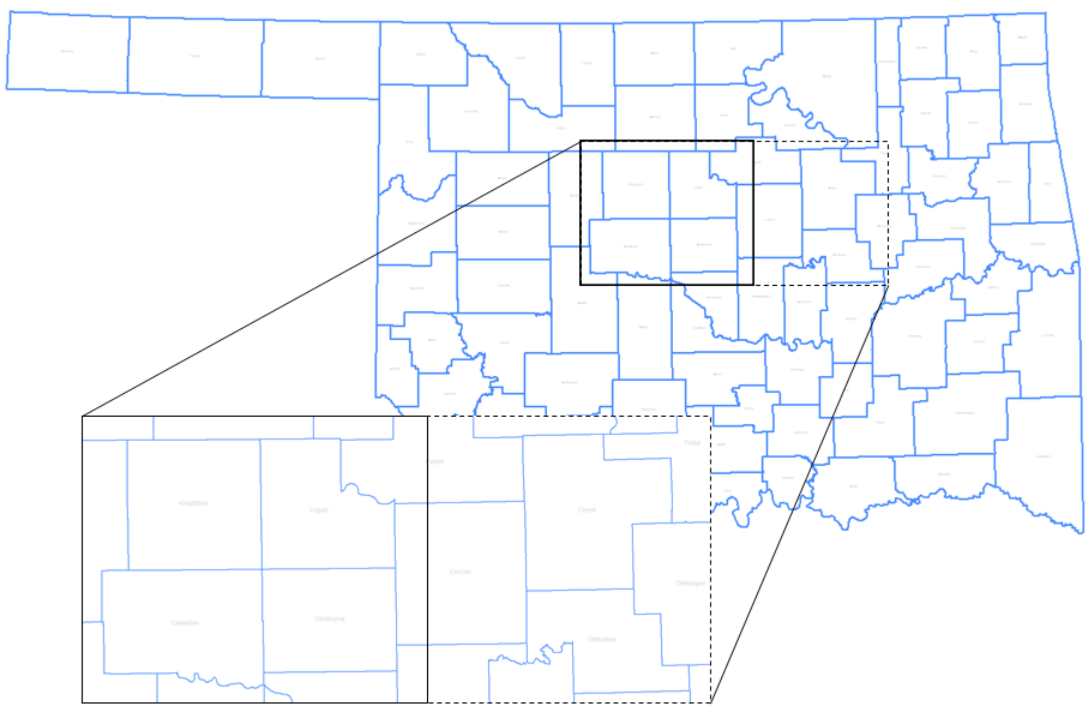

Figure 1: Map of Oklahoma showing the study area. The solid square represents the subsurface study area, whereas the dashed square includes the area where cross sections extended to the outcrop.

The “Subsurface Cleveland interval” contains two major depositional cycles that contain radioactive (“hot”) shales: the Lake Neosho Shale and the Nuyaka Creek Shale. These two hot shales, which represent maximum flooding surfaces (Heckel 1986), are present in the rock record across a large portion of the Midcontinent Region, North America. They are prominent in areas of the Anadarko Basin and are critical to the interpretation of a sequence-stratigraphic framework. However, in areas affected by the Nemaha Uplift, these flooding surfaces are not evident because the depositional setting changed enough to prevent the deposition of typical deeper/stratified water facies. The inability to recognize these hot shale markers is a primary reason that many geologists often incorrectly name Pennsylvanian sandstones in the Midcontinent Region. Finding and correlating the Nuyaka Creek Shale and other flooding surfaces is vital in separating the Skiatook Group and the true Cleveland sandstone from sandstones that may occur in the underlying Marmaton Group.

Surface Stratigraphy

In the subsurface of central Oklahoma, the Pennsylvanian section contains numerous sandstones; the “Cleveland Interval” contains several. In many areas, it is unclear which sandstones in this interval correlate to the true Cleveland Sandstone identified outcrop. The petroleum industry has not been concerned with the difference and in most cases name any sandstone “Cleveland” that is found between the regionally extensive Checkerboard limestone and thick Marmaton carbonate or the Little Osage Shale/Excello Shale where carbonate is not developed. This conventional approach to naming is simple, but disregards the outcrop stratigraphy. True Cleveland sandstone that is observed at outcrop is restricted to sandstones that occur above the Nuyaka Creek Shale in the Skiatook Group. When the Nuyaka Creek is correlated into the subsurface, the number of sandstones that occur in the true Cleveland interval is greatly reduced. Many sandstone bodies previously named “Cleveland” occur below the Nuyaka Creek Shale and thus are sandstones within the Marmaton Group.

The Nuyaka Creek Shale is the boundary between the Marmaton Group and the overlying Skiatook Group (Figure 3). However, the absence of the Nuyaka Creek Shale radioactive marker bed on wireline logs makes finding the top of the Marmaton Group much more difficult in parts of the study area. To the northeast, thick (approximately 42 meters (140 feet)) Marmaton carbonates immediately overlie the Little Osage Shale, a flooding surface that is recognized across the entire study area. To the southwest, these carbonates above the Little Osage Shale thin until they disappear entirely. In this area, the conventional industry boundaries (Checkerboard Limestone and Little Osage Shale) for the Cleveland interval are used. Therefore, there is an increasing probability of misnaming sandstone bodies in this interval. If the stratigraphy of this interval is to be deciphered, it is necessary to establish the position of the Nuyaka Creek Shale and the Lake Neosho Shale flooding surfaces and subdivide the interval based on depositional cycles.

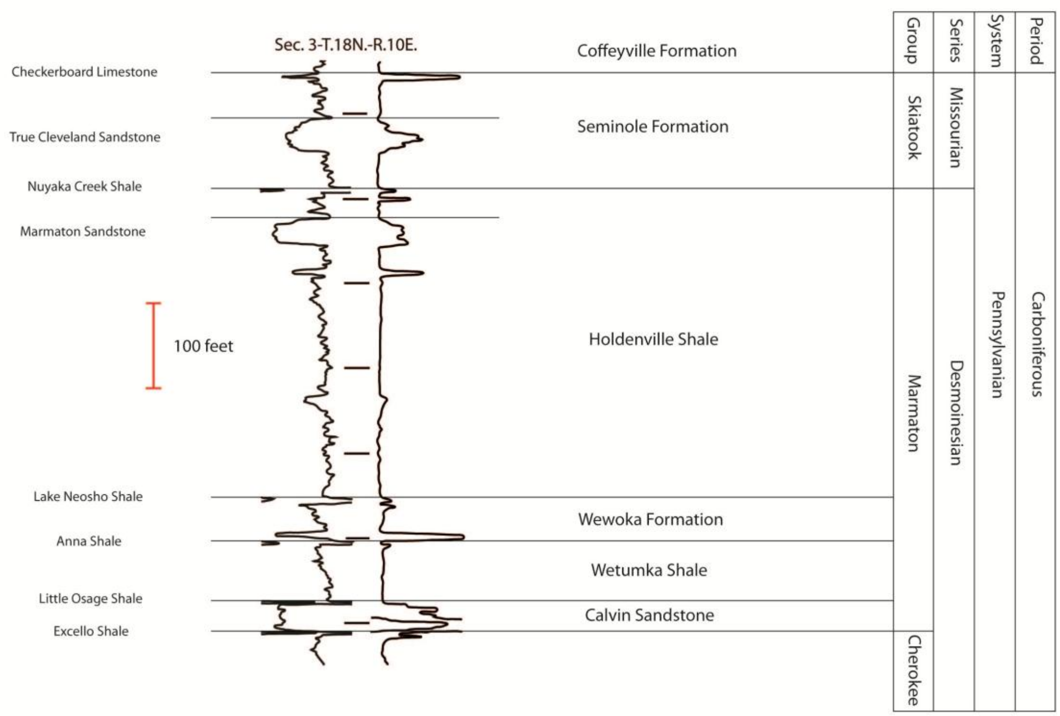

Figure 2: Wireline log signature and equivalent outcrop stratigraphy from T.18N., R.13E., Tulsa County, OK. Note the positions of radioactive “hot” shales.

Methods

This study establishes a depositional framework and then interprets the depositional setting and environments for sandstones within the Cleveland interval. Key surfaces such as the hot shale Maximum Flooding Surface (MFS) were be used to establish the boundaries required for the stratigraphic framework. Initially, cross sections of the area were constructed using well logs. This study emphasizes the identification of the Lake Neosho and Nuyaka Creek radioactive "hot" shales to help anchor a sequence-stratigraphic framework (Figure 3). Maps were constructed to show the impact of paleogeography on deposition and interpret paleobathymetry. Seven cores were evaluated and correlated to wireline log data to identify specific depositional environments and establish electrofacies. Cores were sampled for thin sections and core plugs taken to establish diagenetic history for the sandstones and determine factors controlling reservoir enhancement and degradation.

Cross sections were initially produced using Petra®. All well information, including wireline logs was acquired from DrillingInfo and both the Oklahoma Well Log Library in Tulsa and the Oklahoma City Geological Society Library in Oklahoma City. Cores were observed at the Oklahoma Geological Survey Oklahoma Petroleum Information Center (OPIC) in Norman. Core plugs were provided by OPIC for porosity and permeability tests as well as thin section analysis.

Geologic Setting

Most of the study area is located on the Central Oklahoma Platform and the northern shelf of the Anadarko Basin. The Nemaha Ridge runs directly through the center (Figure 2) and its influence on deposition is readily evident as the "Cleveland interval", which thins across the ridge and thickens both eastward and westward from it.

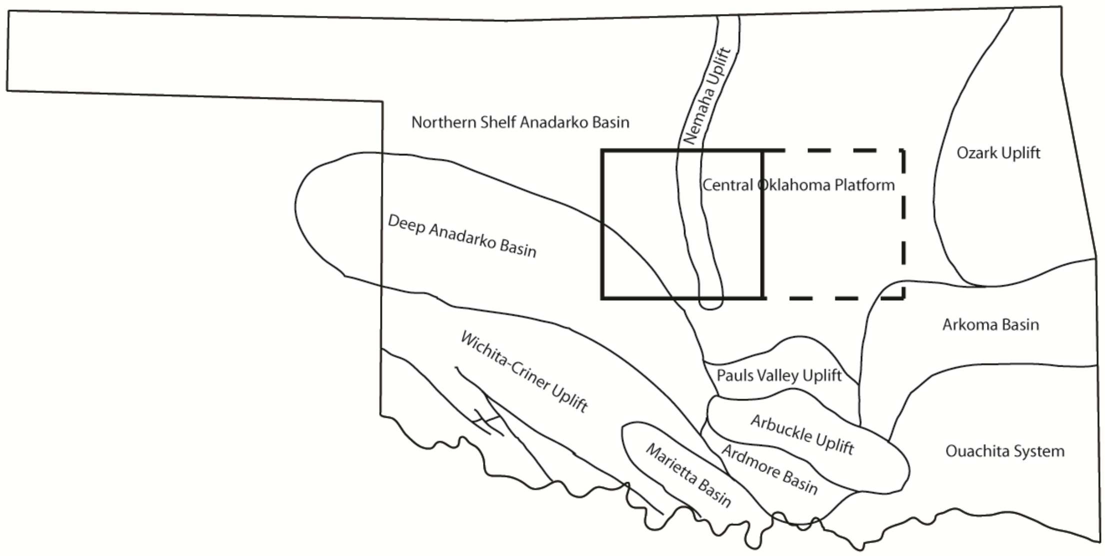

Figure 3: Location of the study area in relation to major geologic provinces (After Arbenz, 1956).

Previous Investigations

The Cleveland sandstone of north-central Oklahoma was previously investigated by Kousparis (1975), Campbell (1997), Rottmann (1997), and Knapp and Yang (1997). Kousparis (1975) mapped various electrical parameters for "Cleveland" sandstone in the eastern portion of Logan County, Oklahoma. Campbell (1997) investigated stratigraphy, nomenclature and depositional environment of the "Cleveland Sandstone". Rottmann (1997) focused on the Pleasant Mound Field in Lincoln County, Oklahoma. He described the local stratigraphy and structure along with production history and secondary recovery. Knapp and Yang (1997) examined reservoir properties for the "Cleveland sandstone" in Pleasant Mound Field. Most of these studies make no attempt to define the true position of the Cleveland sandstone. Exceptions are Gigstad (2008), Hentz (1992, 1994a, b, 2011), Hentz and Ambrose (2010), Ambrose and Hentz (2011), and Ambrose et al. (2011), who recognized the importance of the Nuyaka Creek surface and subdivided the Cleveland interval in western Oklahoma and the eastern Texas Panhandle into two: the Cleveland siliciclastic interval and Marmaton siliciclastic interval.

CHAPTER II

REGIONAL STRATIGRAPHIC FRAMEWORK

Introduction

Establishing the stratigraphic framework of the "Cleveland interval" is necessary because the petroleum industries' conventional informal stratigraphy does not consider the established outcrop nomenclature. The primary reason for this disconnect between outcrop and subsurface stratigraphy is the lack of marker beds in the subsurface that have wireline log responses that are distinct and correlatable. As a result, the two more easily recognizable beds on wireline logs, the Checkerboard Limestone and the Marmaton Group carbonates (Big Limestone and/or Oswego Limestone) became the upper and lower boundaries, respectively and any sandstone occurring between these two marker beds was called Cleveland sandstone.

Correlation of subsurface units is made even more difficult by the paleogeography and sediment dispersal system that existed during deposition of "Cleveland interval" sediments. The interval thins across the Nemaha Uplift and thickens eastward and westward into the Cherokee and Anadarko basins, respectively. To help resolve these problems, regional cross sections were constructed that extend from the outcrops in eastern Oklahoma to the study area in central Oklahoma.

The Nuyaka Creek Shale separates the Seminole Formation of the Skiatook Group from the underlying Holdenville Shale of the Marmaton Group (Figure 3). The Dawson coal is subjacent to the Nuyaka Creek Shale and traceable in the subsurface near the outcrop. Figure 3 shows subsurface units and outcrop stratigraphy. Cross section A-A' (Plate 1) was constructed from the study area eastward to Tulsa County for the purpose of correlating the important outcrop surfaces such as the Nuyaka Creek, Lake Neosho, Anna, Little Osage and Excello shales. Wireline logs show that the gamma-ray intensity (API value) of many of these shales decreases as they approach the Nemaha Uplift (Plate 1). The loss of radioactivity is interpreted as a change in the depositional setting and likely shallower, more oxygenated water (Watney 1995). Although the gamma-ray value decreases, its position is recognized in certain areas where deflections in resistivity/conductivity that correspond to the interval of high gamma-ray values. The use of correlated gamma-ray and resistivity/conductivity curve patterns allows recognition of markers when the high-value gamma-ray signature is weak or absent. The result is a more accurate and dependable correlation of the Nuyaka Creek Shale and other key surfaces.

The "Cleveland interval", as defined by industry, in north-central Oklahoma is composed of many different formations. However, due to changes in thickness and lateral changes in facies, some of these formations are not as easily recognized in the subsurface as others. The more widely recognized units in the Skiatook and Marmaton Groups are the Little Osage Shale, Nuyaka Creek Shale/Dawson coal, and Checkerboard Limestone. Other major surfaces that are important, but not always distinguishable, are the Anna Shale and Lake Neosho Shale.

Marmaton Group

The Marmaton Group is composed of the Excello Shale, Blackjack Creek Limestone, Little Osage Shale, Higginsville Limestone, Labette Shale, Pawnee Limestone, Lake Neosho Shale, Altamont Limestone and the Nuyaka Creek Shale. The presence of carbonate of variable thickness and lateral continuity causes subsurface units of the Marmaton to be more difficult to recognize and define than other more regionally consistent strata. The Marmaton Group is largely carbonate towards the north, especially in Logan and Kingfisher counties. These carbonate facies are completely absent in the southern region in T.11N., R.9W.-10W. Water depth and circulation likely affected the development of the Marmaton carbonate. As a result, to the north in T.17N.-19N., R.9W.-R.1E. the carbonate is better developed, with thicknesses ranging from around 30 meters (100 feet) up to 60 meters (200 feet). Immediately to the south, around T.16N., thicknesses begin to decrease so that any carbonate that can be identified on wireline logs is absent in the southernmost area. Since the thickness of the Marmaton carbonate varies widely and is missing in areas of the study, the Little Osage Shale is often adopted by industry as the Marmaton marker The combined Anna Shale, Little Osage Shale, and Excello Shale (Cherokee marker) becomes the top and base of the Marmaton Group when all carbonate is absent. Neither the carbonate nor the Little Osage Shale is the true top of the Marmaton Group as defined by outcrop stratigraphy, but this usage illustrates the need to establish a stratigraphic framework for this interval.

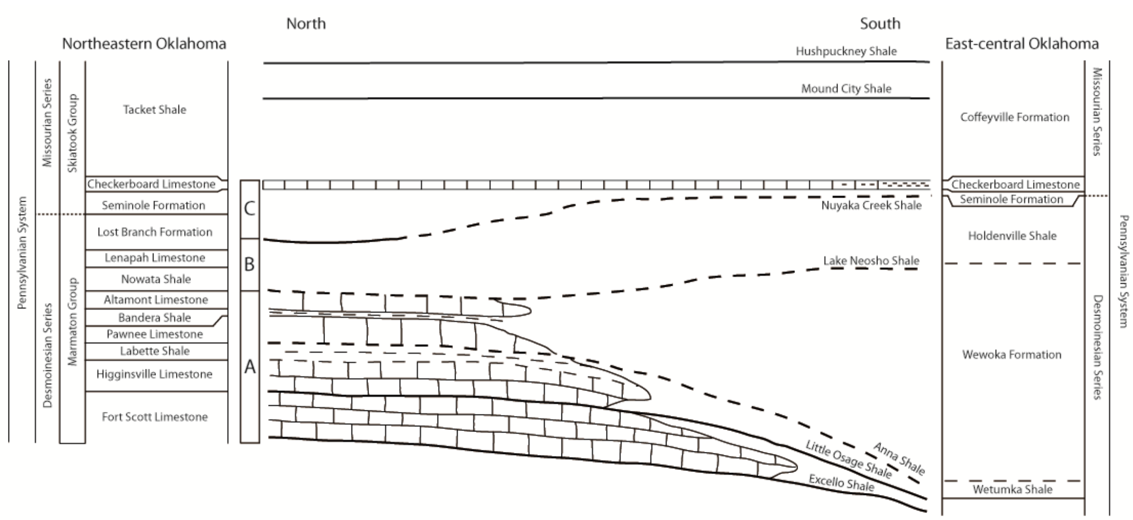

Figure 4: North-south schematic cross section displaying variation in thickness and lateral changes in facies. Stratigraphy of northeastern Oklahoma was determined from Heckel (1991) while the stratigraphy of east-central Oklahoma was from Ries (1954).

Little Osage Shale

The uppermost highly radioactive (hot shale) found in the Ft. Scott Limestone (Oswego Limestone of the subsurface) is the Little Osage Shale (Figure 3). The Little Osage Shale can be identified throughout the entire area with ease and is often used as the marker for the base of the "Cleveland interval" when the Marmaton carbonates are not developed. Because it is the most widespread and easily recognized horizon, it was used as a lower boundary for the study interval. The thickness of the Little Osage Shale is consistently between 1.5 meters (5 feet) to 3 meters (10 feet). In the southwestern portion of the study area, in T.11N.-12N., R.8W.-10W., the carbonates are not developed and the Little Osage and Excello "hot" shale markers are adjacent, which makes determining thickness more difficult. As the Little Osage Shale is an excellent marker bed, it was used to establish regional tectonic dip.

Nuyaka Creek Shale/ Dawson coal

The Nuyaka Creek Shale is the most difficult unit to recognize in the subsurface because it does not always display a "hot" signature. The present tectonic dip of the Nuyaka Creek starts as a westerly dip and begins to change to a southwesterly dip around R.2W. In outcrop in Tulsa County, the Dawson coal/Nuyaka Creek Shale occurs approximately 45 meters (150 feet) beneath the Checkerboard Limestone. Moving to the west, in T.17N.-19N., R.9W.-1E. the Nuyaka Creek occurs about 30 meters (100 feet) beneath the Checkerboard. However, toward the south, the interval between the Checkerboard Limestone and the Nuyaka Creek Shale decreases until it is approximately 1.5 meters (5 feet) to 4.5 meters (15 feet) beneath the limestone. Although modern log data is limited in the area where the Nuyaka Creek Shale directly underlies the Checkerboard Limestone, the convergence of the Nuyaka Creek Shale and Checkerboard Limestone is evident in cross sections (Plates 3, 4, and 5). Cross sections that extend to outcrop (Plates 1(T.18N.) and 2

(T.14N.)) are essential to the correct correlation of the Nuyaka Creek Shale, while detailed core descriptions from (Hemish, 1987) in Okfuskee County also support the correlation.

Skiatook Group

Checkerboard Limestone

The Checkerboard Limestone is a regionally pervasive marker bed that can be observed throughout the entire area of study and is generally no thicker than 9 meters (30 feet). It is thickest in the eastern half of Canadian County and the western half of Oklahoma County where it is roughly 6 meters (20 feet) to 9 meters (30 feet). Throughout the rest of the area, the Checkerboard Limestone is approximately 1.5 meters (5 feet) to 6 meters (20 feet) thick. The area of enhanced thickness occurs in the southern part of the study area and may represent the optimum depositional setting near the shelf edge where shallow, warm, and nutrient-rich water was available to facilitate carbonate growth.

Confusing Nomenclature

The lack of a persistent Nuyaka Creek Shale marker and the variable thickness of the Marmaton carbonates have contributed to the confusion in subsurface nomenclature and in particular, the identification and proper placement of the Cleveland Sandstone. True Cleveland Sandstone at outcrop is found between the Checkerboard Limestone and the Nuyaka Creek Shale/Dawson coal (Figure 3). The Nemaha Uplift positive area apparently affected the deposition of the Nuyaka Creek Shale and as a result, the Nuyaka Creek Shale does not display a “hot” gamma-ray signature near the uplift. Because the Nuyaka Creek Shale could not be detected, geologists named sandstones occurring between the Checkerboard Limestone and the top of the carbonate within the Marmaton Group as the Cleveland Sandstone. Sandstones toward the top of the interval are often labeled “upper Cleveland”, while those near the Marmaton carbonates, “lower Cleveland.”

In the literature the nomenclature usage varies; some use the proper Checkerboard-Nuyaka Creek/Dawson interval (Krumme, 1981), while others use the incorrect Checkerboard-Marmaton carbonate interval (Cole, 1970). Jordan, (1957) published a compilation of subsurface stratigraphic names in Oklahoma in an effort to minimize the confusion involved in subsurface nomenclature. Recent work by Gigstad (2008), Hentz (1992, 1994a, b; 2011), Hentz and Ambrose (2010), Ambrose and Hentz (2011), and Ambrose et al. (2011) utilize the Nuyaka Creek Shale to mark the boundary between the Cleveland interval and the Marmaton Group in the Anadarko Basin.

The Cleveland sandstone is also often divided into separate sandstone bodies with unique local names, such as the Jones Sandstone and the Dillard Sandstone. Other names have been applied to sandstones within the improperly defined interval, but Cleveland is the most frequently used term. However, these upper and lower "Cleveland" sandstones are in many cases separated by the Nuyaka Creek Shale/Dawson coal. As we know from outcrop, true Cleveland Sandstone lies above these juxtaposed formations. If any "Cleveland" sandstone bodies lies beneath them, they cannot be true Cleveland Sandstone and therefore must belong in the Marmaton Group.

Depositional Setting

As a result of the changing thickness of the Marmaton carbonate, a structure map of the Marmaton Group with the datum as the top of the Marmaton carbonate differs greatly from a map with the datum as the top of the Nuyaka Creek Shale. The regional dip of the Marmaton carbonate is towards the southwest, however, the angle of dip increases as the total thickness of carbonate decreases. The structure map of the Nuyaka Creek displays a much more uniform dip toward the southwest.

The locations of depocenters during Marmaton and Cleveland time were determined by mapping the thickness of the section between the Checkerboard Limestone and the Little Osage

Shale as they are the most consistent marker beds associated with the Cleveland interval in the study area. It is interesting that as these same beds are often used as the boundary of the Cleveland interval by geologists working with subsurface data and include all of Marmaton Group and the true Cleveland interval, the maps generated by industry are effective in defining the basin depocenter. North-south cross sections across R.8W., R.5W., and R.2W. (Plates 3, 4, and 5 respectively) show thickening of the Little Osage-Checkerboard interval towards the south, with the R.8W. cross section showing a greater increase. This trend is interpreted to be evidence that the depocenter is located to the southwest. A southwest-northeast cross section confirms a dramatic thickening of the Checkerboard to Little Osage interval to the southwest of the study area.

Since correlation of the Nuyaka Creek Shale can be problematic, especially without the benefit of modern logs. West-east cross sections were constructed across T.18N. and T.14N. (Plates 1 and 2 respectively) to confirm the location of the Dawson coal/Nuyaka Creek Shale in the “Cleveland interval”. The Dawson coal/Nuyaka Creek Shale outcrop is near Tulsa, Oklahoma; the location of these formations in relation to the Cleveland Sandstone is known. Therefore, the T.18N. and T.14N. cross sections were correlated to the outcrop to provide supporting evidence for a proper correlation of the surface units to subsurface ones. The T.18N. cross section displays thickening of the interval toward the outcrop and thicker Marmaton carbonate in the west. The T.14N cross section shows thickening of the interval between the Checkerboard Limestone and the Little Osage Shale toward the east into the Cherokee Basin and westward into the Anadarko Basin.

Throughout the four county study area, the interval from the Checkerboard Limestone to the Marmaton carbonate can be divided into three separate intervals: “A”, “B”, and “C”. These intervals are defined by “hot” shales, more specifically, the Lake Neosho Shale and the Nuyaka Creek Shale (Figure 4).

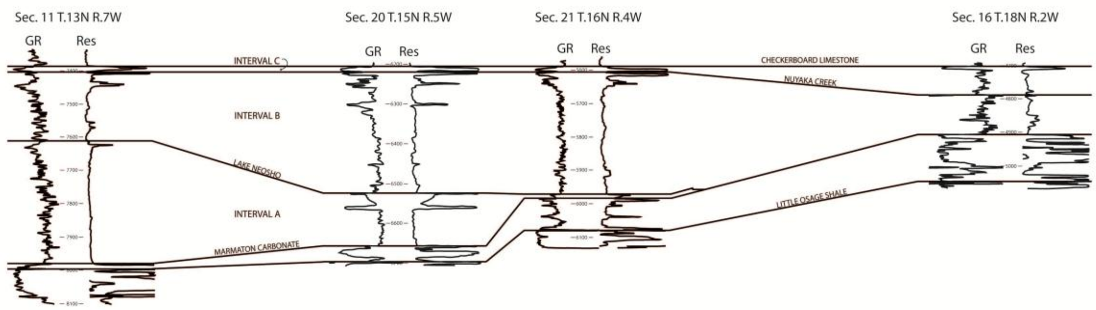

Figure 5: Southwest-northeast trending schematic cross section showing variation in thickness of intervals A, B, and C.

Interval A (Figure 4, 5) is a package of shale that thickens in a south-southwesterly direction; the top of this interval is marked by a hot shale (possibly the Lake Neosho Shale) which occurs at the top of a coarsening/cleaning upwards zone referred to as “the silty zone” (Figure 4). The “silty zone” is recognized by increasing resistivity and decreasing gamma-ray. The SP deflection across the zone is often indistinct. In some areas, a thin “hot shale” (believed to be the Lake Neosho) is almost detectable on wireline logs immediately above the “silty zone” (Plates 3, 4, and 5). The silty zone is often marked as “Cleveland”, “Cleveland sand”, or some form of “Cleveland” sandstone on wireline logs. However, it occurs below the Nuyaka Creek Shale and is Marmaton in age; therefore, any name involving “Cleveland” is a misnomer. This interval is thickest in T.12N., R.10W. at around 260 meters (860 feet) and is absent where it appears to onlap and/or changes facies to the Marmaton carbonate along an east-west trend subparallel to the boundary between T.16N. and T.17N.

Log characteristics of the silty zone are easily recognizable at its point of apparent onlap. To the south, it becomes more difficult to identify. Typically, the silty zone displays gamma-ray values ranging from approximately 65API near the base to approximately 100 API near the top of the coarsening upwards profile. The SP measurements exhibit little to very little deflection and, if observable, ranges from 10 to 40 millivolts.

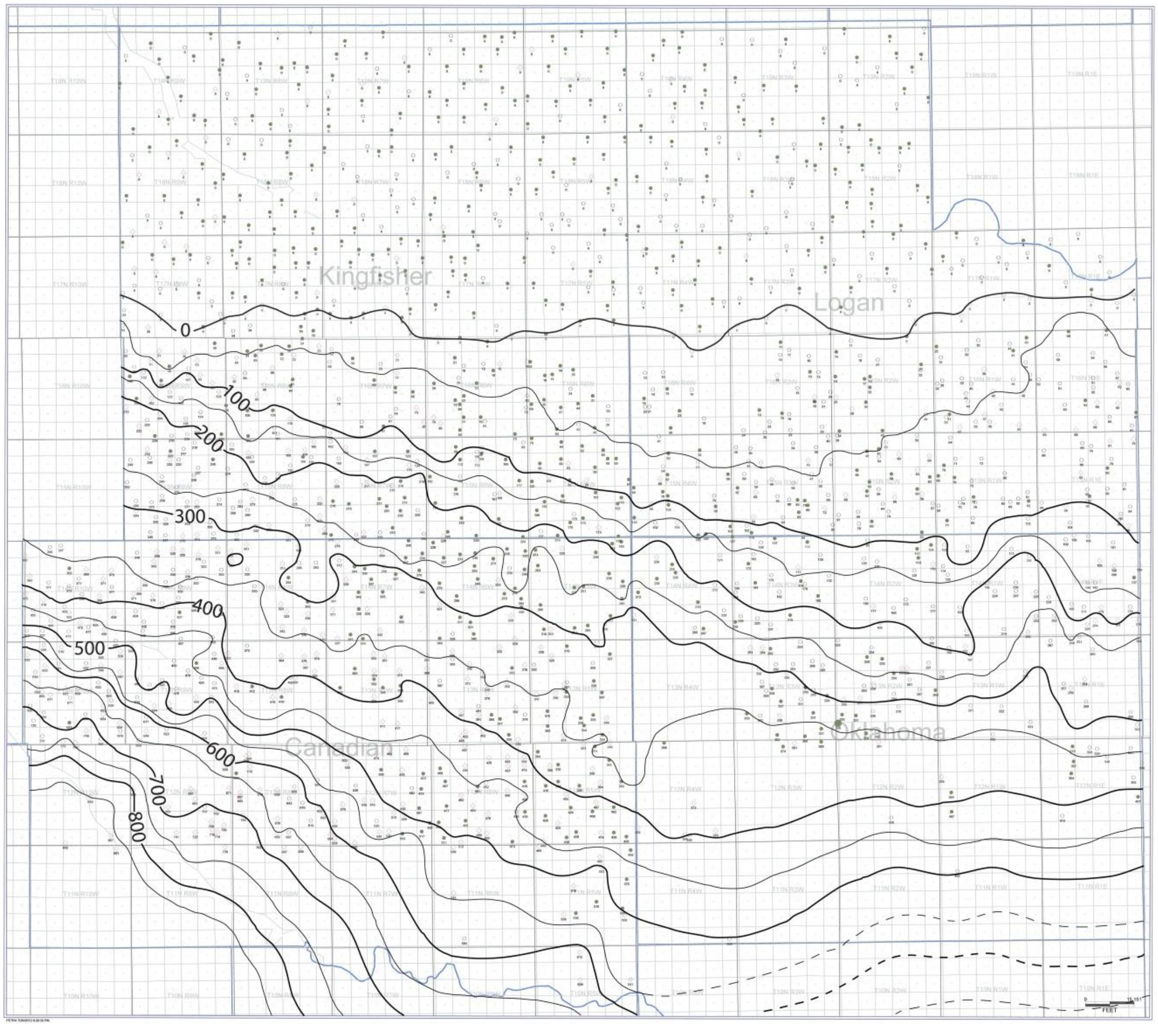

Figure 6: Thickness of Marmaton siliciclastic Interval A in the study area that onlaps and/or changesfacies to carbonate along an east-west trend approximately T.16N.-T.11N.

Interval B (Figure 4, 5), which immediately overlies Interval A, is bound by two “hot” shales, the Lake Neosho Shale at the base and the Nuyaka Creek Shale at the top. Interval B thickens towards the east and ranges between 21 meters (70 feet) to 128 meters (420 feet) thick. The area of thinnest siliciclastic interval B occurs in T.19N., R.2W.-R.3W. and the thickest in T.15N., T.16N.-R.1E. Interval B is similar to Interval A in that it is predominantly shale, especially where the interval is thicker. The sandstone that is frequently marked “Cleveland” in the southern portion of the study area lies within Interval B.

The shale that makes up Interval B (Figure 4) displays a gamma-ray value of approximately 90API - 135API units. Occasionally, thin (<3 meters (10 feet) – 4.5 meters (15 feet) thin) silty, sandy, and/or limey zones appear in Interval B. These zones do not occur frequently enough to map and often are located immediately beneath the Nuyaka Creek Shale.

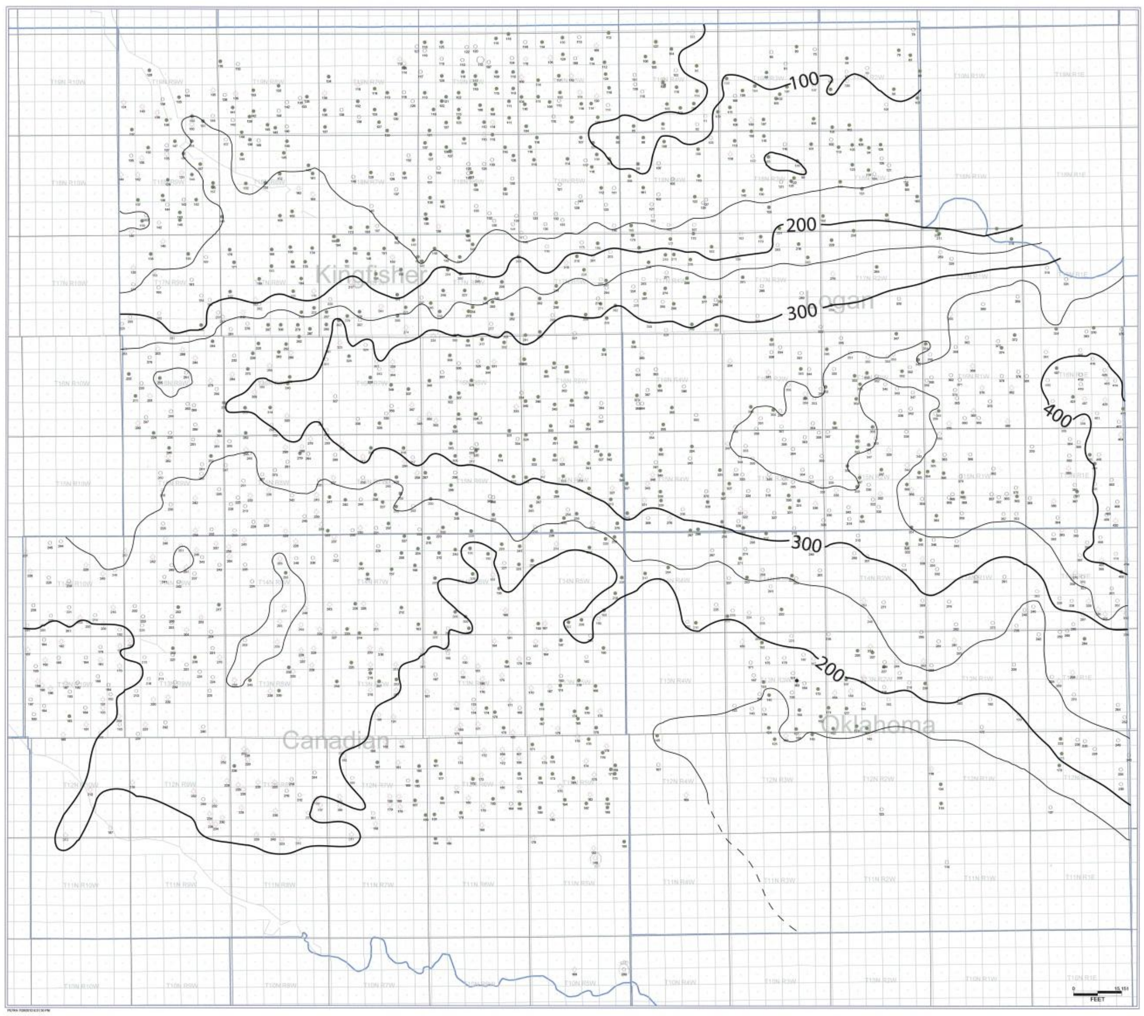

Figure 7: Thickness of the Marmaton silicilastic Interval B across the study area The base of Interval B is the Lake Neosho Shale, the top is the Nuyaka Creek Shale.

Interval C (Figure 4, 5) is the youngest interval in the studied interval. It extends upward from the Nuyaka Creek Shale to the Checkerboard Limestone and hosts the true Cleveland Sandstone in the outcrop in Tulsa County. Interval C ranges in thickness from 1.5 meters (5 feet) to 32 meters (106 feet) and is found throughout the entire study area (Figure C). The greatest thickness is found in T.19N.-T.18N. and in T.17N., R.6W., R.8W., R.9W. The area with the thinnest Interval C is T.16N., R.4W.-R.1E. and T.15N., R.4W.-R.1E. as well as the western half of Canadian County. Sandy shale is present in the townships with the greatest Interval C thickness.

Log characteristics of Interval C vary depending on the location within the study area. The base of this interval (Nuyaka Creek Shale) converges on the Checkerboard Limestone in areas and the interval generally thins toward the south. SP deflections are 20-50 millivolts. To the south of approximately T.16N., across the entire study area, the sandy shale is no longer present and the Nuyaka Creek Shale closely underlies the Checkerboard Limestone.

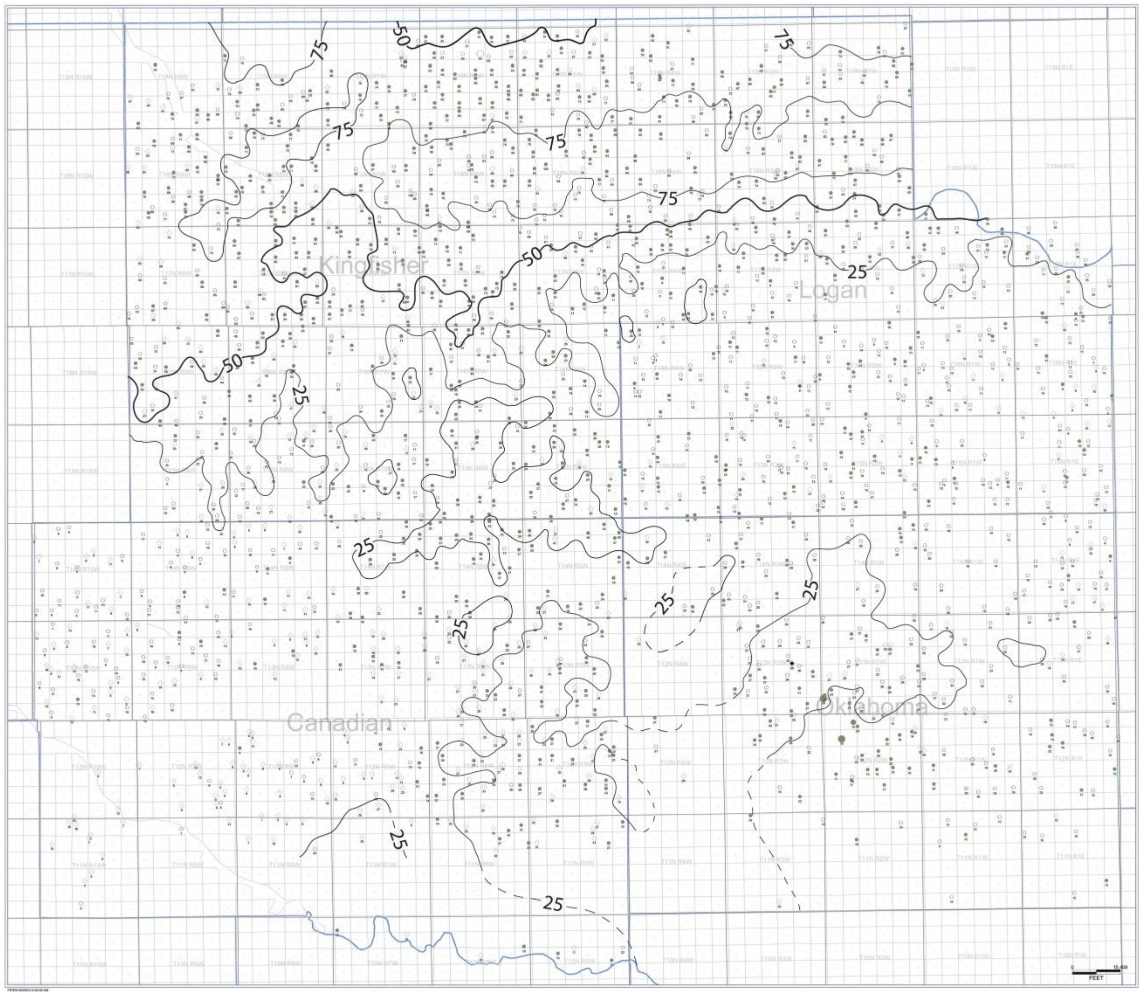

Figure 8: Thickness of Cleveland siliciclastic Interval C in the study area. The base of this interval is the Nuyaka Creek Shale and the top is the Checkerboard Limestone.

The thicknesses of the three intervals are complementary as the thickest Interval A is located in the southern third of the study area (Figure 6), the thickest portion of Interval B in the central third of the study area (Figure 7), and the thickest part of Interval C in the northern third of the study area (Figure 8). As these three intervals filled in succession, the thickness of each appears to have been influenced by the thickness of the underlying interval. If this is the case, filling of accommodation influenced sediment dispersal in the next unit. In areas where water was shallower and less stratified, the “hot” gamma-ray values characteristic of the Nuyaka Creek Shale and Lake Neosho Shale are not evident on wireline logs.

During the precipitation/deposition of the Marmaton carbonate in the northern area there was a large input of mud from the north-northeast that filled the accommodation in basinal areas. In southern parts of the study area, the sandstone that is often marked as “Cleveland” on wireline logs occur in the upper portion of interval “A” and appears to represent shallowing toward the top of this interval. To the northwest, interval A appears to onlap the Marmaton carbonate. Without biostratigraphy, the exact relationship between the shale-dominated interval A and the carbonate to the north cannot be resolved. However it is expected that the shales are coeval with well recognized Marmaton units such as the Fort Scott Limestone (Oswego Limestone), Labette Shale, Pawnee and Altamont Limestone (Oologah Limestone).

Cross Sections

Regional cross sections were constructed throughout the study area. In addition to north-south cross sections, east-west cross sections were built for the purpose of using outcrop stratigraphy to resolve the naming issues that plague the “Cleveland interval” in north-central Oklahoma. A total of 5 cross sections, 3 north-south and 2 east-west, were constructed; these are Plates 1-5.

North-south cross sections show that the interval between the Little Osage Shale and the Checkerboard Limestone thickens toward the south. They also reveal that there is a change in facies along the north-south direction. Carbonate belonging to the Marmaton Group thins to the south until it is no longer apparent on wireline logs, whereas the MFSs associated with these carbonates are relatively consistent throughout the entire study area. The Little Osage and Excello “hot” shales, although consistent, converge on each other as Marmaton carbonate disappears. In T.11N., R.10W., it appears that the Anna, Little Osage, and Excello shales converge into what is known as the “Cherokee Marker” in the Anadarko Basin. These cross sections are Plates 3-5.

The north-south trending cross section through R.2W. shows a loss of Marmaton carbonate to the south with simultaneous thickening of the Little Osage Shale-Checkerboard Limestone interval from about 91 meters (300 feet) in Sec. 16-T.19N.-R.2W. to 198 meters (650 feet) in Sec. 29-T.11N-R.2W. In T.18N., R.2W., the Marmaton consists of thin carbonates that are separated by shale. The Nuyaka Creek Shale-Checkerboard Limestone interval thins to the south because pre-Nuyaka Creek accommodation was filled by Marmaton siliciclastic mud.

The north-south trending cross section through R.5W. shows thinning of Marmaton carbonate to the south and a thickening of the Little Osage Shale-Checkerboard Limestone interval from around 85 meters (280 feet) in Sec. 10-T.19N.-R.5W. to approximately 243 meters (800 feet) in Sec. 16-T.10N.-R.5W. Filling of accommodation by pre-Nuyaka Creek Marmaton siliciclastics in the southern part of the study area appears to have greatly reduced post-Nuyaka Creek accommodation, resulting in a thin interval between the Checkerboard Limestone and the Nuyaka Creek Shale.

The north-south trending cross section through R.8W. shows that the Marmaton carbonate in the western part of the study area is much more developed and forms massive-clean carbonate bodies whose amalgamated thickness reaches around 76 meters (250 feet) thick in T.17N. Other north-south cross sections (R.2W. and R.5W.) show the Marmaton carbonate to be less developed with a tendency to split into separate thinner carbonate bodies. The thicker carbonate north of T.17N. thins in T.16N. and continues to thin to the south. The interval between the Little Osage Shale and the Checkerboard Limestone consistently thickens to the south ranging from around 106 meters (350 feet) in Sec. 34-T.19N.-R.8W. to 295 meters (970 feet) in Sec.9-T.11N.-R.8W. The Nuyaka Creek Shale is separated further from the underlying Marmaton carbonate section to the south where Marmaton siliciclastics filled the accommodation.

East-west cross sections were constructed from the subsurface to the outcrop locations in both Okfuskee county (T.14N.) and Tulsa County (T.18N.). It is important that these cross sections connect to the outcrop to properly correlate the accepted surface stratigraphy to the subsurface. The T.14N. cross section that extends into Okfuskee County shows thinning of Marmaton carbonate and the subsequent convergence of “hot” shales in T.14N.-R.4E. In T.14N.-R.6E., these MFSs begin to diverge, but there is no longer any carbonate present. While constructing these cross sections, a trend of eastward thickening was noted; however, in Sec.36-T.12N.-R.8E., the “Cleveland interval” thinned unusually and appears to be faulted with approximately 48 meters (160 feet) of missing section. East of this fault, the section continues to thicken as it did west of the fault. These cross sections are Plates 1 and 2.

The cross section that correlates to the Tulsa County outcrop in T.18N. shows minor thickening of Marmaton carbonate to the east from R.9W. to R.4W., whereas further east, the carbonate begins to thin. The interval between the Little Osage Shale and the Checkerboard Limestone is fairly consistent from R.9W. to R.5E. at roughly 91 meters (300 feet) to 121 meters (400 feet). In R.7E., the Little Osage-Checkerboard interval begins to thicken to upwards of 128 meters (600 feet). Where this interval thickens, there is a loss of carbonate and evidence of a major influx of Marmaton siliciclastics that filled accommodation. The thicker carbonate in the western ranges of T.18N (R.1E. through.9W.) is likely the result of the position of this area on the northern shelf of the Anadarko Basin or the Central Oklahoma Platform (Arbenz 1956).

The “hot” shales are persistent in some areas, but become difficult to recognize in others. On Plates 1-5, the Little Osage and Excello shales are marked where indicated by logging. These shales are correlated on Plates 1-5 by solid and dashed lines. Within this interval, these shales are commonly “hot” and therefore make it easier to determine the location of other important surfaces.

The Anna Shale is interpreted on Plates 1-5 as solid and dashed lines. This shale is more difficult to distinguish than the Little Osage and Excello Shales. However, the three of these shales appear to converge in the southwestern-most part of the study area. In the Anadarko Basin, when these shales converge, the hot shale package is commonly referred to as the “Cherokee marker”.

The Lake Neosho is interpreted as a dashed line on Plates 1-5. This shale marks the top of interval A which changes facies laterally from carbonate in the northern townships to thick packages of siliciclastic in the southern townships; this shale occasionally displays a “hot” signature where it directly overlies the “silty zone”. The Lake Neosho Shale follows a trend similar to the Nuyaka Creek Shale in which it appears to move up section in response to large amount of siliciclastics that filled accommodation prior to Lake Neosho deposition.

The Nuyaka Creek is correlated on Plates 1-5 with a dashed line. This MFS is the key to defining true Cleveland sandstone, so it is imperative to interpret its stratigraphic position. However, due to its lower radioactivity in parts of the study area, finding its true stratigraphic position on wireline logs is difficult and cannot be chosen with as much confidence as other “hot” shales such as the Little Osage and Excello shales.

On the far eastern end of the southern east-west cross section (T.14N.), the Mound City and Hushpuckney shales are shown to facilitate correlation of the upper part of the Cleveland interval. The Mound City and the Hushpuckney shales occur in the Kansas City Group immediately above the position of the Checkerboard Limestone. These shales (Excello, Little Osage, Anna, Lake Neosho, Nuyaka Creek, Mound City, and Hushpuckney) indicate how widespread MFSs provide chronostratigraphic markers that are necessary to correlate these intervals.

CHAPTER III

LOCALIZED DEPOSITIONAL ENVIRONMENTS

Introduction

Within the four county study area, there are two areas with mappable sandstone bodies: 1) T.19N., R.5W.-R.6W. (which will, for the rest of this paper be referred to as the Northern Area) and 2) T. 12N.-T.13N., R.2W.-R.3W. (which is referred to as the Southern Area). The Northern Area was more extensively mapped due to the abundance of well control. The Southern Area is located near Oklahoma City, Oklahoma, where there is a scarceness of wells and logs. This area, however, is home to multiple "Cleveland sandstone" cores and will be discussed in some detail.

Using over 3,400 wireline logs collected from the Oklahoma Well Log Library in Tulsa as well as information from DrillingInfo and core data from the OGS core library, subsurface maps were constructed to aid in the interpretation of the depositional environments of the sandstone within the Cleveland interval. These logs were utilized to find the distribution of the sandstone bodies. Dual induction logs with gamma-ray curves are ideal for constructing these maps. However, due to the scarceness of wells in some areas, there is a lack of modern logs with gamma-ray curves.

Since most wireline logs in the study area lack gamma-ray curves, it was necessary to use resistivity and spontaneous potential (SP) curves to identify unit boundaries. SP logs give an indication of permeability (Kreuger Jr., 1968) so their values can be altered by the presence of cements and clays that occupy pore space. In an attempt to mitigate the problems of a scarceness of gamma-ray logs and the unreliability of SP curves, the relationship between the SP, resistivity and gamma-ray curves across subunit boundaries was established in areas with modern well logs and extended to areas where mostly vintage logs were available. Patterns of resistivity/conductivity were particularly useful in establishing the correlations used to delineate stratigraphic subunits.

Cores

A total of seven wells were located within the study area (Figure 13) that reportedly cored the Cleveland Sandstone. When the cored intervals were plotted on their respective wireline logs it became evident that all of the cores reported as being from the Cleveland sandstone were from the interval below the Nuyaka Creek Shale and thus represent Marmaton Group rocks. Core lithology and sedimentary and biogenic structures were described and photographed (Figure 10, 11, and 12). Wireline logs of these cores were available, however in most cases, they are SP and resistivity logs. An exception is the Ward Petroleum Marisa 1-10 in Sec.10 T.19N., R.6W., which has gamma-ray and resistivity curves. This well is the only one in which there are documented sedimentary structures and gamma-ray determined sandstone body geometry, important components used to determine depositional environment. In other cores SP curves were used in conjunction with rock features and sandstone distribution to interpret depositional environment. Notable features from select cores can be seen in Figures 10, 11, and 12.

Sedimentary Structures

A variety of sedimentary structures occur in the Marmaton sandstones. These structures include: burrows, planar and trough cross bedding, bidirectional cross bedding, rip-up clasts, lenticular bedding, soft sediment deformation, massive bedding, and possible symmetric ripples. Some of these structures can be seen in Figures 14, 15, 16, 17 and are summarized in Figure 9.

Lithologic, Sedimentary, and Biogenic Features in Cored Intervals		
Northern Area		**Figures**
N-4	shale and sandy shale, burrowed-bioturbated	18,15
N-3	sandstone, sandstone w/clay clasts	14,22
N-2	sandstone, planar to trough cross bedding	17,16
N-1	sandstone with thin shale laminae, crinoids, possible bidirectional cross bedding	
Southern Area		**Figures**
S-4	limestone, crinoidal grainstone	24
S-3	shale, varigated (exposure surface)	23
S-2	sandstone-shale laminae, burrowed	21,19
S-1	sandstone, massive	20

Figure 9: Summary of sedimentary and biogenic features identified in cores of Marmaton sandstones.

Paleontology

Numerous fossils occur in the cored intervals, especially in the southern area. Crinoids are the most common fossil type and occur in sandstone, limestone, and shale intervals. Brachiopods are also quite common and along with crinoids are indicative of a marine origin. Thin section petrography of a limestone cored in the Gulf Oil Corporation's Meyers Estate 1 (Sec. 10-T.12N.-R.2W.) also revealed the presence of few small fragments of gastropods and trilobites. Other constituents identified in cores are: clay clasts, ooids, and a unique "poker-chip" appearance of shale which is attributed to coring-induced breakage.

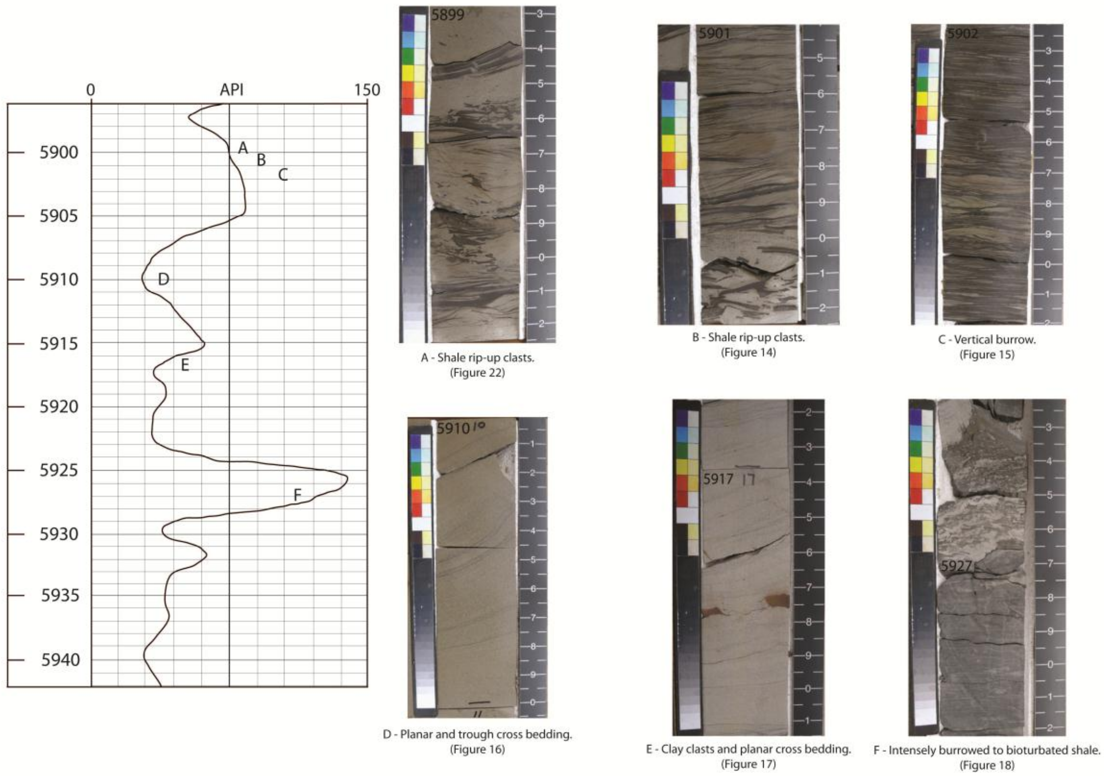

Figure 10: Select core pieces showing lithologic, sedimentary, and biogenic features of the Marisa 1-10 core (Sec. 10-T.19N.-R.6W.) (northern area) with their relative position indicated on the gamma-ray curve. The Marisa 1-10 core contains burrowed sandy shale (F) overlain by sandstone with planar to trough cross beds (D and E). The sandstone contains rip up clasts, but no obvious features typical of marine or marginal marine deposition. Burrowing is again evident in the Marisa core in the shale interval above the sandstone. A detailed description of the Marisa 1-10 core is in Appendix A. Larger pictures of select core pieces can be seen in Figures 14-18, and 22.

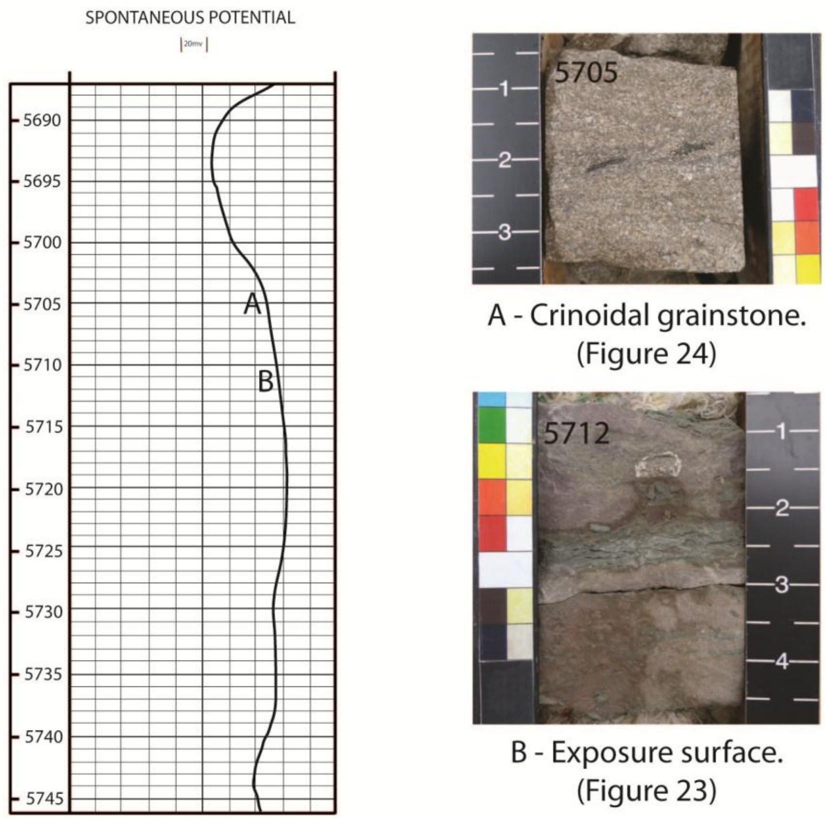

Figure 11: Select lithologic features of the Holtzschue 1 core (Sec. 8-T.12N.-R.2W.) (southern area) alongside a wireline log. The Holtzschue 1 core contains evidence of sea level drop and exposure at 5702 feet followed by flooding and deposition of high energy marine sediment at 5705 feet. Complete core description in Appendix A. Larger pictures of select core pieces can be seen in Figures 23 and 24.

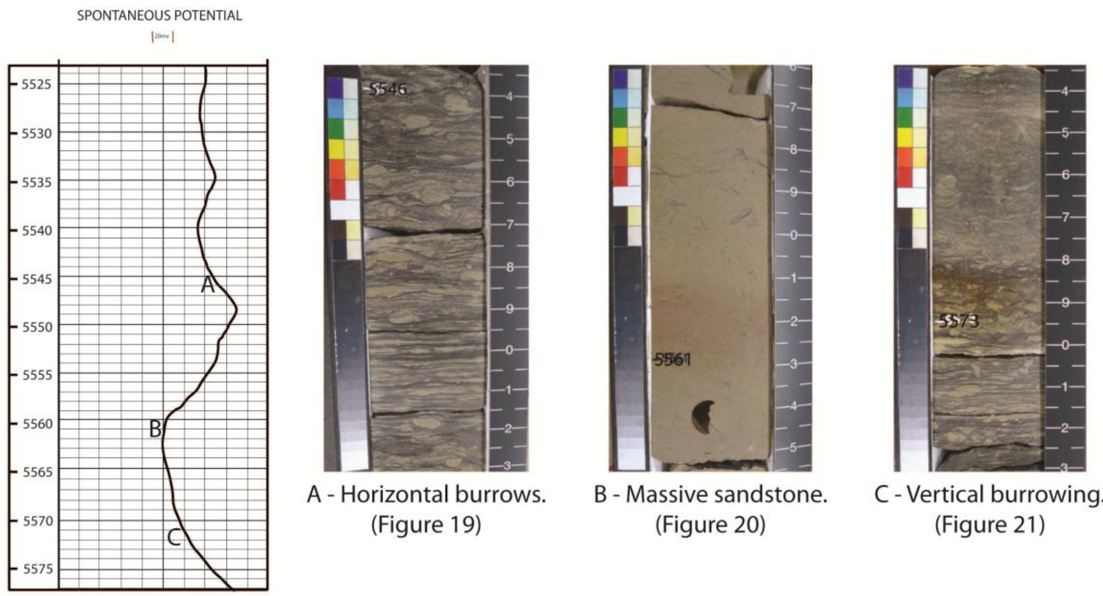

Figure 12: Select core pieces showing lithologic, sedimentary, and biogenic features of the Schroeder 1 core (Sec. 3-T.12N.-R.2W.) (southern area). These core pieces document cleaning/coarsening upward from vertically burrowed interbedded sandstone and shale (C) at 5573 feet to massive sandstone (B) at 5560 feet. The shale above (A) is burrowed, which marks a return to a lightly deeper-water setting.

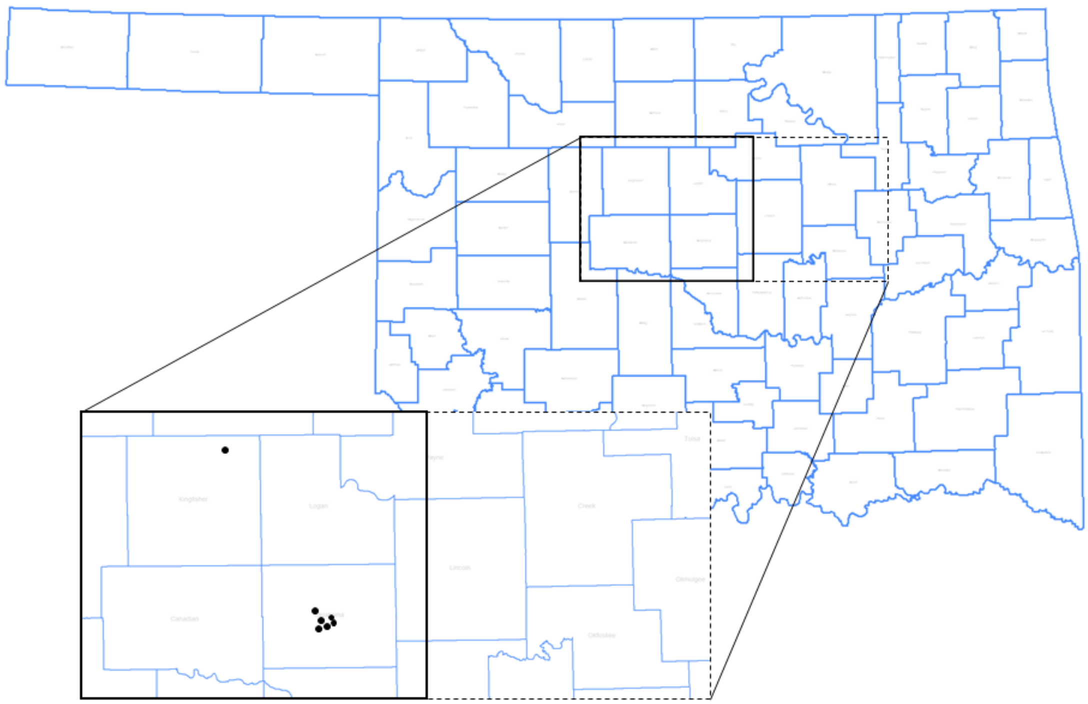

Figure 13: Location of cores (black dots) described and sampled for thin sections and core analysis. The core in the northern area, Kingfisher County is the Ward Petroleum, Marisa 1-10. Cores examined in the southern area, Oklahoma County, are the Gulf Oil Corporation, Holtzschue 1, Meyers Estate 1, Miley C1, Perkins 1, Schroeder 1, and Wright Heirs 1. Location of cores can be found in Appendix A.

Figure 14: Shale rip-up clasts. Ward Petroleum Marisa 1-10. Depth 5901 feet.

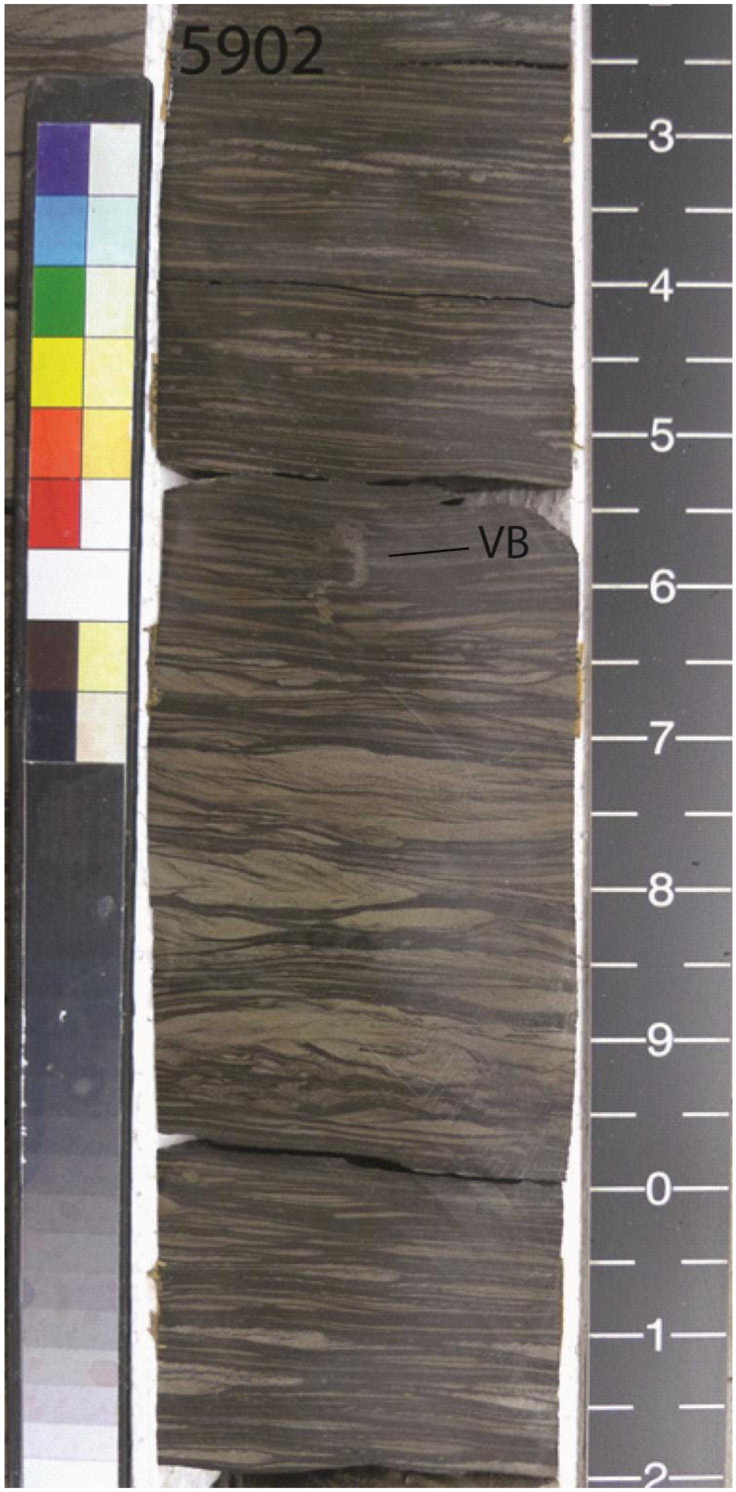

Figure 15: Vertical burrow (VB). Ward Petroleum Marisa 1-10. Depth 5902 feet.

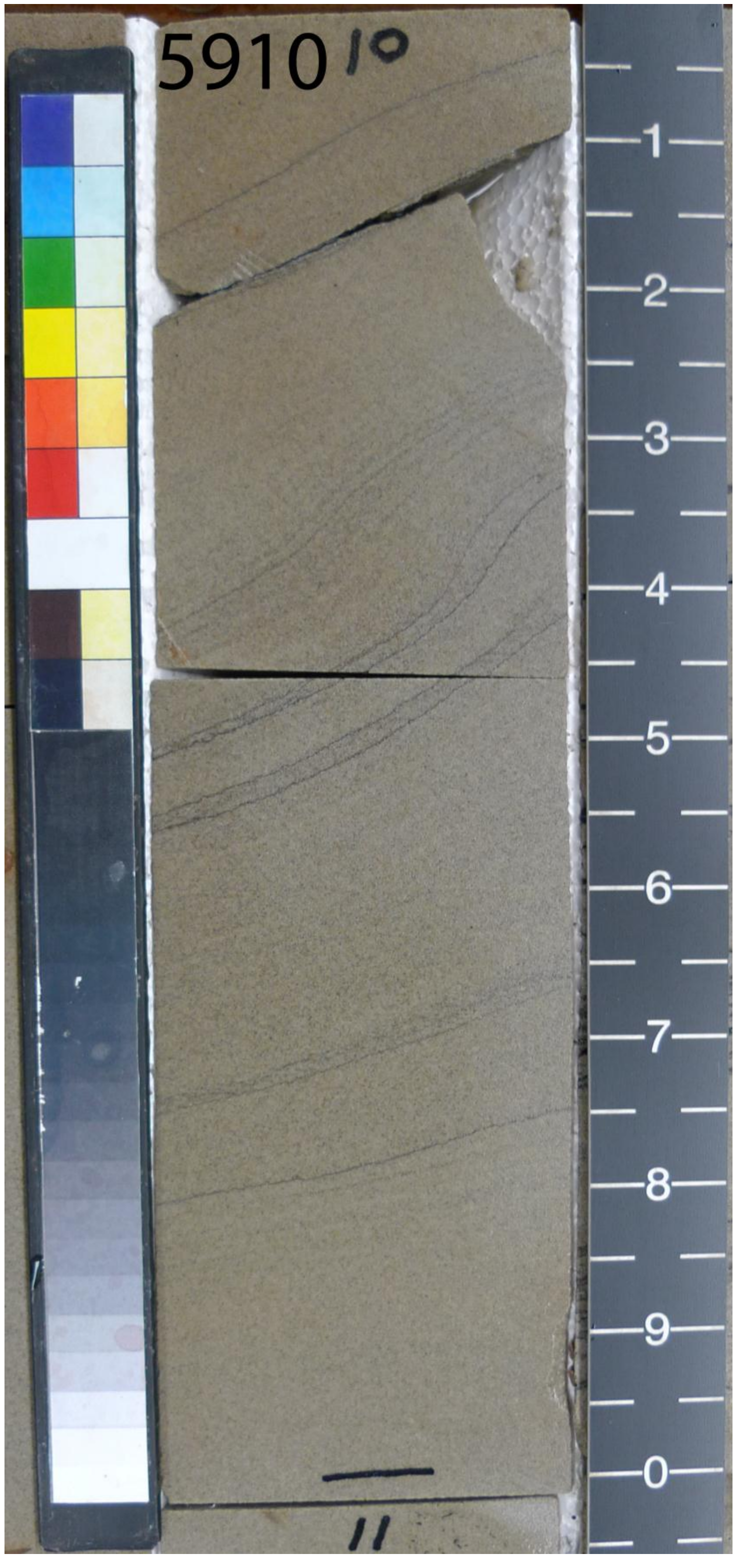

Figure 16: Planar and trough cross bedding. Ward Petroleum Marisa 1-10. Depth 5910 feet.

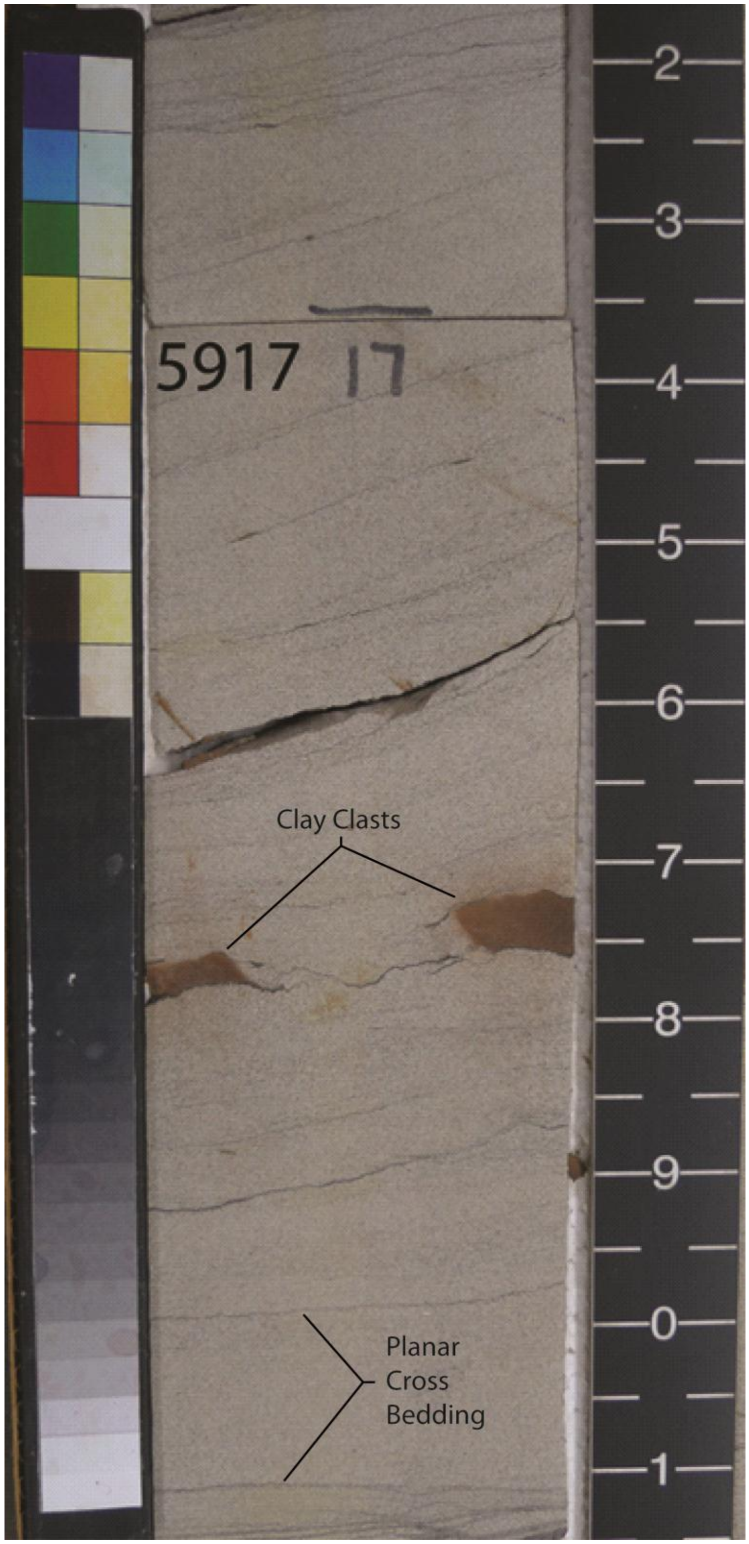

Figure 17: Clay clasts and planar cross bedding (arrows). Ward Petroleum Marisa 1-10. Depth 5917 feet.

Figure 18: Intensely burrowed to bioturbated sandy shale. Ward Petroleum Marisa 1-10. Depth 5927 feet.

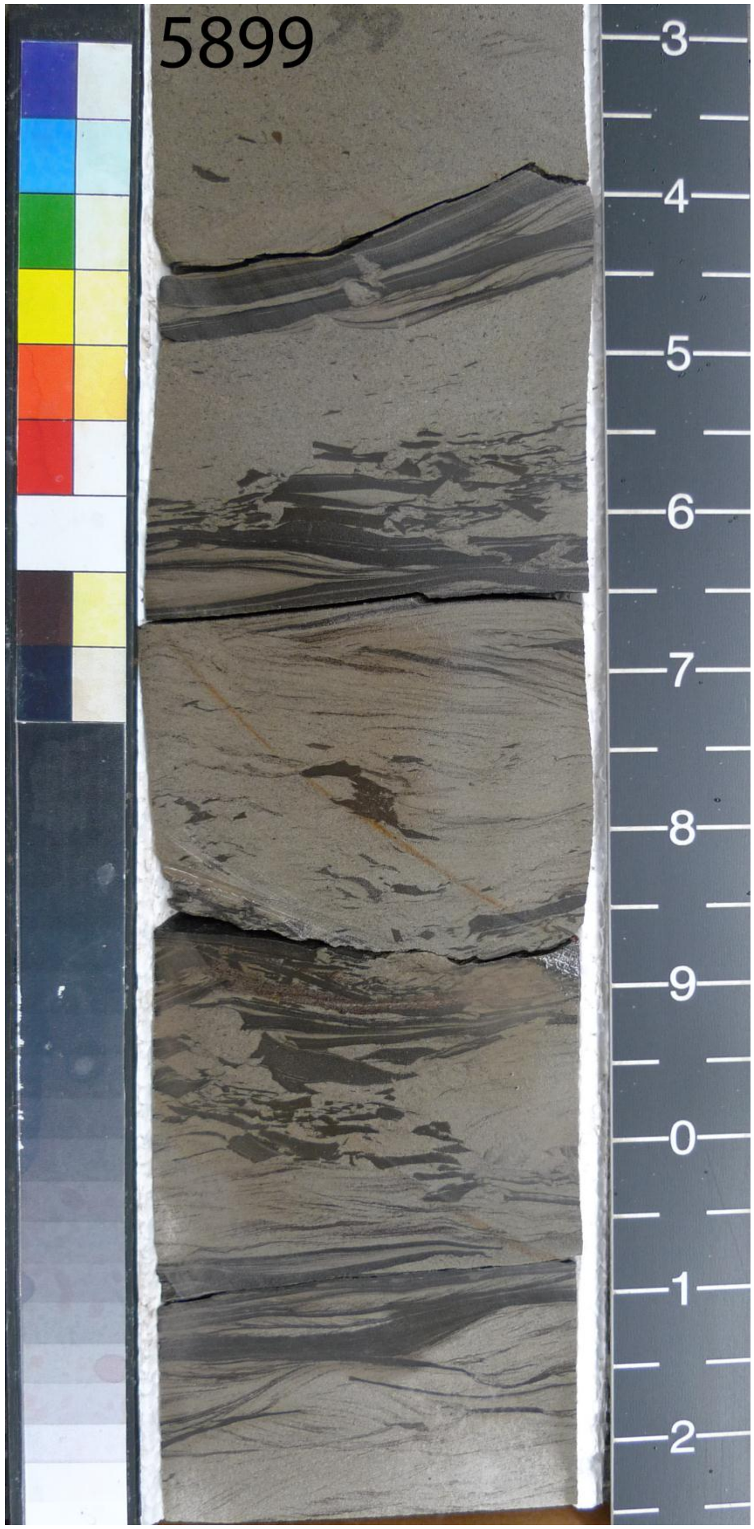

Figure 19: Shale rip-up clasts. Ward Petroleum's Marisa 1-10. Depth 5899 feet.

Figure 20: Massive sandstone. Gulf Oil Corporation’s Schroeder 1. Depth 5561 feet.

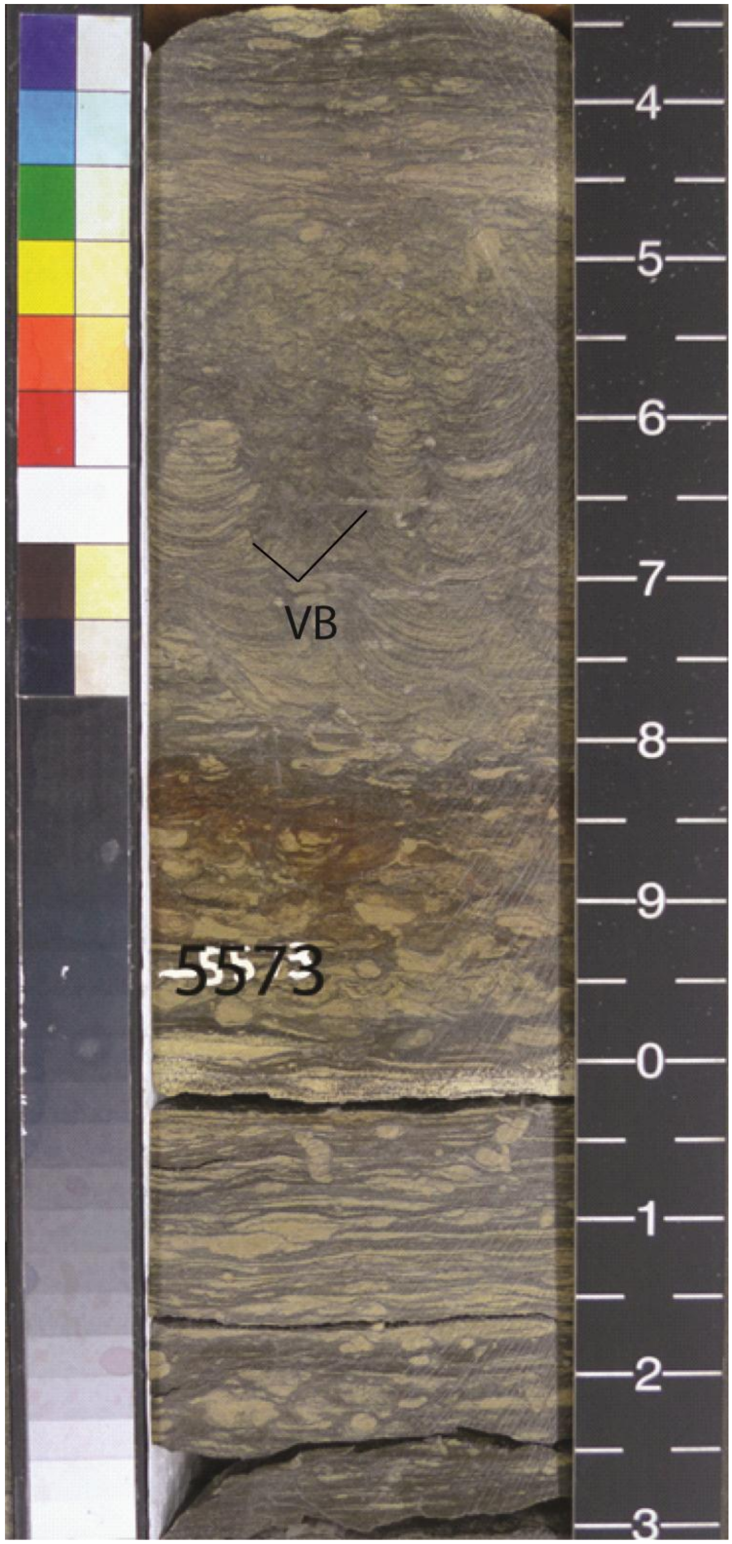

Figure 21: Vertical burrowing (VB) belonging to *Skolithos?* (Boggs 2006). Gulf Oil Corporation's Schroeder 1. Depth 5573 feet.

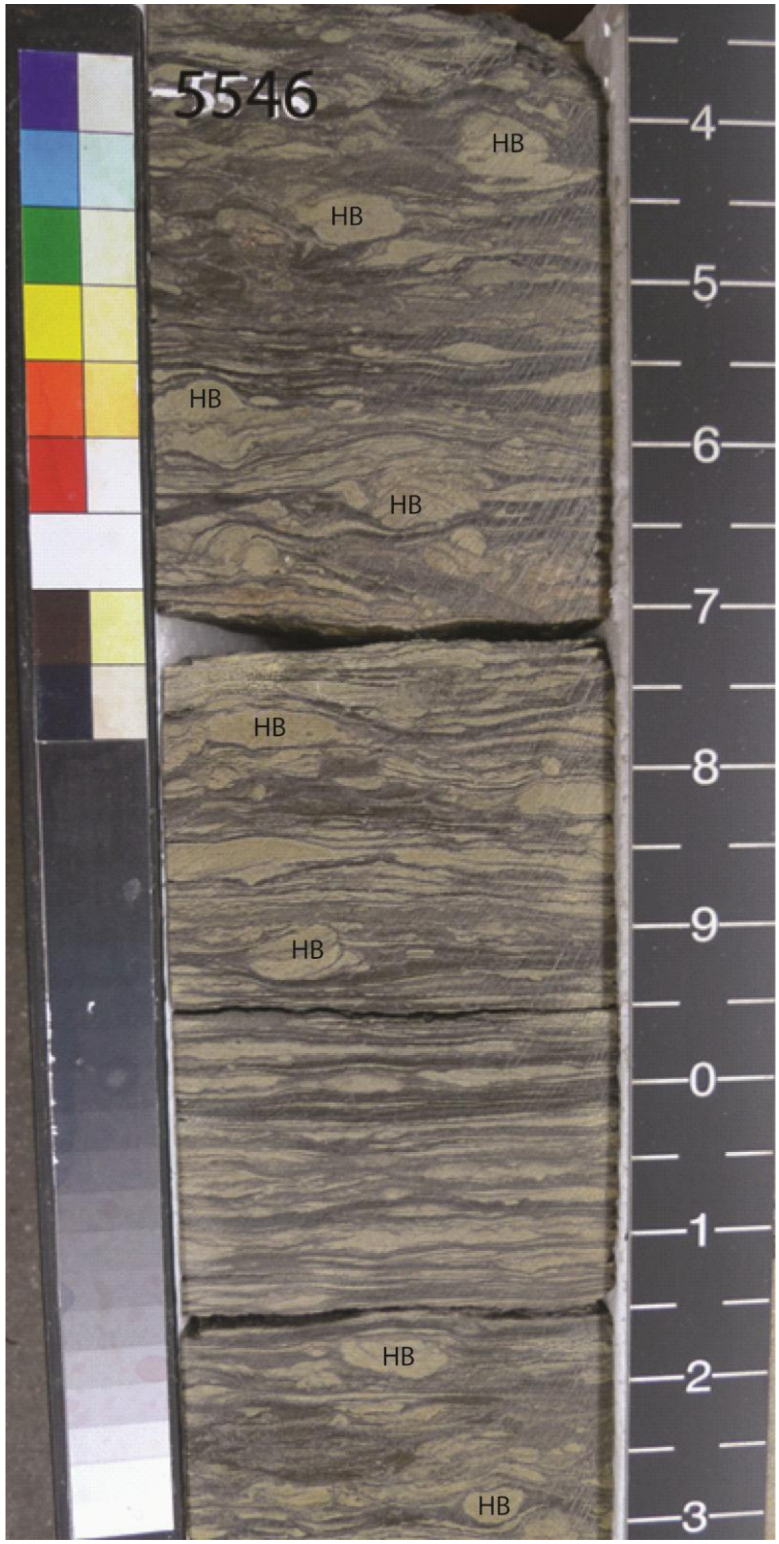

Figure 22: Horizontal burrows (HB). Gulf Oil Corporation's Schroeder 1. Depth 5546 feet.

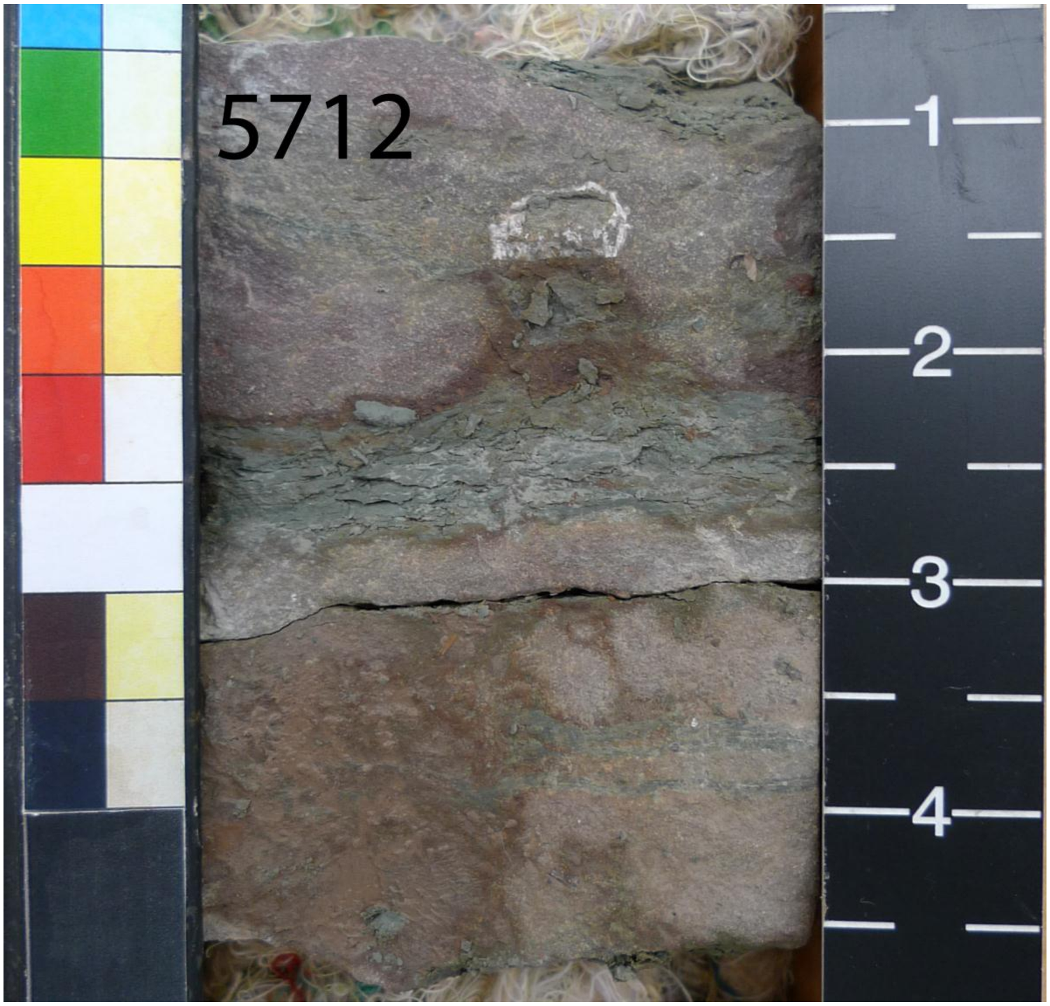

Figure 23: Clayey shale, red and green color typical of oxidized zone and exposure surface. Gulf Oil Corporation’s Holtzschue 1. Depth 5712 feet.

Figure 24: Crinoidal grainstone (Dunham, 1962). Gulf Oil Corporation's Holtzschue 1. Depth 5705 feet.

Sandstone Distribution

The sandstone bodies that are mapped were chosen for their similar electric log characteristics or electrofacies (Figure 30 and 29). Time synchronous facies were mapped according to their patterns and where they are located in relation to the depocenter. Again, since there is an overall lack of modern logs containing gamma-ray curves, it is rather difficult to establish these electrofacies. However, in the Ward Petroleum Marisa 1-10, sandstone body geometries that clean upward resemble the geometry of a marine bar or marginal marine sandstone whereas, fining-upward electrofacies are interpreted as channel-fill (Krueger Jr., 1968 and Brown Jr., 1979).

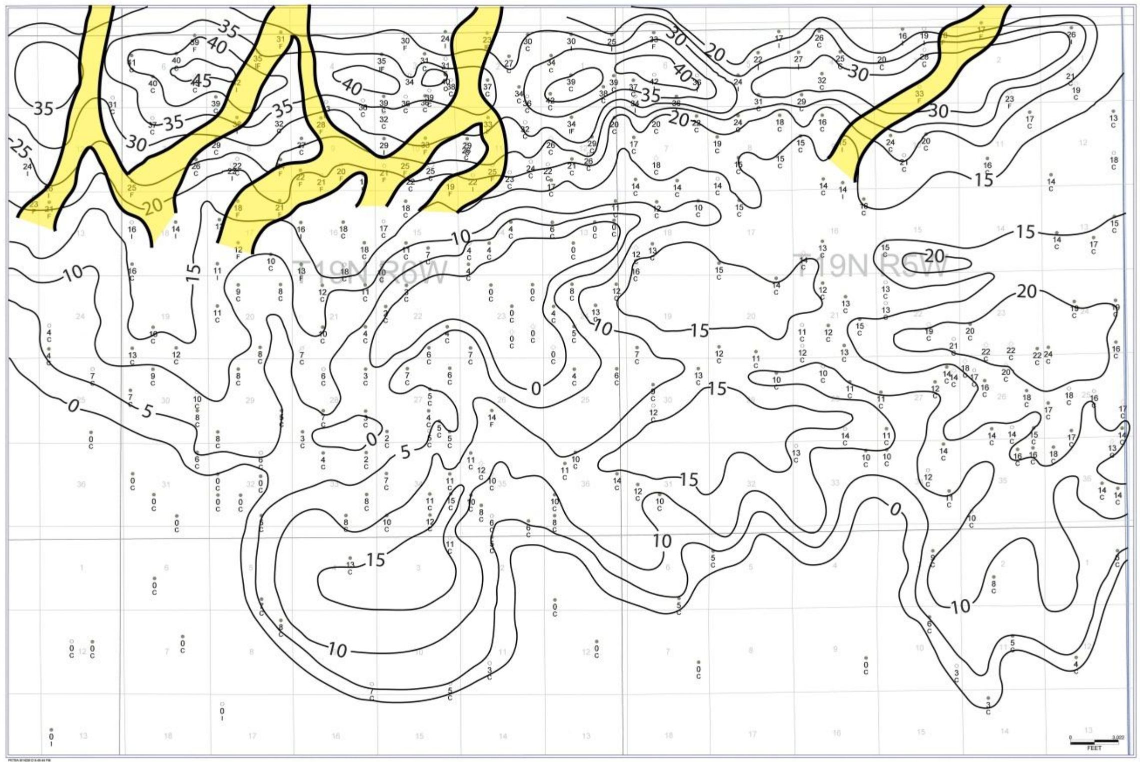

Figure 25: Thickness of sandstone in Interval B-1 in the Northern Area. Sandstone is defined as having approximately 70 API gamma-ray deflection or approximately negative 40mv SP deflection from the representative shale baseline.

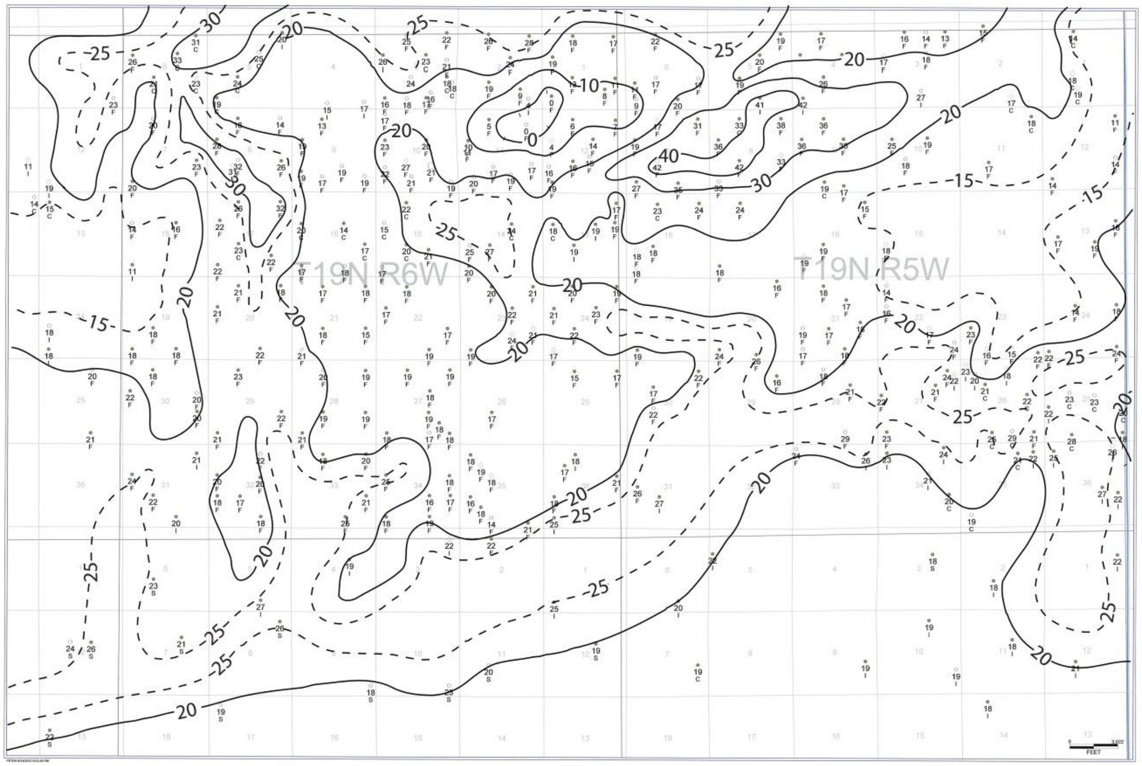

Figure 26: Thickness map showing sandstone distribution in Interval B-2 of the Northern Area. Sandstone is defined as having approximately 70 API gamma-ray deflection or approximately negative 40mv SP deflection from the representative shale baseline.

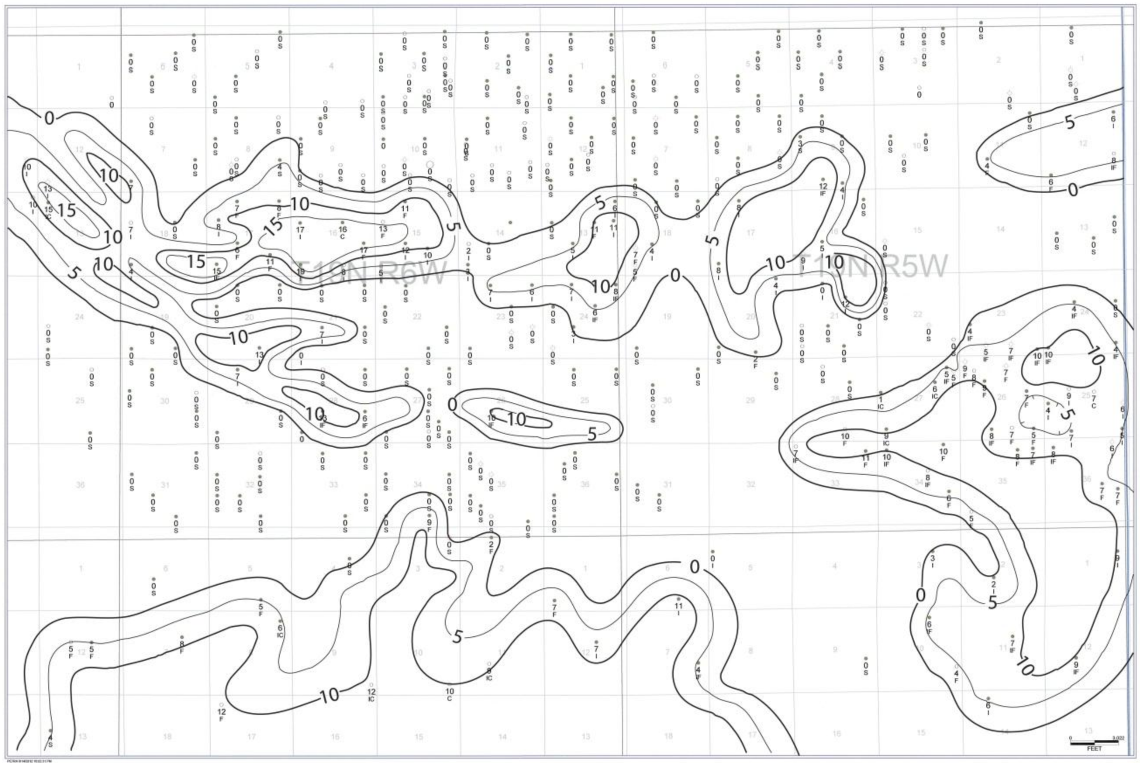

Figure 27: Thickness map showing the distribution of sandstone in Interval B-3, Northern Area. Sandstone is defined as having approximately 70 API gamma-ray deflection or approximately negative 40mv SP deflection from the representative shale baseline.

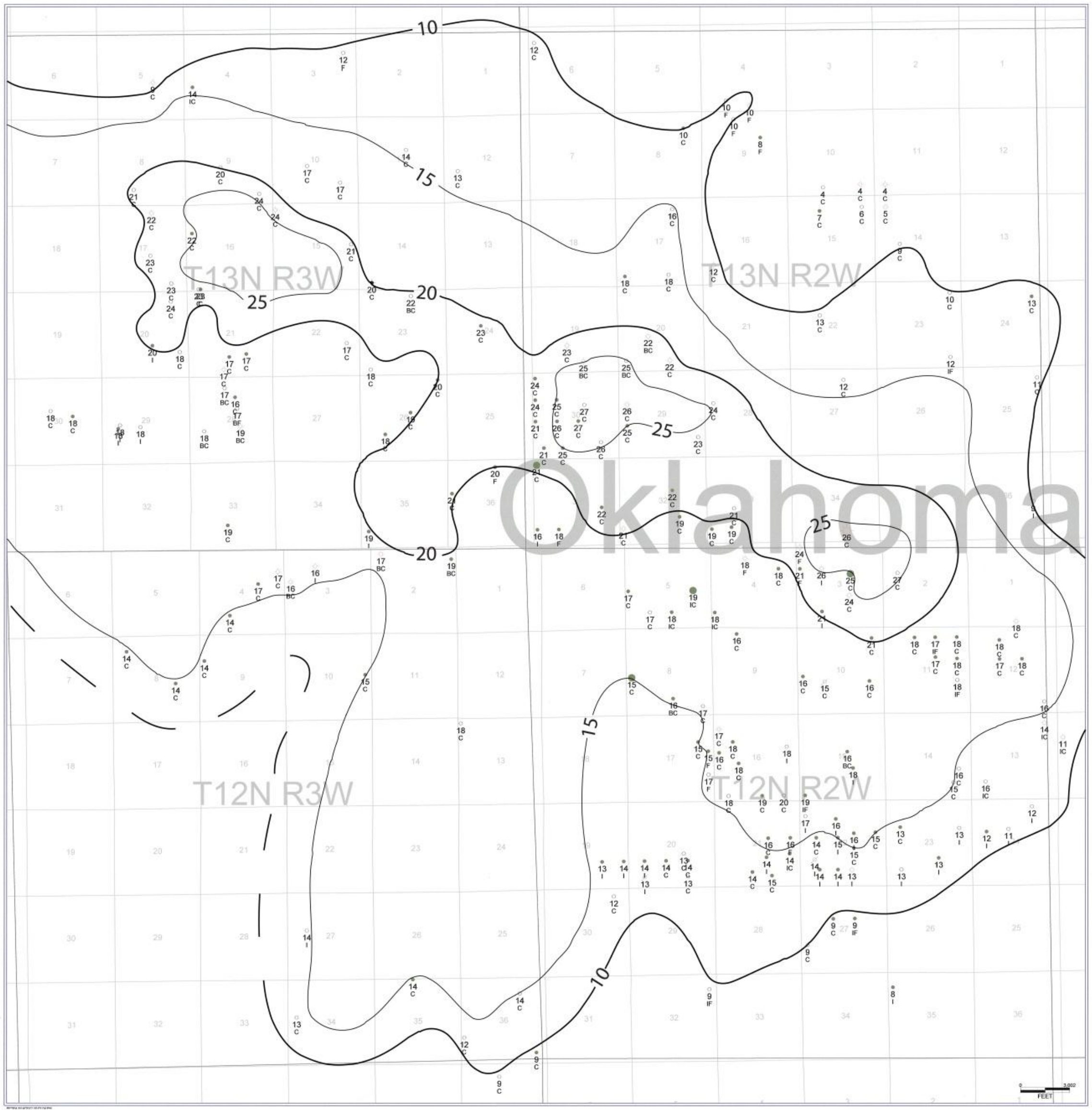

Figure 28: Thickness map showing the distribution of sandstone at the top of Interval A in the Southern Area. Sandstone is defined as having approximately 70 API gamma-ray deflection or approximately negative 40mv SP deflection from the representative shale baseline.

Key to Electrofacies Patterns

F	-	Fining Upwards
C	-	Coarsening Upwards
I	-	Indescript
-IF	-	Indescript, possibly Fining Upwards
-IC	-	Indescript, possibly Coarsening Upwards
S	-	Shale
B	-	Blocky
-BF	-	Blocky, possibly Fining Upwards
-BC	-	Blocky, possibly Coarsening Upwards

Figure 29: Key to electrofacies patterns found on thickness maps.

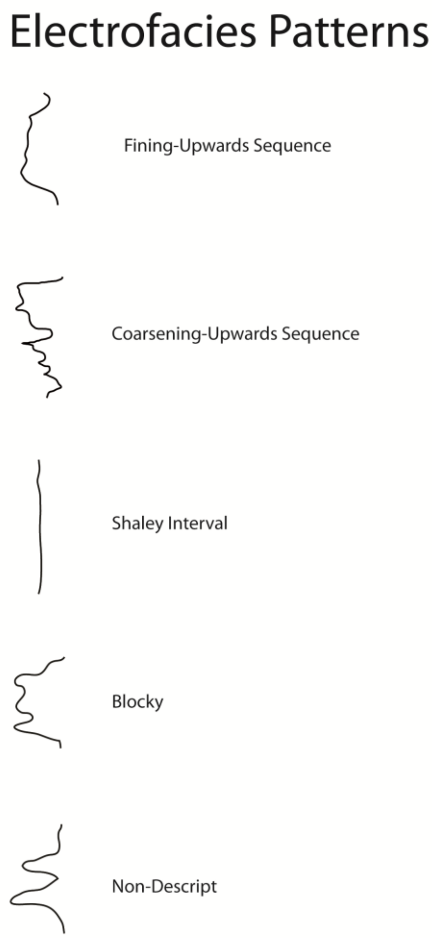

Figure 30: Electrofacies patterns `observed on wireline (SP and gamma-ray) logs for Marmaton sandstones in the “Cleveland interval”.

Distribution of Sandstone

Sandstone was defined on SP logs as having a negative deflection of approximately 40mv and/or gamma-ray signature of approximately 70 API units.

Northern Area

Interval 1 (Figure 25) sandstone is located in the northern part of T.19N., R.5W.-6W. and is thickest in Sec. 5-6, T.19N.,R.6W. at 13 meters (45 feet); it is an elongate lobe trending west-east. In parts of Sec. 23-26, T.19N., R.5W., there is sandstone over 6 meters (20 feet) in thickness, whereas in Sec. 23, T.19N., R.6W. and surrounding sections, there is no sandstone present. With exception to these two areas, thickness generally decreases to the south until is no longer present below the northern half of the underlying township.

Interval 2 (Figure 26) sandstone is located throughout T.19N., R.5W.-6W. with exception of parts of Sec. 1-2, 11-12, T.19N., R.6W. The thickest portion of interval 2 sandstone is found in Sec. 4, 5, and 7, T.19N., R.5W. at 12 meters (42 feet). It is trending northwest-southeast except for the southern part of the field which trends southwest-northeast.

Interval 3 (Figure 27) sandstone is the most sparse of the three intervals within the Northern Area. This sandstone is absent in approximately half of the field. The thickest part of this interval is 5 meters (19 feet) in Sec. 16, T.19N., R.6W. and is part of a slight northwest-southeast trend. Other areas with thicker sandstone are the northern half of T.18N., R6W. and Sec. 23-28, 33-36, T.19N., R.5W. and Sec. 1-3, 10-12, T.18N., R.5W.

Southern Area

The southern area lacks the density of data that can be found in the northern area, with the available data; there is only one sandstone that is mappable. Having only one sandstone map does not mean that this is the only sandstone present. There are multiple sandstones present surrounding this Marmaton Sandstone, however, they are not mappable from the data made available to me. The sandstone found in T.12N.-13N., R.2W.-3W. (Figure 28), has a northwest-southeast trend, is elongate and is no thicker than 8 meters (27 feet). This elongate sandstone is parallel to subparallel to depositional strike and is located on the shelf. Cores in this area contain marine fossils and support the idea that this sandstone is interpreted to be a marine bar.

CHAPTER IV

PETROGRAPHY

Introduction

Cores were sampled for thin section petrography to determine detrital and authigenic constituents and establish the diagenetic history. As some cores were smaller or poorly preserved, it was not possible to sample as frequently as wished. However, a total of 9 thin sections were obtained from 5 separate cores and thin-section petrography was determined for each.

Detrital Constituents

The most common detrital constituent is quartz (Figure 31, 32 ,33, 34, 35, 36); it is dominantly monocrystalline and rarely appears as polycrystalline. The amount of quartz ranges from approximately 39 to 84 percent, with the average being around 64 percent. When observed in thin section, individual quartz grains are subrounded to subangular and exhibit subhedral to euhedral faces. Feldspars are not common; they occur as plagioclase feldspar that exhibits albite twinning and does not exceed more than 4 percent. Rock fragments are a much more common detrital constituent than feldspars and make up anywhere from less than 1 to 13 percent. Of all the types of rock fragments, chert is the most abundant and it ranges from less than 1 to 13 percent. Other fragments observed are very minuscule pieces of metamorphic rock fragments (MRFs) and volcanic rock fragments (VRFs) although they are frequently too small to properly identify. Very minor constituents include pyrite, muscovite, glauconite, and zircon. To confirm the presence of pyrite, incidental reflected light was used to test for pyrites' signature brassy reflected color (Scholle, 1979). These constituents are not common and make up less than one percent of the total rock in thin sections in which they are present.

Diagenetic Constituents

The authigenic constituents found in thin section consist of cement and clays. Authigenic cements occur largely as carbonate and occasionally as syntaxial quartz overgrowths. These constituents have potential to greatly affect porosity by either preservation or occlusion. Cements are dominantly carbonate, usually in the form of calcite (Figure 31). In rare cases, an unusual cement is present; it only occurs in one well-the Perkins 1 at 5543.5 feet (Figure 35, 36). Its composition was difficult to determine, but it is thought to have been anhydrite cement that was transformed into gypsum cement due to hydration during or following the coring process. Syntaxial quartz overgrowths are common, but not volumetrically important, and occur throughout the thin sections (Figure 33). They exhibit euhedral crystal faces and have a "dust rim" composed of clay. Where they occur, they are poorly developed on monocrystalline quartz grains due to the dust rims limiting the surface area available for nucleation sites. Authigenic clays can be found as pore filling, pore lining and grain coating such as "dust rims". When these clays entirely coat a grain, it can prevent the growth of syntaxial quartz overgrowths.

Porosity

Porosity is found to some degree in all thin sections. In most cases, primary porosity has been occluded by calcite cement and syntaxial quartz overgrowths, so the overall amount of primary porosity is reduced. Secondary porosity has been produced from partial dissolution of various grains such as feldspar, quartz, chert, schistose metamorphic rock fragments, and very minor amounts of fossil fragments. Primary porosity is usually found in the form of intergranular porosity, whereas secondary porosity is usually intragranular. Carbonate cements are precipitated in intergranular pore spaces from fluid that is transmitted through the rocks pores; these cements clog up the pores and occlude porosity (Figure 34). Syntaxial quartz overgrowths nucleate from the faces of monocrystalline quartz grains and also occlude intergranular porosity.

Porosity and permeability were measured from core plugs using Core Laboratories PORG-200 porosimeter and PERG-200 permeameter. This process begins by measuring each core plug to find its total volume. Once the total volume is known, these instruments use nitrogen gas to infiltrate the core plug and fill the void space. Knowing the total volume and the volume of void space, porosity can be calculated. Permeability is determined from the amount and speed of gas flowing through the core plug.

A total of 9 usable core plugs were obtained for use in this study. Of these 9 core plugs, 9 thin sections were created for thin section analysis and 6 core plugs were of adequate volume and uniformity to be used for porosity and permeability measurements. Porosity values obtained using porosimeter range from approximately 10 to 20 percent and with permeability values obtained by permeameter range from 0.45 to 68 millidarcies. Thin section point counting resulted in porosity values that range from <1 to 19 percent.

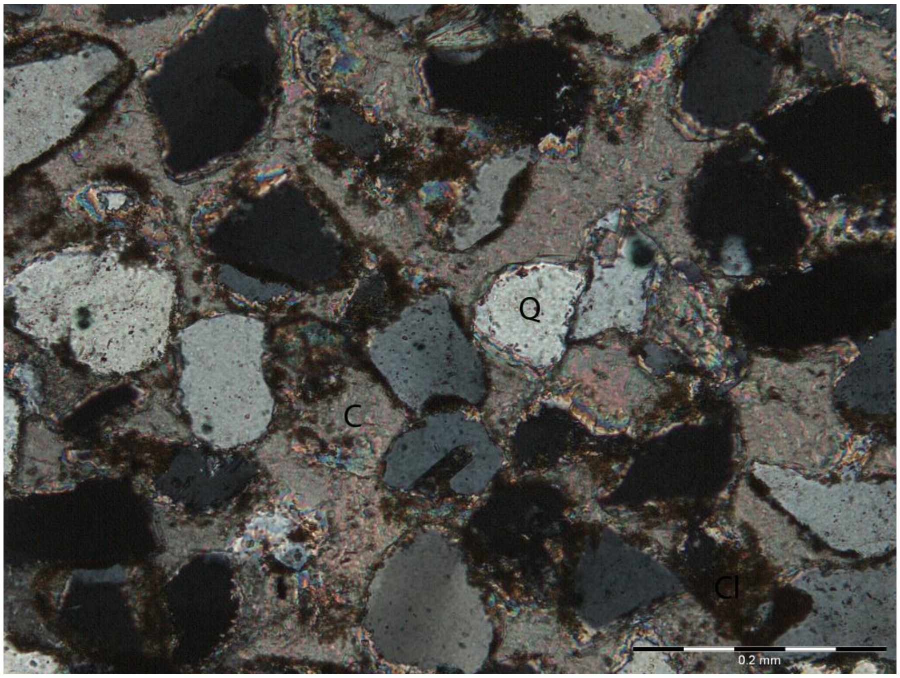

Figure 31. Photomicrograph of quartz grains (Q) surrounded by clay (Cl) and calcite cement (C). Miley C1, Depth 5678 feet. (10x CPL)

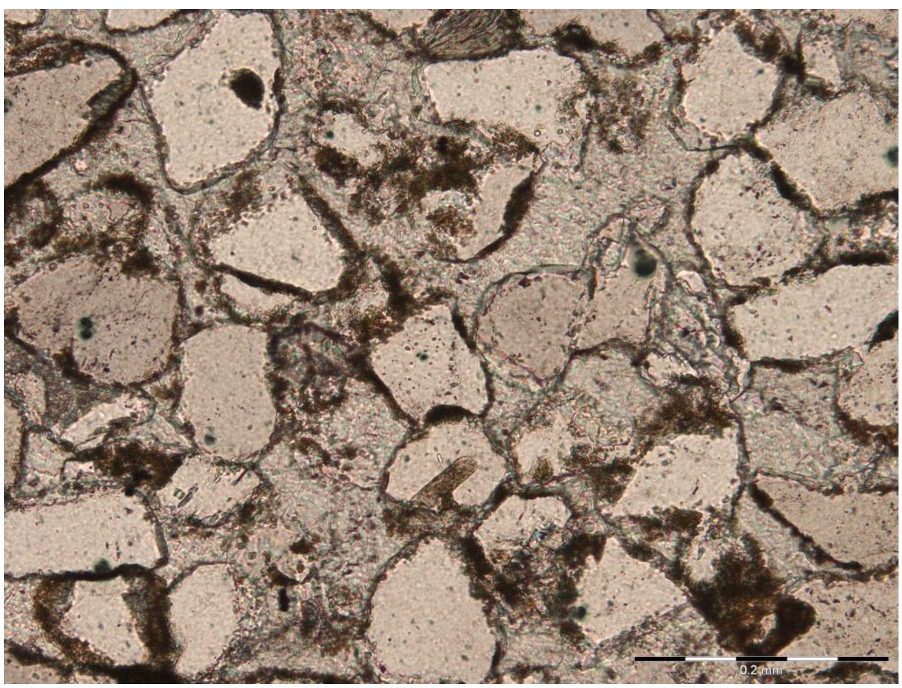

Figure 32. Photomicrograph of clay coated quartz grains that are calcite cemented. Miley C1, Depth 5678 feet. (10x PPL)

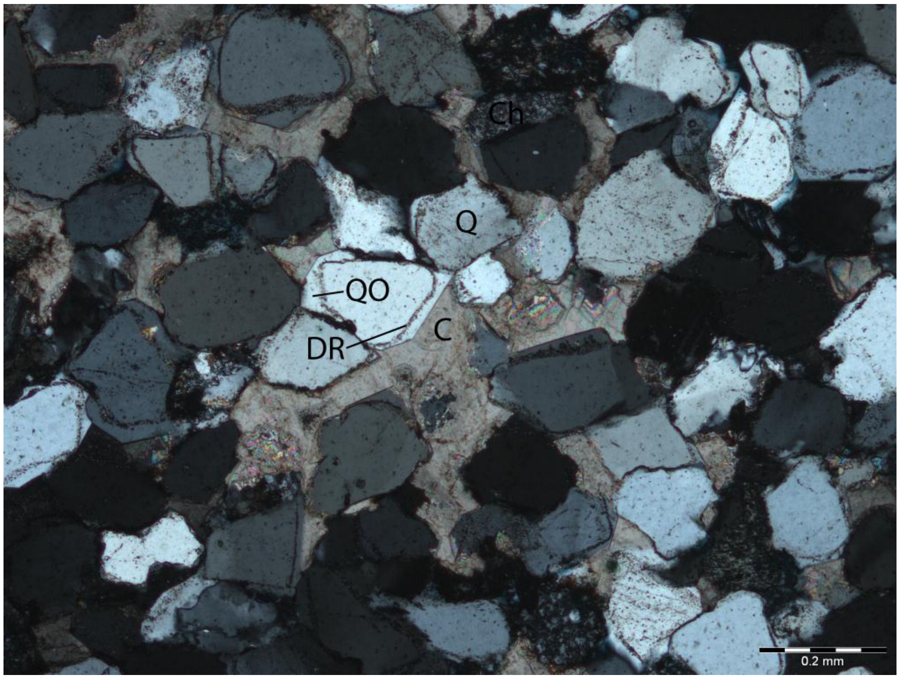

Figure 33. Photomicrograph of monocrystalline quartz grains (Q) exhibiting “dust rims” (DR) with syntaxial overgrowths (QO) surrounded by calcite cement (C). and minor amounts of Chert (Ch). Holtzschue 1, Depth 5691.5 feet. (5x CPL)

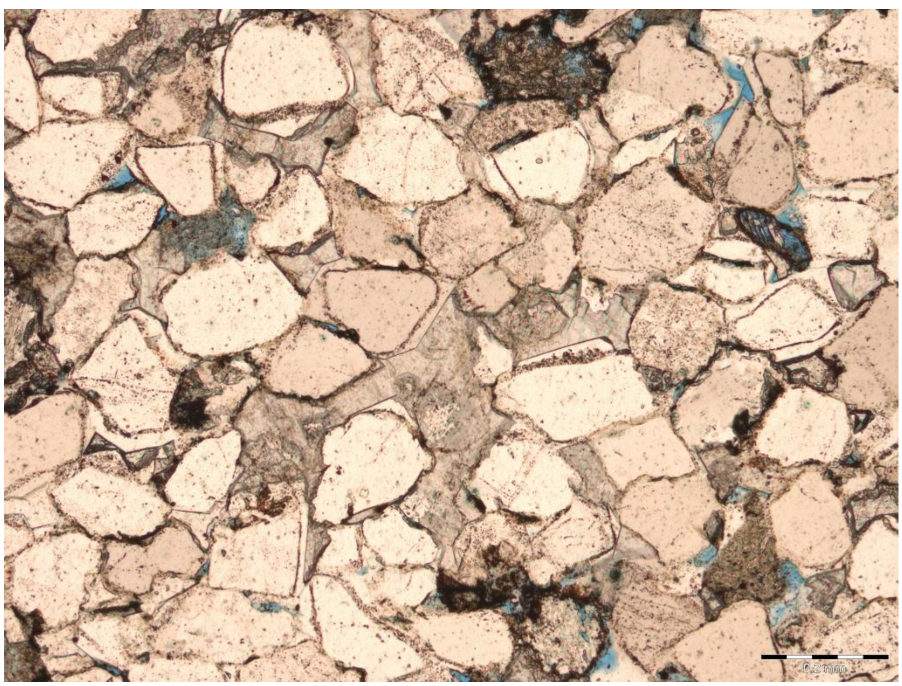

Figure 34. Photomicrograph demonstrating the occlusion of porosity by carbonate cements and syntaxial quartz overgrowths on quartz grains. Holtzschue 1, Depth 5691.5 feet. (5x PPL)

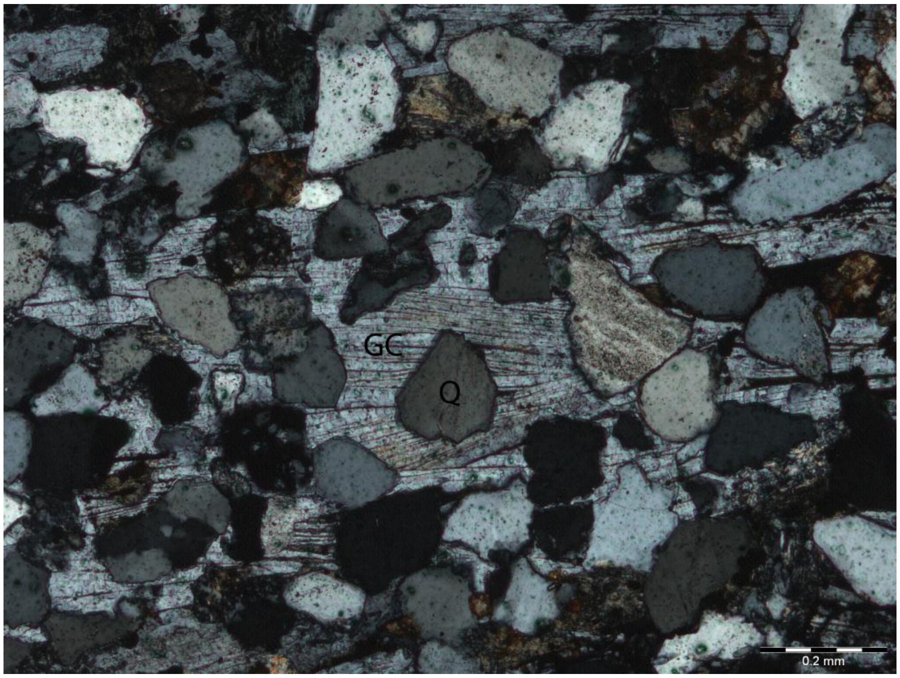

Figure 35. Photomicrograph of a fibrous cement composed of gypsum(?) which was possibly anhydrite that was hydrated during the coring process. Perkins 1, Depth 5543.5 feet. (5x CPL)

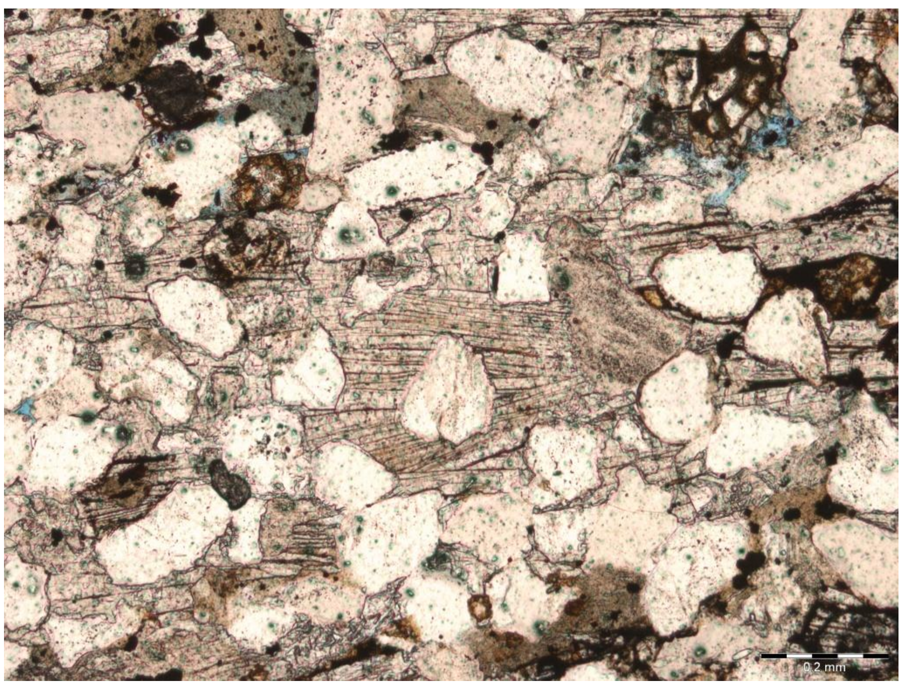

Figure 36. Photomicrograph of a fibrous cement composed of gypsum(?) which was possibly anhydrite that was hydrated during or after the coring process. Perkins 1, Depth 5543.5 feet. (5x PPL)

Sandstone Classification

Observation of thin sections consisted of completing eight point counts of 60 points totaling 480 points for each thin section. The main goal of point counting was to determine detrital and authigenic constituents and to qualify and quantify primary and secondary porosity. The total number of detrital quartz grains, rock fragments, and feldspars were normalized to 100 percent. These normalized percentages were plotted using a ternary quartz, rock fragment, and feldspar (QRF) diagram (Folk, 1974). Of the 9 thin sections, all were plotted on a QRF ternary diagram. These "Cleveland" (Marmaton) sandstones are predominantly sublitharenites, with more rock fragments than feldspars; other sandstones classify as quartzarenites (>95% quartz) (Figure 37). Grain size commonly varies from coarse silt to medium-grained sand although it is dominantly very fine- to fine-grained sand.

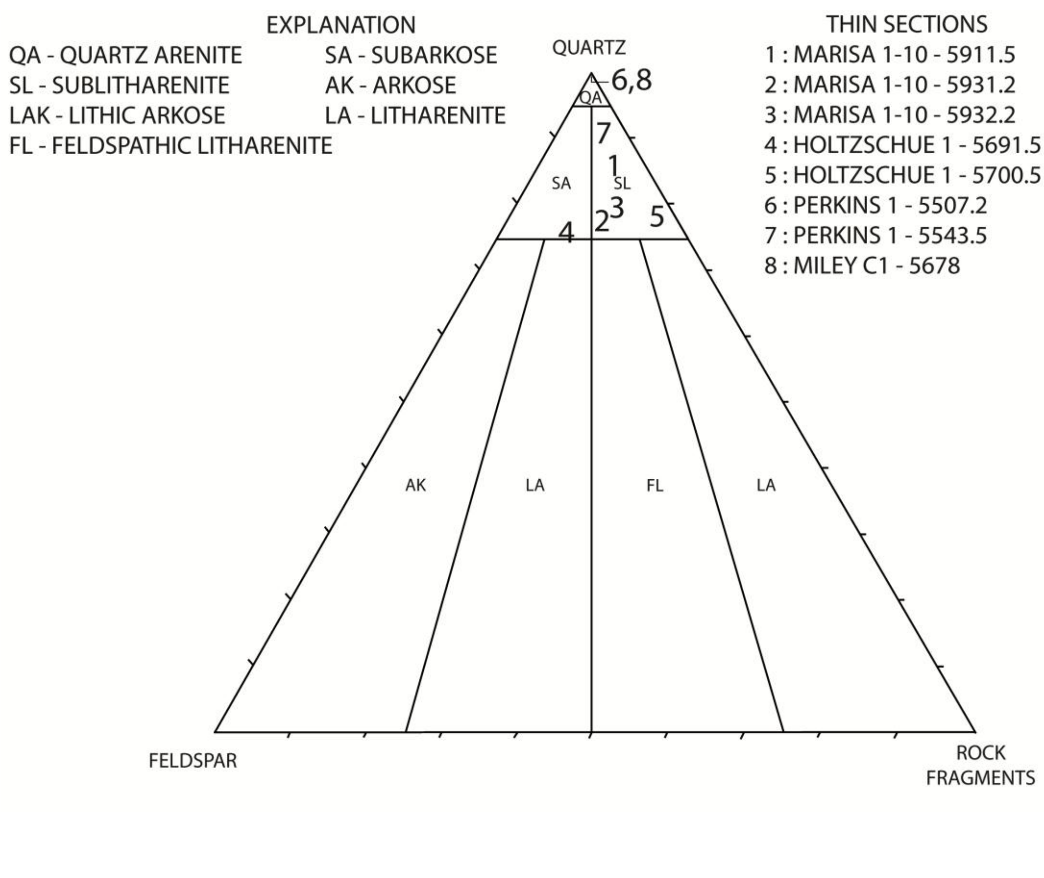

Figure 37: QRF diagram displaying the classification of the Marmaton sandstone based on detrital composition of framework grains.

Diagenesis played a large role in the evolution of Marmaton sandstone reservoirs. Quartz and calcite cementing reduced porosity, but partial dissolution of feldspars and rock fragments generated secondary porosity in the form of intragranular and moldic porosity.

CHAPTER V

DISCUSSION AND RESULTS

Introduction

Correlation of outcrop stratigraphy into the subsurface reveals that much of the interval called Cleveland by the petroleum industry is actually Marmaton. Marmaton siliciclastics in the Southern Area are coeval with carbonate of the Northern Area. Sandstone in the study area is mostly Marmaton and contains depositional and biogenic features that are indicative of two different depositional environments. In the Northern Area, shale is burrowed, but sandstone does not contain marine indicators. Based on this evidence, sandstone in the Northern Area is interpreted as a deltaic distributary; whereas sandstone to the south appears to represent shallow marine deposition.

The Ward Petroleum Marisa 1-10 in Sec. 10-T.19N.-R.6W. provides essential data for interpreting the depositional environment of the Marmaton sandstone in the Northern Area. This well is the only one in which core data and thin sections are available along with a suite of logs including SP, gamma-ray, and resistivity measurements.

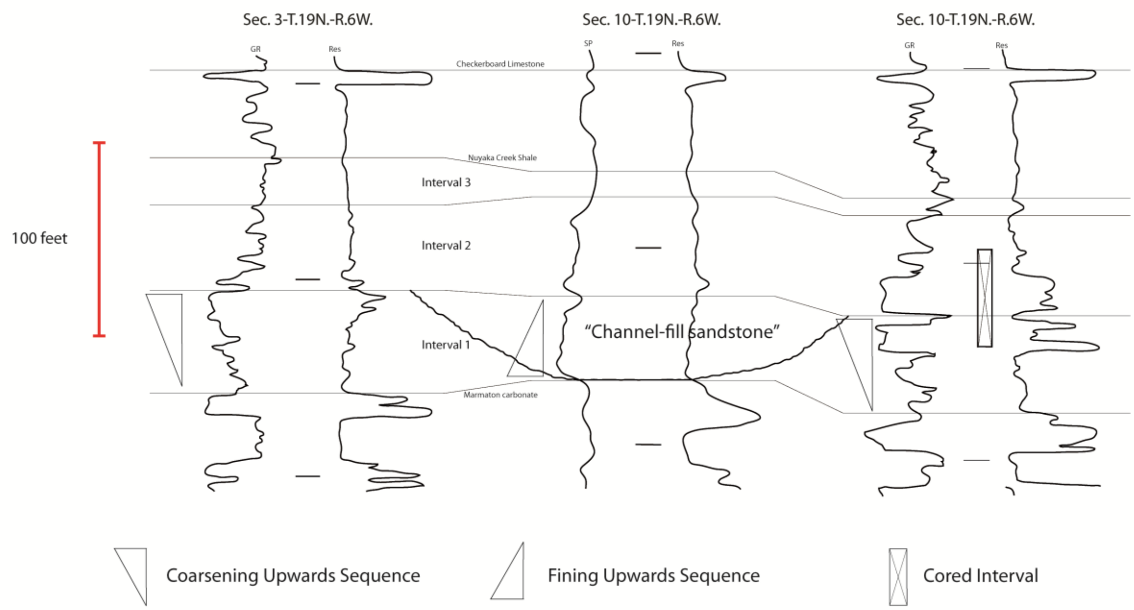

Figure 38: Cross section displaying a channel-fill sandstone present within Interval 1 of the North Field.

Stratigraphic Position of Sandstone

Nearly all of the sandstone in the area of study is not true Cleveland when subsurface units are correlated to outcrops. To be true Cleveland, the sandstones would be above the Nuyaka Creek Shale/Dawson coal. Although the Nuyaka Creek is difficult to correlate in some areas, all cores that were labeled "Cleveland" by the petroleum industry occur beneath the Nuyaka Creek Shale/Dawson coal, in the Marmaton Group.

Marisa 1-10

Geometry of Sandstone Bodies

Ward Petroleum's Marisa 1-10 core lies within the interval between the Nuyaka Creek Shale and the Marmaton carbonates and exhibits two separate geometries, an underlying coarsening upwards sequence and an overlying fining upwards sequence; the core penetrates both of these sequences (Figure 38).

Sedimentary Features

Sedimentary features found in the coarsening upwards interval of the Ward Petroleum Marisa 1-10 includes: crinoid fragments and horizontal and vertical burrows (Figure 18, 15). In contrast, the overlying fining upwards interval contains clay clasts (Figure 17), planar cross bedding (Figure 16, 17), shale rip-up clasts (Figure 14, 22), lenticular bedding, and soft-sediment deformation.

Distribution of Sandstone Bodies

The distribution of sandstone bodies in the Northern Area was better defined and is more detailed due to higher well density and the presence of a greater number of gamma-ray logs. This abundance of data allowed for the mapping of three separate sandstones: 1, 2, and 3.

Determining depositional environments requires three components: sandstone body geometry, sedimentary structures, and distribution of sandstone bodies. The underlying coarsening upwards sequence is indicative of a marginal marine deposit (Andrews, 1997) and core data shows that this sandstone is calcareous and the presence of crinoids supports this interpretation. The overlying fining upwards sequence is indicative of a fluvial process, possibly a channel. There is a sharp basal contact and a lack of normal marine fauna as well as the presence of clay clasts and shale rip-up clasts, all of this supports the interpretation that this fining upwards sequence is a channel.

Schroeder 1

Geometry of Sandstone Bodies

Gulf Oil Corporation's Schroeder 1 core lies within the interval between the Nuyaka Creek Shale and the Little Osage Shale. The use of SP logs to determine sandstone body geometry is difficult; however, sandstone in the Schroeder 1 core appears to be coarsening upwards.

Sedimentary Features

Burrowing is quite common throughout the cores within the study area. Notably unique burrows in this area possibly belong to *Diplocraterion* (Figure 21) in the Gulf Oil Corporation's Schroeder 1 well (Boggs, 2006). Horizontal burrows are also present.

Distribution of Sandstone Bodies

Mappable sandstone found in T.12N.-13N., R.2W.-3W., has a northwest-southeast trend, is elongate and is no thicker than 8 meters (27 feet). This elongate sandstone is subparallel to depositional strike and is located on the shelf.

Holtzschue 1

Geometry of Sandstone Bodies

Gulf Oil Corporation's Holtzschue 1 core also lies within the interval between the Nuyaka Creek Shale and the Little Osage Shale. Despite difficulties in determining sandstone body geometry from SP logs, the Holtzschue 1 appears to be coarsening upwards.

Sedimentary Features

Sedimentary feature present in the Holtzschue 1 core include: burrows, crinoids, and brachiopods.

Distribution of Sandstone Bodies

This sandstone is the same as the one described in Gulf Oil Corporation's Schroeder 1 core. It is found in T.12N.-13N., R.2W.-3W., and trends northwest-southeast. This elongate sandstone is subparallel to depositional strike and is no thicker than 8 meters (27 feet).

Upper Desmoinesian Paleogeography

Maps depicting the paleogeography of the Mid-Continent during the late Desmoinesian (Figure 39) show that the major source of siliciclastics comes from the Ouachita Mountains to the southeast (Rascoe and Adler 1983). Paleogeographic maps correspond with the interpreted depositional environments. Rascoe and Adler have divided the late Desmoinesian into different depositional environments. When looking specifically at the marine environment, mainly marine, and marine clastics environments, it matches my interpretations. The thick mud-dominated siliciclastics are found in the marine clastics, whereas shale with sporadic sandstone and limestone lies within the mainly marine environment. As expected, the thick carbonates of the shelf of the Anadarko Basin are found in the marine environment.

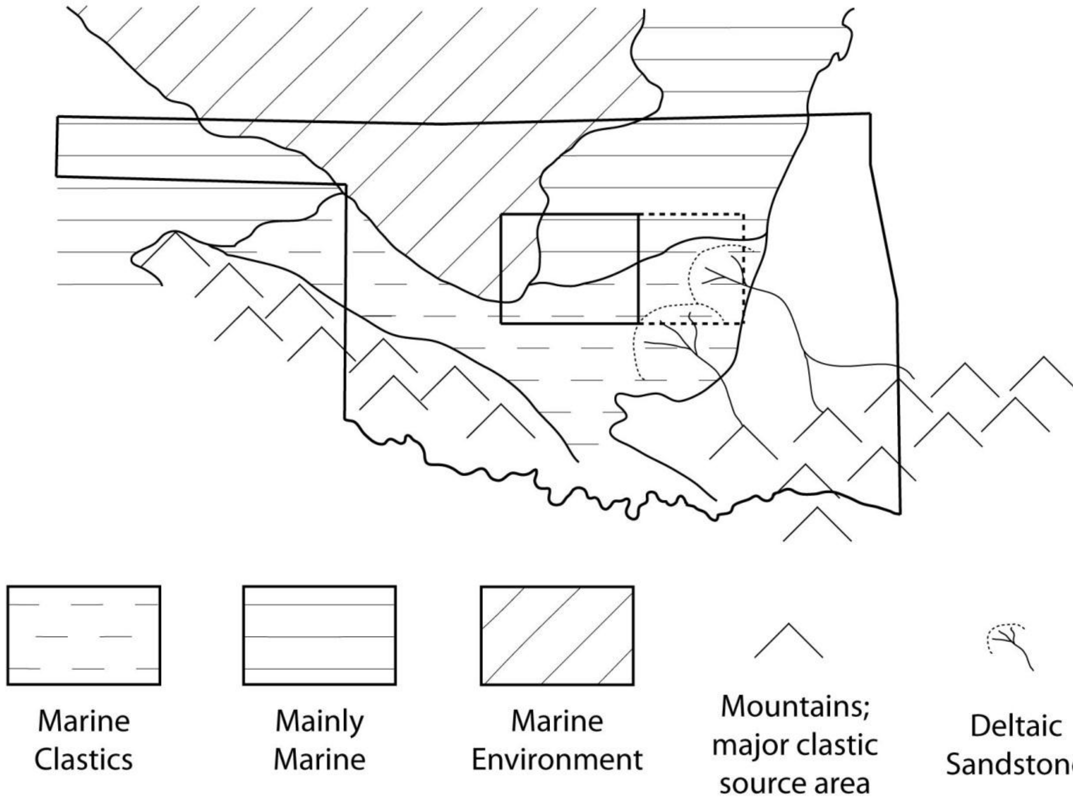

Figure 39: Paleogeographic map depicting depositional environments of the late Desmoinesian (After Rascoe and Adler 1983).

Sequence Stratigraphy

The interval from the Excello Shale through the Nuyaka Creek Shale was interpreted using a sea level curve from Heckel (1986). The Excello Shale is interpreted as a MFS that represents maximum transgression. During the subsequent highstand, regressive carbonate that became the Fort Scott Limestone, was deposited. Following the deposition of the Fort Scott carbonate, it is expected that a forced regression resulted in the peat bogs of the Summit coal in Missouri (Figure 40). The manifestation of this regression is not evident on wireline logs, but could be represented by a channel sandstone in the Wetumka Shale that incises marine shales (Puckette, 2012, personal communication). Transgression and widespread inundation led to the deposition of the Little Osage Shale, another MFS. The Little Osage Shale is succeeded by the Higginsville Limestone, a regressive carbonate that is evident in the Northern Area and represents deposition during the highstand systems tract. Following the Higginsville, another likely forced regression resulted in the Labette Shale. A transgression following the Labette Shale culminated in the deposition of another MFS, the Anna Shale. Declining sea level allowed for the deposition of another regressive carbonate, the Pawnee (Oologah) Limestone. During a regression following the Pawnee Limestone interval, the Wewoka deltas were active in southern Oklahoma. Coeval units in Kansas and Missouri include the Bandera Shale and Mulberry coal (Heckel, 1986). The following transgression culminated with the Lake Neosho Shale, which represents the MFS following the transgression responsible for the Altamont Limestone. Regression resulted in the deposition of the Nowata Shale/Holdenville Formation followed by a relative transgression which resulted in the Lenapah Limestone. Regression led to subaerial exposure and the formation of the peat bogs that resulted in the Dawson coal, which outcrops near Tulsa, but is too thin to be resolved on wireline logs. Transgression followed that led to deposition of the Lost Branch Formation (Heckel, 1991), which is represented on wireline logs by the MFS, the Nuyaka Creek Shale (Figure 40). The exact position of the Desmoinesian/Missourian boundary cannot be identified on wireline logs. However, the Mound City Shale and Hushpuckney Shale, both of which are radioactive, occur in the lower part of the Missourian. Both are regional flooding events and are traceable into Kansas and Missouri (Heckel, 1968) (Figure 40).

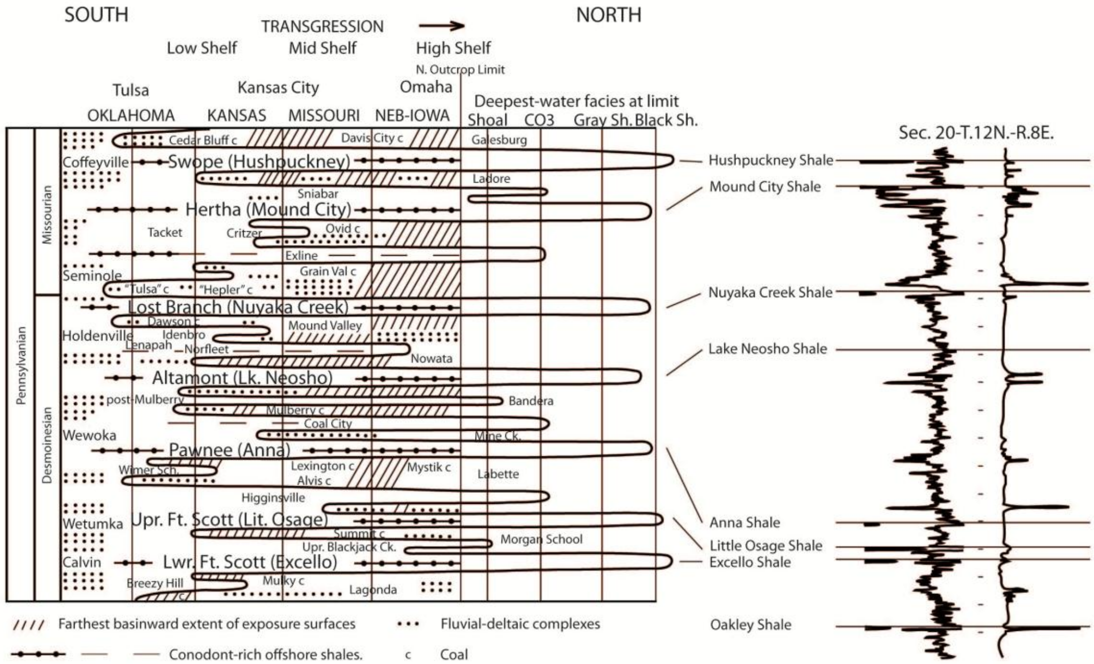

Figure 40: Sequence stratigraphic surfaces recognized in the subsurface that are correlateable to Pennsylvanian sea level curve and outcrop stratigraphy of Heckel (1986).

Conclusions

Outcrop, core, and well log data were interpreted as follows:

1. The Cleveland sandstone identified by the petroleum industry in the study area is essentially all Marmaton sandstone, equivalent to the Holdenville Shale of the Marmaton Group.
2. The dark radioactive shales, which represent maximum flooding surfaces in the Pennsylvanian depositional cycles (Heckel, 1986), are effective chronostratigraphic markers and were essential to defining the stratigraphic framework for the “Cleveland Interval” in the study area.
3. In the Northern Area, these sandstones represent deltaic distributaries and marginal marine sandstone bodies.

4. In the Southern Area, the mappable sandstone represents shallow marine deposits and is interpreted as a marine bar that formed sub-parallel to depositional strike.
5. Marmaton carbonates in the Northern Area are coeval with thick siliciclastic mud-dominated intervals to the south associated with the Holdenville deltaic system.
6. The informal Marmaton intervals (A and B) and Cleveland interval (C) thicken and thin in a complementary fashion that suggests changes in localized depocenter in response to filling of accommodation by the previous interval.
7. Porosity in Marmaton sandstone is mostly secondary and results from partial dissolution of rock fragments and feldspars.

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APPPENDICES

Appendix A – Core Description

Core Description Symbols

Sedimentary Structures

- Symmetric Ripples
- Rip-Up Clasts
- Lenticular Bedding
- SSD Soft Sediment Deformation
- Burrows
- Cross Bedding
- Bidirectional Cross Bedding
- Exposure Surface

Thin Sections

- Thin section taken at depth
- Porosity derived from Porosimeter
- Porosity derived from point counting

Paleontology

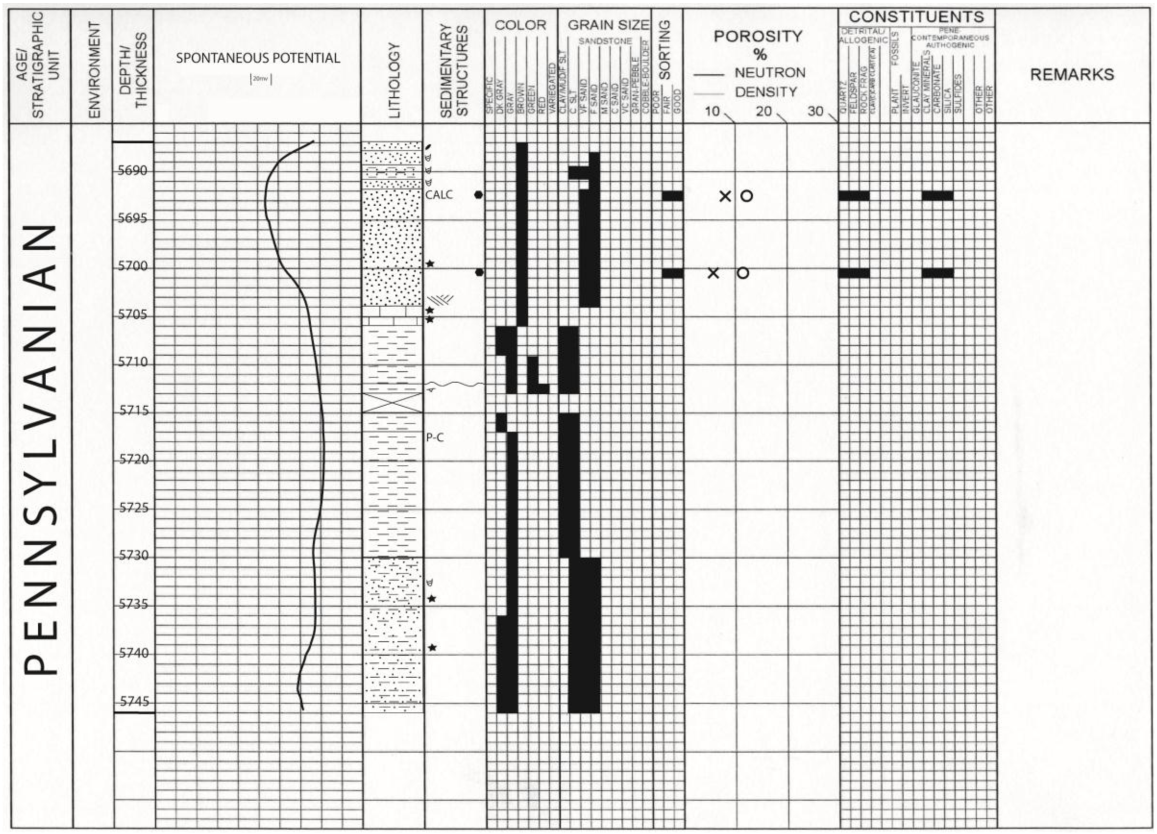
- Crinoids
- Brachiopod
- Gastropod
- Trilobite

Miscellaneous

- Clay Clasts
- CALC Calcareous
- P-C "Poker-Chip" Shale
- Sharp irregular contact
- Oolitic Contains Ooids

Gulf Oil Corporation – Holtzschue 1, Sec. 8 T.12N. R.2W., Oklahoma County.

Cored interval: 5687.0 – 5746.0 (59) ft.



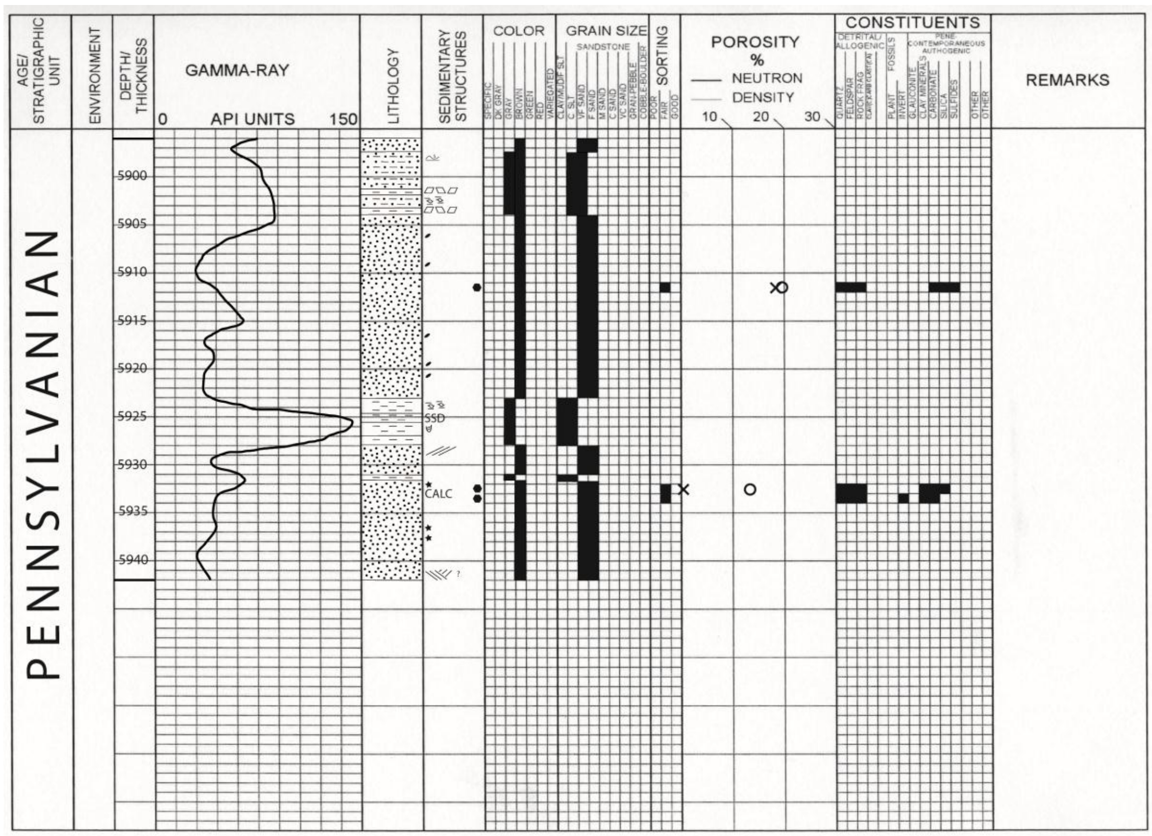
Gulf Oil Corporation – Holtzschue 1, Sec. 8 T.12N. R.2W., Oklahoma County.

Cored interval: 5687.0 – 5746.0 (59) ft.

Core Depth (ft.)	Core Description
5746.0 - 5730.0	shale, sandy; increasing sand content upwards; contains crinoids; few burrows.
5730.0 - 5717.0	shale; “poker chip” appearance.
5717.0 - 5715.0	shale, grey; similar color to “poker chip” shale, although no longer exhibiting the weathered appearance.
5715.0 - 5713.0	MISSING CORE.
5713.0 - 5712.0	shale, green/red, clayey-sticky when wet; exposure surface present at 5712.0.
5712.0 - 5706.0	shale, grey, weathered, clayey-sticky when wet. The interval of 5710.5 – 5707.8 is slightly green in color.
5706.0 - 5704.0	limestone; contains abundant crinoids.
5704.0 - 5691.7	sandstone; calcareous with a presence of crinoids; bidirectional cross bedding found at the base.
5691.7 – 5690.8	sandstone; contains crinoids.
5690.8 - 5689.2	sandstone; interbedded sandstone and shale; increasing shale content upwards.
5689.2 - 5687.9	sandstone; thin shale interbeds.
5687.9 - 5687.0	sandstone; contains clay clasts.

Ward Petroleum – Marisa 1-10, Sec. 10 T.19N. R.6W., Kingfisher County.

Cored interval: 5896.0 – 5942.0 (46) ft.



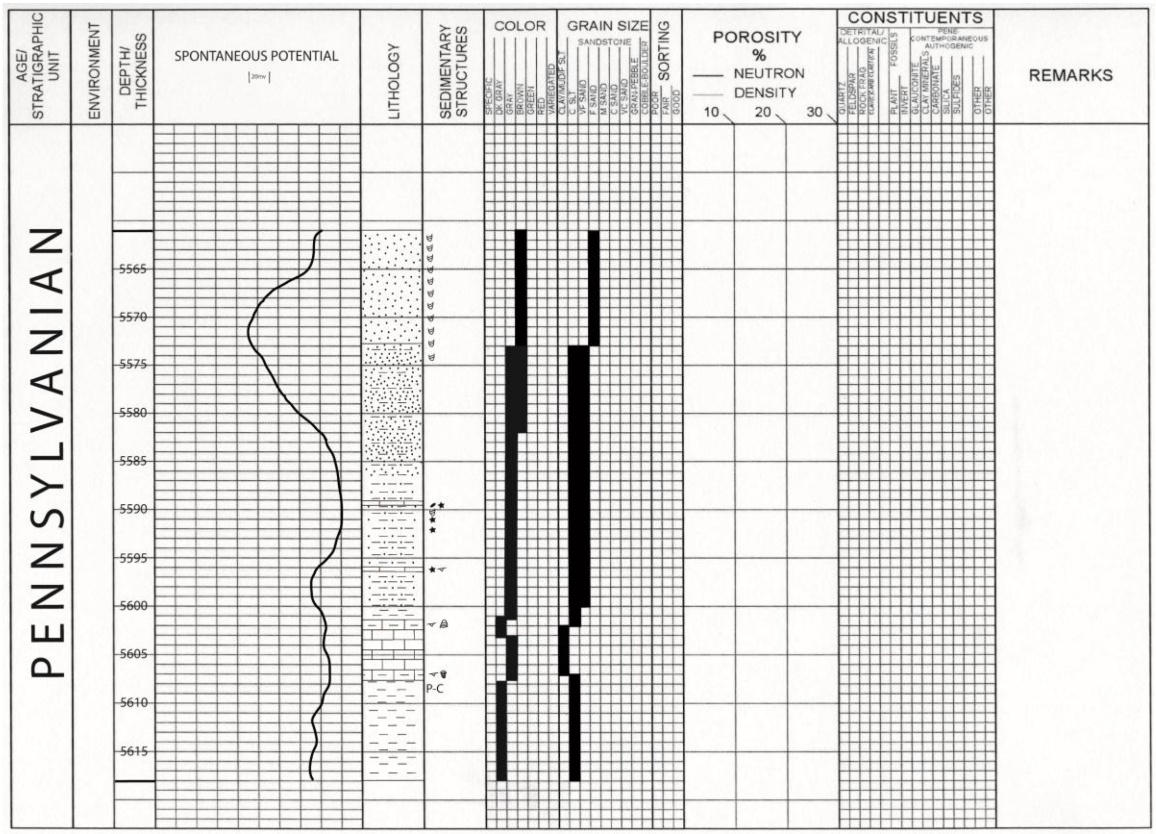
Ward Petroleum – Marisa 1-10, Sec. 10 T.19N. R.6W., Kingfisher County.

Cored interval: 5896.0 – 5942.0 (46) ft.

Core Depth (ft.)	Core Description
5942.0 - 5931.5	sandstone, effervescent, sparse thin shale streaks; contains crinoids; possible bidirectional cross bedding found at base.
5931.5 - 5931.0	shale, grey.
5931.0 - 5928.0	sandstone, planar cross beds.
5928.0 - 5927.0	shale, grey.
5927.0 - 5925.6	shale; burrows present.
5925.6 - 5924.6	shale, grey; soft sediment deformation.
5924.6 - 5923.1	sandstone; lenticular bedding.
5923.1 - 5903.9	sandstone; few thin shales streaks with occasional clay clasts.
5903.9 - 5903.3	shale, rip up clasts.
5903.3 - 5901.9	sandstone, lenticular bedding.
5901.9 - 5901.3	shale, rip up clasts.
5901.3 - 5897.4	sandstone and shale, possible symmetric ripples.
5897.4 - 5896.0	sandstone.

Gulf Oil Corporation – Meyers Estate 1, Sec. 10 T.12N. R.2W., Oklahoma County.

Cored interval: 5561.0 – 5618.0 (57) ft.



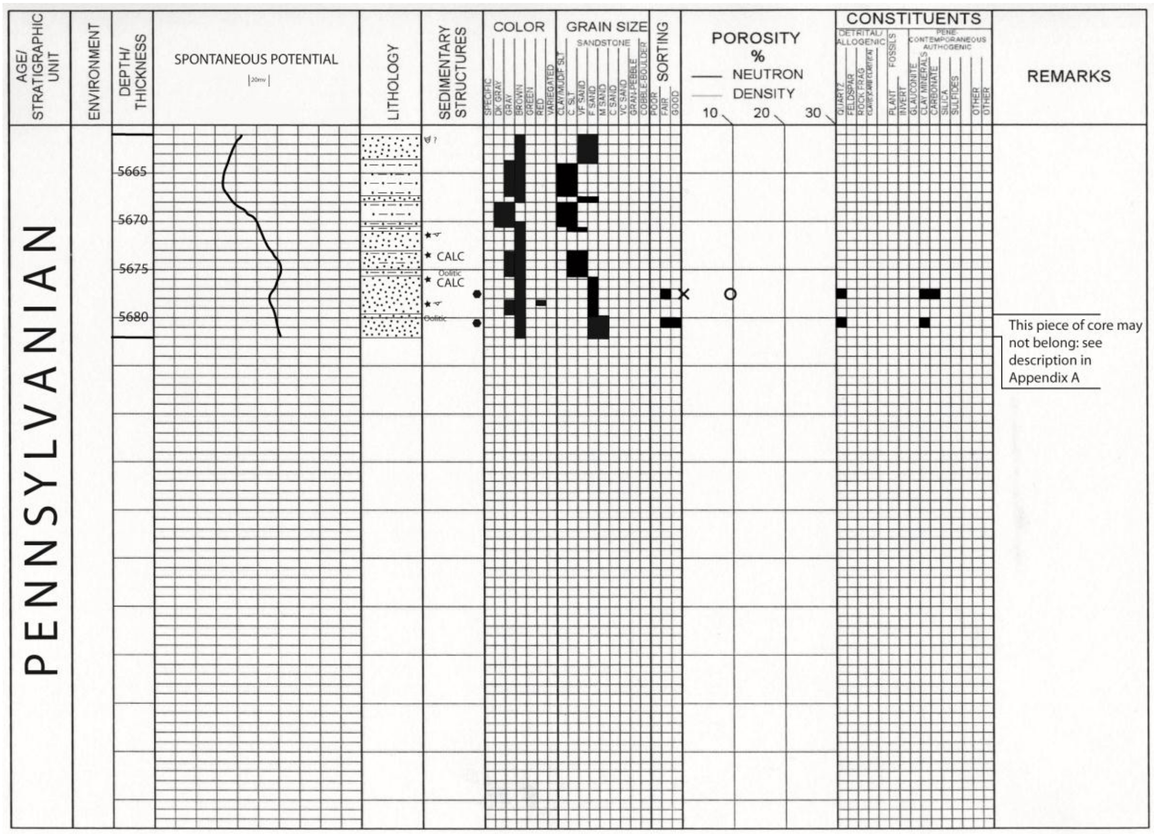
Gulf Oil Corporation – Meyers Estate 1, Sec. 10 T.12N. R.2W., Oklahoma County.

Cored interval: 5561.0 – 5618.0 (57) ft.

Core Depth (ft.)	Core Description
5618.0 - 5607.6	shale, "poker chip" appearance.
5607.6 - 5606.6	limestone, shaley, red, possible exposure surface; contains brachiopods, trilobites can be seen in thin section.
5606.6 - 5602.4	limestone; red bed at 5602.7.
5602.4 - 5601.4	limestone, shaley, red, possible exposure surface; contains abundant crinoids, some gastropods.
5601.4 - 5596.4	sandstone and shale, interbedded
5596.4 - 5595.9	limestone, marine hash made up of crinoids and brachiopods.
5595.9 - 5589.5	sandstone and shale, interbedded; upper portion of interval is burrowed.
5589.5 - 5589.1	limestone, storm deposit containing crinoids and clay clasts.
5589.1 - 5572.7	sandstone and shale, interbedded with sand content increasing upwards; burrows found from 5577-5572.5.
5572. 8 - 5561.0	sandstone, very fine grained, burrowed.

Gulf Oil Corporation – Miley C1, Sec. 31 T.13N. R.2W., Oklahoma County.

Cored interval: 5561.0 – 5682.0 (21) ft.



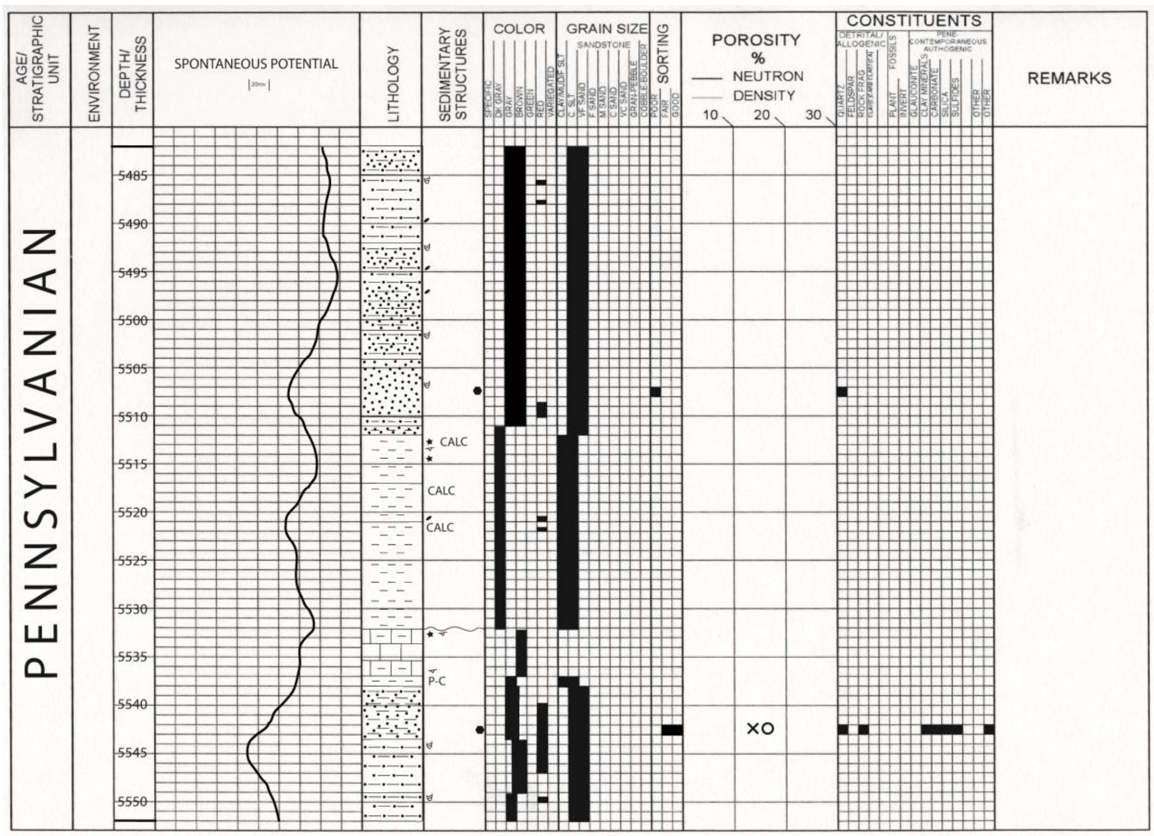
Gulf Oil Corporation – Miley C1, Sec. 31 T.13N. R.2W., Oklahoma County.

Cored interval: 5561.0 – 5682.0 (21) ft.

Core Depth (ft.)	Core Description
5682.0 - 5679.6	sandstone, medium grained; (this piece of core was very uncharacteristic of all other cores and thin sections observed; it was likely misplaced in the Miley C1 box).
5679.6 - 5675.7	sandstone, thin shale interbeds; calcite cemented, contains brachiopods and crinoids.
5675.7 - 5673.0	sandstone, thin shale interbeds; calcite cemented, contains crinoids.
5673.0 - 5671.0	sandstone, contains crinoids, brachiopods.
5671.0 - 5670.5	sandstone, thin shale interbeds.
5670.5 -5668.0	sandstone, interbedded with thin shale.
5668.0 - 5667.4	sandstone.
5667.4 - 5663.6	sandstone, interbedded with thin shale.
5663.6 - 5661.0	sandstone, possible burrows in upper foot of interval.

Gulf Oil Corporation – Perkins 1, Sec. 34 T.13N. R.2W., Oklahoma County.

Cored interval: 5482.0 – 5584.0 (102) ft.



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Gulf Oil Corporation – Perkins 1, Sec. 34 T.13N. R.2W., Oklahoma County.

Cored interval: 5482.0 – 5584.0 (102) ft.

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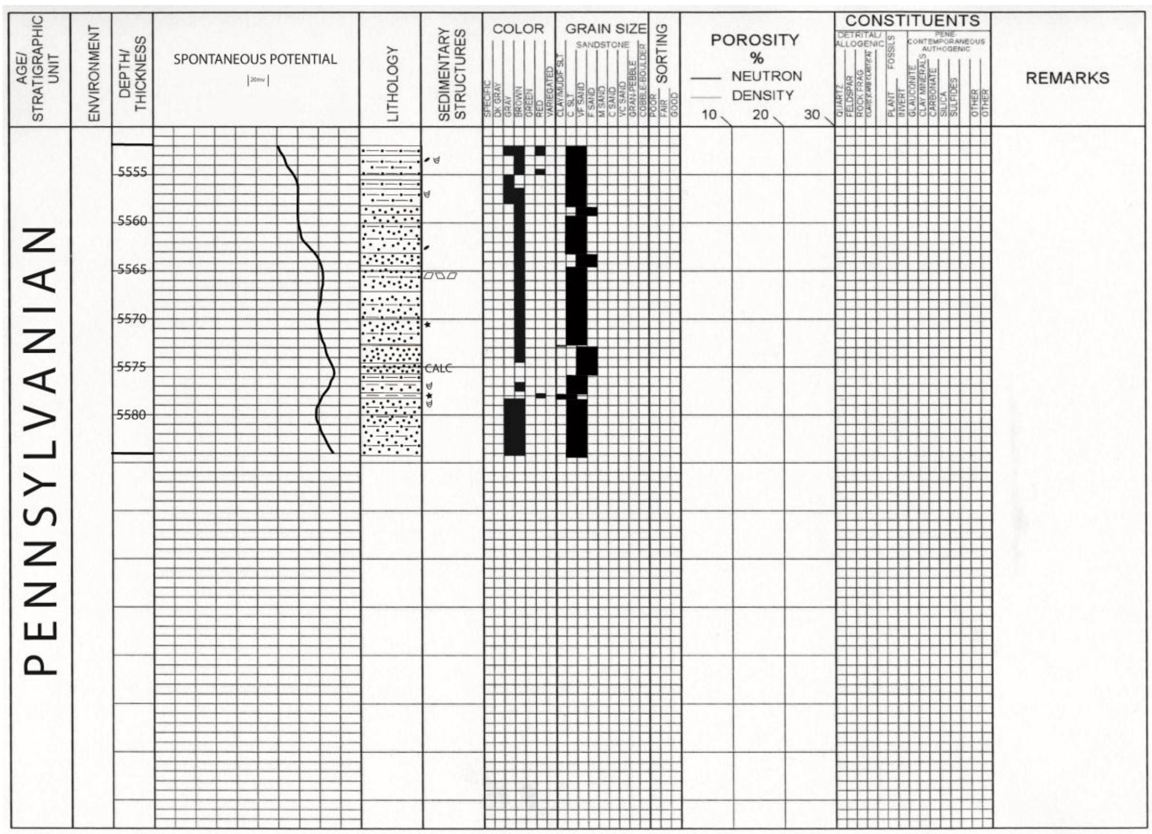


Gulf Oil Corporation – Perkins 1, Sec. 34 T.13N. R.2W., Oklahoma County.

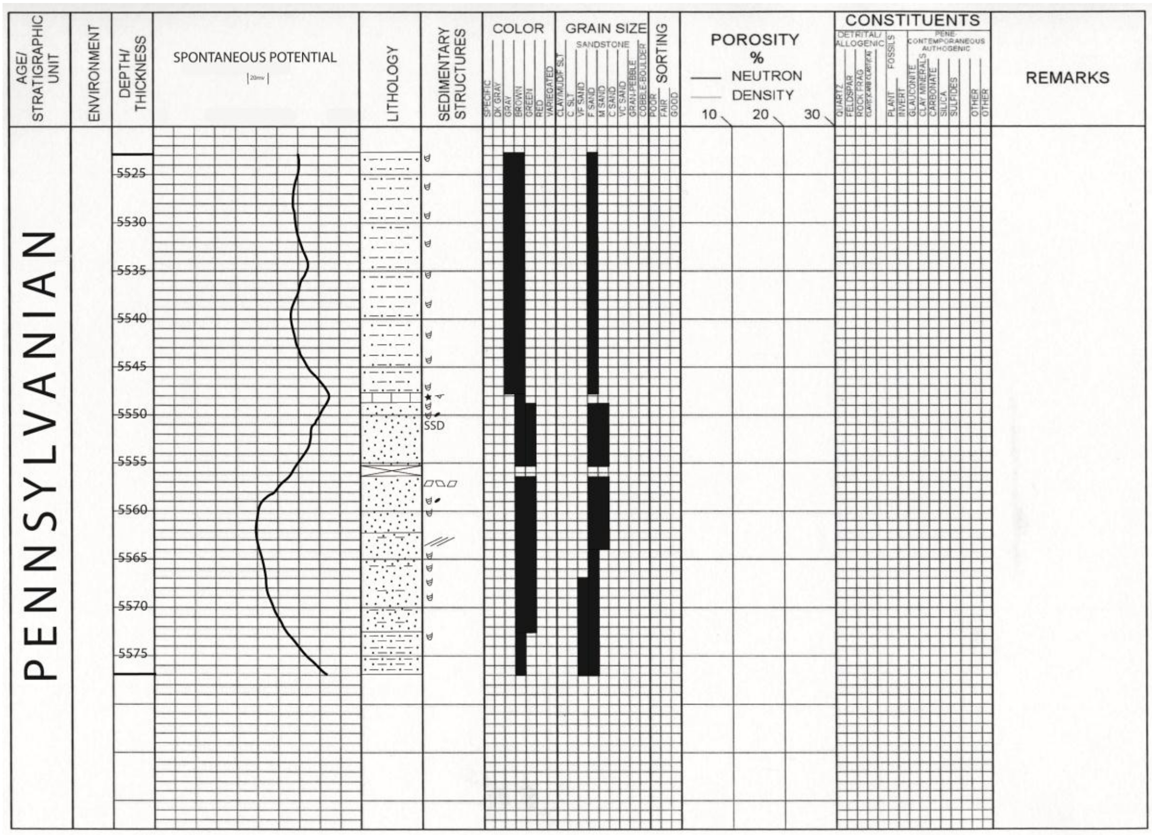
Cored interval: 5482.0 – 5584.0 (102) ft.

Core Depth (ft.)	Core Description
5584.0 - 5578.2	sandstone and shale, interbedded, slightly burrowed.
5578.2 - 5577.7	red bed, contains crinoids.
5577.7 - 5576.4	sandstone and shale, interbedded, slightly burrowed.
5576.4 - 5575.7	sandstone and shale, interbedded.
5575.7 - 5574.6	sandstone, calcareous.
5574.6 - 5572.5	sandstone.
5572.5 - 5572.4	shale, thicker than surrounding shale streaks.
5572.4 - 5567.0	sandstone, thin shale streaks; crinoids present.
5567.0 - 5564.4	sandstone, shale rip up clasts.
5564.4 - 5563.0	sandstone.
5563.0 - 5559.1	sandstone, thin shale streaks and shale rip up clasts and clay clasts, red color.
5559.1 - 5558.2	sandstone.
5558.2 - 5556.4	sandstone and shale, interbedded, slightly burrowed.
5556.4 - 5555.5	sandstone, thin shale streaks.
5555.5 - 5553.0	sandstone and shale, slightly burrowed; intermittent red beds; clay clasts.
5553.0 - 5549.0	sandstone and shale, burrowed.
5549.0 - 5543.5	sandstone and shale, burrowed, intermittent red beds.
5543.5 - 5538.0	sandstone and shale, thin red beds.
5538.0 - 5537.0	shale, slight "poker chip" appearance.
5537.0 - 5532.0	limestone, 5537.0-5536.0 contains shell fragments and brachiopods; 5533.0-5532.0 contains whole brachiopods and

	crinoids; higher shale content in the intervals of 5537.0-5535.5 and 5533.5-5532.0.
5532.0 - 5521.0	shale, slightly effervescent; exposure surface at 5532.
5521.0 - 5517.0	shale, similar to underlying with an increase in effervescence, clay clasts at base.
5517.0 - 5512.0	shale, slightly effervescent; crinoids, brachiopods present at 5512.5-5511.5.
5512.0 - 5511.0	sandstone.
5511.0 - 5510.0	shale, sandy.
5510.0 - 5504.0	sandstone, decrease in effervescence upwards.
5504.0 - 5501.0	sandstone, thin shale interbedding; few burrows.
5501.0 - 5492.0	sandstone and shale, interbedded, slightly burrowed; clay clasts at 5490.0 and 5495.0.
5492.0 - 5485.0	sandstone and shale, interbedded, slightly burrowed.
5485.0 - 5482.0	sandstone and shale, both thin interbeds.

Gulf Oil Corporation – Schroeder 1, Sec. 3 T.12N. R.2W., Oklahoma County.

Cored interval: 5523.0 – 5577.0 (54) ft.



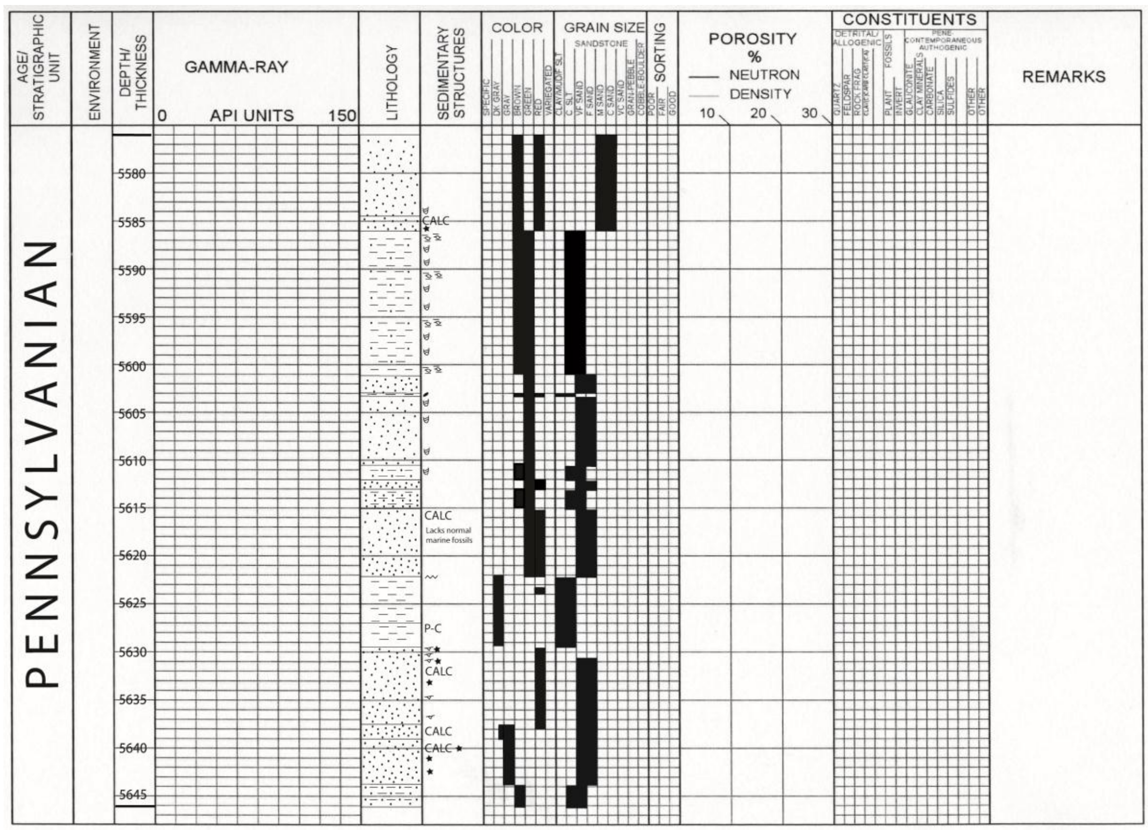
Gulf Oil Corporation – Schroeder 1, Sec. 3 T.12N. R.2W., Oklahoma County.

Cored interval: 5523.0 – 5577.0 (54) ft.

Core Depth (ft.)	Core Description
5577.0 - 5572.6	sandstone and shale-dominantly shale, interbedded, dark grey to black, low effervescence, bioturbated.
5572.6 - 5562.2	sandstone, thin shale streaks decreasing in frequency upwards; bioturbated; planar cross beds.
5562.2 - 5556.4	sandstone; rip up clasts; burrows; clay clasts.
5556.4 - 5555.2	MISSING CORE
5555.2 - 5548.7	sandstone, locally red, slightly bioturbated; some soft sediment deformation; few very thin shale streaks; clay clasts.
5548.7 - 5547.7	limestone, contains crinoids and brachiopods.
5547.7 - 5523.0	shale and sandstone, interbedded, shale is dark grey to black low effervescence, bioturbated.

Gulf Oil Corporation – Wright HRS 1-B, Sec. 3 T.12N. R.2W., Oklahoma County.

Cored interval: 5576.0 – 5646.0 (70) ft.



Gulf Oil Corporation – Wright HRS 1-B, Sec. 3 T.12N. R.2W., Oklahoma County.

Cored interval: 5576.0 – 5646.0 (70) ft.

Core Depth (ft.)	Core Description
5646.0 - 5643.7	sandstone and shale, thin interbeds.
5643.7 - 5639.0	sandstone, tan, slightly effervescent; thin shale interbed/rip up clast at 5640.8.
5639.0 - 5637.5	sandstone, light grey, effervescent.
5637.5 – 5629.4	sandstone, highly effervescent, contains crinoids and whole brachiopods.
5629.4 - 5627.0	shale, “poker chip” appearance.
5627.0 - 5622.1	shale, grey, very abrupt upper contact at 5622.1.
5622.1 - 5615.0	sandstone, slight red color, effervescent lacks normal marine fossils.
5615.0 - 5613.0	sandstone, thin shale streaks from 5613.5-5613.0.
5613.0 - 5612.0	sandstone, oxidation at base.
5612.0 - 5610.5	shale; sandy, bioturbated.
5610.5 - 5603.2	sandstone, very thin shale streaks; burrowed.
5603.2 - 5602.9	shale, grey, contains red clay clasts sharp planar contact at base, while the upper contact is sharp and irregular.
5602.9 - 5601.1	sandstone, small shale streaks.
5601.1 - 5586.0	sandstone and shale, interbedded, low sand content, bioturbated; locally lenticular bedded.
5586.0 - 5584.5	sandstone, effervescent; contains crinoids.
5584.5 - 5576.0	sandstone, few small shale interbeds; red coloration from 5583.0-5586.

VITA

Michael Cody Bacon

Candidate for the Degree of

Master of Science

Thesis: STRATIGRAPHIC FRAMEWORK AND RESERVOIR PROPERTIES, MARMATON/"CLEVELAND" INTERVAL, NORTH CENTRAL OKLAHOMA

Major Field: Geology

Biographical:

Education:

Graduated from Metro Christian Academy, Tulsa, Oklahoma in May of 2006. Completed the requirements for a Bachelor of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in 2010. Completed the requirements for a Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in December 2012.

Experience:

Geology intern, Performance Operating Company, Barnsdall OK, summer 2011. Graduate and undergraduate teaching assistant, Boone Pickens School of Geology, 2010-2011.

Professional Memberships:

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Name: Michael Cody Bacon Date of Degree: December, 2012

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: STRATIGRAPHIC FRAMEWORK AND RESERVOIR PROPERTIES, MARMATON/"CLEVELAND" INTERVAL, NORTH CENTRAL OKLAHOMA

Pages in Study: 86 Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study:

A stratigraphic framework was established for the Marmaton/"Cleveland" interval of north central Oklahoma by constructing subsurface maps and cross sections alongside core and thin section data. Surface stratigraphy was correlated into the subsurface to clear up the confusing nomenclature that plagues this interval.

Findings and Conclusions:

The Cleveland sandstone identified by the petroleum industry in the study area is essentially all Marmaton Sandstone, equivalent to the Holdenville Shale of the Marmaton Group.

The dark, radioactive shales, which represent maximum flooding surfaces in the Pennsylvanian depositional cycles (Heckel, 1986), are effective chronostratigraphic markers and were essential to defining a stratigraphic framework for the "Cleveland Interval" in the study area.

In the Northern Area, these sandstones represent deltaic distributary and marginal marine sandstone bodies.

In the Southern Area, the mappable sandstone represents shallow marine deposits and is interpreted as a marine bar that formed sub-parallel to depositional strike.

Marmaton carbonates in the Northern Area are coeval with the thick siliciclastic mud-dominated intervals to the south associated with the Holdenville deltaic system.

The informal Marmaton intervals (A and B) and Cleveland interval (C) thicken and thin in a complementary fashion that suggests changes in of localized depocenter in response to filling accommodation by the previous interval.

Porosity in Marmaton sandstone is mostly secondary and results from partial dissolution of rock fragments and feldspars.

ADVISER'S APPROVAL: Dr. Jim Puckette