DISTRIBUTION, THICKNESS AND RESERVOIR PROPERTIES OF THE LOWER MORROW SANDSTONE ON THE NORTHERN SHELF OF THE ANADARKO BASIN IN HARPER, WOODS AND WOODWARD COUNTIES, OKLAHOMA

By

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PREFACE

This study involves the use of well log data acquired from northwest Oklahoma to construct stratigraphic correlation sections, isopach, structure, and production maps. These interpretations were integrated with core data, which included thin section and electron microprobe analysis, to establish the depositional environments, sandstone trends and rock properties of the lower Morrow sandstone.

I would like to thank ORCA Petroleum and EOG Resources for providing financial support to conduct this thesis research. Special gratitude is extended to my academic advisor Dr. James Puckette because he suggested that I work on the lower Morrow sandstone in northwest Oklahoma and without his continuous guidance and support, this thesis would not have been possible. I also wish to thank Dr. Stan Paxton and Dr. Surinder Sahai for their support during my research. I also want to thank Robert Campbell at Chesapeake Energy Corporation for his discussion about the exploration of Morrow sandstone in northwest Oklahoma. Special appreciation is extended to Jeff Gigstad, of EOG Resources for his discussions throughout the thesis research.

I want to thank Bradley Nichols and Geoffrey Hale for their help with the electron microprobe analysis. I would like to dedicate this thesis to my entire family who have always believed in me and provided me with unconditional support through out my life. A very special thank you is extended to my fiancé, Niki Gibbs, for her patience and emotional support through out the research.

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CHAPTER I

INTRODUCTION

General Statement

The “Morrow Formation” is an informal name used by the petroleum industry to describe the strata of the lowermost Pennsylvanian Morrowan Series (Rascoe and Adler, 1983; Bates and Jackson, 1987; Al-Shaieb et al., 1995). The Morrow Formation on the shelf and in the deeper parts of the Anadarko basin in western Oklahoma has produced significant volumes natural gas since the late 1950’s. Recent discoveries have shown that the Morrow Formation is still an important oil and gas play today and will continue to be important in the future. In northwestern Oklahoma, eastern Colorado and western Kansas, the Morrow has shallow drilling depths (~ 4000 feet - 6000 feet) (Bowen and Weimer, 2003) and has produced greater than 8 tcf of gas (Bowen and Weimer, 2004). The Morrow sandstones have a distinct log signature, which allows them to be mapped easily across a wide area. Due to the huge exploration and production success with the Morrow reservoirs in Colorado, Kansas and Oklahoma, the Morrow Formation has been extensively researched (Benton, 1971; Swanson, 1979; Sonnenberg et al., 1990; Al-Shaieb et al., 1995; Puckette et al, 1996; Bowen and Weimer, 2004).

The Morrow Formation in northwest Oklahoma is situated immediately below strata of the lower Pennsylvanian Atokan age and immediately above the upper

Mississippian Chesterian rocks. The Morrow Formation has been informally subdivided into upper, middle and lower units by Forgotson et al. (1966). Swanson (1979) subdivided the Morrow Formation into upper and lower units. For this study, which is primarily based on electrofacies interpreted from wireline log signatures, the Morrow is subdivided into the Morrow shales and the lower Morrow sandstones. Sub-sea elevation of the top of the lower Morrow ranges from 4000 feet in the north to over 5500 feet towards the southern portion of the study area.

Purpose and Objectives

The primary purpose of this study is to establish a depositional model for the lower Morrow sandstones in the study area. The lower Morrow has previously been identified as deltaic, shallow marine and valley fill within northwestern Oklahoma. The proper depositional model will enhance exploration for the lower Morrow sandstone reservoirs. This study involves using subsurface mapping, core-derived data, well-log signatures and electron microprobe derived data to determine the general depositional setting, structural trends, production trends and internal features of the lower Morrowan sandstone. Ultimately, these data will be used to achieve a better understanding of the factors controlling oil and gas production from the sandstone. All data were integrated to develop a better understanding of the sandstone trends in the study area and interpret depositional environment. Subsurface mapping includes constructing isopach, structure and production maps.

The objectives of this study are as follows:

- Establish a correlation of the stratigraphic units that comprise the lower Morrow sandstone and the overlying and underlying units within the study area.
- Determine the thickness and the extent of the lower Morrow sandstone.
- Determine the general structural attitude of the lower Morrow sandstone.
- Determine the depositional setting and the depositional environments, of the lower Morrow sandstone
- Determine the composition of the lower Morrow sandstone using electron microprobe analysis.
- Explain the general petroleum geology of the Morrow reservoirs.

Study Area

The study is located in Harper, Woods and Woodward Counties, Oklahoma (Figure 1) and includes Townships 24-27 North and Ranges 17-21 West. The study area is located on the northern shelf of the Anadarko basin (Figure 2), which is one of the most prolific oil and gas producing basins in North America.

Methodology

Raster images containing wire-line logs for over 1500 wells across the townships in the study area were acquired for analysis. The logs provided gamma-ray, resistivity, neutron-density porosity and bulk density signatures that were used to distinguish between strata of the Atoka, Morrow and the Chester intervals. Well data, including production information for the numerous wells across the area were also obtained for the study. Four cross sections were constructed as well as structure, isopach and production maps to better understand the lateral extent, structure, distribution patterns, thickness and trends of the sandstones.

Internal features and geometry of the lower Morrow sandstones were determined using core, thin section, and electron microprobe analyses. The core was used to determine depositional features, the nature of structural boundaries and the physical properties of the Morrowan interval. Thin sections from the core were used to establish detrital and authigenic constituents and determine controls of porosity and permeability. The electron microprobe was used to establish a better understanding of the chemical composition of detrital grains and cements.

The integration of all of the various methods listed above is considered vital to obtaining a better understanding of the general geology, structure and depositional environment of the lower Morrow on the northwestern shelf of the Anadarko basin and this in turn is important for the petroleum exploration of the Morrow reservoirs. These methods can also be used to interpret the general petroleum geology in the area.

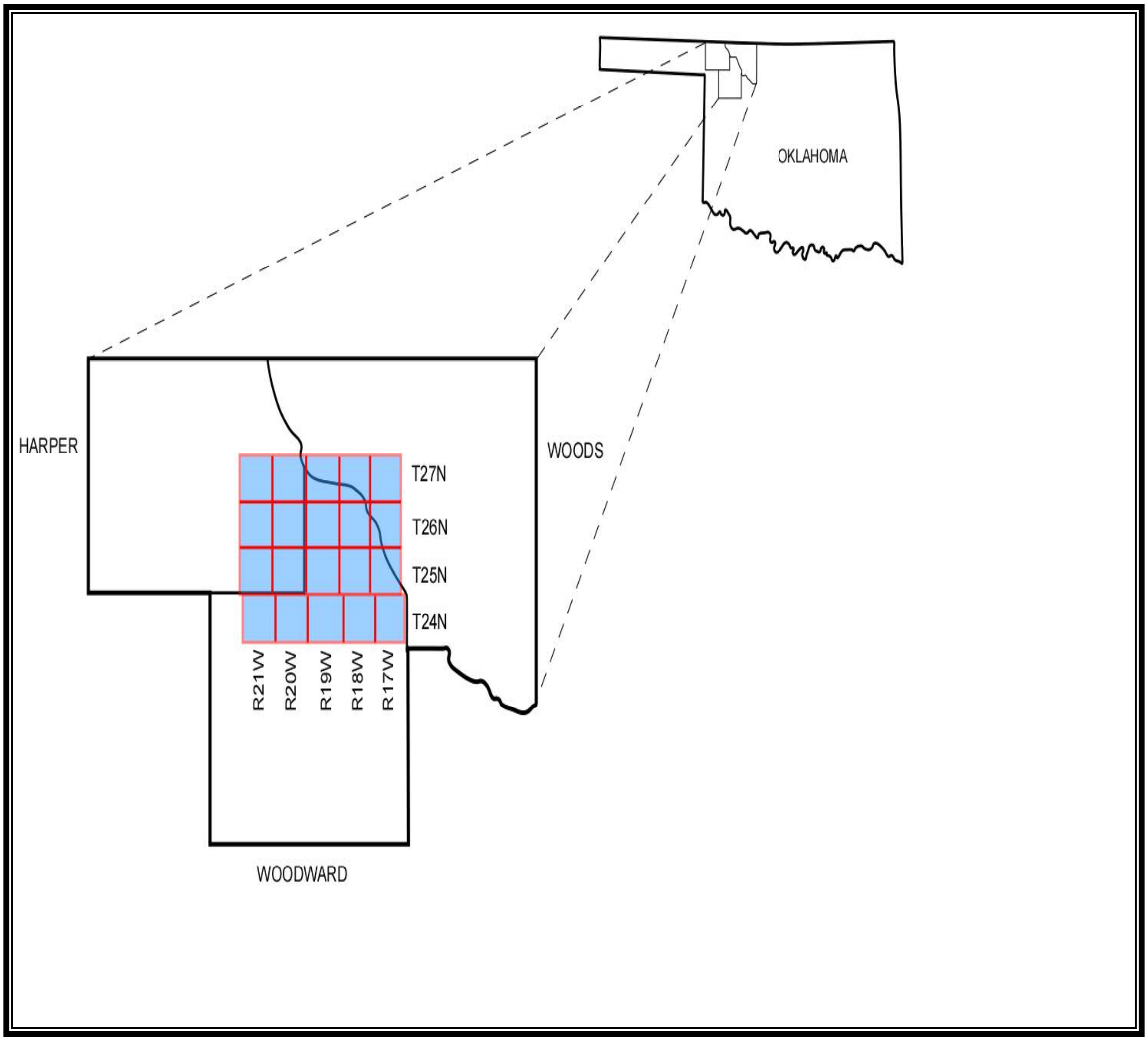


Figure 1. Study area located in Harper, Woods and Woodward Counties, Oklahoma.

Previous Investigations

Due to its economic importance, the Morrow sandstones have been of great interest in the oil and gas industry. Based on the volume of available literature, it appears that the upper Morrow has been studied more frequently than the lower Morrow. Interest in the lower Morrow sandstone is increasing because of advances in exploration technology. The interpretation of the depositional environment for the Morrow Formation has continuously changed as more data become available. Much of change is attributed to advances in technology, including seismic data. In western Oklahoma, 3-D seismic data is becoming available and being utilized to improve the interpretation of the unit (Gigstad, 2006; Campbell, 2006).

Moore et al. (1944) described the Morrow as the lowermost series of the Pennsylvanian system in the Mid-Continent. Arro (1965) suggested that the upper Morrow sandstone of the Oklahoma and Texas Panhandles were upper to lower shore face deposits. Benton (1971) investigated the rocks of the Morrowan series in Texas County, Oklahoma and concluded that the upper unit was deposited within a fluvial system that eroded Morrowan paleotopography. Swanson (1979) studied the Morrow rocks in the western portion of the Anadarko basin and concluded that a variety of coastal plain to deltaic depositional environments, including point bars are represented by depositional features present in late Morrowan age rocks in the embayment. Godard (1981) described the lower Morrow unit as a fluvio-deltaic sandstone and suggested that the Morrow Formation trended in a northwest to southeast direction. Gerken (1992) described the lower Morrow sandstone as a transgressive valley-fill deposit.

Franz (1984, 1985) interpreted the lower Morrow in Kansas as regionally extensive offshore shales and shoreface and offshore bar sandstones. Sonnenberg (1985) suggested that the fluvial valley fill deposits were related to sea level fluctuations during Morrowan time. Weimer et al. (1988) inferred that there were four major unconformities associated with valley-fill deposits in Colorado. Alberta (1987), Johnson (1989) and Al-Shaieb and others (1989) suggested that the upper Morrow chert-conglomerate reservoirs along the southern margin of the Anadarko basin were fan-delta and alluvial fan deposits. The incised valley fill model for the Morrow Formation in eastern Colorado and western Kansas was suggested in studies by Emery and Sutterlain (1986), Krystinik and Blakeney (1990), Sonnenberg (1990), and Wheeler et al (1990).

Al-Shaieb et al (1995), Puckette et al (1996), Luchtel (1999), Bowen and Weimer (2003) and Bowen and Weimer (2004) all described sedimentary features that were similar to those identified in the Colorado studies, and proposed that the incised valley fill model was applicable to the upper Morrow in the Oklahoma and Texas Panhandles.

The study area is located adjacent to area examined by Godard (1981). One of the primary objective of the research is to determine if the lower Morrow has features more similar to the fluvial-deltaic model of Godard (1981) on the valley fill model of Gerken (1992)

CHAPTER II

GEOLOGIC SETTING

Regional Structure

The study area is located on the northern shelf of the Anadarko basin. The Anadarko basin is a petroleum rich basin that is located in southwestern Kansas, the northeastern Texas Panhandle, southeastern corner of Colorado and most of western Oklahoma (Figure 2). The Anadarko basin is bounded to the north by the central Kansas uplift (including the Hugoton Embayment) and to the south by the Amarillo-Wichita uplift. The Anadarko basin is bounded to the west by the Cimarron arch and by the Las Animas arch on the northwest. The basin is bounded to the east by the Nemaha ridge.

The Anadarko basin contains a maximum of 45,000 feet of strata just north of the Amarillo-Wichita uplift (Rowland, 1974). The Pennsylvanian rocks in the Anadarko basin are mostly shales, with lesser amounts of sandstone and occasional limestones. The Morrow sandstones are major hydrocarbon producers across the basin. The pre-Morrowan cratonic epeirogeny and the middle Pennsylvanian tectonic activities were the two main episodes that affected the tectonic evolution of the Hugoton embayment during the Carboniferous (Rascoe and Adler, 1983). Rascoe and Adler (1983) suggested that the

Cambridge arch and the central Kansas uplift were formed during the time of the pre-Morrowan epeirogeny.

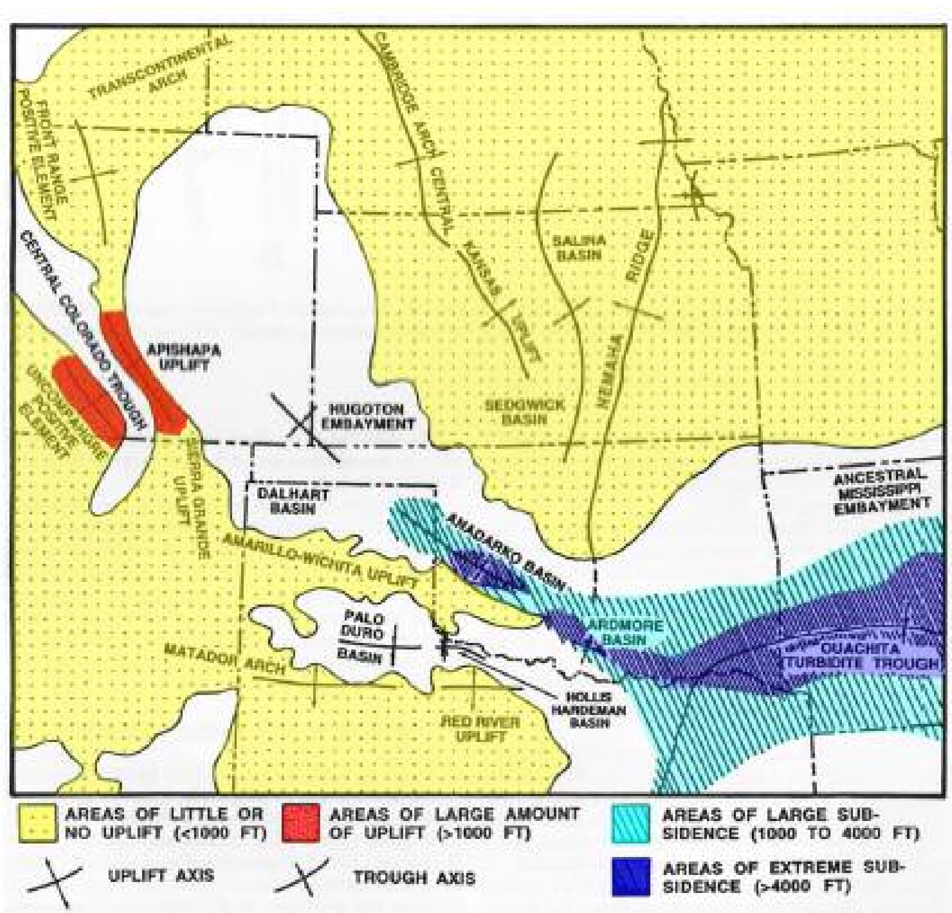
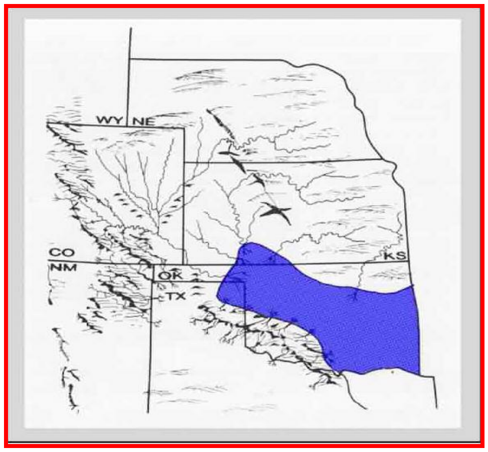


Figure 2. Geologic setting of the Anadarko basin. Areas of subsidence, uplift and trough axis are shown on the map (from Sonnenberg et al., 1990).

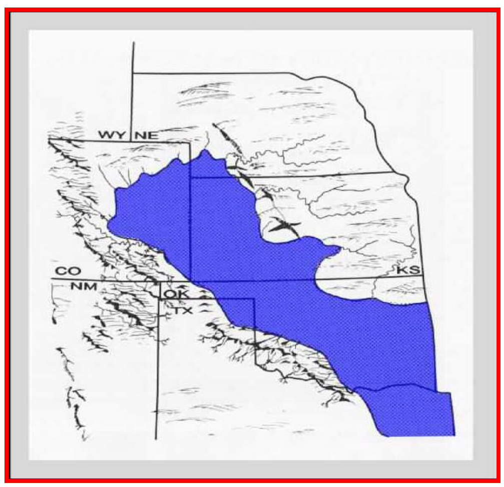
The early middle Pennsylvanian tectonic episode is referred to as the Wichita orogeny (Rascoe and Adler, 1983). The Wichita orogeny occurred as a result of the collision of the North American and South American-African plates (Kluth and Coney, 1981). Sonnenberg et al.(1990), suggested that during the Wichita orogeny, the Amarillo-Wichita Mountains, Ancestral Rockies, Apishapa uplift, Cimarron arch and small structures on the Las Animas arch were formed (Figure 2). The events of the Wichita orogeny associated with the middle Pennsylvanian tectonic activity affected the Hugoton embayment. Evidence for the initiation of the orogeny during the Morrowan is provided by the accumulation of thick sequences of upper Morrowan chert conglomerates along the Wichita Mountain front (Puckette et al., 1996).

Pennsylvanian Paleoclimate

Structural and climatic activities affected sediment supply and distribution patterns during the Morrowan. During the Pennsylvanian, the climate of the Mid-Continent area was tropical or subtropical (Schopf, 1975). Swanson (1979) modeled the paleogeography of the Mid-Continent during Morrowan time. Regional Morrow paleogeography indicates major differences during periods of low and high sea level stands (Figure 3). Habicht (1979) suggested that the Mid-Continent region was near the equator during the Carboniferous (Figure 4). Even though the Mid-Continent region was located close to the equator during the Pennsylvanian, Crowell (1999) indicated that sediments of the Morrow Formation were deposited during a period when the Earth's climate was much cooler than present.



(A)



(B)

Figure 3. Paleogeography of Morrowan time, (A) Exposed shelf during shows sea level lowstand, (B) Extent of shelf flooding during sea level highstand (From Krystinik and Blakeny, 1990)

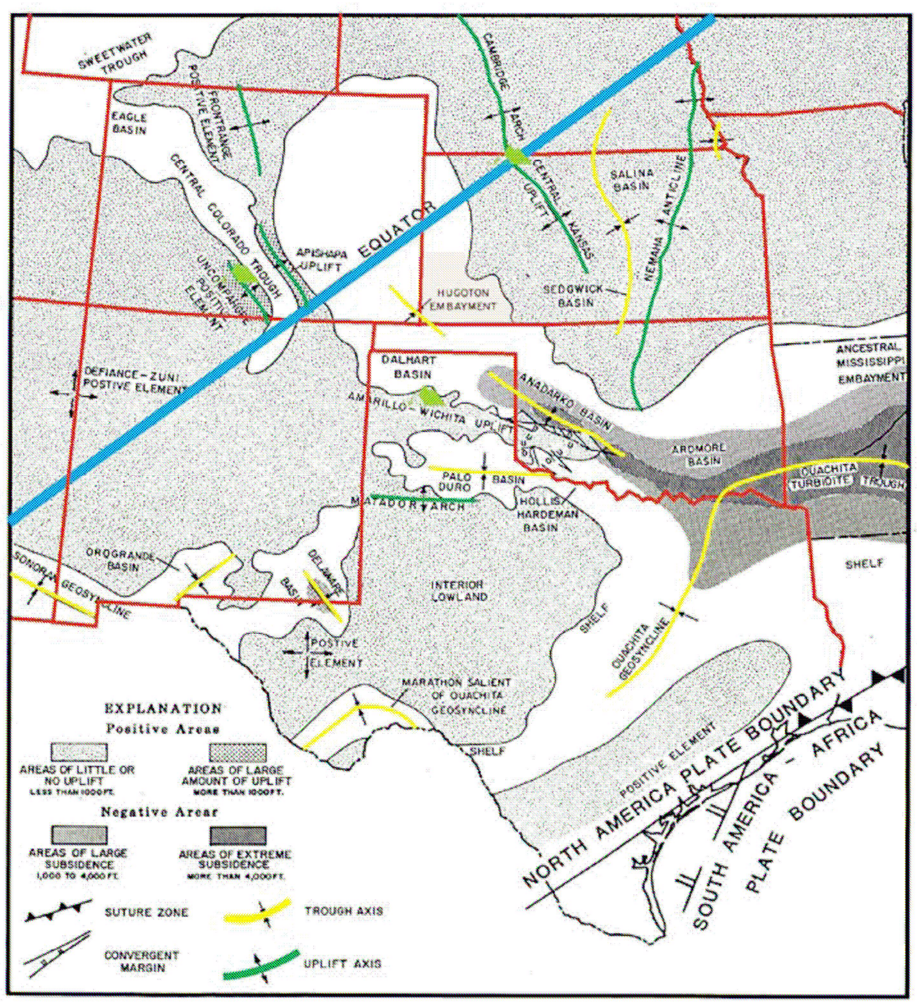


Figure 4. Map showing reconstruction of paleogeography, equator position and late boundaries during Morrowan time (From Sonnenberg et al., 1990).

Morrowan Transgressive - Regressive Cycles

Transgressive-regressive cycles are caused by the rise and fall in sea level. Vail et al. (1977) established a system of stratigraphic analysis based on cycles of changes in sea level. The rise and fall of sea level can be caused by change in rate of ocean trench activities, change in sea floor spreading rates, changes in the volume of ocean basins, orogenic activities and glaciation (Ross and Ross, 1988).

Ross and Ross (1988) developed a world wide coastal onlap curve for the Carboniferous and Permian shelf sediments (Figure 5) and this is used as an indication of sea level changes. The Morrowan experienced the lowest sea levels during the Carboniferous and was punctuated by seven world wide sea level changes (Ross and Ross 1988). The cycles controlled the style of deposition and types of sediments that accumulated during Morrow time. In the study area, core of two Morrowan transgressive regressive cycles are preserved. These are represented by the lower Morrow dark shale (cycle 1) and the lower Morrow sandstones and overlying shale (cycle 2). It is believed that the evidence of upper Morrow cycles was removed by erosion associated with the pre-Atokan unconformity.

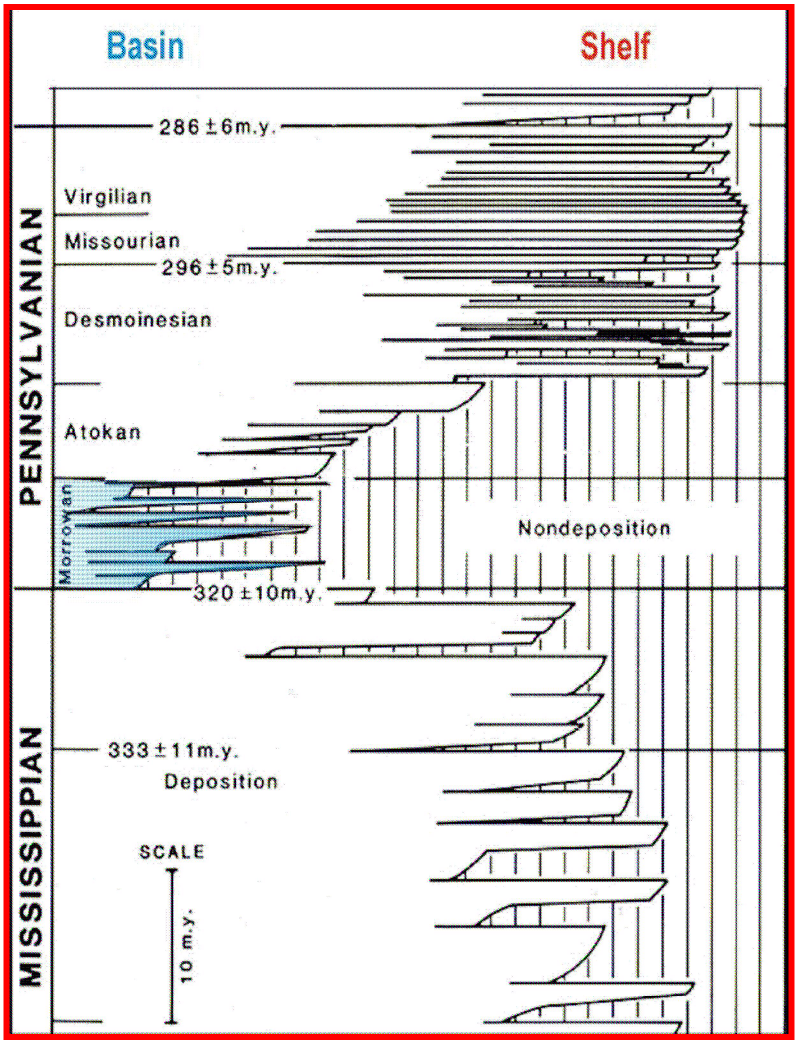


Figure 5. Coastal onlap curve for Mississippian, Pennsylvanian, and Permian shelf sediments (modified from Ross and Ross, 1988)

CHAPTER III

STRATIGRAPHIC FRAMEWORK

Regional Stratigraphy

Adams (1904) described and named the Morrow Formation. Moore et al. (1944) raised the Morrow to the rank of series and suggested that the Morrowan was the lowermost series of the Pennsylvanian system in the Mid-Continent. For this study, the name Morrow Formation, which follows petroleum industry convention, is used to describe the strata of the Morrowan Series.

The Morrow Formation of southeastern Colorado, southwestern Kansas and northwestern Oklahoma is situated below the Atokan (Atoka) and above the Mississippian (Figure 6**).** In the study area, the Morrow Formation rests unconformably on the Mississippian Chester limestone. The gamma ray and resistivity curves on wireline logs indicate that there is a sharp change in lithology across the boundary between the lower Morrow shale and the Chester limestone.

The Morrow Formation is unconformably overlain by the Pennsylvanian Atoka Series in southeastern Colorado (Abels, 1959). The Atokan "Thirteen Finger" Limestone is a sequence of thin limestones and shales that show a distinctive log signature that is easily recognized on gamma ray wireline logs (Figure 7). The Morrow Formation was been further divided by Forgotson et al. (1966) and Swanson (1979). The formation was divided based on lithologic changes. Bebout (1993) constructed a stratigraphic column (Figure 6) and described the lower Morrow as the Keyes Sandstone; this nomenclature was adopted for this study.

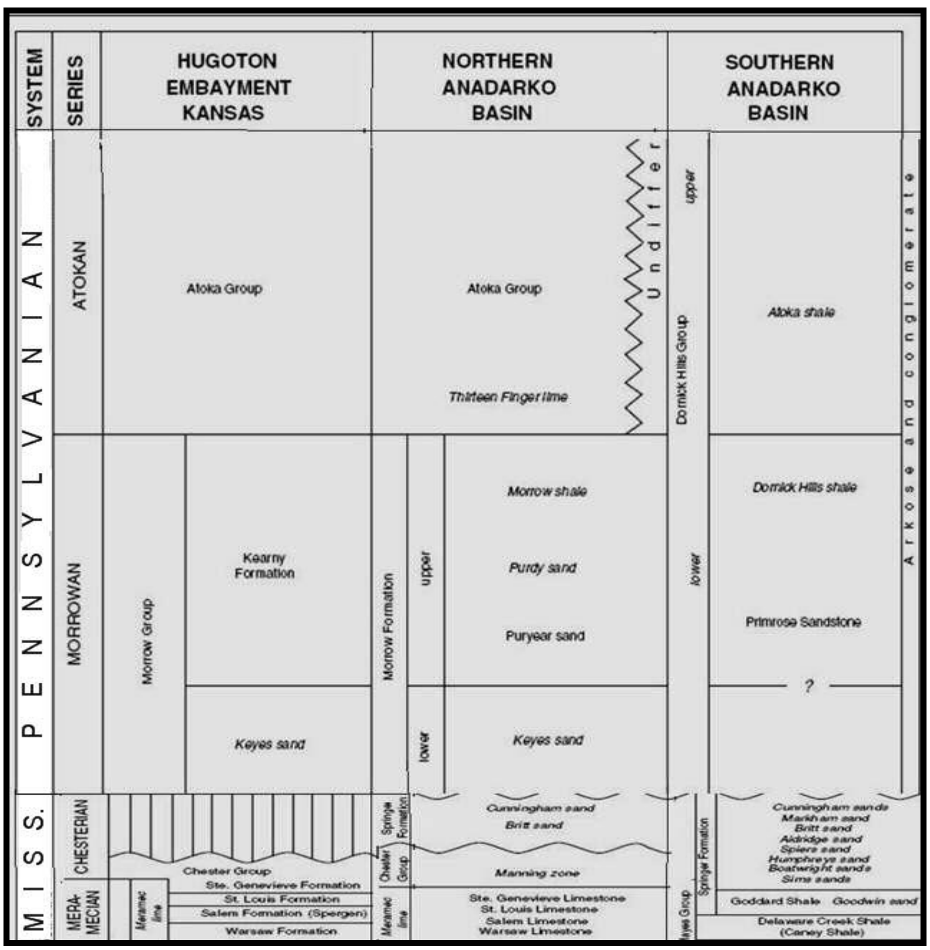


Figure 6. Stratigraphic column showing subsurface nomenclature for the Morrowan and adjacent overlying and underlying units (modified from Bebout el al., 1993)

Subsurface Identification

For this study, the cored Morrow Formation has been subdivided into three sub-units based on the wireline log signatures. The upper unit (Morrow shale) is a mudrock unit that is distinguishable from the sand-dominated middle (Keyes Sandstone) and the basal unit. The gamma ray curve readings across the upper interval are higher, which causes a shift towards the depth track. The upper Morrow shale is the first sub-unit and is situated immediately below the base of the Atoka Thirteen Finger Limestone. On the resistivity log curve, the upper Morrow shale was identified as the lower resistivity (4 ohms) shale unit below the more resistive (10 ohms) signature of the Atokan Thirteen Finger Limestone. The log signature for the Atokan limestone is indicated by the distinct fluctuations of the gamma ray curve.

The lower Morrow Keyes Sandstone is situated immediately below the Morrow shale and immediately above the unconformity that separates the Morrow from the underlying Mississippian Chester (Figure 7). The lower Morrow is composed mostly of sandstone, which is shaley in some areas. The top for the lower Morrow sandstone is identified on wireline logs as the sandstone unit situated underneath the Morrow shale. The gamma ray curve across the lower Morrow Keyes Sandstone usually deflects to the left by approximately 50 API units (Figure 7). On the logs, the base of the lower Morrow is indicated as the bottom of the sandstone unit, which is characterized by gamma ray reading of approximately 15 to 35 API units. In most cases, the base of the sandstone

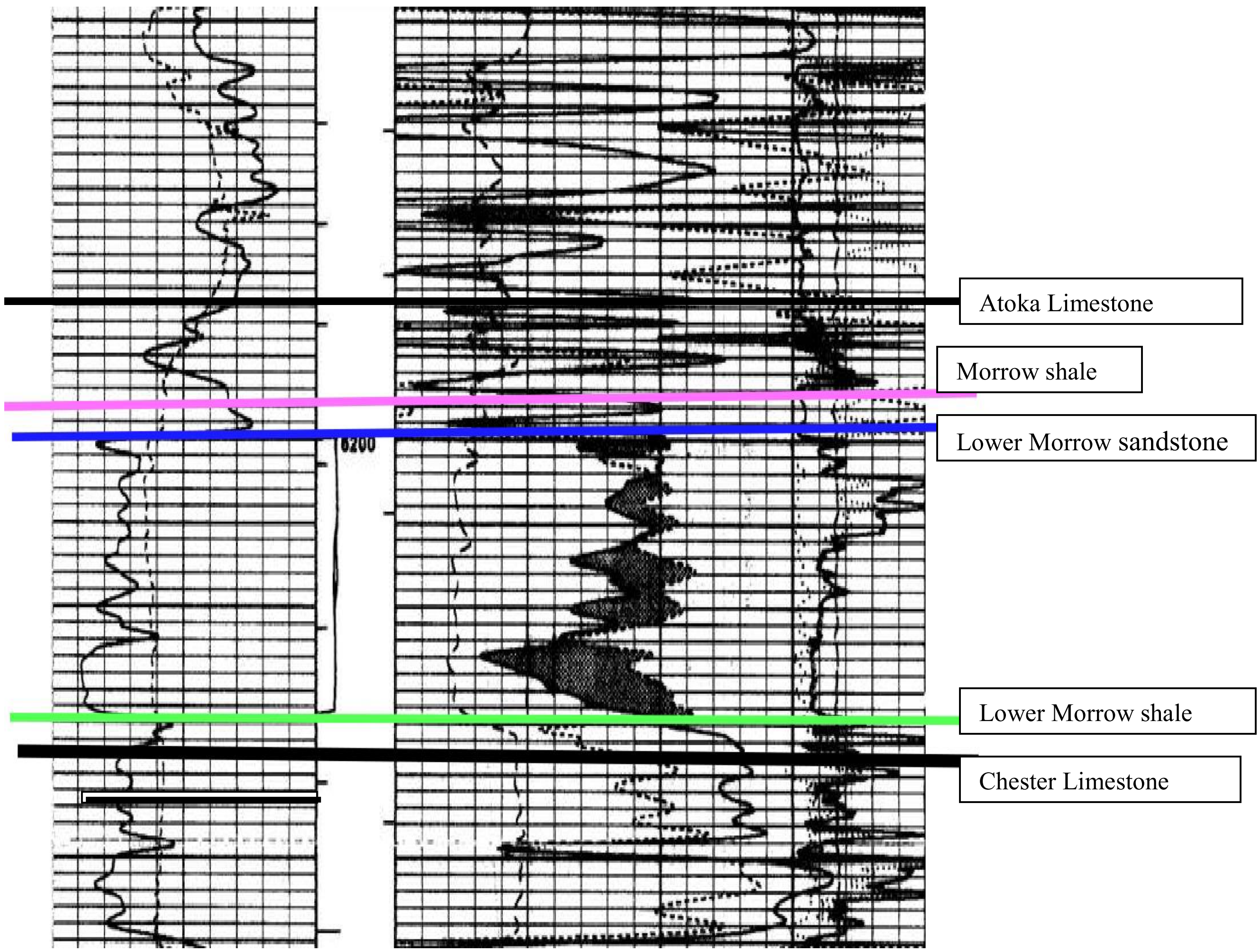


Figure 7: Wire line log characteristic of the Morrowan stratigraphic interval and adjacent units for a representative well from the central part of the study area.

“rests on” or is separated from the Chester limestone by one to five feet of shale. The Chester limestone, usually exhibits a lower porosity and higher resistivity measurements than the lower Morrow interval. The thickness of the lower Morrow Keyes Sandstone ranges from 0 feet in the eastern part of the study area to over 40 feet in the southern portion of the study area. Godard (1981) reported that the lower Morrow extended from 0 feet in the east to over 200 feet in deeper parts of the basin.

Stratigraphic Correlation

The raster images of over 1500 wells drilled within the study area were used to identify the lower Morrow Keyes Sandstone and adjacent units. Regional stratigraphic correlation of the Keyes Sandstone was established across the study area using raster images that covered adequately large vertical sections to show the relationship of the Keyes Sandstone to overlying and underlying units (Appendix). Cross sections were constructed along north to south and west to east trends. A total of four cross sections were constructed. Lines A to A’ and B to B’ (Appendix) show stratigraphic correlation in a north to south direction. Lines C to C’ and D to D’ (Appendix) show the stratigraphic correlation in a west to east direction.

Several cross section lines were constructed to be in close proximity of a core of the lower Morrowan interval from a well located in section 20, T.26 N., R.19 W**.** The interpretations from the cross sections were correlated to the core sample characteristics**.**

The cross section lines (Appendix) show that the lower Morrow Keyes Sandstone generally increases in thickness from a northwest to southeast direction. Based on isopach maps, the lower Morrow interval also thickens and thins across the study area. The lower Morrow Keyes Sandstone thins toward the eastern part of the study area and is ultimately truncated beneath the unconformity at the base of the overlying Atokan unit. The cross sections also show that the lower Morrow sandstone fills depression eroded into the top of the Chester Formation and this evidence was used to interpret the lower Morrow sandstone as an incised valley fill (Appendix).

Incised Valley-Fill Deposits

Incised valleys serve as containers for the Morrow reservoirs. Morrow valley-fill deposits, which can be quality reservoirs with high porosity and permeability are common in eastern Colorado, western Kansas, northwestern Oklahoma and the Texas Panhandle (Wheeler et al. 1990). Weimer (1988), Al-Shaieb et al (1995), Puckette et al (1996) indicated that two types of unconformities are recognized in the Morrow. The lowstand surface of erosion (LSE) boundary occurs during low sea level. During this stage, erosional drainages were incised into older marine deposits and thus an incised valley is formed. As sea level rises, the erosional drainages are filled with fluvial and estuarine sands and mud. The continued rising sea level causes a marine transgression. As the shoreline moves landwards, a transgressive surface of erosion (TSE) associated with shoreface erosion may remove a portion of the valley-fill deposit. With a continuing rise in sea level, marine mud is deposited over the incised valley-fill.

A vertical profile of the Morrowan sequence would show that it is composed of a valley-fill fluvial sandstone deposit (Figure 8) with an erosional contact at its base (LSE). The valley-fill sandstone is normally fluvial at the base, but shows estuarine influence towards the top (Sonnenberg et al., 1990). With continuous marine transgression, a TSE formed, which was covered by superjacent marine muds. The sequence is terminated by the subsequent LSE (Sonnenberg et al., 1990). Weimer et al. (1988) identified four major LSE unconformities associated with the valley-fill deposits in southeastern Colorado. Ross and Ross (1989) indicated that there might be seven major LSE unconformities associated with the Morrow (Figure 5). As a result of valley erosion and subsequent filling, the Morrow marine shales encase the transgressive valley-fill deposits.

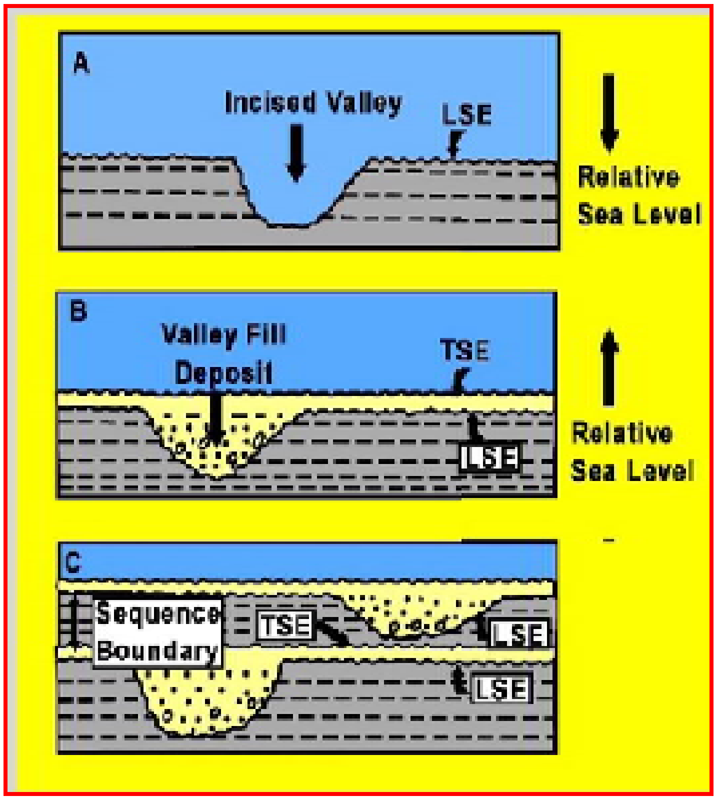


Figure 8. Diagrammatic Morrowan sequence (from Sonnenberg, 1990)

CHAPTER IV

DISTRIBUTION OF THE LOWER MORROW SANDSTONE

Morrow Regional Thickness

Swanson (1979) constructed a regional isopach map (Figure 9) for the Morrow formation that extended from Texas to Oklahoma to Colorado and Kansas. Swanson also suggested that the Morrow Formation is absent towards the northeast and ranges in thickness 0 feet in the northern shelf to about 3000 feet in the deeper parts of the basin.

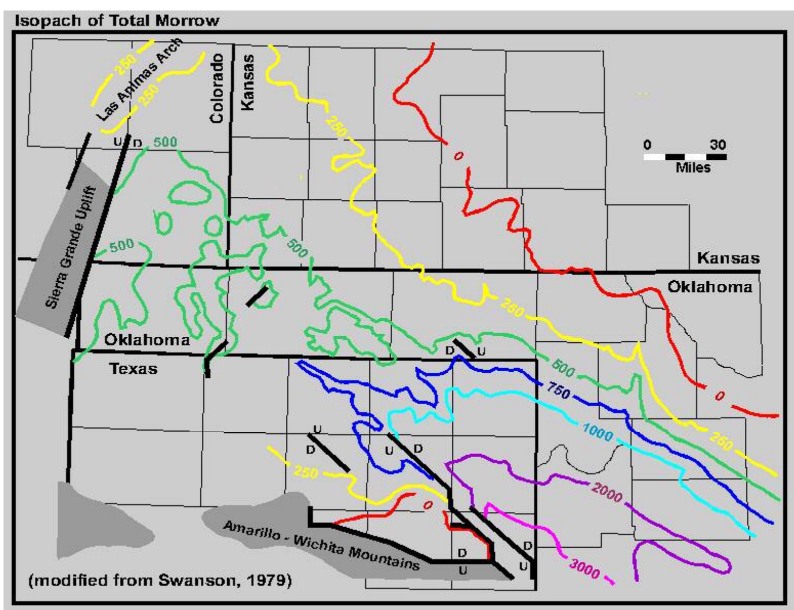


Figure 9. Regional isopach map of the Morrow Formation (modified from Swanson 1979).

Lower Morrow Thickness

An isopach map was constructed of the interval between the top of the lower Morrow sandstone and the top of the Chester (Figure 10) to establish the thickness of the lower Morrow. The map was created using Morrow sandstone and Chester carbonate boundaries obtained from raster images of wireline logs of wells. The map indicates that the lower Morrow Keyes sandstone ranges in thickness from 0 feet in the northeast to about 40 feet in the southwest. The entire Morrow package is absent in the northeast portion of the study area. The cross sections showed that the lower Morrow thins towards the east and is truncated beneath the Atokan Formation. In the eastern portion of the study area (T.27 N., R. 17 W. and T.26 N., R. 17 W.), the Atokan Formation rests unconformably on the underlying Chester Formation. The isopach map indicates that there is a thickening that may represent a channel feature. The thickness of the lower Morrow sandstone in the eastern portion of the study area (T.27 N., R. 18 W. and T.26 N., R. 18 W.) ranged from 0 feet to 10 feet in the outermost portion of the channel. The lower Morrow sandstone continuously thickens from 10 feet along the margin of the channel to 40 feet in the thickest part of the channel. This thickens part of the channel covers most of Townships 24-27 North and Ranges 19-20 West.

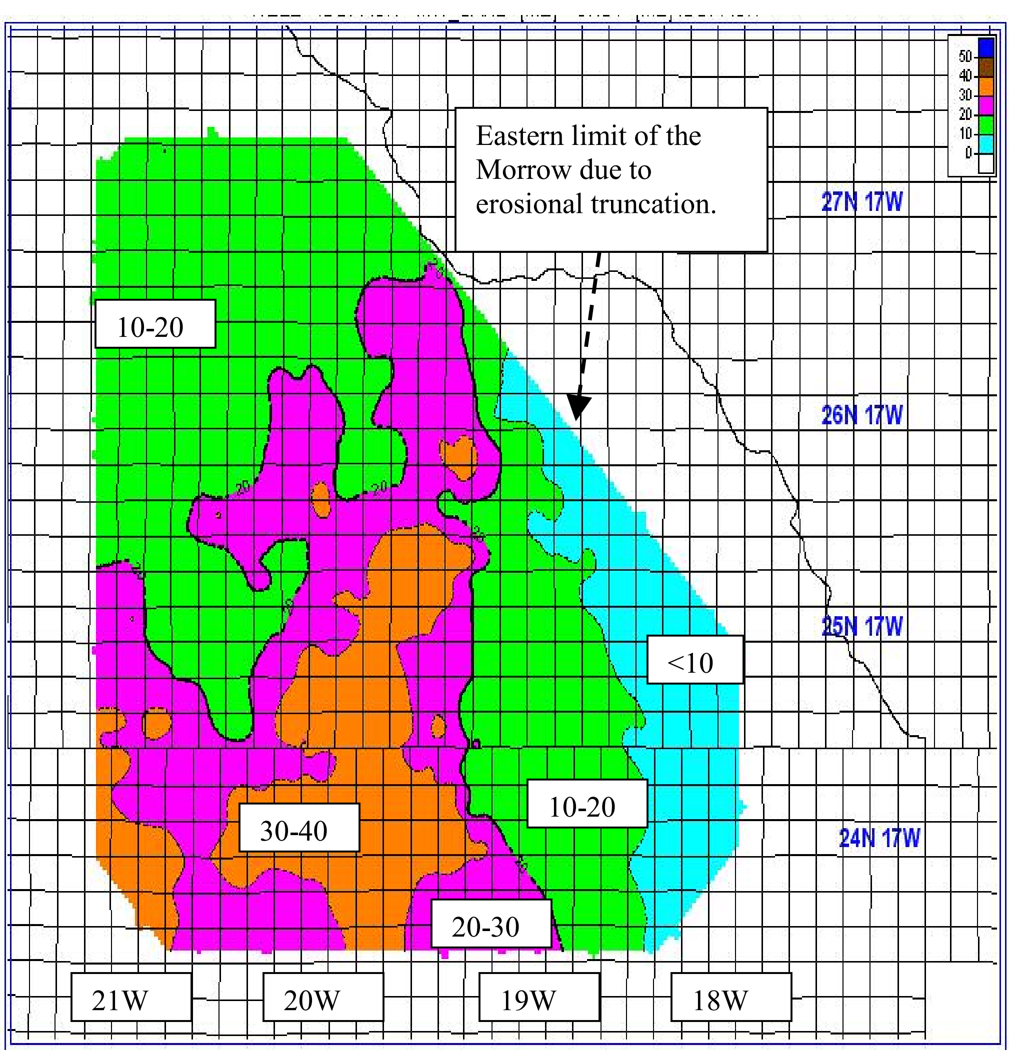


Figure 10. Lower Morrow sandstone isopach map. Colors indicate thickness. Thickness increases from blue to green to pink to orange respectively.

Lower Morrow Sandstone Structure

Structural contour maps were constructed using the formation tops obtained from the raster images of wireline logs data across the Atoka, Morrow and upper Chester intervals. In most of the area, the top of the Chester was used as the marker bed for the base of the lower Morrow. The structure map for the lower Morrow (Figure 11) indicates that the lower Morrow strikes east-west and dips in a northwest to southeast direction.

The wireline logs for the wells across the eastern portion of the map (T. 24 N.-T. 27 N., R.17 W.) suggest that the lower Morrow sandstone was truncated in that area. The structure map indicates that the sub-sea depths for the lower Morrow Keyes sandstone tops range from 4000 feet to over 5500 feet (5800-7200 feet actual depth) in the study area. The shallower sub-sea depths (4000 feet to 4500 feet) for the lower Morrow sandstone tops are present towards the northern portion of northern shelf of the Anadarko basin (T. 26 N.-T. 27 N., R. 18 W.-R. 21 W.). The deeper depths for lower Morrow sandstone, reflect the deeper portion of the northern shelf of the Anadarko basin (T. 24 N.-T. 25 N., R. 17 W.-R. 21 W.). Towards the southwestern portion of the map (T. 24 N., R. 20 W.), there is a southward plunging anticlinal fold (“nose”). This southward dipping feature is present through-out the western portion of the map, but it is not pronounced. The dip direction for the feature is similar through-out the western portion of the map.

The Chester limestone was present and mappable in the eastern portion of the map (T. 24 N.-T. 27 N., R.17 W.), unlike the lower Morrow sandstone that was absent in

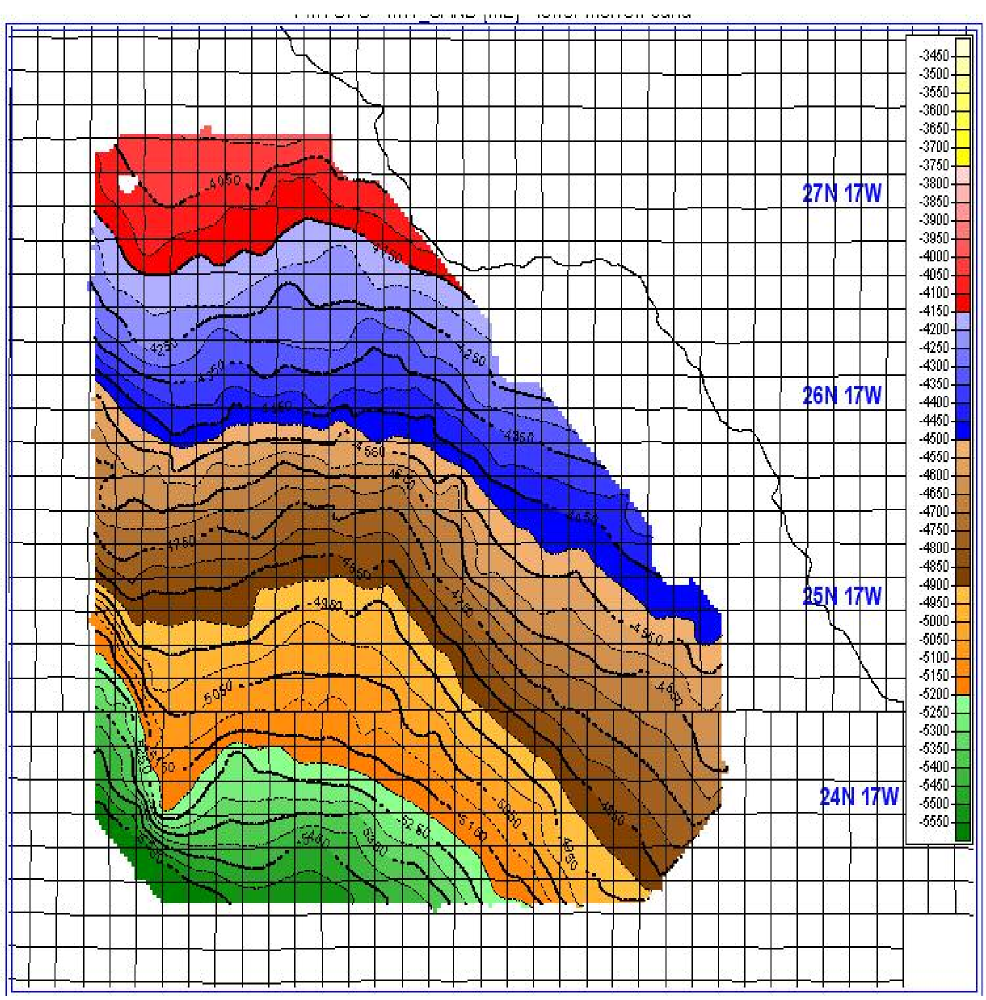


Figure 11. Lower Morrow Keyes Sandstone structure map (Depth increases from red to blue to green to orange respectively)

the east. The general dip direction for the Chester limestone was also northwest to southeast direction. Towards the northern portion of the map (T. 27 N., R. 17 W.-T. 27 N., R. 21 W.), the dip direction of strata is south and strike is in an east –west orientation. Towards the deeper portions of the shelf of the Anadarko basin, the general dip direction for the Chester limestone strata was predominantly in a northeast to southwest direction (Appendix). The southward dipping "nose" feature that was evident in the lower Morrow structure map is evident in the southwestern portion of the Chester map.

CHAPTER V

INTERNAL FEATURES

General Overview

A core was provided from Orca Exploration that includes the base of the Atokan, the Morrow and the top of the Chester. The core was taken from a well drilled in section 20 of Township 26 North, Range 19 West in Woodward County, Oklahoma. The cored interval is approximately 52 feet thick. The upper part of the core (6185 feet-6186.9 feet) is a limestone, which is believed to be the base of the Thirteen Finger Limestone. The middle section of the core (6187 feet-6228.4 feet) is a sandstone and shale interval that is believed to be the Morrow Formation. The basal section (6228.5 feet–6237.5 feet) is a limestone that is believed to represent the Chester limestone.

The cored interval contains a thin bed of the Morrow shale (6187 feet-6192 feet) that is subjacent to the Atokan limestone. The lower Morrow Keyes sandstone (6193 feet-6228.5 feet) occupies most of the rest of the cored interval. Towards the base of the core (6229 feet-6237.5 feet), there is a change from sandstone and shale to a more calcareous unit, which is described as the top of the Chester limestone. A general view of part of the cored interval is shown in Figure 12.

Various sections of the core were sampled for thin section analysis to determine detrital and authigenic constituents and reservoir properties of the sandstone. The electron microprobe was also used to determine the elemental composition of the lower Morrow sandstone.

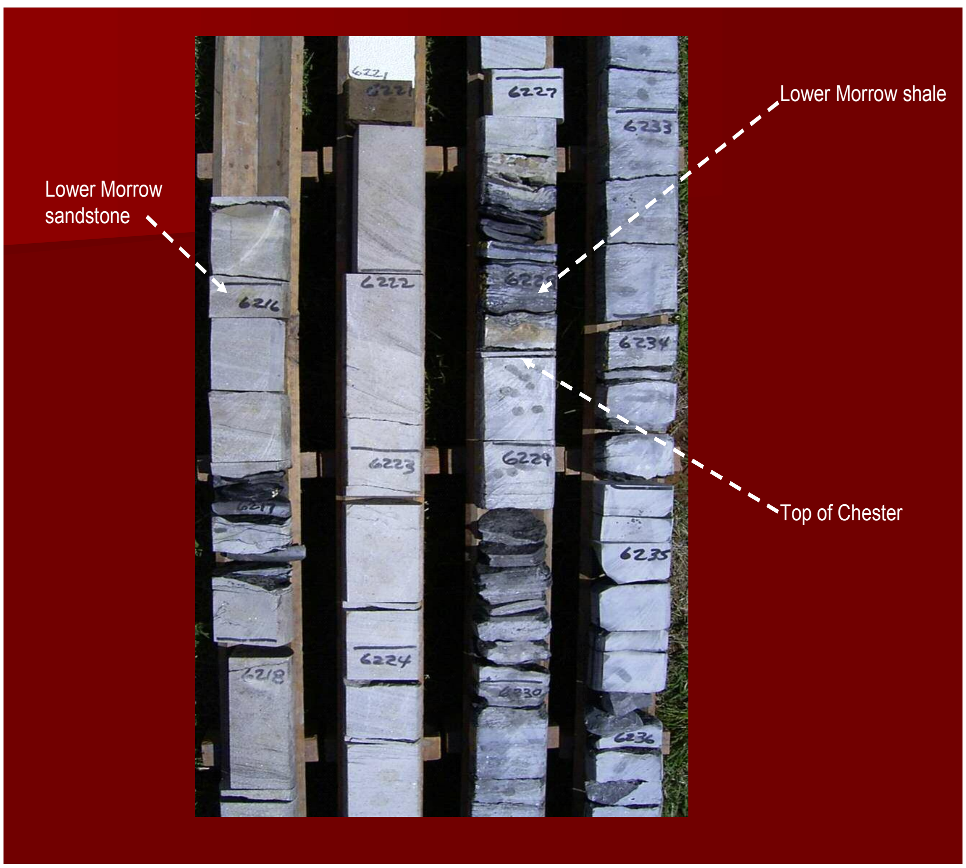


Figure 12. General overview of a section of the cored interval from Woodward County, Oklahoma

Core Description

A core from the Marjo Operating Claudia #1 - 20 well in Section 20 T. 26 N., R.19 W., (6185 feet-6237 feet) was examined. This core was used to determine sedimentary features in the lower Morrow sandstone and establish the nature of the contact between the Atokan, Morrowan and Chesterian strata. The core was sampled for thin section and electron microprobe analysis.

The top section of the core (6185 feet-6192 feet) consists mostly of a gray, very fine, crystalline limestone and shale. Most of this section of the core effervescences readily with dilute (10%) hydrochloric acid with the exception at the interval from 6186-6187 feet and 6190-6191 feet. The wireline logs across this interval exhibit characteristics that support the interpretation of the interval as shaley limestone and limestone. Macro-invertebrate fossils including crinoids are present. The gamma ray curve (Figure 13) (6178-6187 feet) reads relatively low (45 API units), which also suggests a limestone. This section of the core was interpreted to be the base of the Atokan Thirteen Finger Limestone. Beneath the Thirteen Finger Limestone is a crumbly dark shale from 6187-6192.5 feet. This shale, which appears to be void of marine fossils, is believed to be Morrowan.

The next section of core (6192.3-6197 feet) is gray to tan, fine grained sandstone and shale. Horizontal bedding and iron oxide staining are present. The shale layers were very thin and dark gray in color. This represents the top of the lower Morrow sandstone.

The sandstone at 6197-6198 feet is very fine grained and appears to be silica cemented. Organic debris laminae are present in this interval.

Horizontal and wavy bedding occur in the next interval (6198-6210 feet). Gray colored sandstone and light gray to green shale interbeds / laminae are present from 6198-6203 feet. Most of the sandstone is fine grained and moderately sorted. Toward the base of 6203 feet, the sandstone becomes gray colored, fine grained and effervescences in acid, indicating that it contains calcite cement. The sandstone from 6203-6206 feet is wavy bedded and contains evidence of flowage. At 6207 feet, the sandstone contains burrows, and appears to represent deposition in a low energy environment.

The section from 6208 feet to 6214 feet is gray, fine grained sandstone with a dark shale interbeds / laminae. The sandstone is massive to wavy bedded and contains occasional inclined beds. At 6204 feet, the sandstone exhibits cross bedding, which continues to the base at 6227.5 feet. Trough and planar cross bedding is evidence of high energy fluvial deposition. A channel-lag conglomerate occurs at 6227.4 feet. Beneath the lower Morrow sandstone is a thin (6227.5-6228.4 feet) dark fossiliferous shale (Figure 14). Subjacent to the shale is an oxidized zone and limestone of the Chester interval.

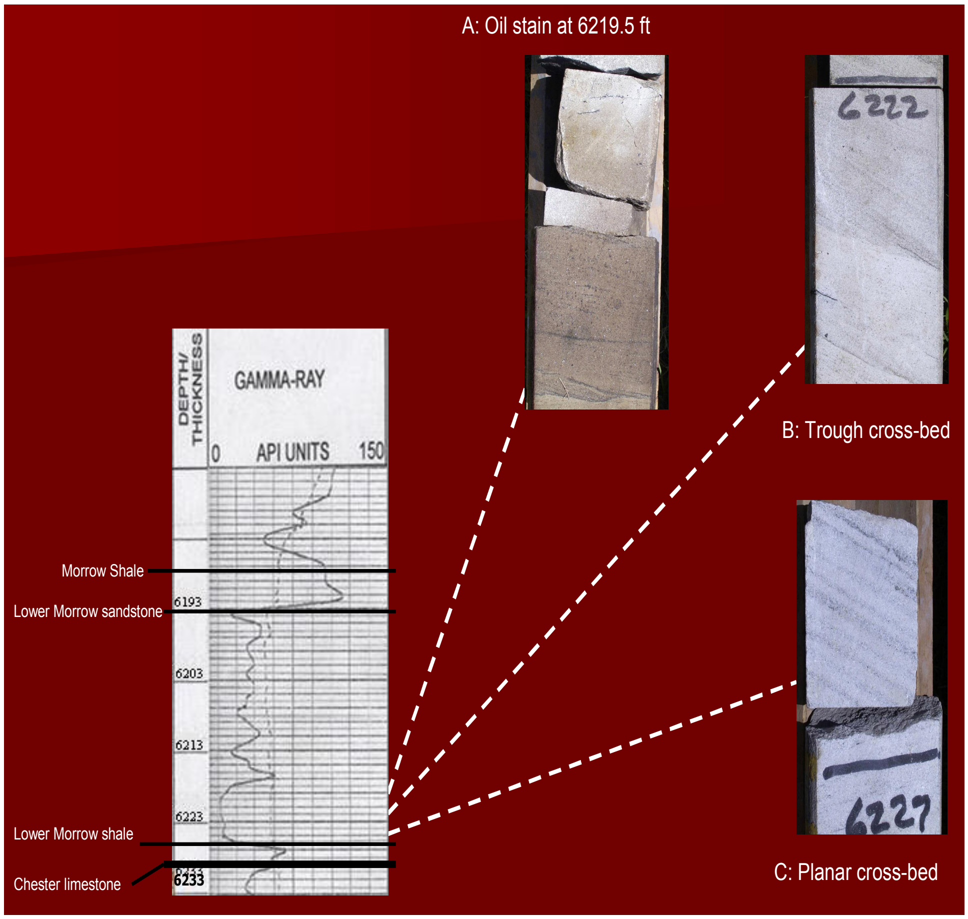


Figure 13. Gamma-ray log signature and representative core pictures showing relative positions of the oil stained interval and trough and planar core beds

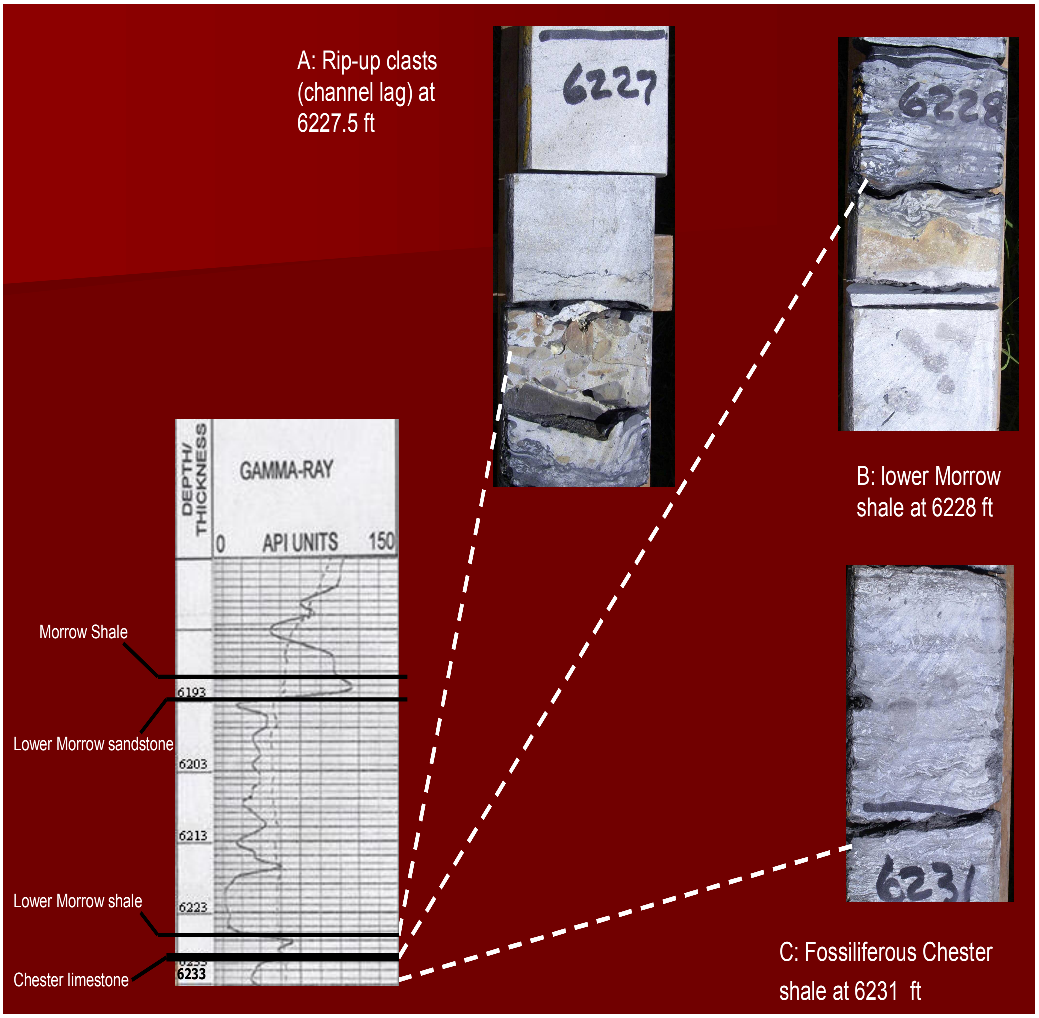


Figure 14. Gamma-ray log signature and core pictures showing the channel lag conglomerate, the contact between the lower Morrow shale and the Chester limestone, and fossiliferous Chester shale

Thin sections were made to determine detrital and authigenic constituents and characterize reservoir properties. Figure 15 contains photomicrograph images showing various detrital and authigenic constituents of the sandstone.

Detrital Constituents

The dominant detrital grain is quartz (Figure 15). The quartz grains vary from fine to medium grained and are mostly sub-rounded. Chert and chalcedony are relatively abundant. Phosphate, composite quartz and sedimentary rock fragment occur infrequently. Tourmaline, glauconite and mica are rare. Feldspar grains are not evident. Godard (1981), Al-shaieb et al (1989), Puckette et al (1996), suggested that feldspars were very common in the upper Morrow. The lower Morrow sandstone is classified as quartzarenite, which agrees with the finding of Godard (1981).

Authigenic Constituents

Authigenic components in the lower Morrow sandstone include quartz cement, calcite, kaolinite, dolomite and pyrite. The most abundant cement is calcite, which reduces porosity and permeability. Dolomite also occur as pore filling cement. Pyrite is a common constituent. Kaolinite is common as a pore filling clay. Godard (1981) also indicates that calcite cement and quartz overgrowth occurred in the lower Morrow.

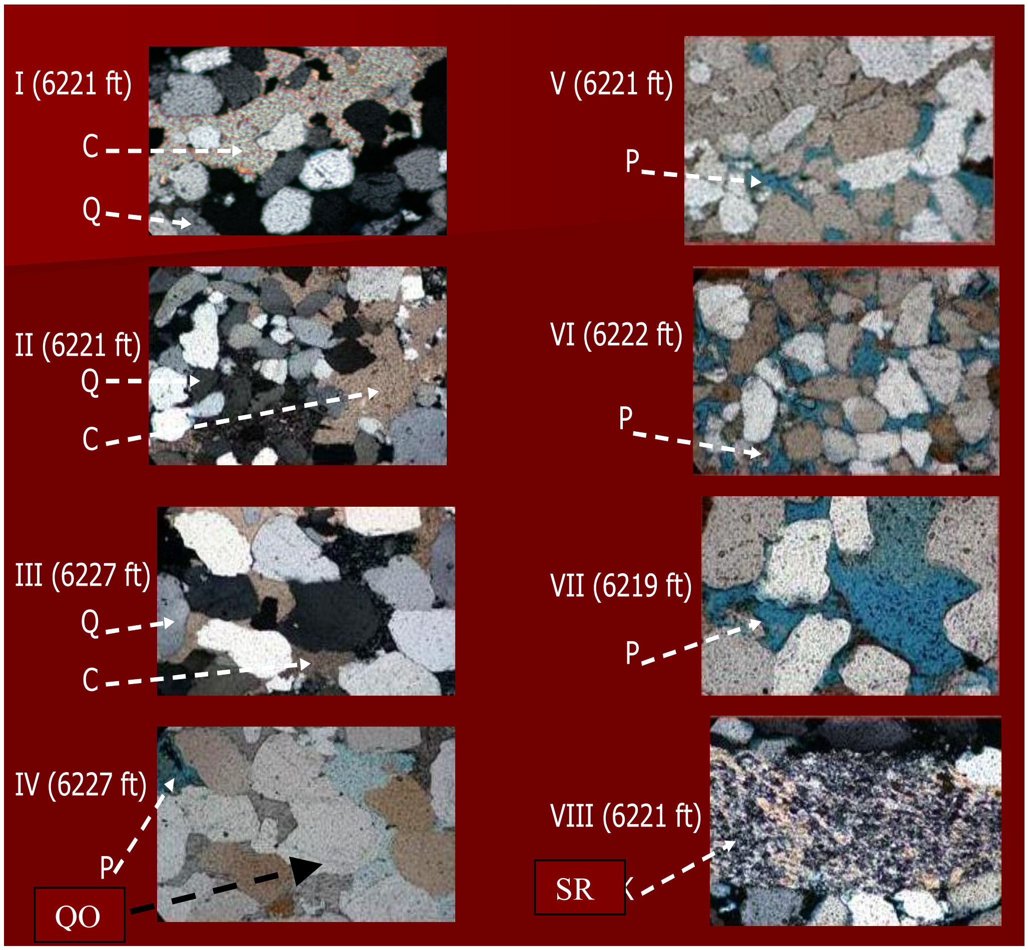


Figure 15. Images of thin section photomicrographs of the lower Morrow sandstone. Frames I-III: C-calcite; Q-quartz. Frame IV: QO-quartz overgrowth, low porosity sandstone (P-porosity) with silica cement. Frames: V-VII: porous sandstone (P-porosity). Frame VIII: sedimentary rock fragment (SR).

Electron Microprobe Analysis

Electron microprobe analysis was used to confirm mineral composition determined by thin section analysis. An electron microprobe is a microscope that allows the chemical analysis of small areas of a sample. Samples are stabilized in a vacuum, and bombarded by a focused electron beam. Bombardment causes the emission of x-rays, which are spectrally analyzed to determine elemental composition. Both qualitative and quantitative data can be generated. The electron beam generates secondary electrons, backscattered electrons, characteristic x-ray, and continuous x-rays. Each element emits distinct characteristic x-ray spectra that are produced when the ionizing beam hits an atom. Electrons in the atom are dislodged and replaced. Electrons are released as a characteristic x-ray of the element of interest.

Accuracy for the electron microprobe is about +/- 1% and the detection limits are usually at about 50 ppm (Catlos, 2005). Electron microprobe analysis was used to determine the element composition of sandstone samples taken from the core obtained from Section 20 T. 26 N., and R. 19 W. in Woodward County, Oklahoma.

Methods

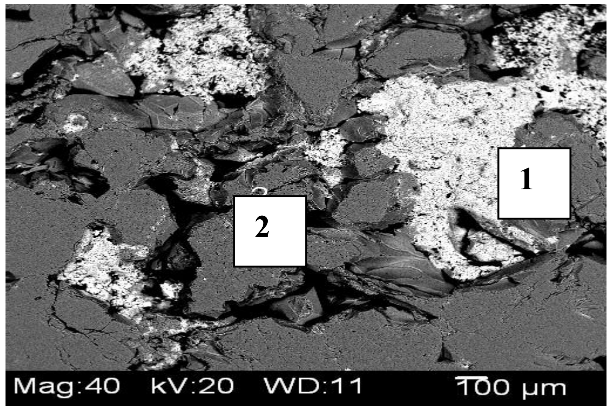
Representative samples were taken from the core and prepared for analysis. Each sample was cleaned using a cleaning solution, and distilled water. Samples were placed in the sonicator as part of the cleaning process. The sonicator removed any remaining contaminants from the coring and sampling process. The samples were placed in a brass rings and a hardening solution was added prior to analysis. Each sample was examined to determine the sandstone composition. Backscattered images were obtained to map each sample and show the elemental distribution. Figure 16 shows a list of images obtained from the electron microprobe and brief descriptions.

Image	Type	Brief Description
Figure 16	Backscattered Image	Sample 1 x-ray image
Figure 17	Backscattered Image	Sample 2 x-ray image
Figure 18	EDS spectra	Sample 1 Compositional peaks
Figure 19	EDS spectra	Sample 2 Compositional peaks
Figure 20	Element Map (3D)	Sample 1 Compositional data

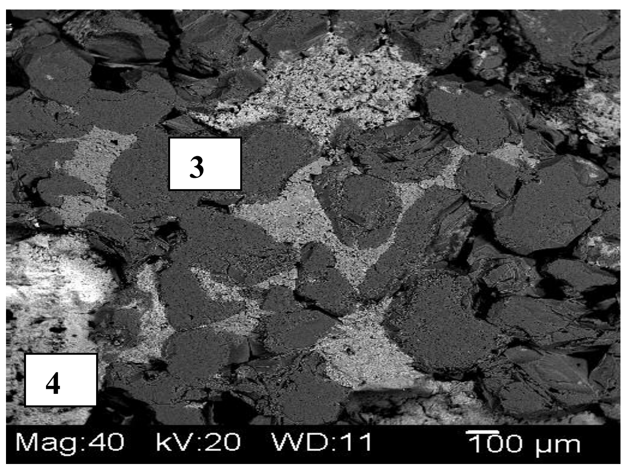
Figure 16. Table showing electron microprobe analysis data

The first image (Figure 17 A) is a back scattered image of a section of the first sample (sample 1). Figure 18 is a backscattered image for sample 2. The back scattered image indicates that two major elements are evident. The bright and dark colored elements are labeled #1 and #2 respectively. The energy dispersive spectra (EDS) of the light and dark colored elements are shown in Figures 19 (A) and (B) respectively. The Fe peak in Figure 19 (A) indicates that, the bright spot (location #1) in Figure 17 (A) is composed of mostly iron (Fe) and is likely the mineral pyrite. The presence of pyrite was confirmed by thin section microscopy. The EDS spectra (Figure 18 B) indicates that the dark colored matrix (location #2) found in Figure 17 (A) is composed of mostly silica along with traces of oxygen. The presence of elemental silica is interpreted as an indication of the mineral quartz.

Figure 17 B, is a back-scattered image of a different surface area of sample 1. This indicates that there are dark and light colored elements that dominate the surface of the sample. The light colored element appears to be different from the bright colored element seen in the previous image. The EDS spectrum obtained for this sample indicates that the light colored mineral contains a high percentage of calcium. The presence of calcium is interpreted as an indication of the mineral calcite.

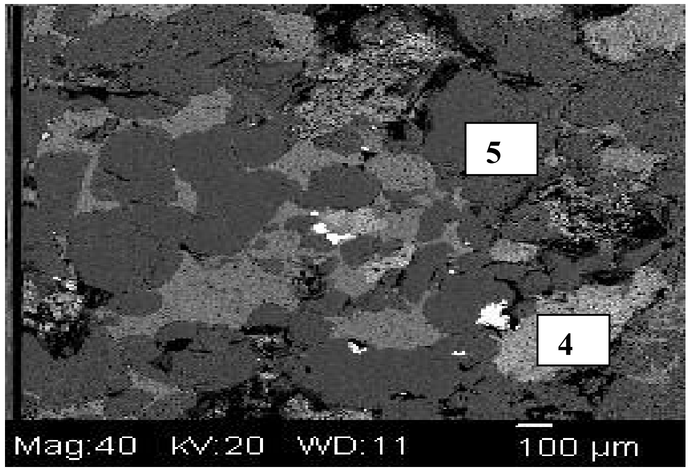


(A)

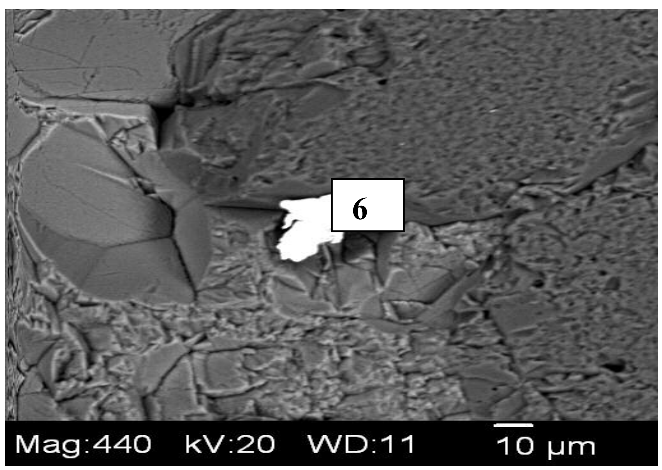


(B)

Figure 17. Back-scattered images for sample 1, showing the elemental composition of the lower Morrow sandstone.
(A) Light colored grains [1] represents pyrite, dark colored grain [2] represents quartz.
(B) Dark colored grains [3] represents quartz, light colored grain [4] represents calcite.



(A)



(B)

Figure 18. Back-scattered images for sample 2 showing the elemental composition of the lower Morrow sandstone.
(A) Light colored grains [4] represents pyrite, darker colored grain [5] represents quartz.
(B) Light colored grain [6] represents copper.

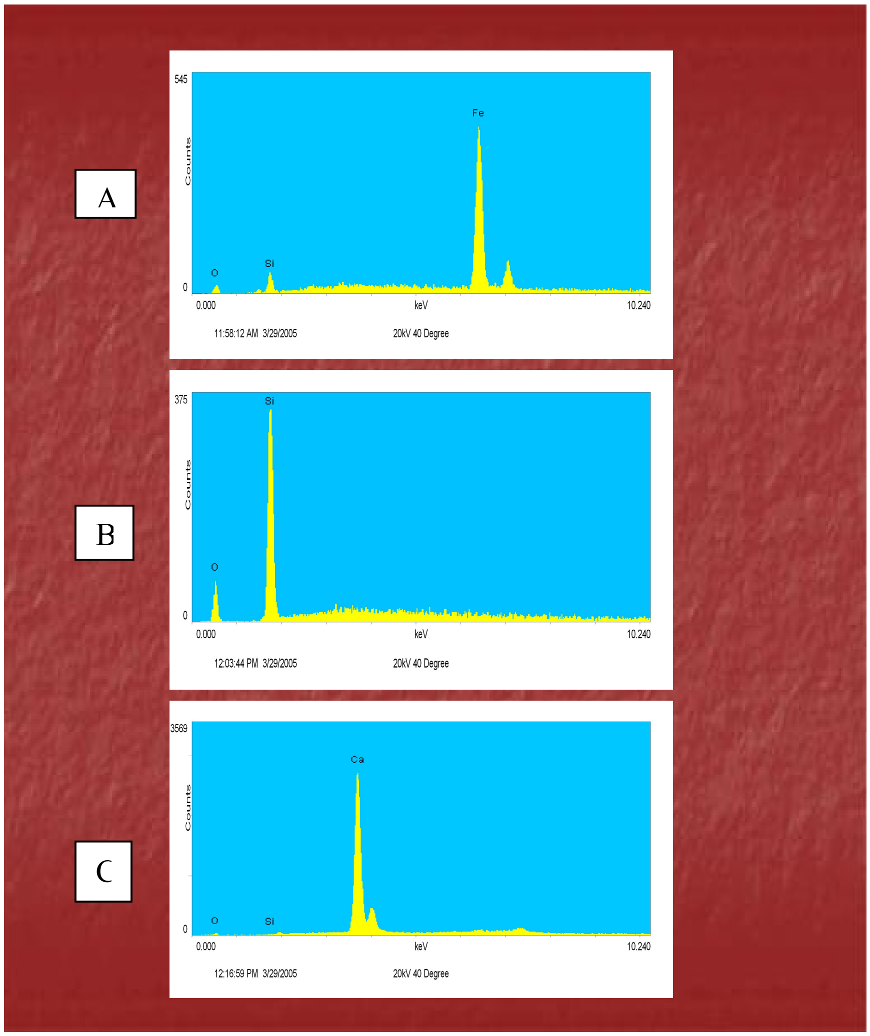
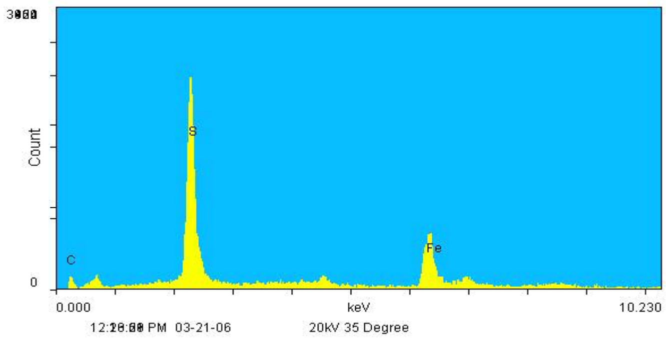


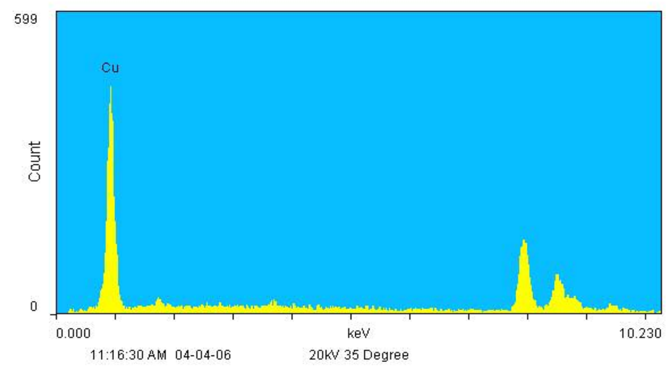
Figure 19. Energy dispersive spectrum (EDS) from sample 1 of the lower Morrow sandstone.
(A) EDS spectra with characteristic peak for Fe; (B) EDS spectra with characteristic peak for Si; (C) EDS spectra with characteristic peak for Ca.

Figures 18 A and 18 B are back-scattered images of sample 2 from the cored interval. This image is very similar to the back scattered image obtained from sample 1. Figure 20 is an energy dispersive spectra (EDS) image for the bright portion of the sample 2 shown in Figure 18. The EDS spectrum image also indicates that the two samples (1 and 2), have similar elemental composition. The sample contains iron, sulfur, silicon, oxygen, calcium, carbon and copper. The iron, sulfur and copper, are believed to be derived from pyrite. The other elements indicate that the minerals quartz and calcite are present.

The very dark colored holes evident in the back scattered images (Figures 17 and 18) represent the voids in the core sample. These voids represent general types of porosity in the sandstone. The back scattered images also indicate that the pyrite and calcite are distributed between grains and occupy the pore spaces.



(A)



(B)

Figure 20. EDS spectrum for sample 2 of the lower Morrow sandstone.
(A) EDS spectra for elemental C, S and Fe; (B) Elemental spectra for Cu

The 3-d image (Figure 21) is an element map of sample 1 that shows the relative percentages of the various elements in a sample. The image indicates that the analyzed sample is approximately 60% silicon (quartz), 15% calcium (calcite), 15% iron (pyrite) and about 10% is empty (porosity). The wireline log for the core also suggests an average of 10% porosity. The sample is sandstone; the high percentage of silica compared to the rest of the elements reflects the expected abundance of quartz. The presence of calcium and iron, infers that calcite and pyrite cements are common. Thin section analysis confirmed the abundance of calcite and pyrite cementation in the sample.

The electron microprobe analysis confirms the constituents of the lower Morrow sandstone that was indicated from the thin sections. Godard (1981), Al-shaieb et al (1989), Puckette et al (1996), suggested that feldspars were very common in the upper Morrow. Elements such as aluminum, potassium and sodium were not present in the EDS images and this also confirms that feldspars are not apparent in the lower Morrow sandstones. The lack of feldspar in the lower Morrow, distinguishes it from the upper Morrow. This could be the result of longer sediment transport or different provenance for the respective units.

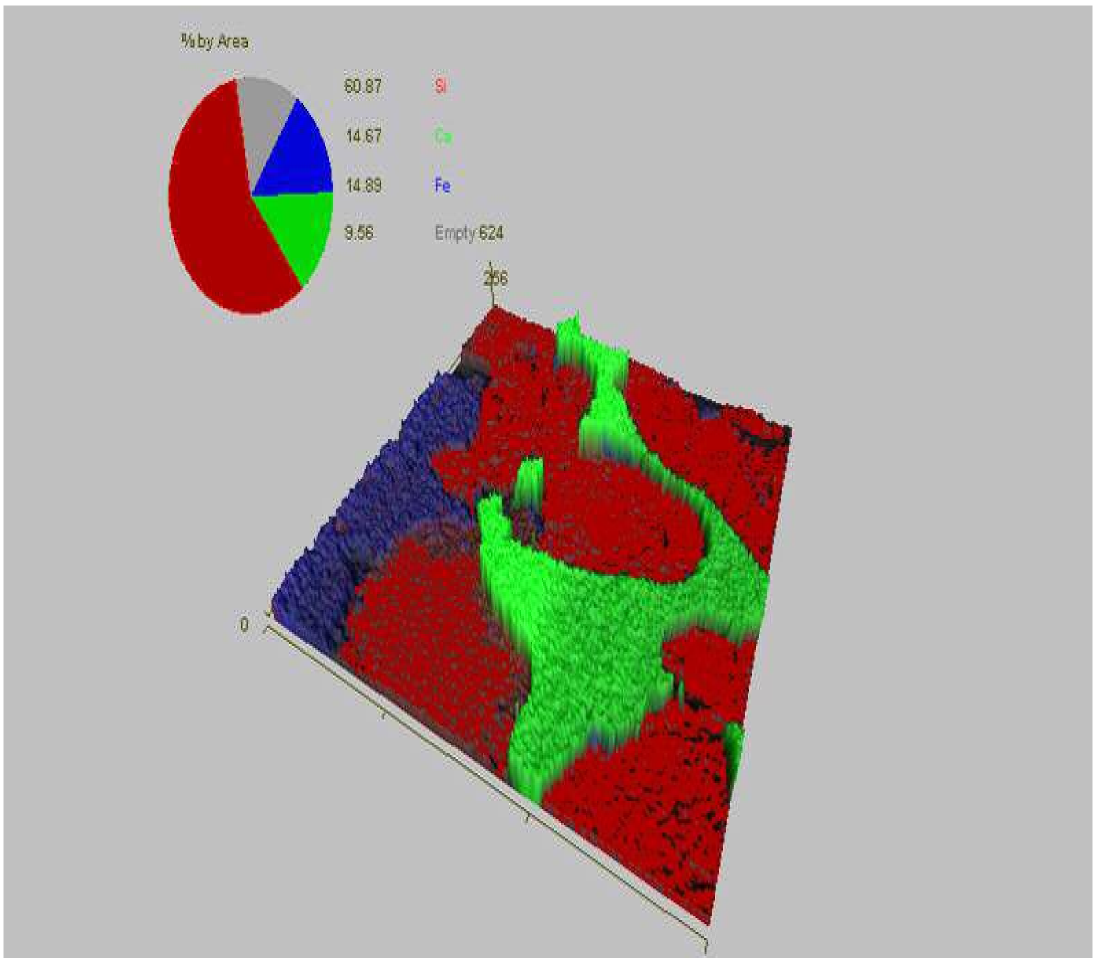


Figure 21: 3D Image map showing color coded element proportions and individual relationships. (Green-calcite, Blue-pyrite, Red-quartz, Gray-porosity)

CHAPTER VI

DEPOSITIONAL ENVIRONMENT AND PETROLEUM GEOLOGY

The environment of deposition of the lower Morrow interval was determined using integrated data including; core, thin sections microscopy, structure maps, isopach maps, production maps and cross sections. The data indicate the lower Morrow was deposited in one major, sand-dominated setting.

The examination of the core and thin sections reveals that the lower Morrow Keyes sandstones are generally moderate to poorly sorted and contains fining-upward sequences. Sedimentary structures in the Keyes sandstone include ripples, horizontal bedding and medium-scale, planar and trough cross-bedding. Clay and limestone rip-up clasts at the base of the sandstone (6227 feet) are evidence that the lower Morrow sandstone depositional system was high energy and that clasts were sourced from the side and / or base of the channel. Limestone clasts were likely sourced from the underlying Chester limestone.

The Chester carbonate represents the last episode of shallow water Mississippian deposition. The carbonate was weathered (oxidized) prior to being flooded by a marine transgression that is represented by the dark marine Morrowan shale. The marine shale is overlain by the lower Morrow fluvial sandstone, which is juxtaposed on the Morrow marine shale. Succeeding the fluvial sandstone is sandstone with flowage features.

Interbedded shale becomes common. The fine grained nature, lack of cross-beds and burrowing in this interval indicate a low energy and possible estuarine deposition. This interval is succeeded by a crumbly shale which does not appear to contain normal marine fossils. This shale may represent weathering beneath the pre-Atokan unconformity. The uppermost limestone in the core represents the Atokan transgression.

The geometry of the lower Morrow sandstone suggests that the lower Morrow was most likely deposited in a fluvial environment. Correlation of the gamma ray signatures suggest that there was one dominant depositional environment throughout the study area. The gamma ray curve for the lower Morrow sandstone shifted from 15 API units at the base of the interval, to 35 API units at the top. This shift can be described as a fining upward signature. Thin-section microscopy confirmed that there was a general decreasing grain size across the lower Morrow Keyes sandstone interval.

Subsurface mapping, which included structure, isopachs and production maps, was a relevant tool in determining the main environment of deposition of the lower Morrow sandstone. A channel-like pattern was present towards the western part of the study area (T. 24 N.-T. 27 N., R. 18 W.-R. 21 W.). The isopach maps indicated that the lower Morrow sandstones thin towards the eastern part of the map. Sandstone thickness varied from 0 feet in the far east (T. 24 N.-T. 27 N., R. 17 W.) to over 40 feet in the west (T. 24 N.-T. 27 N., R. 18 W.-R. 20 W.). Production maps also indicate that Morrow production is predominantly in the western portion of the study area. Cross sections indicate that the lower Morrow sandstone fills valleys that eroded into the Chester limestone. This relationship is interpreted as evidence for incised valley fill deposition.

The rip-up clasts in the core also indicate that the lower Morrow sandstone represents high energy fluvial deposition that could occur in valley fill deposits.

The integration of the evidence derived from core, subsurface mapping and well log analysis, suggests that the lower Morrow sandstone represents an incised valley fill deposit that is dominated by a fluvial deposition at the base. Specific criteria for an incised valley fill include, (1) the juxtaposition of the fluvial facies on Morrow marine shale or Chester marine limestone, and (2) the erosion of these units prior to lower Morrow sand deposition. The sandstone becomes more clay rich and fine grained toward the top. This interval may be of estuarine origin because of the fine grained nature, lack of cross-beds and burrowing, which indicates a low energy deposition. Sonnenberg (1990) also suggested that the upper portions of the valley fill were mostly of estuarine origin.

Incised valley fill deposits in the Morrowan are recognized as important oil and gas producing reservoirs (Sonnenberg, 1990; Wheeler et al., 1990; Krystinik and Blakeney, 1990; Gerken, 1992; Al-shaieb, 1995; Bowen and Weimer 2004) due to the encasement of the sandstone in Morrow shales. These shales are believed to be the hydrocarbon source rock for Morrow reservoir, and TOC values (18%) for the shales measured by Buruss and Hatch (1989) suggest that the shales had good generation potential. Buruss and Hatch (1989) also suggested that Morrowan organic matter is both oil and gas prone, but gas was produced mostly from the Morrow in western Kansas. Bowen et al., (1990) indicated that production from the Morrow sandstones in eastern Colorado is dominantly gas.

Rascoe and Adler (1983) interpreted the Morrow reservoir origins as valley fill, deltaic, offshore bar and beach deposits. The Morrow reservoirs are often described to be stratigraphically trapped in valleys in which encasing Morrow shales act as a seal (Bowen et al., 1990; Al-Shaieb and Puckette, 2001).

Production from the lower Morrow sandstone is wide-spread across the study-area. The production map (Figure 22), shows that most production is located towards the western portion of the map. Production does not extend into the eastern portion because the Morrow Formation thins towards the east and is eventually truncated (Figure 22).

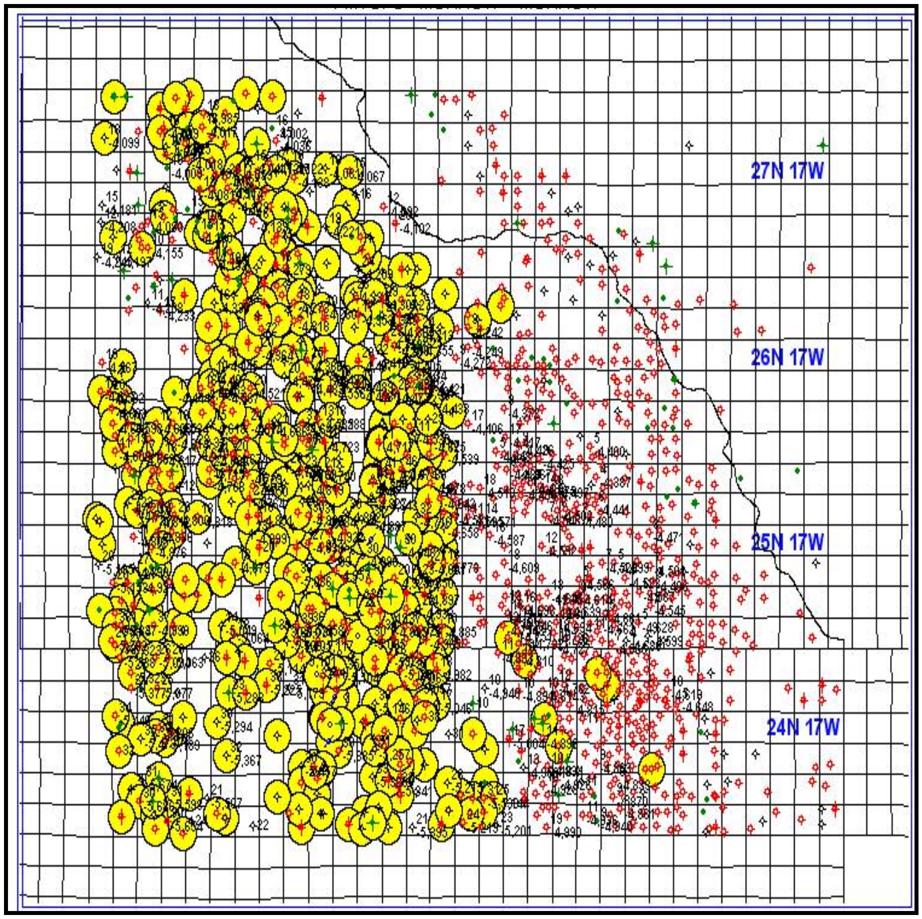


Figure 22. Morrow production map. Yellow circled wells produced from Morrow reservoirs. Map indicates that Morrow production does not extend to the east.

Reservoir Properties and Facies

A correlation of core description to porosity and permeability measurements indicates that in general, the better porosity and permeability occur in the fluvial sandstone. Porosity and permeability values decrease markedly in some estuarine rocks as a result of the presence of detrital clay and carbonate cement. The porosity and permeability data across the core are shown in Figure 23. Average porosity and permeability values obtained from the core for the estuarine sandstones are 10.9 % and 80 md respectively. Average porosity and permeability for the fluvial sandstones are 15 % and 253 md respectively. Thin section photomicrographs showing low porosity estuarine sandstones and high porosity and permeability fluvial sandstones are shown in Figure 24.

Depth (feet)	Porosity (%)	Permeability (md)	Interpreted depositional environment
6193-6193.7	11.8	158	Estuarine
6194-6194.8	15.2	230	Estuarine
6194.9-6152.2	12.4	64.0	Estuarine
6196-6196.6	8.9	7.27	Estuarine
6197.7-6197.9	7.0		Estuarine
6198-6198.4	8.9	0.530	Estuarine

6199-6199.5	9.9	0.467	Estuarine
6200.4-6200.9	11.2	0.568	Estuarine
6201.3-6201.7	11.2	0.368	Estuarine
6202-6202.6	10.5	0.517	Estuarine
6203.6-6203.9-	7.8	0.432	Estuarine
6204.1-6204.6	7.4	0.091	Estuarine
6205.2-6205.4	9.5	24.0	Estuarine
6206.1-6206.6	14.6	101	Estuarine
6207.7-6208	16.3	741	Estuarine
6208-6208.4	15.5	610	Estuarine
6209.2-6209.5	11.3	105	Estuarine
6210-6210.4	12.0	51.8	Estuarine
6211-6211.3	10.6	5.78	Estuarine
6212.2-6212.4	11.3	7.34	Estuarine
6213.4-6214	12.3	62.5	Fluvial
6214.3-6214.9	10.5	33.6	Fluvial
6215-6215.5	9.8	12.0	Fluvial
6216.3-6216.6	12.0	72.4	Fluvial
6217.7-6218	12.3	62.5	Fluvial
6218-6218.7	15.2	267	Fluvial
6219-6219.3	16.5	535	Fluvial
6220.3-6221.0	18.6	649	Fluvial
6221.3-6222	15.5	374	Fluvial

6222.3-6222.8	14.1	274	Fluvial
6223.3-6223.7	13.9	142	Fluvial
6224.6-6224.9	15.6	198	Fluvial
6225-6225.6	13.8	162	Fluvial
6226.1-6226.5	9.3	36.791	Fluvial
6227.3	5.9		Fluvial
6228.7-6229	1.0	0.013	Marine

Figure 23.-Core analysis including porosity, permeability and interpreted depositional environment. The sample at 6228.7-6229 feet is Chester limestone, all others are Morrowan sandstone.

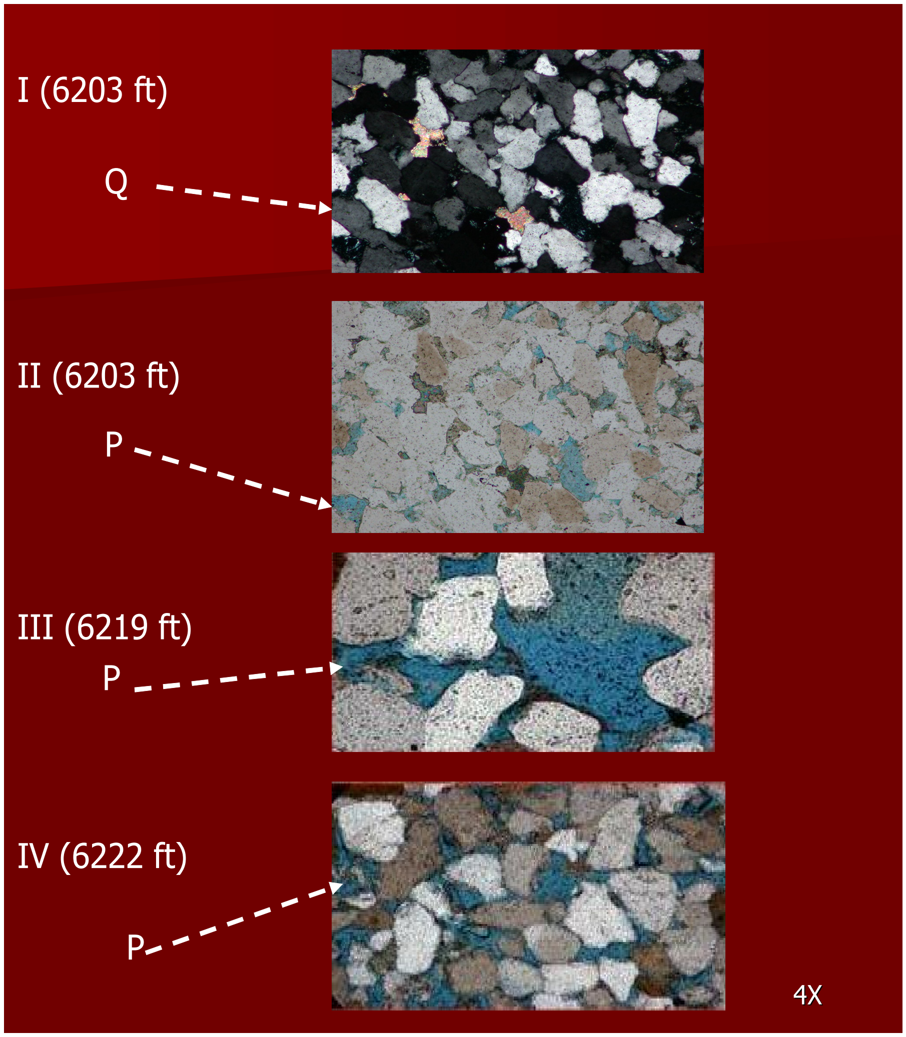


Figure 24: Images of thin section photomicrographs of the lower Morrow sandstone. Frame I: Q-quartz (compaction of quartz grains has reduced permeability). Frame II: lower porosity estuarine sandstone (P-porosity) with silica cement at 6203 feet. Frames III-IV: high porosity and permeability in a fluvial sandstone (P-porosity) at 6219 and 6222 feet.

CHAPTER VIII

SUMMARY

The integration of the various types of data for the lower Morrow sandstone and adjacent beds was used to formulate the following conclusions. The lower Morrow represents deposition in a broad valley that incised the underlying Chester carbonate. The dominant mechanism of deposition appears to be fluvial. The study by Godard (1981), located immediately south of this study suggested that the lower Morrow sands were deposited in a fluvio-deltaic environment. The northern portion of Godard (1981) study overlaps with the southern portion of this study, but there were no indications of a delta-margin deposits in this area. Typical Morrow valley fills are composed of fluvial sandstones at the base and estuarine and margin deposit toward the top. In this study, it is evident that the fluvial sandstones at the base of the valley fill have higher porosity and permeability than the upper estuarine sandstones. The Morrow interval is truncated to the northeast by the pre-Atokan unconformity. Production of gas in the study area is closely related to sandstone thickness. As a result, production is concentrated in the western part of the study area. Specific evidence supporting this interpretation is listed below.

1. Lower Morrow occupies a valley that erodes into the underlying Mississippian Chester.
2. Sandstone distribution patterns indicate north to south trends that suggest channel deposition.
3. Wireline logs indicate sand body geometry that fines upward and is in sharp contact with the underlying shale or carbonate.
4. The core contains sedimentary features such as channel lag conglomerate and planar and trough bedding, indicating fluvial deposition.
5. The lower Morrow sandstone is predominantly quartz, (quartzarenite) but contains chert and authigenic components including kaolininte, pyrite, calcite and dolomite.
6. Sandstone constituents determined by the thin section microscopy was confirmed using electron microprobe analysis.
7. The electron microprobe and thin section microscopy indicated that feldspar is absent in the lower Morrow sandstone and this is different from the findings of the upper Morrow by Godard (1981) and Puckette et al (1996) .
8. The best reservoir properties (porosity and permeability) are in fluvial sandstone (average 15 % porosity and 253 md permeability). Porosity and permeability in estuarine sandstone is significantly decreased (average 10.9 % porosity and 80 md permeability).

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APPENDIX

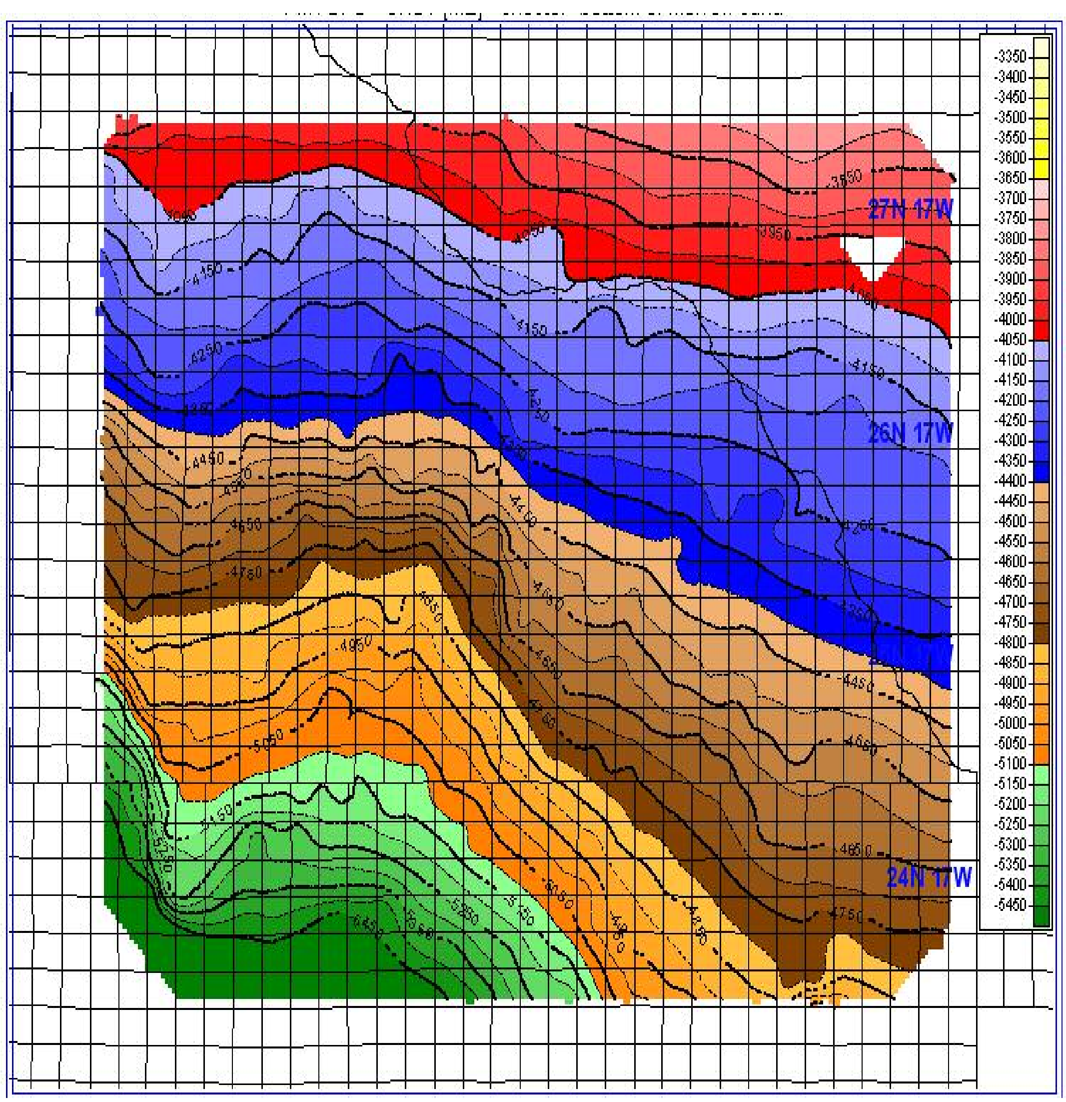

Figure 25. Structure map of Chester limestone (Depth increases from red to blue to green to orange respectively).

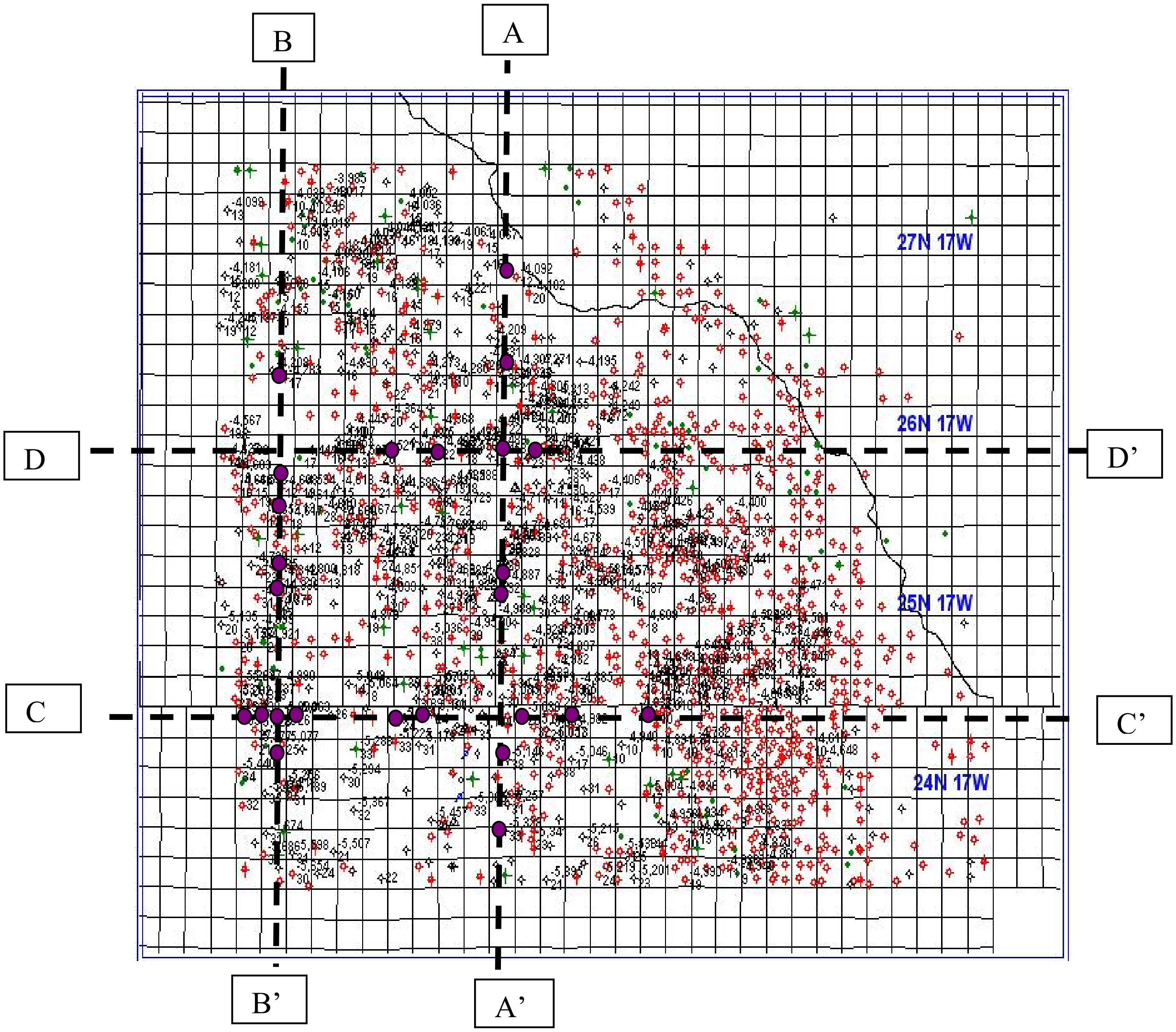

Figure 26. Map of study area showing the locations of cross section lines.

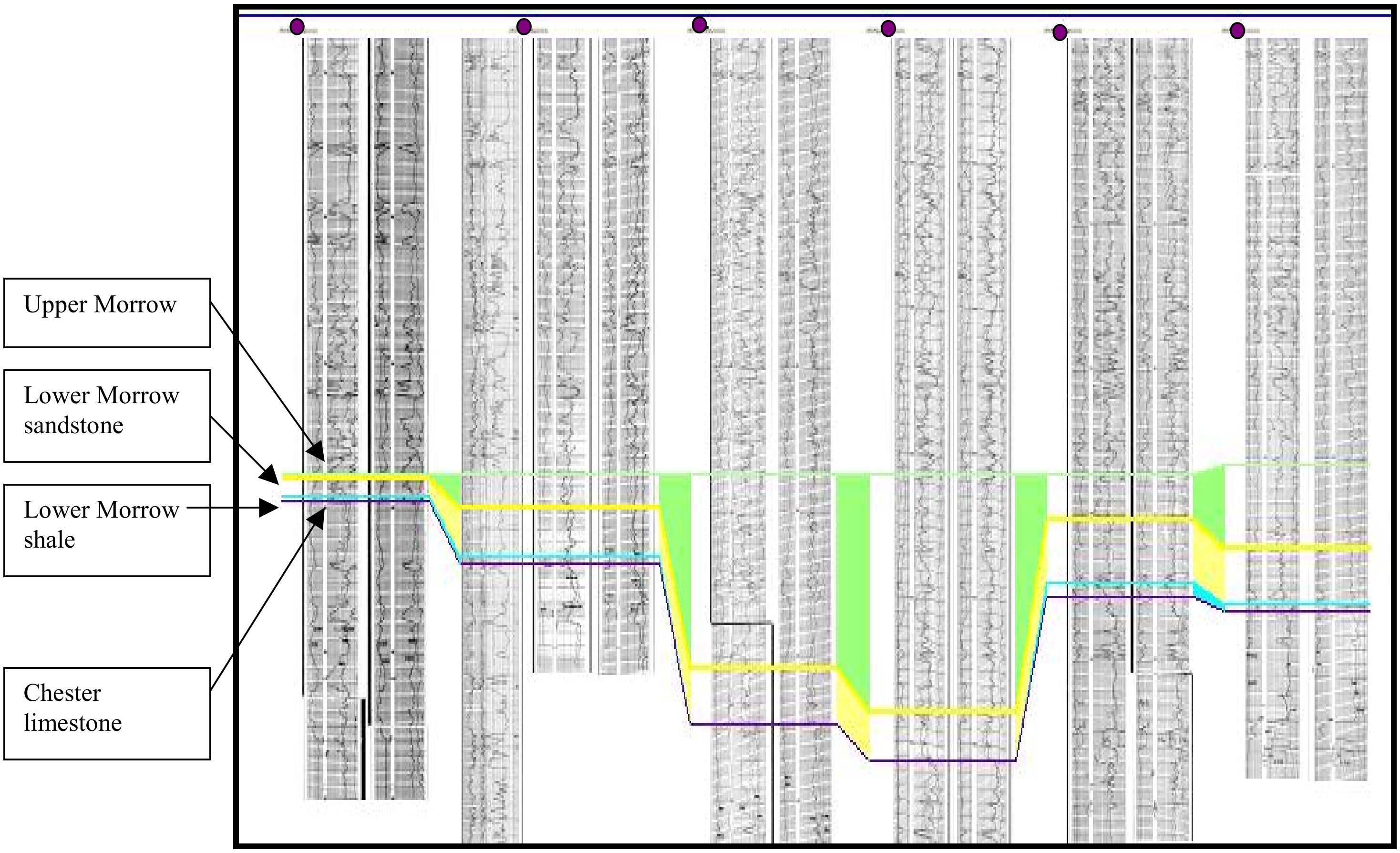

Figure 27. N-S cross section line A-A'. (Green represents top of upper Morrow, yellow is the top of lower Morrow sandstone, blue is the base of lower Morrow sandstone, purple is the top of Chester)

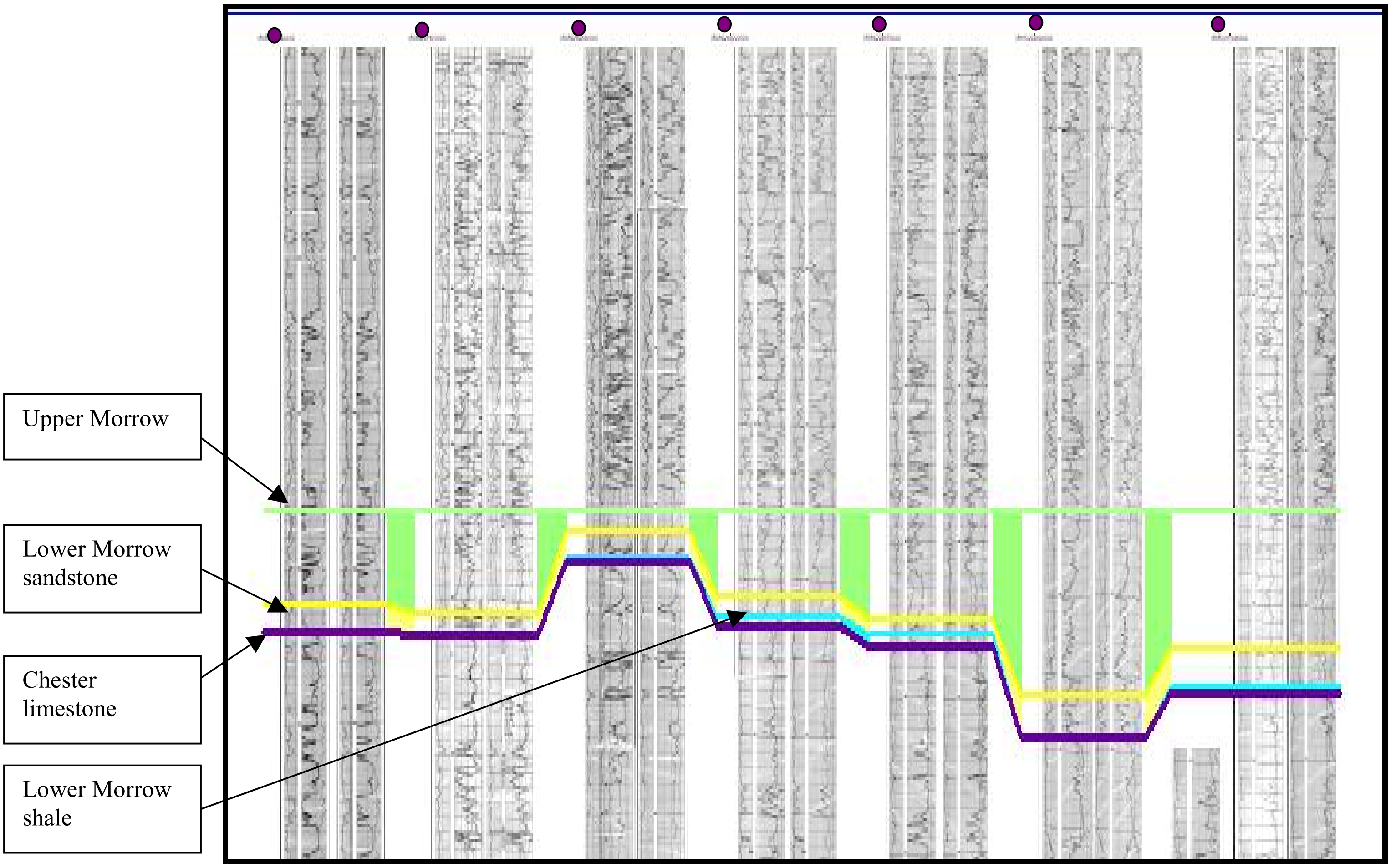

Figure 28. N-S cross section line B-B'. (Green represents top of upper Morrow, yellow is the top of lower Morrow sandstone, blue is the base of lower Morrow sandstone, purple is the top of Chester)

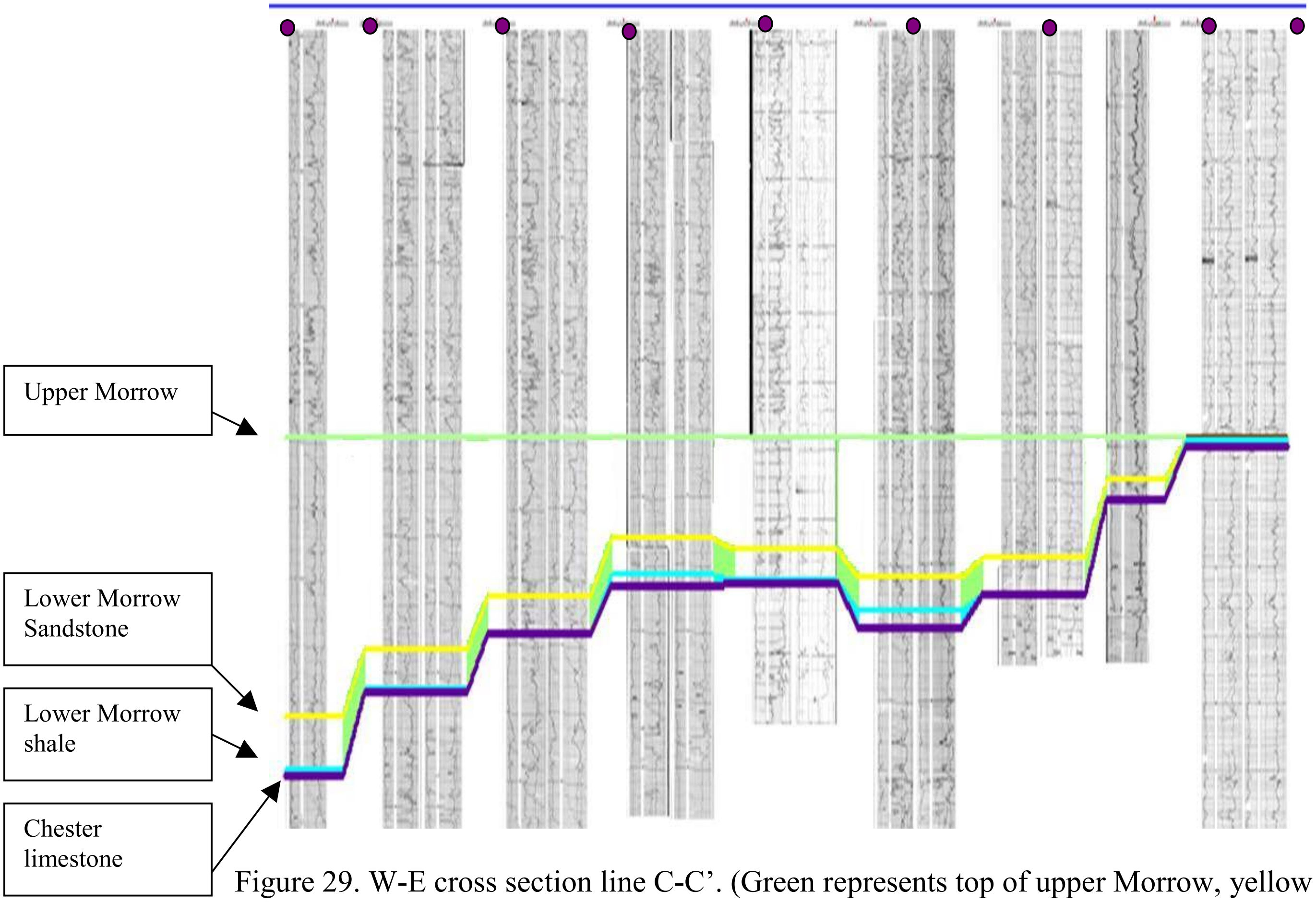

Figure 29. W-E cross section line C-C'. (Green represents top of upper Morrow, yellow is the top of lower Morrow sandstone, blue is the base of lower Morrow sandstone, purple is the top of Chester).

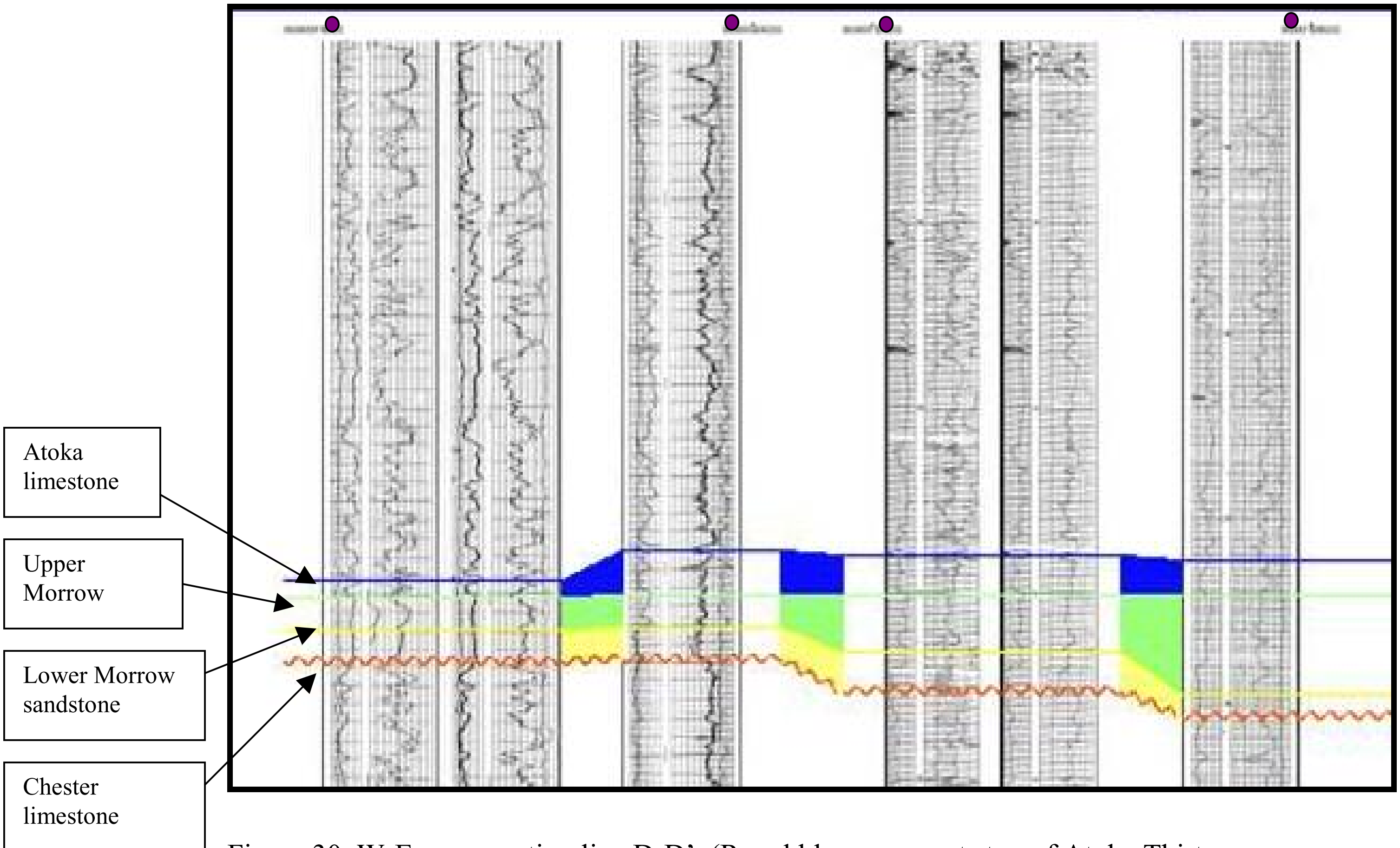

Figure 30. W-E cross section line D-D’**.** (Royal blue represents top of Atoka Thirteen finger limestone, green represents top of upper Morrow, yellow is the top of lower Morrow sandstone, sky blue is the base of lower Morrow sandstone, orange is the top of Chester)

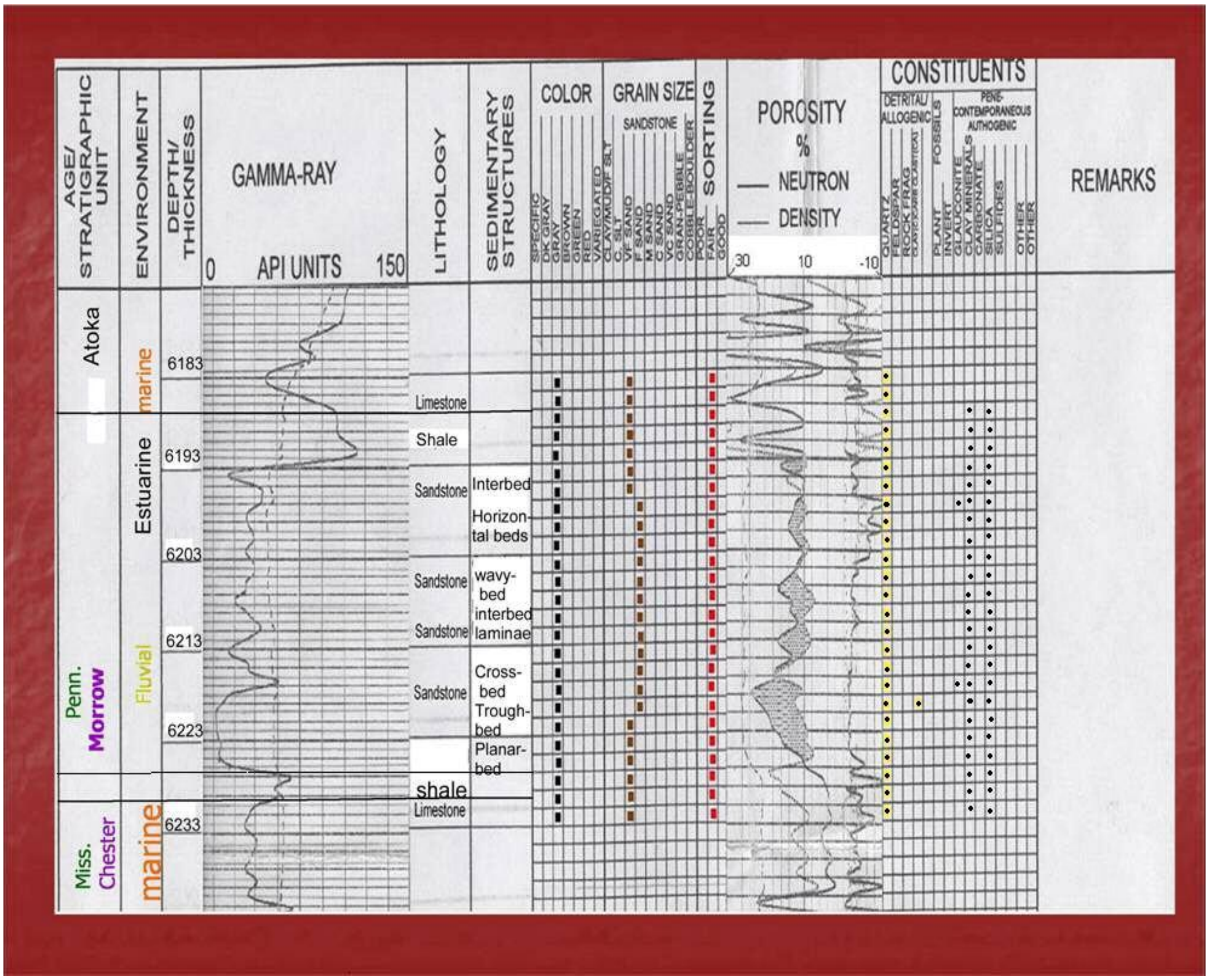

Figure 31. Petrolog for the core from the Marjo Operating Claudia #1 - 20 well in Section 20, T. 26 N., R.19 W. Atoka is situated above the Morrow, which in turn is overlying the Chester. The Atoka and Chester Formations are described as limestones. The Morrow is described as a sandstone with a underlying Morrowan shale unit. Sedimentary structures in the Morrow include horizontal bedding, cross bedding, trough bedding , waxy bedding and planar bedding. Brown, yellow and red colors represent color, grain size and sorting respectively.

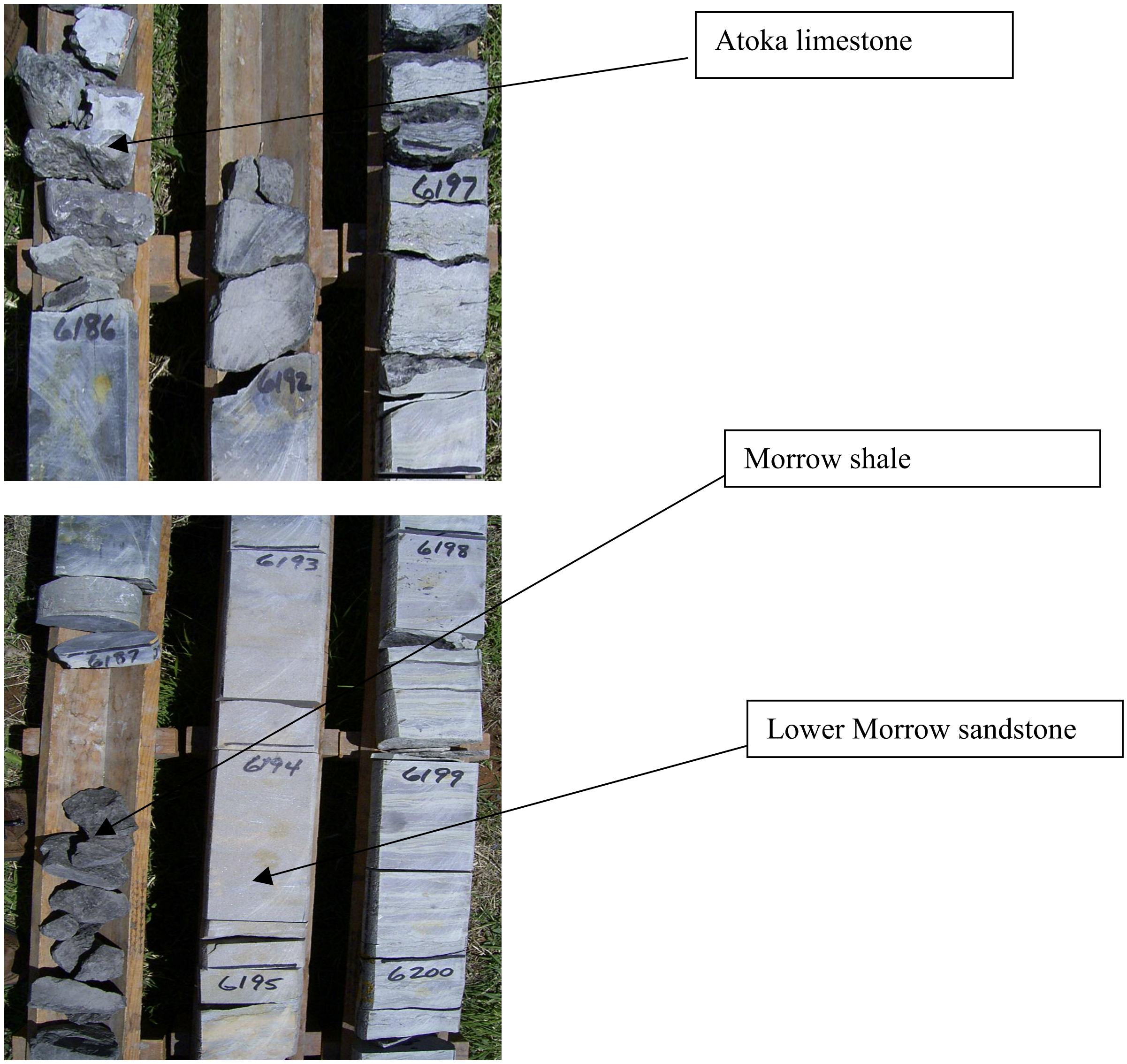

Figure 32. General overview of a section of the cored interval from Woodward County, Oklahoma. Atoka limestone, Morrow shale and lower Morrow sandstone are shown in image.

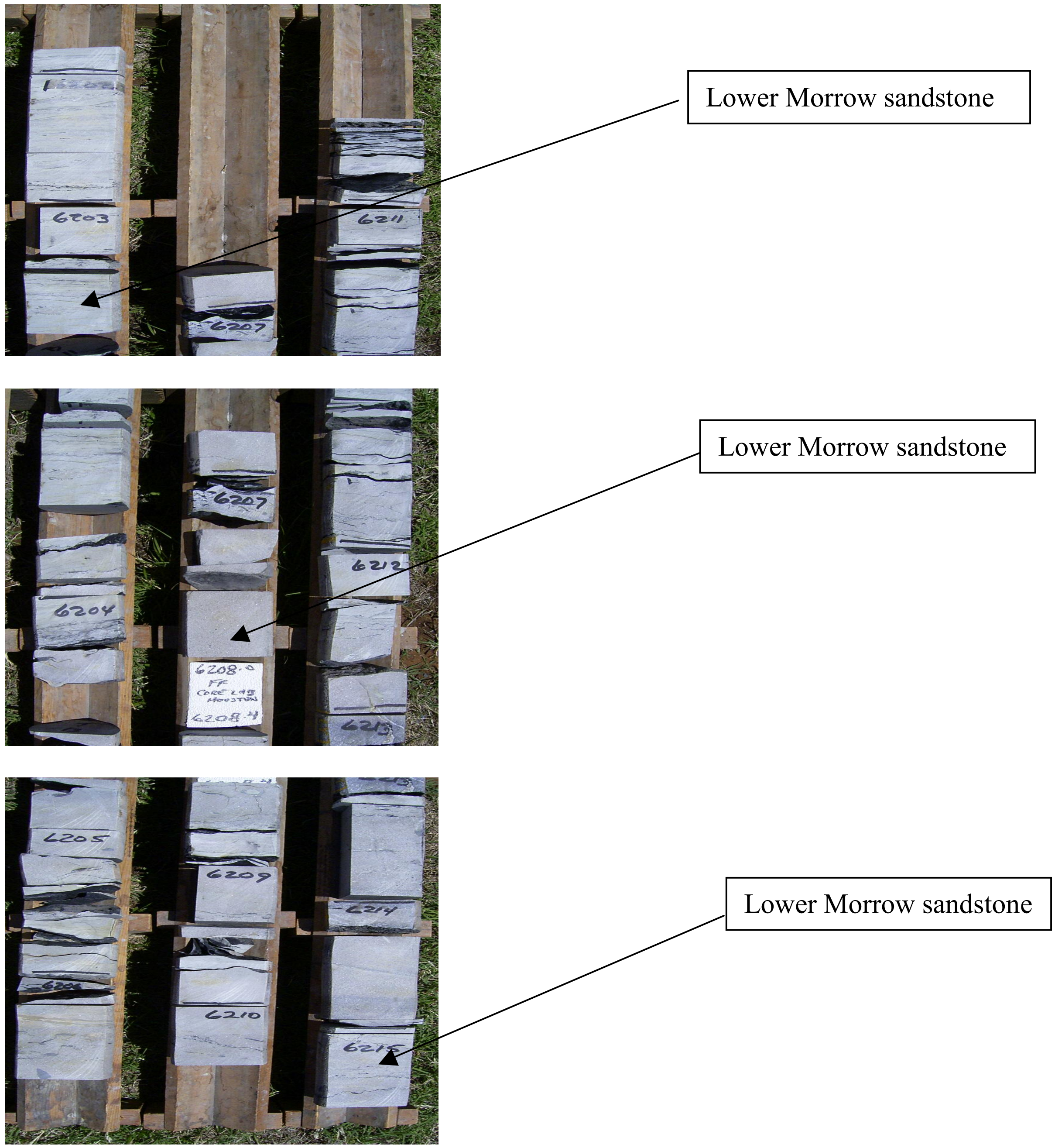

Figure 33. General overview of a section of the cored interval from Woodward County, Oklahoma. Lower Morrow sandstone is shown in image.

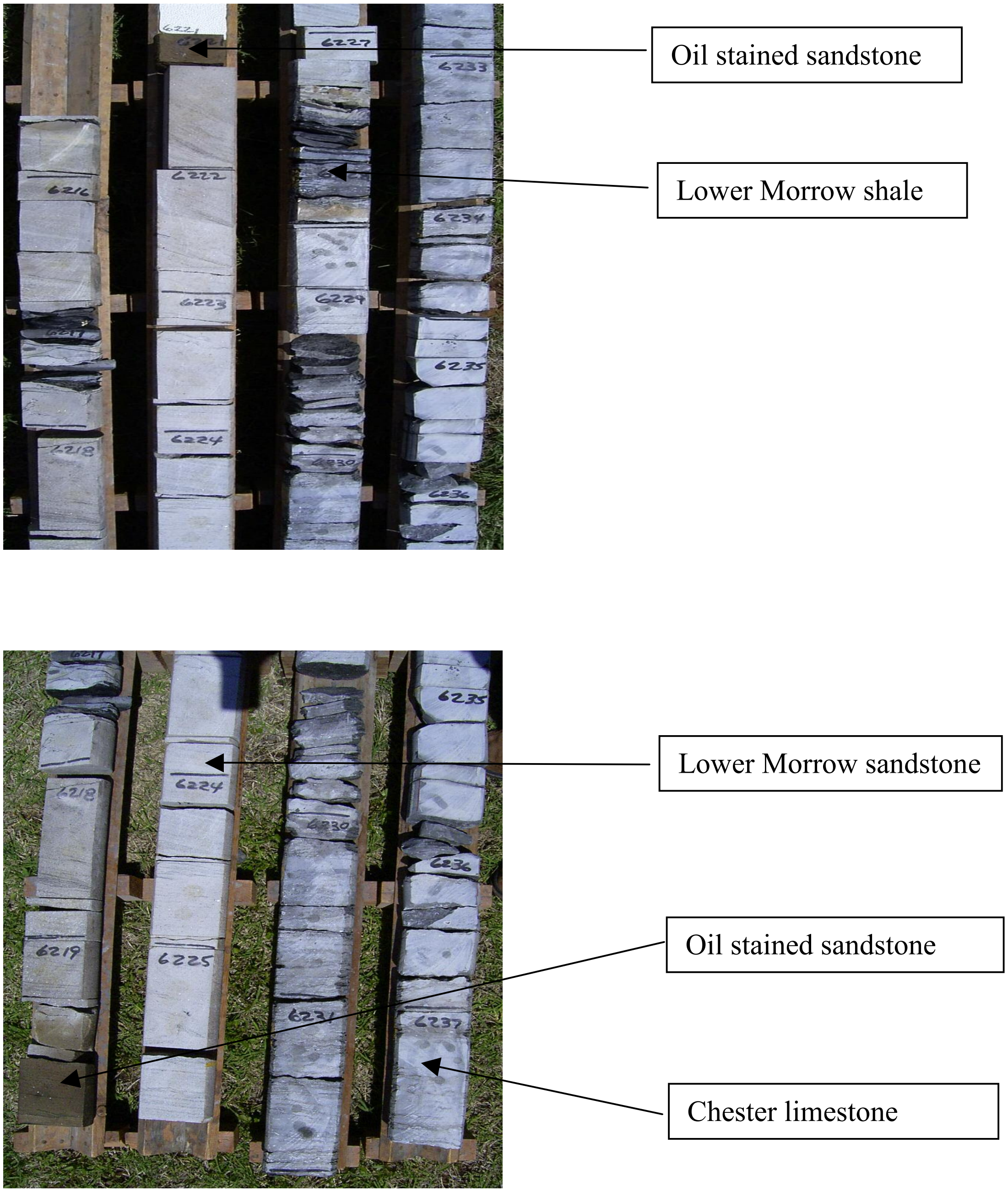

Figure 34: General overview of a section of the cored interval from Woodward County, Oklahoma. Lower Morrow sandstone and Chester limestone are shown in image.

VITA

Temitope Ogunyomi

Candidate for the Degree of

Master of Science

Thesis: DISTRIBUTION, THICKNESS AND RESERVOIR PROPERTIES OF THE LOWER MORROW SANDSTONE ON THE NORTHERN SHELF OF THE ANADARKO BASIN IN HARPER, WOODS AND WOODWARD COUNTIES, OKLAHOMA.

Major Field: Geology

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Experience: Associate Geologist for Chesapeake Energy.

Professional Memberships: SGE, AAPG.

Name: Temitope Ogunyomi Date of Degree: July, 2006

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: DISTRIBUTION, THICKNESS AND RESERVOIR PROPERTIES OF THE LOWER MORROW SANDSTONE ON THE NORTHERN SHELF OF THE ANADARKO BASIN IN HARPER, WOODS AND WOODWARD COUNTIES, OKLAHOMA.

Pages in Study: 72 Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study:

Wire-line logs for over 1500 wells across the townships (T. 24-27 N., R. 17-21 W.) in Woodward, Woods and Harper Counties, Oklahoma were acquired for analysis. The logs provided gamma-ray, resistivity, neutron-density porosity and bulk density signatures that were used to distinguish between strata of the Atoka, Morrow and the Chester intervals. Well data, including production information for the numerous wells across the area were also obtained for the study. Cross sections were constructed as well as structure, isopach and production maps to better understand the lateral extent, structure, distribution patterns, thickness and trends of the sandstones. Internal features and geometry of the lower Morrow sandstones were determined using core, thin section, and electron microprobe analyses.

Findings and Conclusions:

- Lower Morrow occupies a valley that erodes into the underlying Mississippian Chester.
- Sandstone distribution patterns indicate north to south trends that suggest channel deposition.
- Wireline logs indicate sand body geometry that fines upward and is in sharp contact with the underlying shale or carbonate.
- The core contains sedimentary features such as channel lag conglomerate and planar and trough bedding, indicating fluvial deposition.
- The lower Morrow sandstone is predominantly quartz, (quartzarenite) but contains chert and authigenic components including kaolininte, pyrite, calcite and dolomite.
- Sandstone constituents determined by the thin section microscopy was confirmed using electron microprobe analysis.
- The best reservoir properties (porosity and permeability) are in fluvial sandstone (average 15 % porosity and 253 md permeability).

ADVISER’S APPROVAL: Dr James Puckette