5-2014

Subsurface Sequence Stratigraphy and Reservoir Characterization of the Mississippian Limestone (Kinderhookian to Meramecian), South Central Kansas and North Central Oklahoma

Thomas Cahill
University of Arkansas, Fayetteville

Subsurface Sequence Stratigraphy and Reservoir Characterization of the Mississippian Limestone (Kinderhookian to Meramecian), South Central Kansas and North Central Oklahoma

Subsurface Sequence Stratigraphy and Reservoir Characterization of the Mississippian Limestone (Kinderhookian to Meramecian), South Central Kansas and North Central Oklahoma

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Geology

by

Thomas E. Cahill
Pennsylvania State University
Bachelor of Science in Geosciences, 2012

May 2014
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

____
Dr. Walter L. Manger
Thesis Director

______________________________ ______________________________
Dr. Doy L. Zachry Dr. Christopher L. Liner
Committee Member Committee Member

ABSTRACT

Both conventional and unconventional Mississippian reservoirs in the mid-continent are largely comprised of chert-rich carbonates of Osagean and Meramecan age. The conventional reservoir target is the Mississippian “chat,” a high porosity, chert residuum interval found immediately beneath the Mississippian-Pennsylvanian unconformity. The unconventional reservoir target occurs in the lower porosity, cherty, mud-rich intervals that occur in the lower portion of the Mississippian succession.

There has been considerable debate surrounding the sequence stratigraphic interpretations, depositional models, and formation names applied to the reservoir intervals within the subsurface. Another major issue with regard to the subsurface is the stratigraphic position and origin of tripolitic chert development. Previous outcrop studies within the Mississippian outcrop belt, mud logs, and well log correlations have been utilized to facilitate the application of sequence stratigraphy to the subsurface succession. Reservoir intervals appear to be preferentially developed beneath the Osagean-Meramecian and Mississippian-Pennsylvanian boundaries. The proposed depositional model challenges previous assignments of tripolitic chert development to what has been called the Reeds Spring Formation in the subsurface.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my advisor and thesis chair Dr. Walter L. Manger. He led many field trips to the Mississippian outcrops throughout northwest Arkansas and eastern Oklahoma, which provided countless key observations that contributed to the thesis immensely. I am also grateful that he took me in as in advisee after my original advisor left the university to pursue a new career opportunity. I would also like to thank the committee members Dr. Doy L. Zachry and Dr. Christopher L. Liner. Both committee members provided valuable advice and also taught a majority of the cornerstone courses of the graduate program that will be forever useful.

A special thanks goes to Drilling Info Incorporated and the Kansas Geological Survey online databases, as they were the source of all the data used in the thesis. Without access to these, it would not have been possible to complete this thesis.

Another special thanks goes to my family and friends. Without their constant source of positive encouragement and motivation throughout my college career I doubt I would have made it this far.

Last but certainly not least, I would like to thank the University of Arkansas and the Department of Geosciences. I enjoyed my time here and made many great friends. I look forward to being involved in the department for many years to come.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Mississippian reservoirs of the mid-continent are largely comprised of chert-rich carbonates of Osagean and Meramecian age and are truncated at the basal Pennsylvanian unconformity. The Mississippian reservoirs are known in the midcontinent as Mississippian “chat”. In south-central Kansas and north-central Oklahoma, these reservoirs have been impressive oil and gas producers, yielding 278 million bbl of oil and 2.4 tcf gas in Kansas (Watney *et al.*, 2001) and 105 million bbl of oil and 1 tcf gas in Oklahoma (Rogers, 2001) as of 2001.

Both conventional and unconventional reservoirs are targeted throughout the Mississippian interval. Mississippian fields flank Late Mississippian and Early Pennsylvanian structures in Kansas that also extend into Oklahoma: the Central Kansas uplift, the Pratt Anticline, and Nemaha Uplift (Montgomery *et al.*, 1998; Watney *et al.*, 2001). In Kansas, conventional reservoir lithologies are a spiculitic chert found immediately below the Mississippian-Pennsylvanian boundary that has porosities up to 25% and permeabilities up to 500 md. Down-dip there is a transition to a tight bedded chert interval (Watney *et al.*, 2001; Mazzullo *et al.*, 2009). Due to their lower porosity and permeability, these units were commonly avoided as a target (Watney *et al.*, 2001). After a period of drilling inactivity, the 2000’s brought a revitalized interest in the Mississippian chat, including once avoided tight bedded chert, due to advancements in drilling techniques (Montgomery *et al.*, 1998; Mazzullo *et al.*, 2009).

One disadvantage that has plagued the Mississippian chat was a failure to produce economically on a consistent basis. Major factors contributing to this are reservoir compartmentalization and a complicated digenetic history.

1.1 Previous Work

The Mississippian section has been extensively studied for the past several decades. Initial studies were primarily focused on paleogeography and shelf position, regional stratigraphy, and general structure (Laudon 1939; Merriam and Goebel, 1951; Thorton, 1964; Gutshick and Sandberg, 1983). In the latter years, it was the realized that the Mississippian strata represented a complex post-depositional history with erosion surfaces and lateral heterogeneity (Rogers *et al.*, 1995; Montgomery *et al.*, 1998; Rogers, 2001; Watney *et al.*, 2001, Mazzullo *et al.*, 2009; Kremen, 2010; Friesenhahn, 2012; Costello *et al.*, 2013; Wittman, 2013). Those studies began focusing on reservoir characterization and tying in unconformities to an updated sequence stratigraphic framework.

Rogers *et al.* (1995) specifically focused on the stratigraphy, depositional model and reservoir characterization of the Glick Field in Kiowa and Comanche counties, Kansas. The only reservoir interval within the Glick Field is spiculitic chert of Osagean age (Rogers *et al.*, 1995). That informal term “chat” was coined to emphasize the drill bit “chatters” as it penetrates the chert. Sponge spicule bioherms represent the reservoir interval, and stratigraphic traps develop where the spiculitic facies pinch out into tighter limestones to the south and west (Rogers *et al.*, 1995).

Montgomery *et al.* (1998) presented a comprehensive geologic overview of the Mississippian spiculitic chert reservoirs in southern Kansas. Stratigraphic cross sections, seismic profiles, petrophysical properties, and two field case studies provided basic stratigraphic relationships and noted the occurrences of Mississippian chat. The low resistivity (1-8 ohm-m) and high porosity (>30%) make the chat easily distinguishable in resistivity and porosity well logs (Montgomery *et al.*, 1998). The low resistivity could be caused by high amounts of bound water within microporosity (Montgomery *et al.*, 1998). Three “chat” types were differentiated, the first type being primary *in-situ* chert at the top of the Osage and base of Meramec, the second type being *in-situ* chert that has been weathered at the Osage-Meramec unconformity, and finally the third type being chert conglomerate immediately above the Osage unconformity (not related to the Mississippian-Pennsylvanian unconformity) (Montgomery *et al.*, 1998).

Rogers (2001) looked at the stratigraphy, petrophysics, and diagenesis of Mississippian chat fields near the Nemaha Uplift in north-central Oklahoma. Typically, low resistivity (1-2 ohm-m) and high porosity (>25%) intervals are recognized on resistivity and porosity logs (Rogers, 2001). Archie's equation shows high water saturation values (60-100%), where anything greater than 80% water saturation should be deemed non-commercial (Rogers, 2001). The high water saturation values are attributed to high irreducible water filing microporosity (Rogers, 2001). Proposed diagenetic scenarios recoginzed two different types of chat. Facies are either deposited or transported to a setting below wave base, where silica replacement occurs. Sea level falls causing for meteoric water to create secondary porosity via dissolution processes (Rogers, 2001).

Watney *et al*, (2001) examined eight Mississippian fields in south-central Kansas and suggested shallowing upward cycles, subaerial exposure, and meteoric water play crucial roles in the quality of reservoir within the Mississippian. Transgressive-Regressive cycles (T-R cycles) on the shelf-margin resulted in shallowing up cycles that contained argillaceous, carbonate muds towards the bottom portion transitioning to bioclastic wacke-grainstone shelf deposits at the top, where spicule content would increase upward with increasing cycle thickness (Watney *et al.*, 2001). Shallowing upward cycles are capped by a subaerial exposure surfaces. Subaerial exposure allowed diagenesis to occur from an influx of meteoric water in a limited zone of mixing that did not extend down-dip into cherty facies (Watney *et al.*, 2001).

Mazzullo *et al.* (2009) highlighted a subsurface unit called the Cowley Formation by using hundreds of well logs, well cuttings and samples, seismic sections, and petrography of core/cuttings and samples from Kansas and Oklahoma. The Cowley Formation is a spiculite-dominated heterogeneous succession extending throughout the subsurface of south-central Kansas and parts of north-central Oklahoma that straddles late Osage-early Meramec in age (Mazzullo *et al.*, 2009). Mazzullo *et al.* (2009) interpreted the Cowley Formation as being low-gradient ramp deposits ranging from inner-ramp facies of moderate-energy environments to distal/outer ramp facies of low-energy environments. The proposed depositional model of the Cowley Formation included progradational wedges of transported carbonates down the low-gradient ramp into south-central Kansas to north-central Oklahoma (Mazzullo *et al.*, 2009). Cowley Formation deposition was interrupted by minor subaerial exposure allowing for alteration to occur via meteoric to mixed meteoric-marine water dissolution (Mazzullo *et al.*, 2009).

Three previous University of Arkansas unpublished master's theses (Kreman, 2010; Friesenhahn, 2012; Wittman, 2013) to the east of the present study area provide important stratigraphic and reservoir implications.

Kreman (2010) produced a subsurface study of the Lower Mississippian section in the Cherokee Geologic Province of Osage County, northeastern Oklahoma. Conclusions were that the development of a carbonate platform during the Kinderhookian and Osagean time experienced both aggradation and progradation, similar to the findings of Mazzullo *et al.* (2009).

Freisenhahn (2012) proposed a reservoir characterization study primarily focusing on the unconventional Reeds Spring Formation within the Lower Mississippian. This study was also in the Cherokee Geologic Province of Osage County, northeastern Oklahoma. The middle Reeds

Spring was deemed the best reservoir potential based on an evaluation of petrophysical characteristics.

Wittman (2013) characterized the subsurface sequence stratigraphy and reservoir character of Kinderhookian to Mississippian strata on the Anadarko Shelf, across north-central Oklahoma including Alfalfa, Grant, Garfield, Kay, Major, Woods, and parts of surrounding counties. Over 85 wells with raster images were examined, and the study concluded that active structural features of the Pratt Anticline and Nemaha Ridge influenced clinoform progradation directions, which agree with Mazzullo *et al.* (2009). Reservoir implications are that the best reservoir facies occur immediately below the Osage-Meramec unconformity and the Mississippian-Pennsylvanian unconformity in landward areas that have been sub-aerially exposed for longer lengths of time during regressive cycles (Wittman, 2013).

1.2 Study Area

The thesis study area encompasses a portion of the Anadarko Shelf geologic province, which is to the southeast of the Hugoton Embayment and west of the Cherokee Platform (Figure 1). This includes north-central Oklahoma and south-central Kansas. Counties included in the study area are Woods, Woodward, Major, Alfalfa, Garfield and Grant in Oklahoma and Comanche, Harper and Barber counties in Kansas.

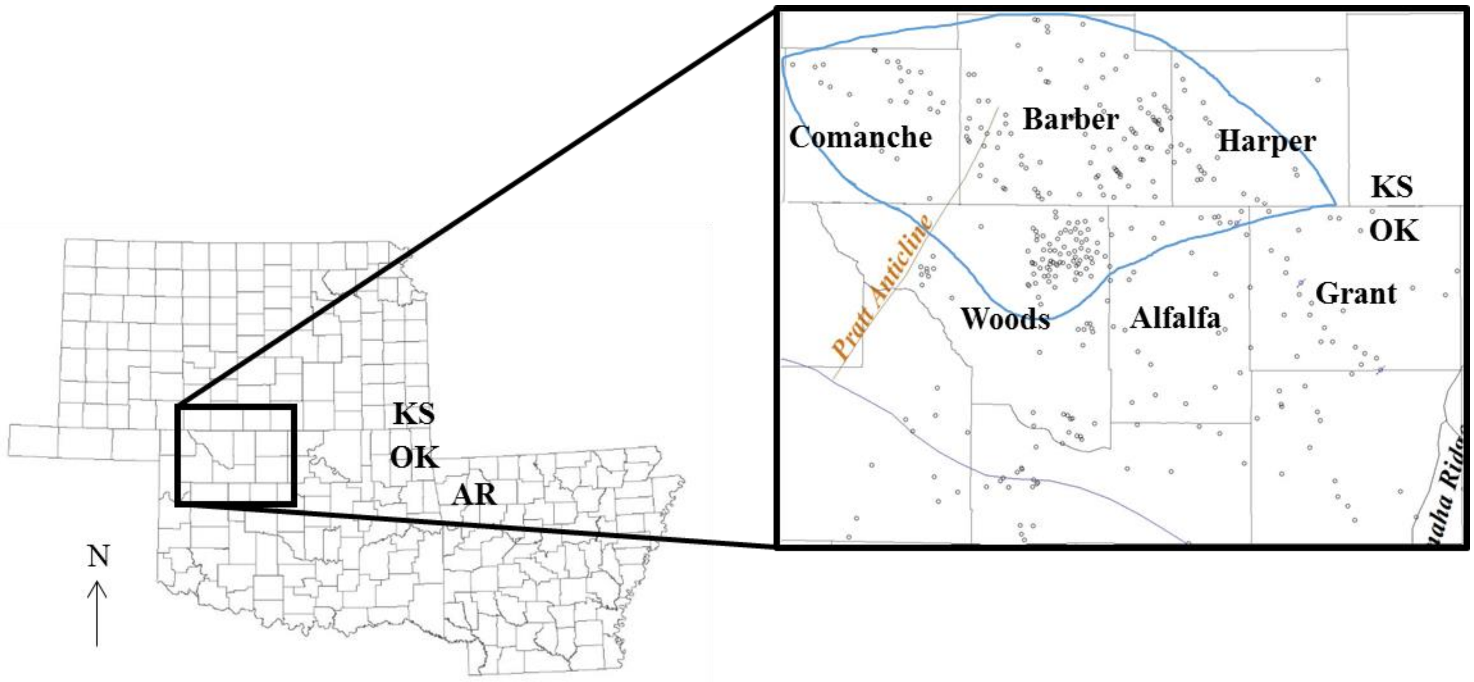

Figure 1: Study area includes north-central Oklahoma and south-central Kansas. Counties included in the study area are Woods, Woodward, Major, Alfalfa, Garfield and Grant in Oklahoma, and Comanche, Harper and Barber counties in Kansas. Over 350 well logs, 60 mud logs, and one core description were used. Main correlation focus area is outlined in blue.

1.3 Significance

Chesapeake Energy Corporation's well, Howell 1-33H, was the first horizontally drilled in the play and achieved an IP of 441bbl/day of oil and 55 mcfd of gas. Located in Woods County, Oklahoma, the frac job consisted of 15% HCl, 1,017,608 gal BW, and 30/70 sand (Manger and Evans, 2012). The target also changed from the conventional "chat" reservoirs that contain porosity greater than 25% and permeability up to 500 md (Rogers, 2001) to low porosity/permeability cherty dolomite mudstones, argillaceous dolomite mudstones, and bioclastic wacke-grainstones (Watney *et al.*, 2001). Due to recent technological advancements in drilling and completions, the Mississippi Lime play has undergone an unconventional revitalization. This revitalization in drilling has provided an ample supply of new data which has the potential to more accurately constrain a subsurface sequence stratigraphic framework for Kinderhookian to Mississippian aged strata.

1.4 Purpose

The purpose of this thesis research was to: 1) extend the high-resolution sequence stratigraphic framework purposed by Wittman (2013) into the study area, 2) create a lithostratigraphic framework utilizing mud logs and core description to demonstrate interval correlation between subsurface and outcrop, 3) test the Thompson (1986) outcrop depositional model in the subsurface, 4) define the stratigraphic position of favorable reservoir intervals

2. GEOLOGIC HISTORY

2.1 Geologic Setting

The Anadarko Basin of the mid-continent is the deepest Phanerozoic sedimentary basin on the North American craton (Perry, 1989). Within this basin, three sedimentary sequences have been recognized (ascending order) 1) Sauk Cambro-Ordovician Arbuckle Group, 2) Tippecanoe Ordovician Viola Group and Siluro-Devonian Hunton Group, and 3) Kaskaskia Mississippian Osage-Meramec-Chester limestone sequence (Fritz and Medlock, 1995). The study primarily focuses on the rocks within the Osage-Meramec-Chester sequence. During the Mississippian, the study area was located on the Anadarko shelf margin in a ramp environment (Figure 2). Numerous prograding lobes of transported carbonates draped the ramp throughout the Mississippian. Deposition is thought to have been punctuated by higher order regressive cycles, creating possible sub-aerial exposure of the shelf (Rogers, 2001, Watney *et al.*, 2001, Mazzullo *et al*., 2009).

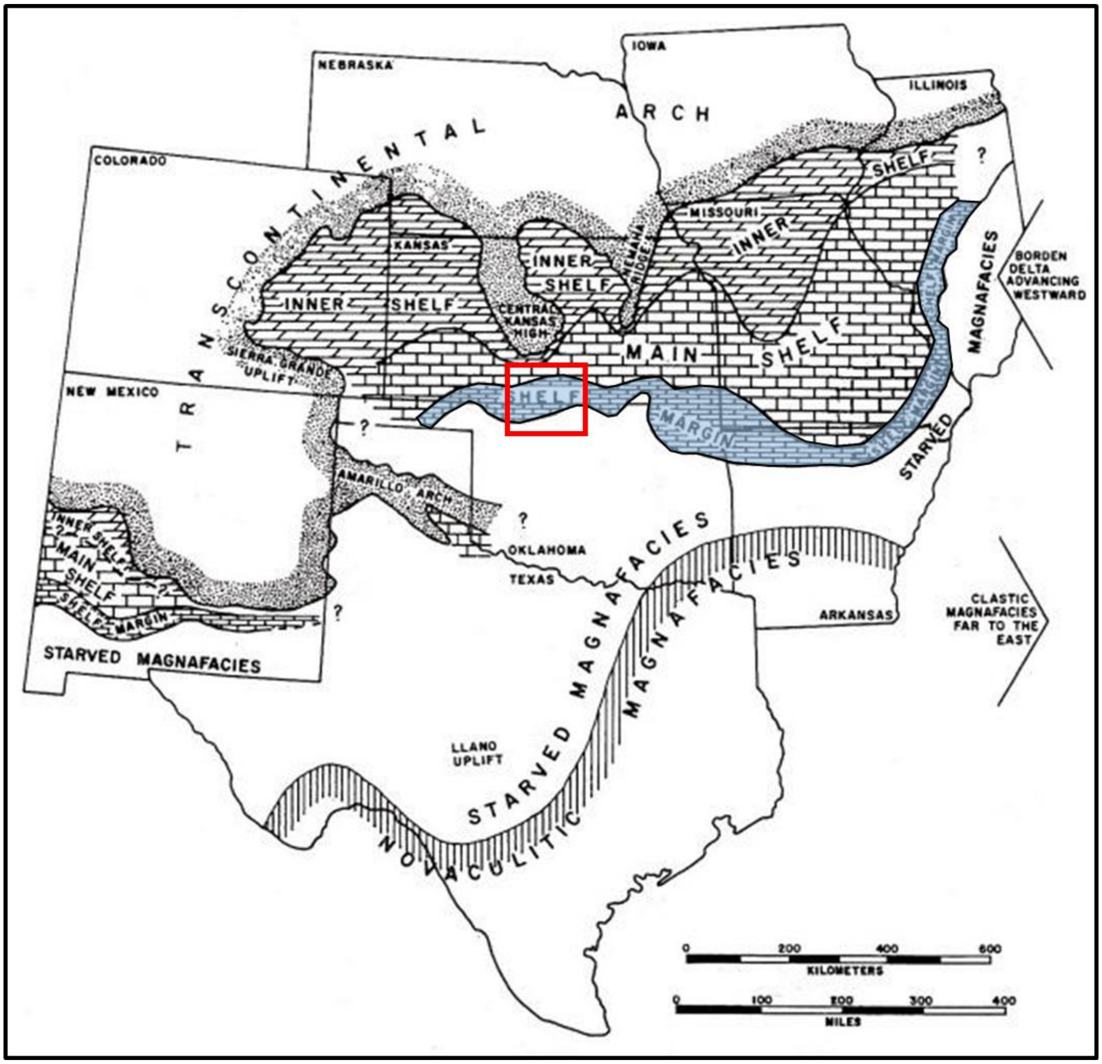

Figure 2: Paleogeographic map of the Osage series modified from Lane and DeKeyser, 1980. Red square is outline of the study area. Blue polygon marks the interpreted shelf edge. The study area encompasses distal shelf margin, shelf margin, and basin environments.

2.2 Tectonic History

In the Early to Middle Cambrian, rifting created the southern Oklahoma aulacogen. Following the rifting phase, the aulacogen began to cool and subside (Perry, 1989). A passive margin existed from Cambrian to Mississippian time (Perry, 1989). Tectonics associated with the Ouachita orogeny caused inversion on the northern flank of the aulacogen, producing the Anadarko basin (Perry, 1989). Several major tectonic entities were active during the Mississippian that affected both deposition and erosion, particularly the Nemaha Ridge and Pratt Anticline (Figure 3). The Nemaha Ridge is a 4-15 mi wide regional plunging anticline that extends from the surface in southeast Nebraska to south-central Oklahoma, where it ultimately terminates against the megashear (Dolton and Finn, 1989; McBee, 2003). Numerous structural and stratigraphic traps occur along the flanks, and the Nemaha Ridge has been suggested as being the fundamental feature that controls the distribution of oil and gas in the Oklahoma and Kansas area (Dolton and Finn, 1989). The Nemaha Ridge also separates the Cherokee Platform from the Anadarko Shelf. The Pratt Anticline is a low-relief southeastern plunging nose of the Central Kansas Uplift where, along its crest, the Mississippian strata are absent, so Pennsylvanian rocks rest unconformably on Ordovician rocks (Rogers *et al.*, 1995; Mazzullo *et al.*, 2009). Like the Nemaha Ridge, an arcuate fairway is present along the flanks of the Pratt Anticline, where stratigraphic and structural traps exist (Montgomery *et al.*, 1998). In the Pennsylvanian, a significant unconformity heavily eroded Mississippian strata within the study area.

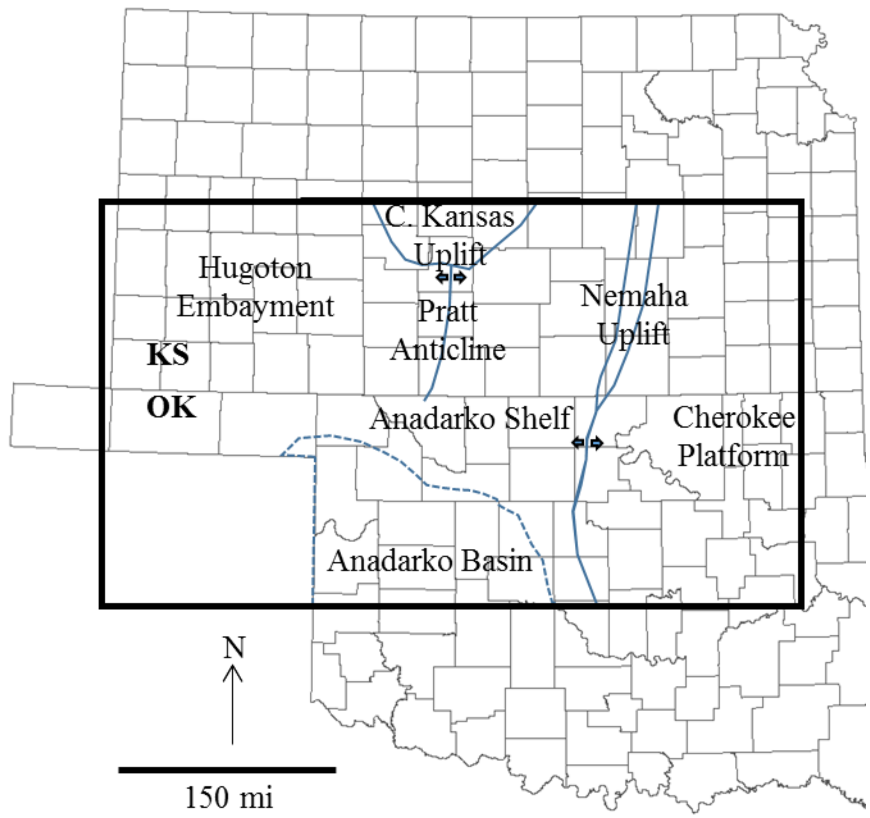

Figure 3: Geologic providences and structural features within the north-central Oklahoma and south central Kansas region. Study area is on the Anadarko Shelf with the Pratt Anticline in the western portion of the study area and Nemaha Ridge to the east**.**

2.3 Enigma of Subsurface to Surface Stratigraphy

There are multiple challenges when applying the Mississippian stratigraphic framework in the Mississippian outcrop belt to the subsurface in north-central Oklahoma and south-central Kansas.

The first challenge is nomenclature, as it is common for both formal and informal names used throughout the subsurface. The Kinderhook Shale, which is of Kinderhookian age, does not have a formal assigned outcrop equivalent, but is used frequently in the subsurface and is regionally correlatable. Mazzullo *et al.*, 2010 suggest the Kinderhook Shale could be the subsurface equivalent to the Bachelor Formation of the St. Joe Group in the Mississippian outcrop belt, but this relationship has not been fully investigated. St. Joe Group, which is also of Kinderhookian age, does have an outcrop equivalent, and is correlatable throughout the outcrop and is also regionally correlatable throughout the subsurface. The St. Joe Group is differentiated into the Bachelor, Compton, Northview and Pierson Formations (Manger and Evans (2012). The Compton, Northview, and Pierson Formations are commonly used throughout the subsurface, but the Pierson is not recoginzed within the study area, because of its high chert content. The Osage, which is of Osagean age, does have a formal assigned outcrop equivalent, and is correlatable throughout the subsurface (Lee, 1940; Thornton, 1964; Rogers *et al.*, 1995; Mazzullo *et al.*, 2009, Rottmann, 2011; Costello *et al*., 2013). The Osage is differentiated into the lower and upper Boone Formation in Arkansas outcrop. The lower and upper Boone Formation names have not been used in the subsurface correlation, as it is nearly impossible to differentiate them with a standard triple-combo log suite. The Meramec, which is Meramecian in age, does have a formal assigned outcrop equivalent and is correlatable throughout the subsurface (Lee; 1940; Thornton, 1964; Mazzullo *et al*., 2009; Rottmann, 2011; Costello *et al.*, 2013). The Meramec is differentiated into the Cowley

Formation in subsurface, then the Warsaw Formation, Salem Formation, St. Louis Formation, and St. Genevieve Formation in outcrop.(Lee, 1940; Watney *et al.*, 2001; Mazzullo *et al.*, 2009). The Mississippian "chat", is an informal term used only in the subsurface that is applied to any weathered chert lithology coupled with a low resistivity and high porosity log character (Montgomery *et al*., 1998).

The second challenge is using both lithostratigraphic and chronostratigraphic methods for correlating in the subsurface. The Kinderhook Shale, Compton Formation, Northview Formation are correlated based on lithologic and well log character. This methodology is lithostratigraphic correlation, which is correlation based on lithologic character. The Osage and Meramec are correlated based on unconformities (Lee, 1940; Thornton, 1964; Rogers *et al.*, 2001; Watney *et al.*, 2001; Mazzullo *et al.*, 2009; Costello *et al.*, 2013). The unconformities represent stratigraphically important surfaces that give a diachronous proxy for time, and are used in for chronostratigraphic correlation (Catuneanu, 2006).

The third challenge is the distance away from formation type localities. The Mississippian outcrop belt is over 200 miles away, so the outcrop nomenclature application to the subsurface could be suspect due to the significant distance (Figure 4).

Nomenclature used in this study is as follows: Kinderhook Shale, St Joe Group (Northview and Compton Formations), Osage, and Meramec (Figure 5). The Osage is only differentiated into the lower and upper Boone where mud logs are available for accurate lithologic correlation. Meramec cannot be differentiated into Cowley Formation, Warsaw Formation, Salem Formation, St. Louis Formation, and St. Genevieve Formation, as nearly all mud logs did not have Meramec present due to erosion from Mississippian-Pennsylvanian unconformity

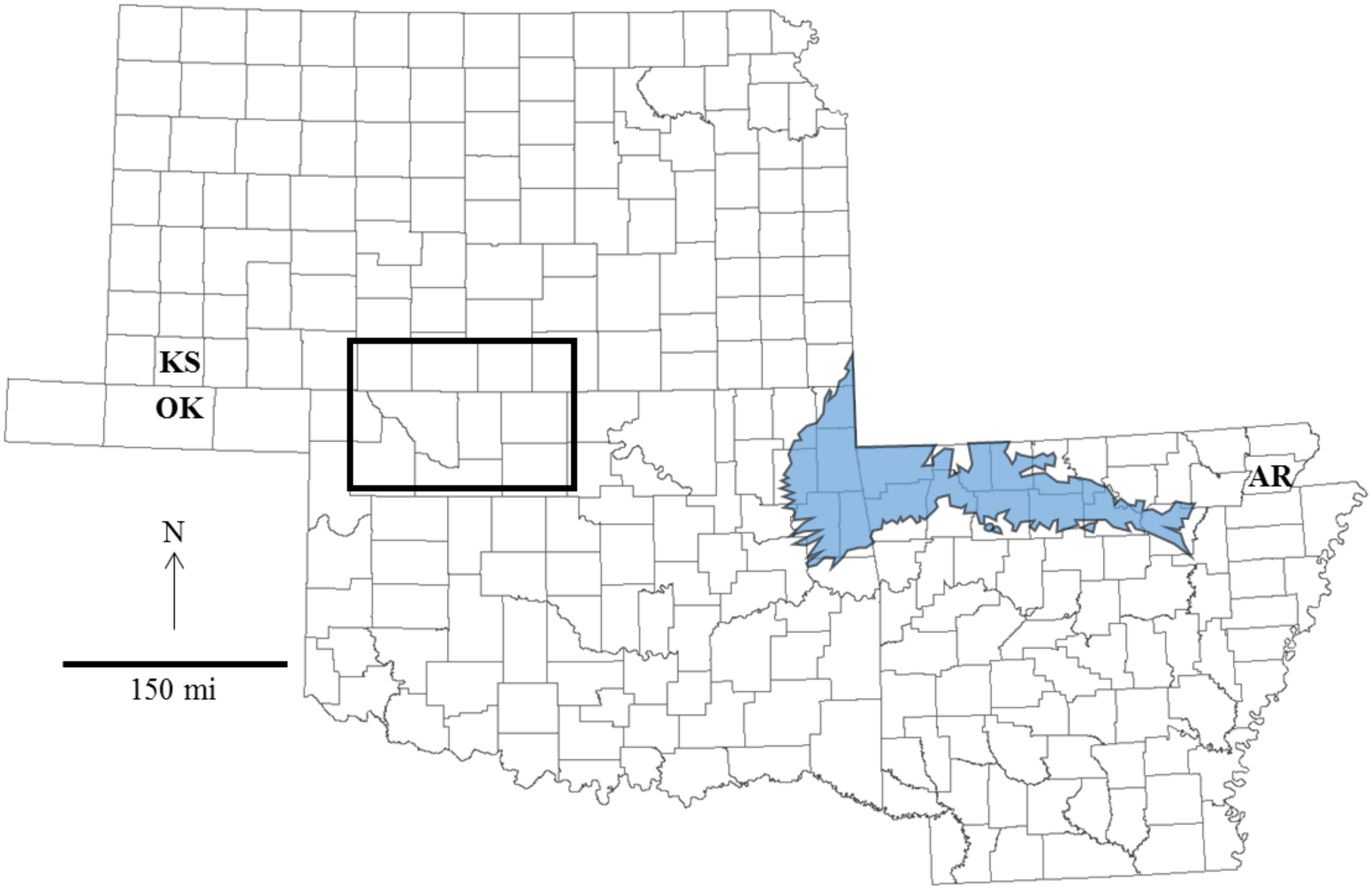

Figure 4: Black square shows the study area and the blue polygon is the Mississippi outcrop belt. The distance between the study area and the Mississippian outcrop belt is roughly 200 miles.

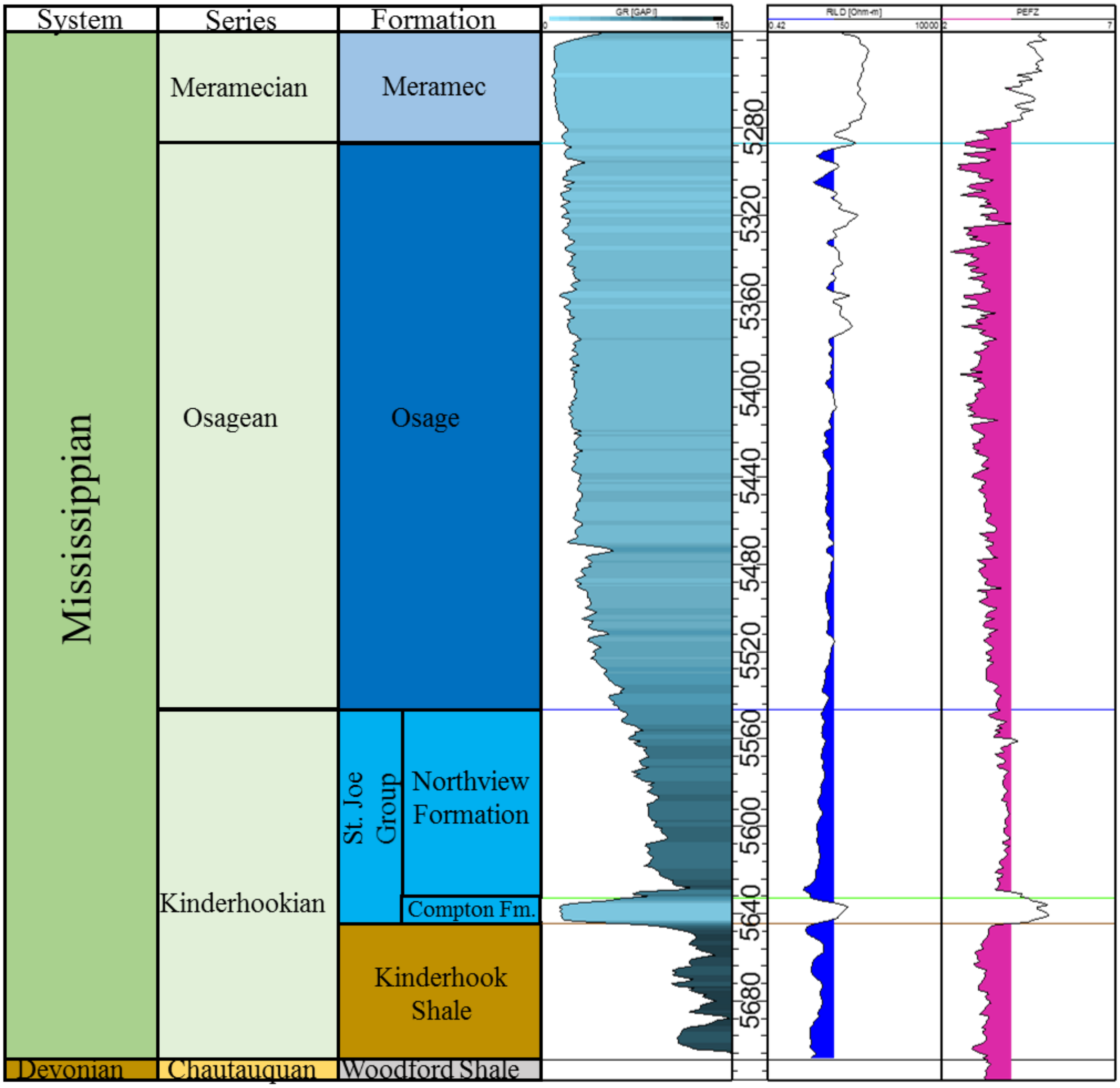

Figure 5: Type log and stratigraphic column for the study area taken from the Leatherman 1-30 well in Woods County, Oklahoma. Well logs from left to right are gamma ray (0-150 API), deep resistivity (.42-10000 ohm-m with a 40 ohm-m blue cut off), and photoelectric effect (2-7 barns/election with a 3.5 barns/electron cut off).

3. METHODOLOGY

3.1 Workflow

The workflow for conducting this subsurface stratigraphic thesis research began with a comprehensive literature review (Figure 6). Following the extensive literature review, the acquisition of all available well log and related data within the defined study area became the next objective. Once all available data were obtained, it was assessed for quality control; if it met and passed certain criteria, the data were used for interpretation. During the interpretation and correlation of well logs, gaps in data were filled by circling back to the data acquisition stage. This resulted in data acquisition being the most time consuming and labor intensive portion of the project. Once data acquisition and all interpretations were finished, a thorough interpretation was produced.

3.2 Data Acquisition and Description

Three previous University of Arkansas masters theses by Kreman (2011), Friesenhahn (2012), and Wittman (2013) developed a geo-database for northeast Oklahoma westward into north-central Oklahoma of raster and digital well logs using geologic interpretation software, IHS Petra. These well logs were obtained through various donations from independent oil and gas companies as well as drillinginfo.com. Additional well logs were acquired and added to the geo-database to further develop interpretations and to accomplish the goals of this study. The well logs were downloaded from drillinginfo.com, and the Kansas Geological Survey website.

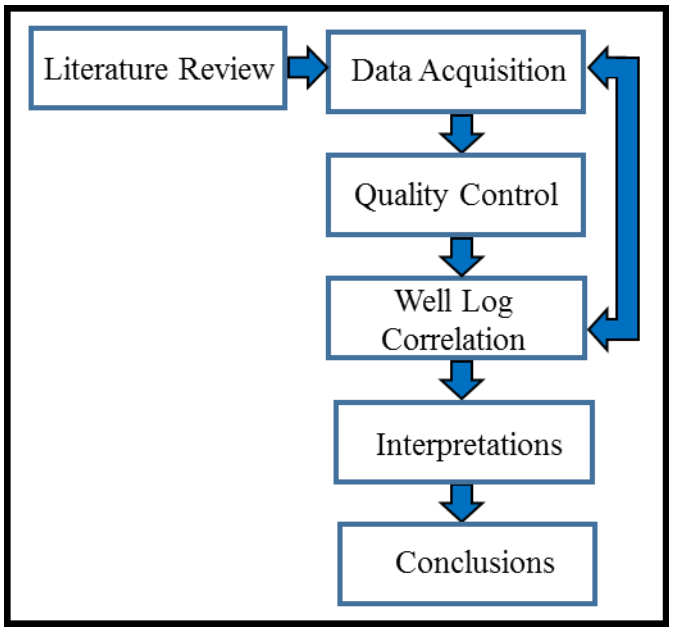

Figure 6: Workflow showing the steps taken in order to complete this thesis research.

The methodology for mining well logs in drillinginfo.com was streamlined during the well log acquisition portion of Wittman (2013), where salt water disposal wells (SWD wells) were favored. All SWD wells target the Arbuckle Formation, which is stratigraphically below the Mississippian section. Drillinginfo.com allowed the search of strictly SWD wells, making this process quick and efficient for gathering bulk amounts of well logs in Oklahoma. Unfortunately, this process was not applicable for mining well logs from the Kansas Geological Survey website. Well logs were hand-picked from an interactive state-wide map of Kansas that showed the locations of each oil and gas well drilled. Once well logs were downloaded, well header information and associated raster images and/or digital well logs were imported into IHS Petra. Raster images had to be depth calibrated, which is mandatory in order to perform well log correlations. Well logs were also digitized in IHS Petra to allow for an easier visual representation as opposed to black and white raster images. It also allowed well log statistics to be calculated using IHS Petra. This process was repeated several times to insure that the study area had the best well control from the log data available.

Well logs which met the criteria of penetrating the full Mississippian section from the Devonian-Mississippian unconformity to the Mississippian-Pennsylvanian unconformity were downloaded. Further quality control required well logs to have gamma ray, resistivity, and density/porosity logs (photoelectric effect, microlog, and mud logs were also desired, but not required) for use in interpretation. This methodology allowed for only the highest quality of well log data to be used and insured that every well log downloaded would be used in this study.

3.3 Formation Identification Criteria

Well-log formation identification criteria were adopted based on literature and industry formation tops obtained from online databases. Parameters for picking the formations within the

St. Joe Group were defined in Mazzullo *et al.,* (2009) and were based on log character of the Compton and Northview Formations. Parameters for dividing the Osage-Meramec boundary within the Mississippian were defined in Mazzullo *et al.*, (2009) and Costello *et al.*, (2013). All major formation tops, such as the Viola, Woodford Shale, Kinderhook Shale, and Mississippian, were defined by industry picks from Drillinginfo.com and the Kansas Geological Survey website.

3.4 Stratigraphic Assumptions

This thesis uses a combination of sequence stratigraphic terminology and approaches outlined in both Handford and Loucks (1993) and Catuneanu (2006). Carbonate depositional sequences and systems tracts were explained in Handford and Loucks (1993). During lowstand, seas become shallower and have a greater potential for siliciclastic input. Significant siliciclastics suppress and restrict carbonate sediment production. Lowstands also cause the shelf to retreat, producing subaerial exposure and karstification, if there was deposition of limestone prior. During transgression, seas begin to rise and siliciclastic input decreases. Deeper portions become starved of sediment. If the carbonate factory is in the right latitude and sediment input has ceased, lime deposition begins. Aggradation takes place as carbonates “catch up” to the rising sea level, and once caught up, progradational shallowing upwards successions ensue. During highstand, carbonate sedimentation rates are greatest, causing continued progradation of the shelf edge. As shelf edges continue to prograde, they can experience oversteepening, which causes a collapse and subsequent gravity flows down the slope towards the basin floor. Fine grained sediment also is derived from the platform via suspension down onto the slope

4. STRATIGRAPHY

4.1 Stratigraphic Overview

Based on the consensus of Paleozoic sea level cyclicity, the Mississippian system falls within the Kaskasia II mega sequence (Figure 7). Two full 3rd order transgressive-regressive cycles are present within the Kaskaskia II, along with a full 2nd order cycle. Within the early Osagean, there is a 3rd and 2nd order transgressive maximum superimposed on eachother. This corresponds to a transgression and maximum flooding interval from the Kinderhookian to Osagean. Following the maxiumum flooding interval within the early Osage, regression occurs until a 3rd order regression at the end of the Osagean. 3rd order transgression then returns in the Meramecian. A sequence boundary at the Mississippian-Pennsylvanian marks the end of the Kaskasia II megasequence.

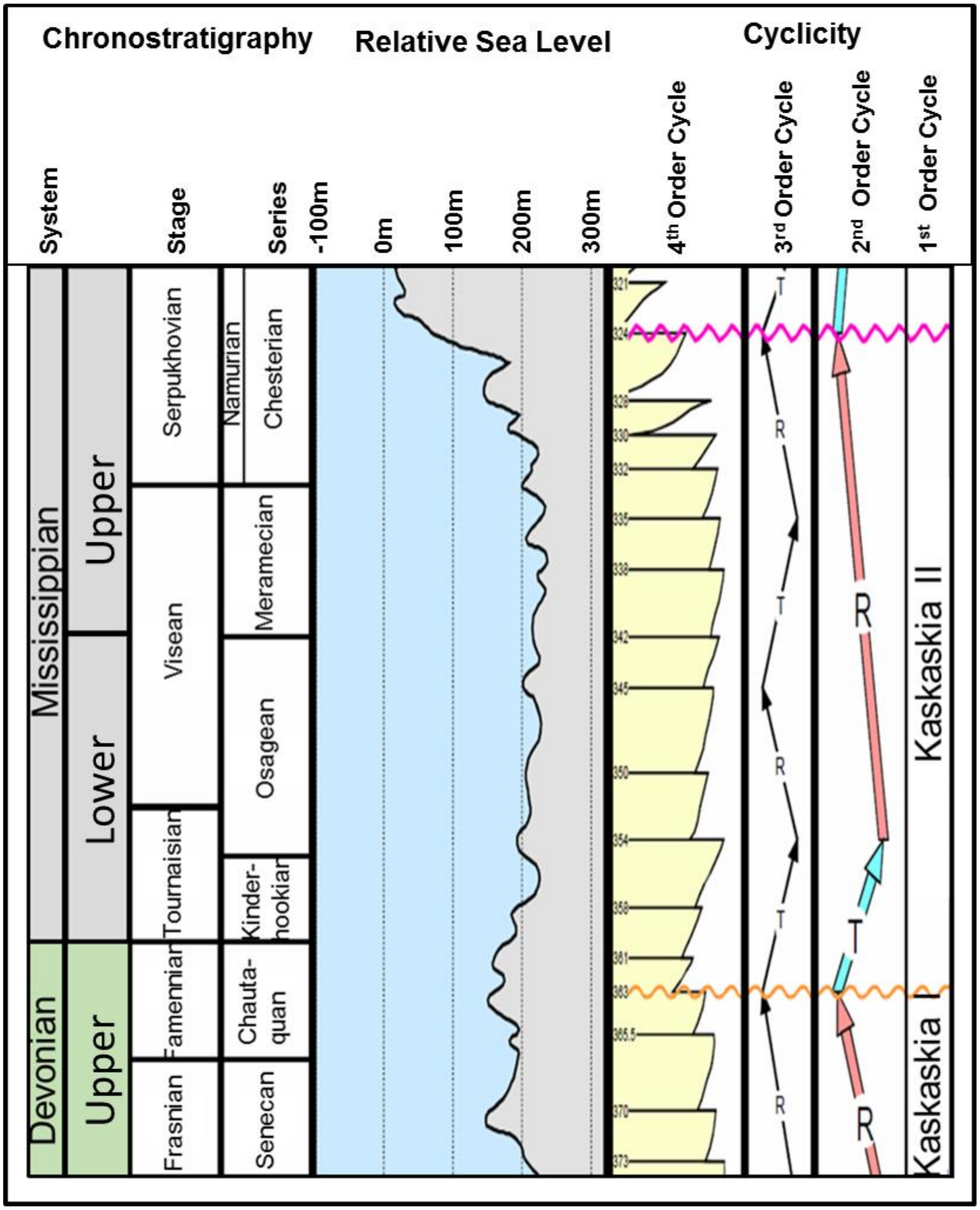

Figure 7: Paleocyclicity of the upper Devonian and Mississippian (modified from Lowell Waite, Pioneer Natural Resources, Dallas, Texas, 2002 version, compiled from various sources). The Mississippian is entirely within the Kaskaskia II 1st order sequence. One full 2nd order cycle and two full 3rd order cycles are within the Mississippian. There is a 2nd order transgression and 3rd order transgression superimposed on one another towards the beginning of the Osage.

4.2 Kinderhookian

The Kinderhookian series comprises the deposition of the Kinderhook Shale and the St. Joe Group. It encompasses both 3rd and 2nd order transgression at the onset of the Kaskaskia II megasequence.

4.2.1 Kinderhook Shale

The Kinderhook Shale marks the basal portion of the Mississippian sequence that lies above the Devonian Woodford Shale. The Woodford shale was deposited in anoxic seas during transgression within the Kaskaskia I megasequence during the Devonian (Lambert, 1993). Transgression was followed immediately by regression, where a second-and third order maximum regression marked the end of the Kaskaskia I megasequence, as well as the Devonian. Following the maximum regression at the end of the Kaskaskia I megasequence, transgression ensued marking the base of the Mississippian system. Sea level rose fairly rapidly in the early Kinderhookian and persisted until first-order maximum flooding in early Osagean series.

In well logs, the boundary between the Woodford Shale and Kinderhook Shale was rather easy to distinguish (Figure 8). Commonly, the Woodford Shale would wrap around gamma ray logs due to high radioactivity. Values typically ranged between 200-400 API units for the Woodford Shale. The Kinderhook Shale, in contrast, would not wrap around as dramatically and has gamma ray values between 70-180 API units. Mud logs also document the difference in lithology between the Woodford Shale and Kinderhook Shale. The Woodford Shale consists of brown, dark grey, to black gritty shale with pyrite. Kinderhook Shale consists of grey to dark grey, silty shale that has sparse pyrite (Figure 9). Within the study area, the Kinderhook Shale has an average thickness of roughly 40 feet, and a range in thickness from less than 15 feet in the western areas to 85 feet in the eastern areas (Figure 10). An area of greatest thickness occurs in northern Alfalfa County, Oklahoma, where a possible shelf edge existed for the Kinderhook Shale.

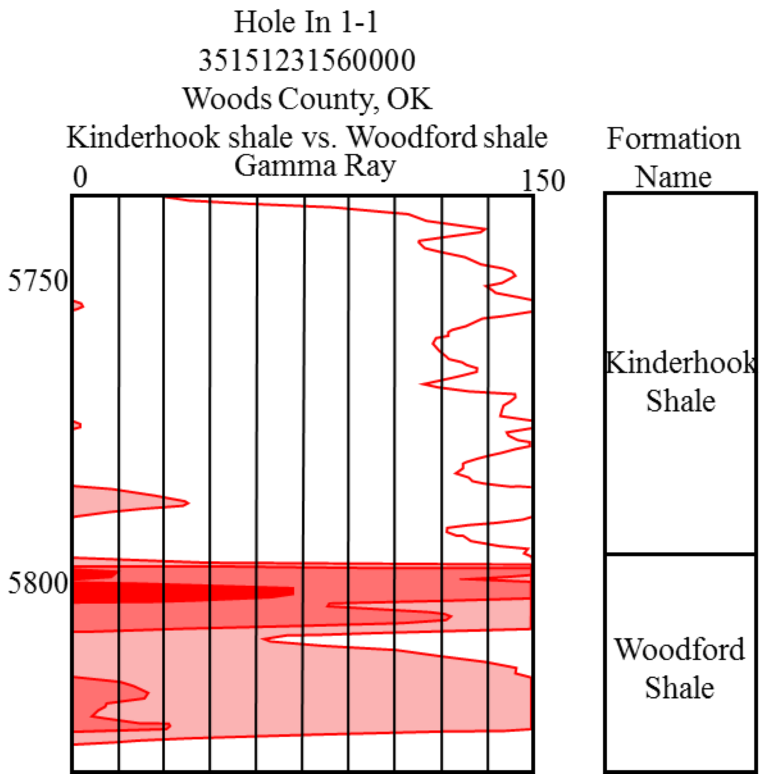

Figure 8: Type log of Hole In 1-1 well in Woods County, Oklahoma. Woodford Shale gamma ray readings fully wrap around typically two to three times, while the Kinderhook Shale gamma ray readings never wrap around fully.

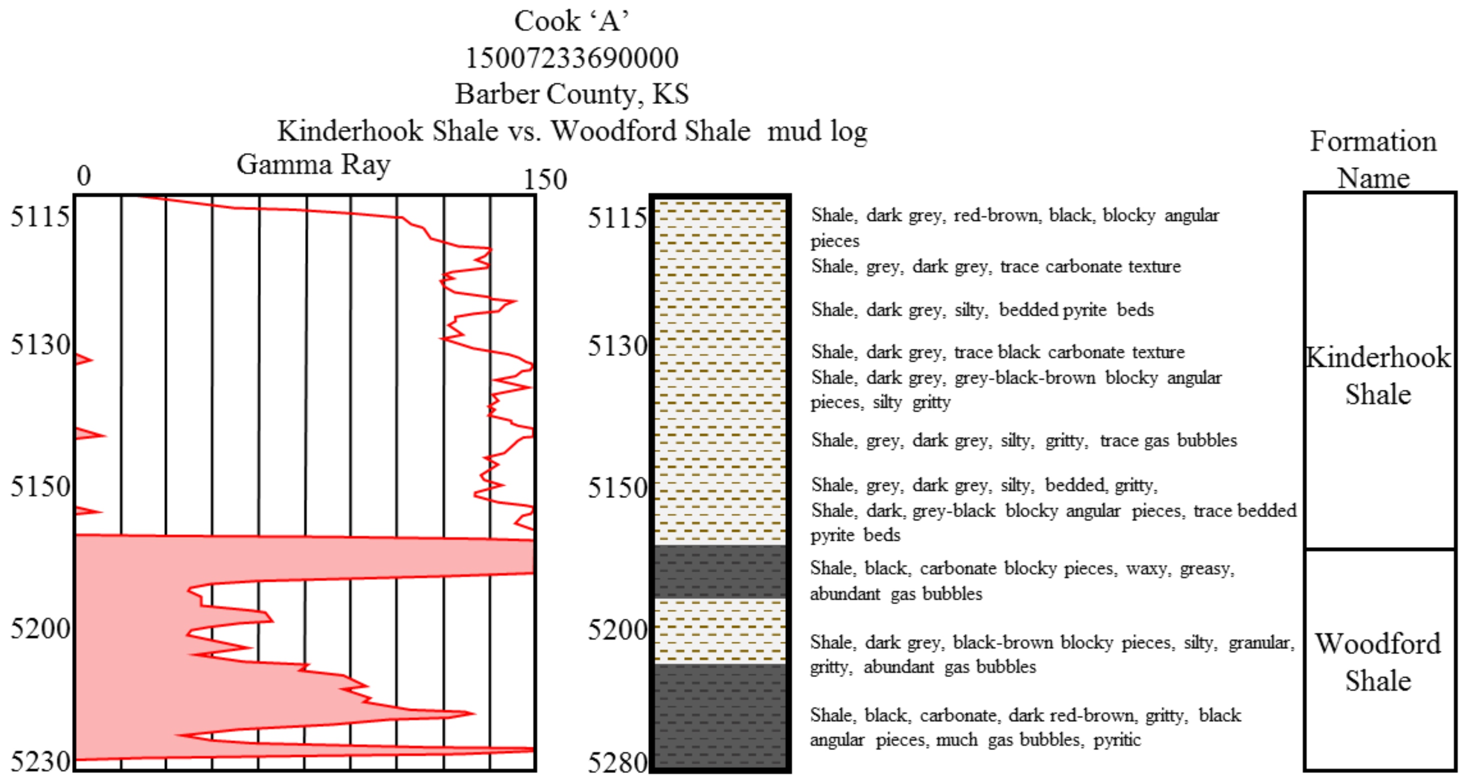

Figure 9: Mud log from Cook 'A' well in Barber County, Kansas. Distinct differences can be seen between the Woodford Shale and Kinderhook Shale. Kinderhook Shale does not have black shale within, only grey to dark grey shale. Kinderhook Shale also contains a higher occurrence of silt.

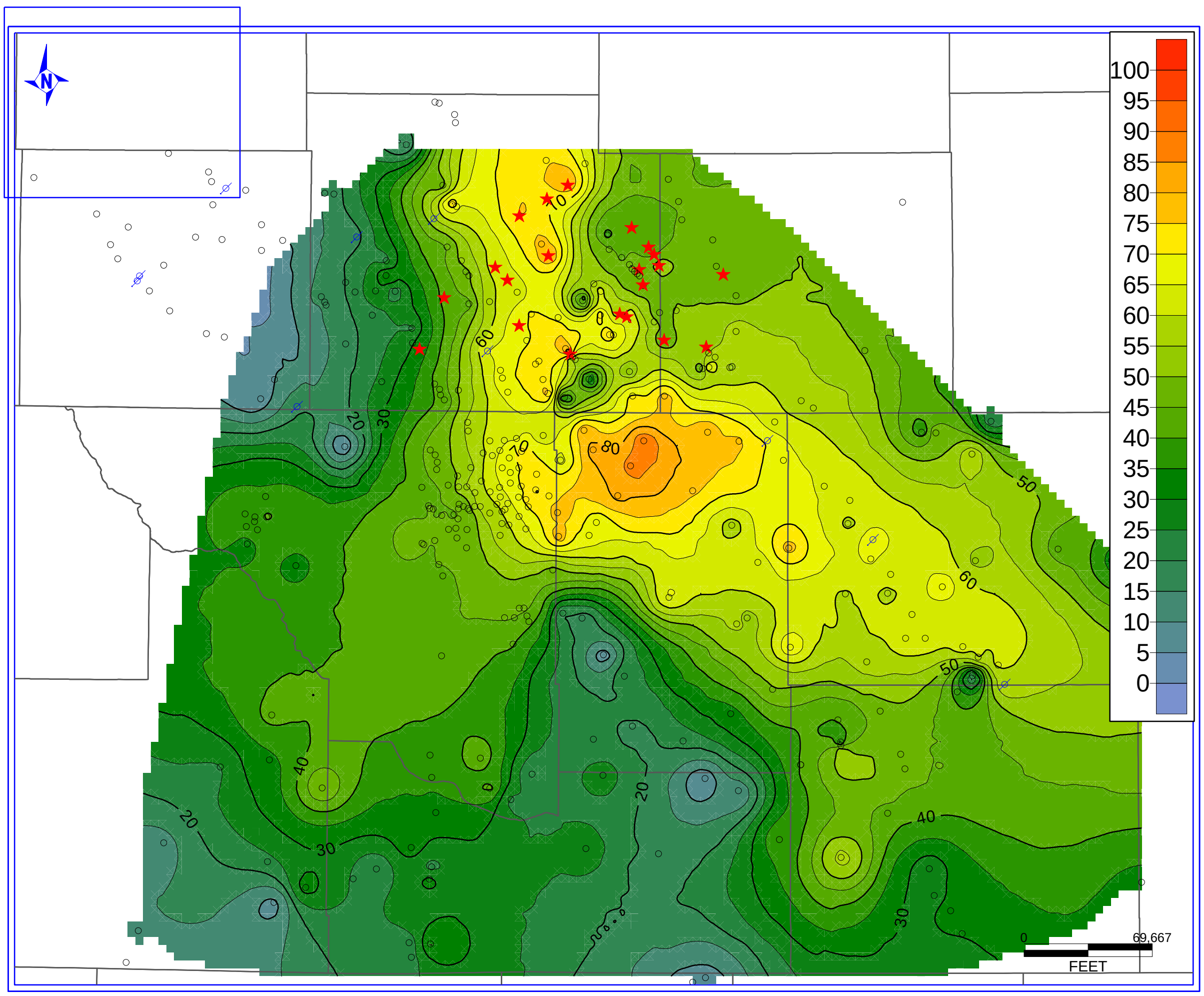

Figure 10: Kinderhook Shale isopach. Contour interval is 15 feet. Thickest Kinderhook Shale corresponds to shelf margin during a lowstand to transgressive systems tract.

The Kinderhook Shale represents lowstand to transgression, where some clastic influx occurred from a northerly source. This clastic influx probably did not allow for organics to be preserved compared with the amounts in the Woodford Shale, resulting in lower gamma ray API readings. The Kinderhook Shale was deposited below storm wave base, but in shallower, oxygenated waters compared to the Woodford Shale. Thickest deposits mark the shelf edge, and thinner units mark areas of condensed sedimentation rates out in the distal portion of the shelf and basin.

4.2.2 St. Joe. Group

The St. Joe Group can be differentiated into the Compton Formation and the Northview Formation. The Compton Formation is predominately limestone and the Northview Formation is predominately shale.

4.2.2.1 Compton Formation

The Compton, is the basal formation of the St. Joe Group, is a relatively clean limestone, with respect to chert content, that can be seen in the outcrops in northwest Arkansas and southern Missouri. In outcrop, the Compton is characterized as crinozoan packstones and wackstones with sparse occurrences of chert nodules (Manger and Evans, 2012).

In well logs, the Compton has gamma ray values between 15-40 API units. Photoelectric effect (PE) values of the Compton ranged from four to five suggesting a clean limestone with minimal chert and abundant calcite. The Compton is also very resistive (100-300 Ohm-m) and has a low porosity with minimal reservoir potential. Description of the Compton in mud logs follows what is seen in the outcrops, as varied amounts of chert can be present (Figure 11).

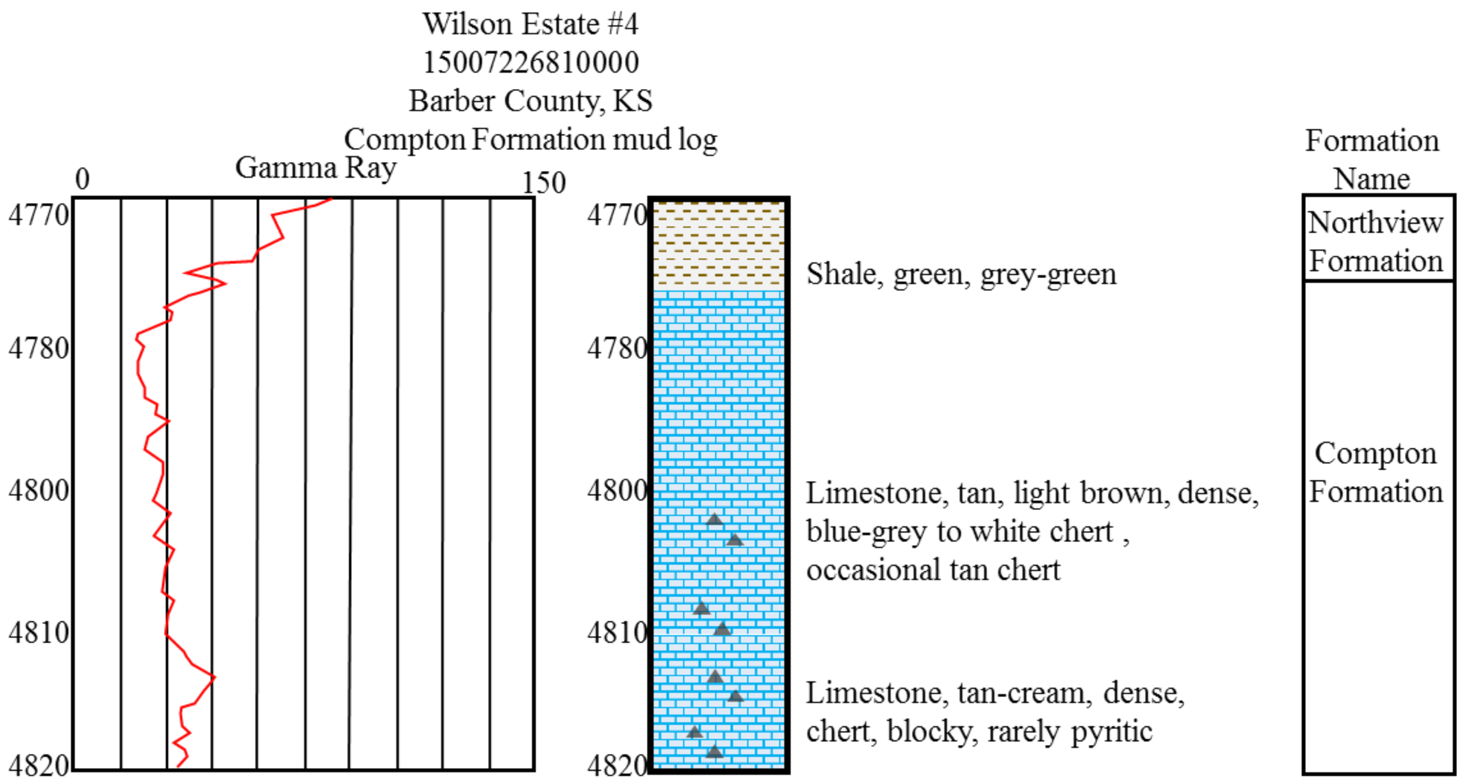

Figure 11: Mud log from the Wilson Estate #4 well in Barber County, Kansas of the Compton Formation. The Compton Formation is fairly clean with respect to chert, but chert content varies throughout the study area. The limestone is also dense with little porosity.

Apparently, these strata now in the subsurface were in a more favorable position for silica replacement to occur than what is seen within the outcrop belt. Within the study area, the Compton has an average thickness of 25 feet, and a range in thickness from less than five feet in the southern areas to almost 90 feet in the northern areas (Figure 12). There are two areas of greatest thickness, one in northeastern Barber County, Kansas and one in northern Comanche County, Kansas.

The Compton represents transgressive to highstand conditions after the waters have fully cleared from the sediment influx from the Kinderhook Shale and allowed carbonate sedimentation. The isopach of the Compton is reminiscent of the outcrop isopach in Handford and Manger (1990) (Figure 13). A lobate pattern exists and the thicker units (>30 ft.) show the position of the transgressive shelf, and thinner units (<30 ft.) show the distal, starved shelf to basin. The lobate geometry is indicative of down-ramp movement (Handford and Manger, 1990). This same model can most likely explain the isopach of the Compton in the study area.

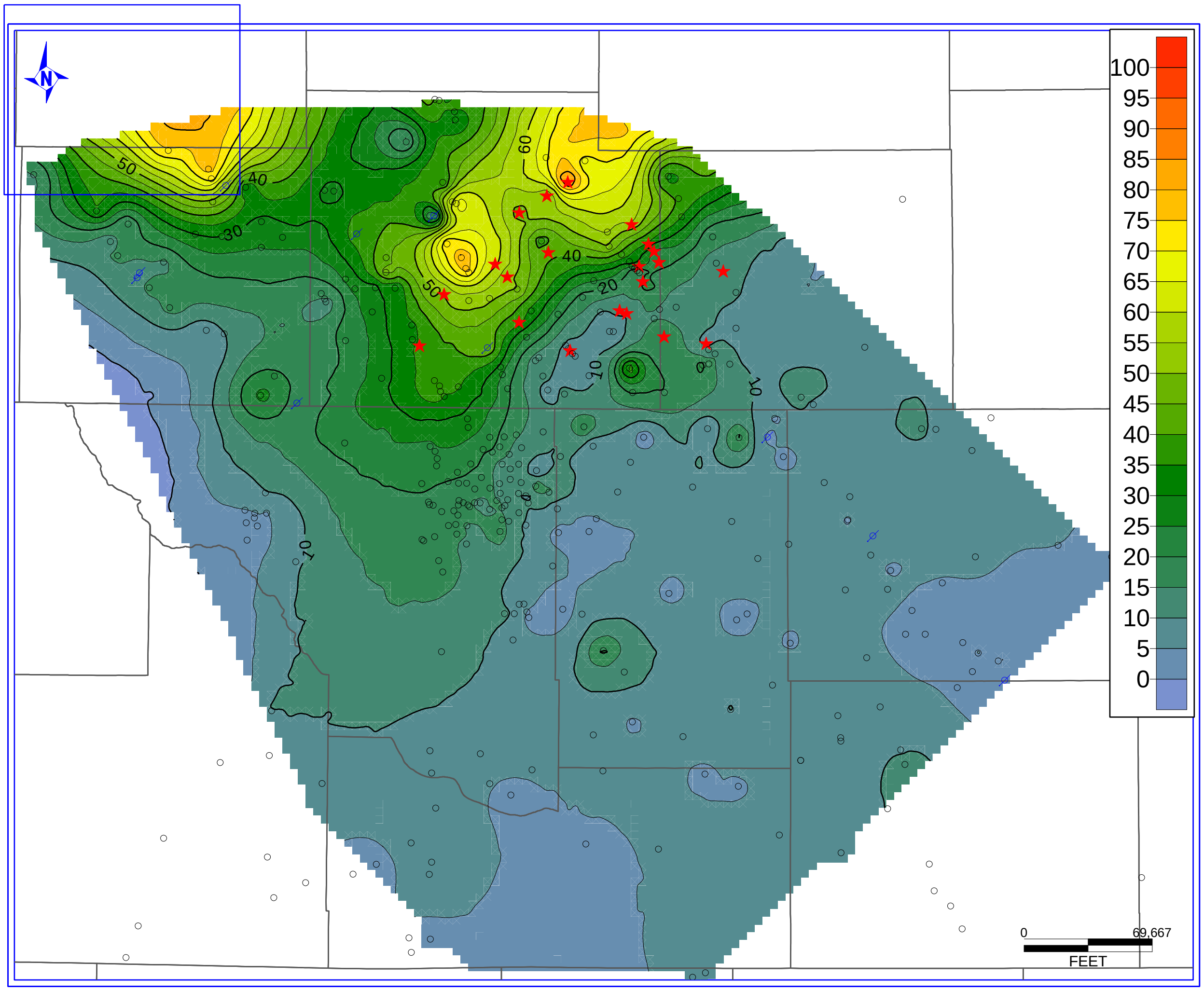

Figure 12: Compton Formation isopach. Contour interval is 15 feet. Thickest Compton Formation is towards the north, corresponding to a shelf margin during transgressive to highstand systems tract.

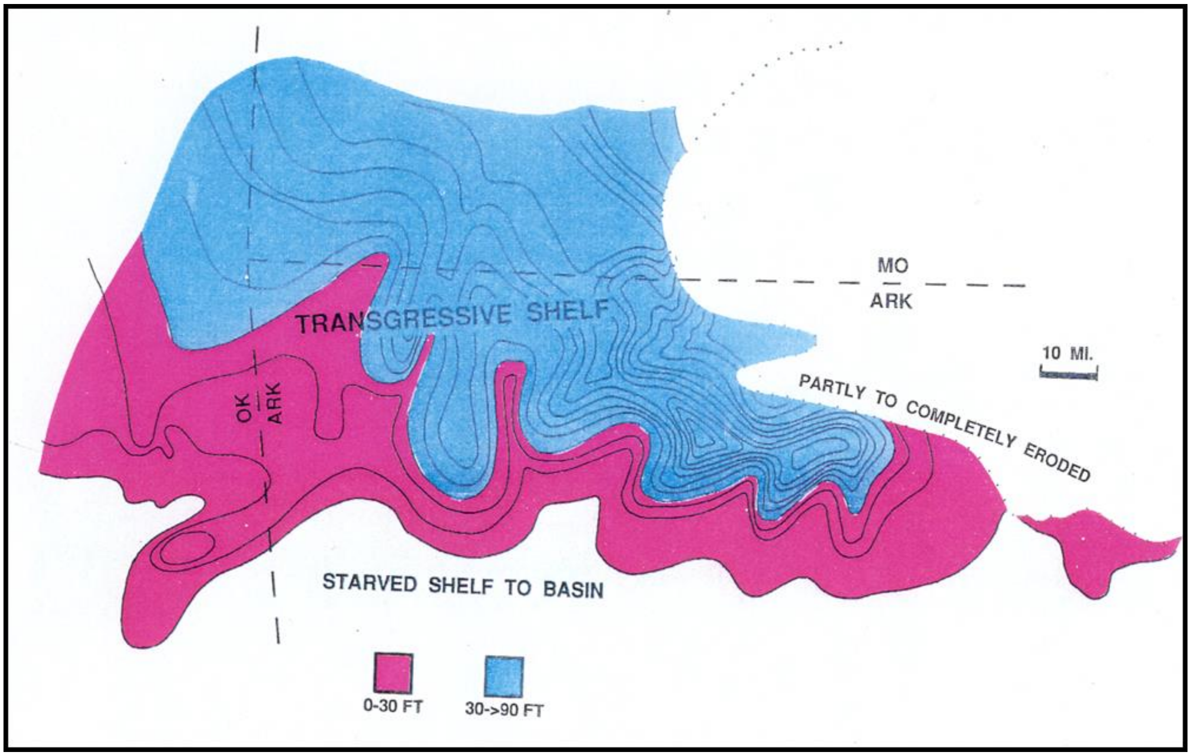

Figure 13: Outcrop isopach map from Handford and Manger (1990) of the Compton Formation in the Mississippian outcrop belt. Lobate geometry indictative to down ramp transport of carbonates to the thinner distal portions.This same depositional style existed within the study area.

4.2.2.2 Northview Formation

Overlying the Compton Formation, the Northview Formation, is a thin light green to grey calcareous shale. Between the Compton and Pierson in the outcrops of northwest Arkansas and southern Missouri (Manger and Evans, 2012).

In well logs, the Northview has gamma ray values between 50-125 API units and resistivity values of 10-30 Ohm-m. Description of the Northview in mud logs is a grey to dark grey shale with trace pyrite and occasional interbedded cream to tan limestones (Figure 14). Thickness of the Northview averages 25 ft. and ranges from 10-130 ft (Figure 15). Mazzullo *et al.* (2009) noted a Compton-like lithology that is sometimes present that adds to the thickness of the unit. The Compton-like lithology mimics the well log characteristics seen within the Compton, where there is a gamma ray reading of 15-30 API units and a higher resistivity of around 100 Ohm-m (Figure 16). This was periodically seen throughout the study area, and higher order 4^{th} and 5^{th} transgressive cycles could explain their origin.

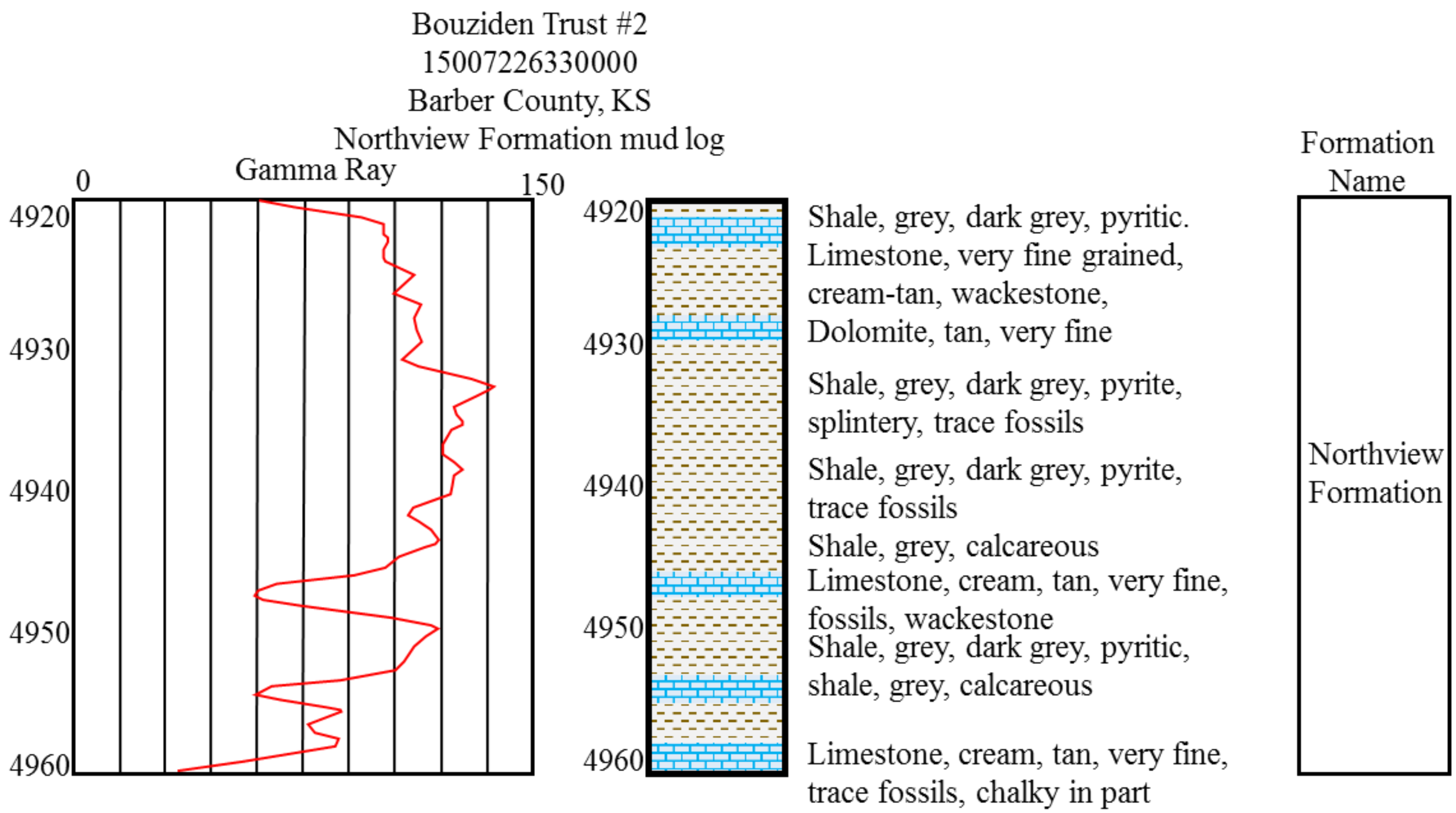

Figure 14: Mud log from the Bouziden Trust #2 well in Barber County, Kansas of the Northview Formation. Mainly consists of grey to dark grey shale with trace pyrite, similar to the Kinderhook Shale. Occasional interbedded limestones occur within the shale.

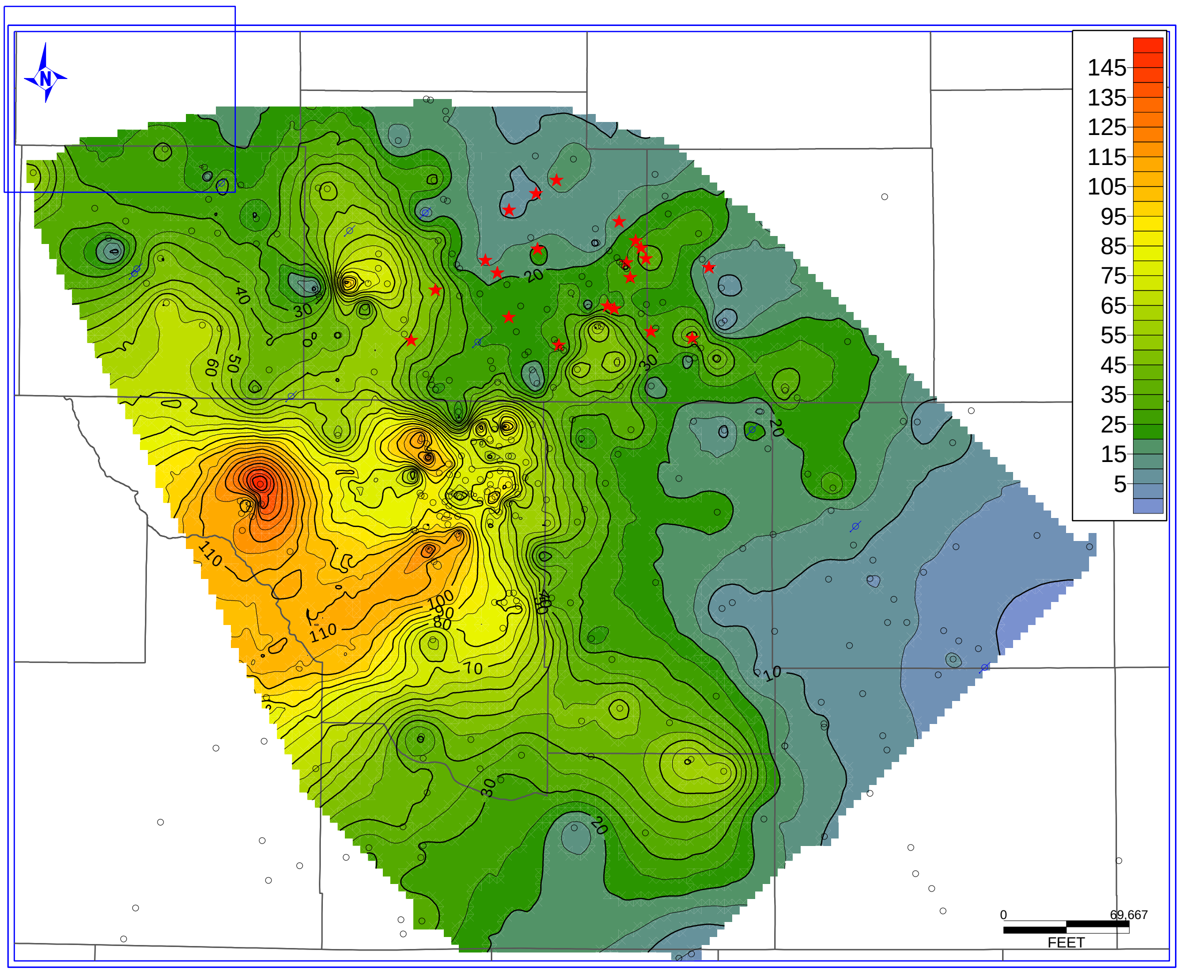

Figure 15: Northview Formation isopach. Contour interval is 15 feet. Thickest Northview Formation corresponds to shelf edge during lowstand systems tract.

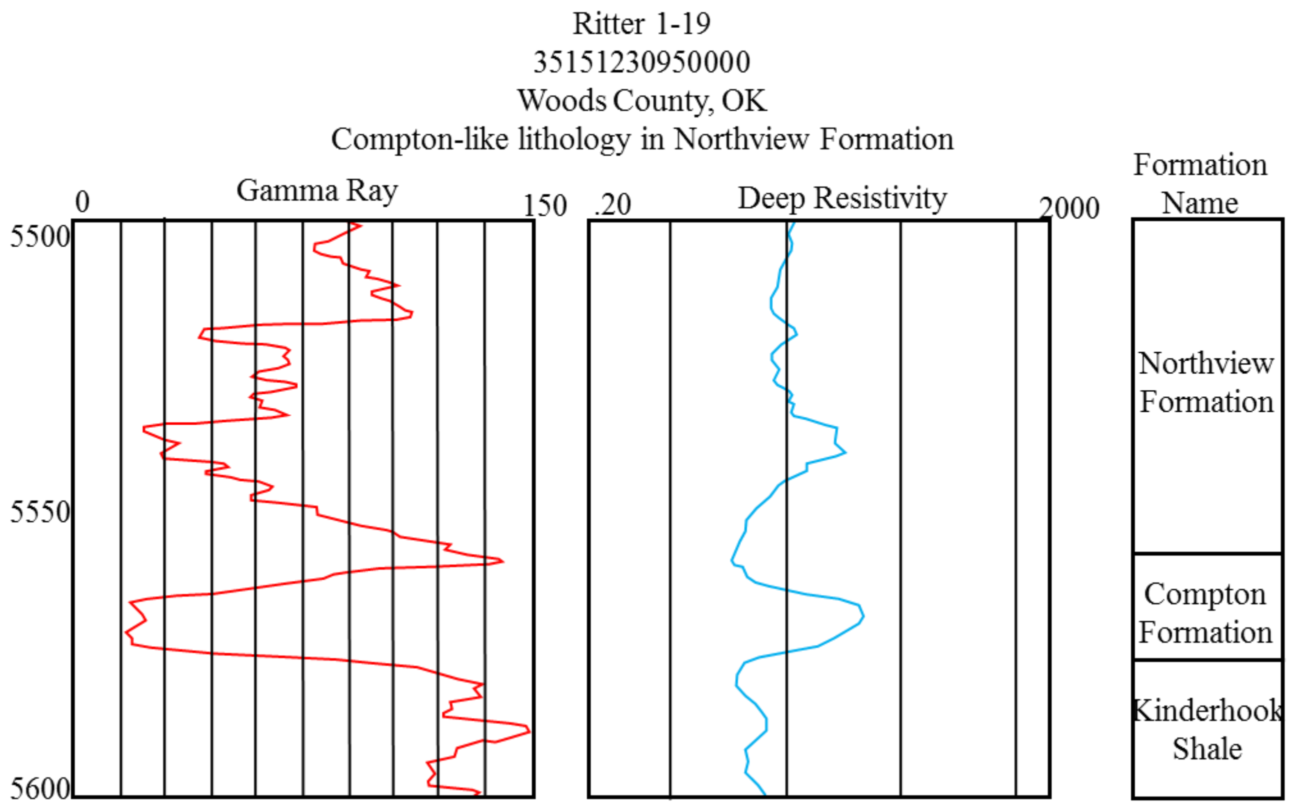

Figure 16: Type log from the Ritter 1-19 well in Woods County, Kansas of the occasional Compton Formation-like log motif within the Northview Formation. Gamma ray (0-150 API) is on the left in red and deep resistivity (.20-2000 ohm-m) is on the right in blue. There are lower gamma ray readings and high resistivity spikes similar to the Compton Formation. This log motif is sporadic and not mappable throught the area, most likely attributed to higher order transgressions.

The Northview represents a lowstand in sea level with an influx of sediments from a northerly source (Handford, 2013; Manger and Evans, 2012). This sufficiently shut off the carbonate production that was seen in the Compton. Handford (2013) and Manger and Evans (2013) state that the Northview has a sigmoidal clinoform geometry indicative of progradation (Figure 17). This can be seen in cross section through the study area (Figure 18). The sigmoidal geometry is thin towards the shoreline, thickest at the shelf edge, and thin at the distal portion of the shelf. Base level fell, which caused sediment influx to outpace the creation of accommodation space, yielding sediment bypass at the shoreline and progradation of the shelf edge.

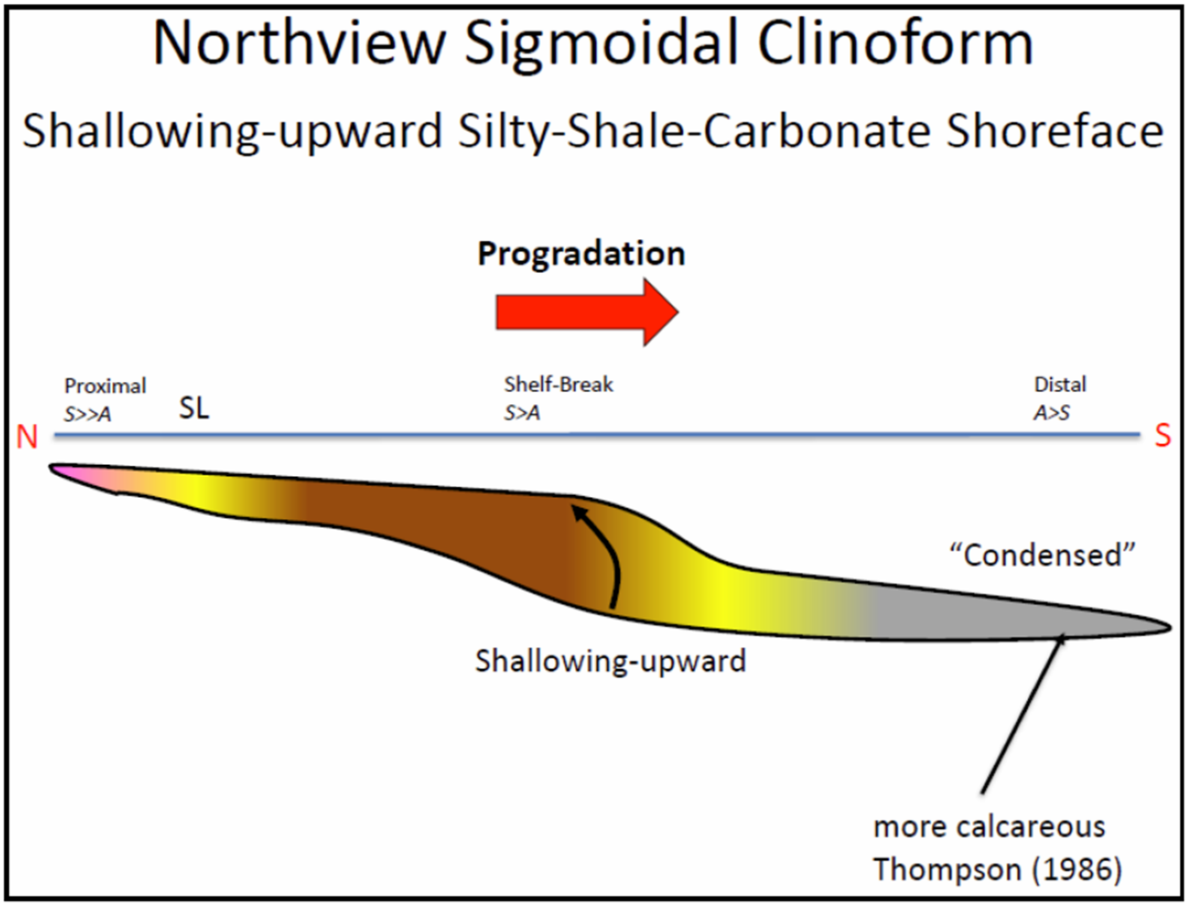

Figure 17: Depositional model from Handford (2013) showing the depositional nature of the Northview Formation based on outcrop isopach maps in the Mississippian outcrop belt. The Northview Formation was deposited during a lowstand, yielding the progradation of sigmoidal clinoforms.

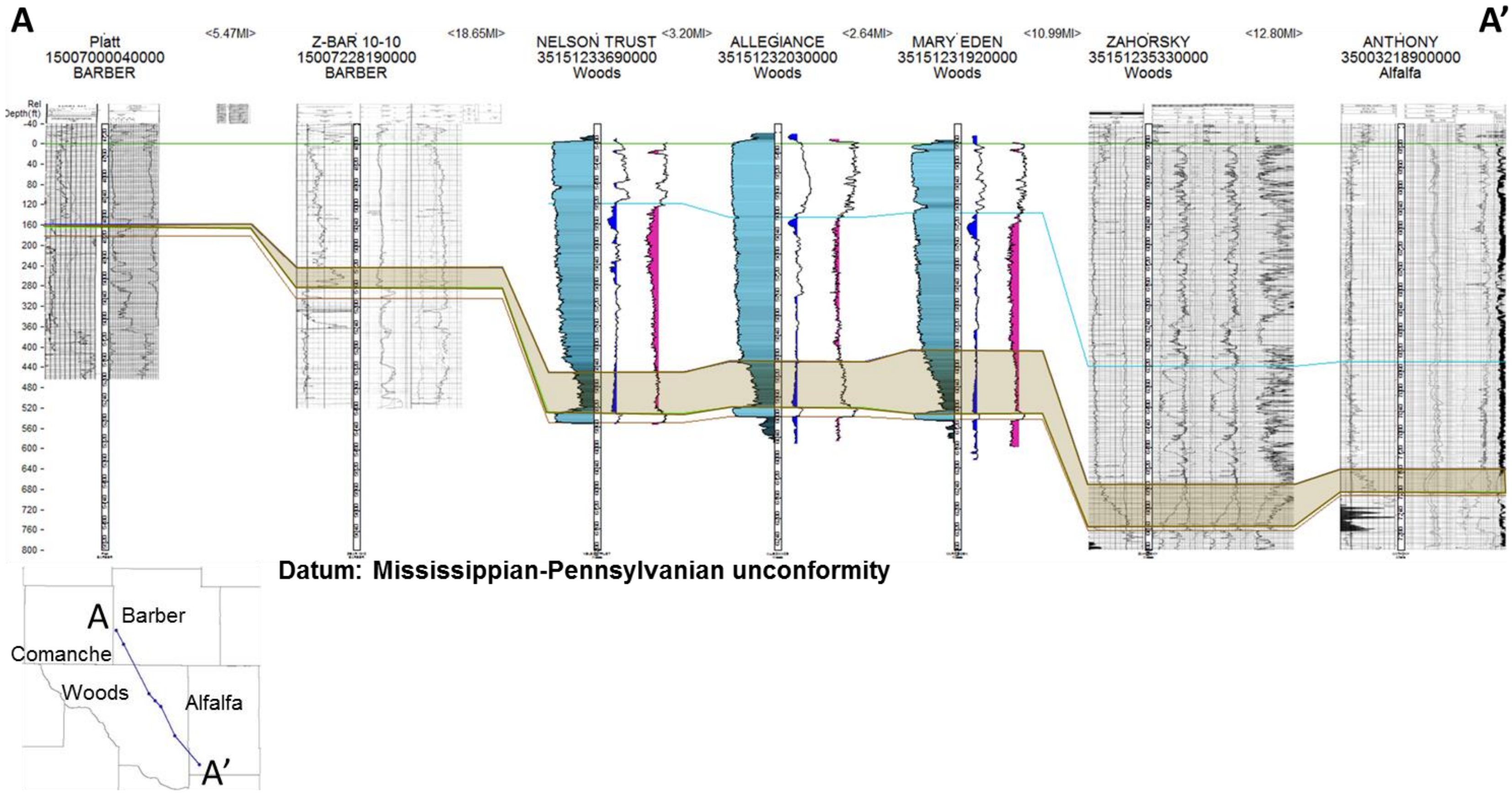

Figure 18: Northwest to southeast cross section through the study area illustrating the sigmoidal clinoform-like geometry of the Northview Formation that is similar to the Handford (2013) depositional model. Progradation direction was to the south-southeast.

4.3 Osagean

The Osagean series comprises the Osage deposition. This chronostratigraphic interval in the lower Mississippian occurs between the Kinderhookian and the Meramecian. It encompasses the maximum flooding interval where 2^{nd} and 3^{rd} order transgression are superimposed on eachother.

4.3.1 Osage

The contact between the Northview and Osage in the subsurface is mostly gradational within the study area. There does not appear to be any way to distinguish between the Pierson Formation and the Osage as possible in outcrop, since there are no changes in log character to reflect a difference in lithology. This could be due to deposition in deeper water than what is seen in the Mississippian outcrop belt, hindering the Pierson Formation facies to develop. The Osage is equivalent to the Boone Formation in northwest Arkansas, where it can be differentiated into a lower and upper Boone based on chert development. For well log correlations, the Osage was not differentiated as it was impossible to do in well logs that did not have a corresponding mud log. Later in this chapter, a method for differentiation was described for wells that had mud logs.

Commonly, a photoelectric effect (PE) value of 3.5 barns/electron or lower is seen within the Osage. When the PE log value is lower than 3.5, it is indicative of increasing silica content, and when the PE log value is above 3.5 it is indicative of increasing calcium content. A cherty limestone gives off a distinctive “zig-zag” pattern between 2-3.5 barns/electron, which has been documented in Freisenhahn (2012) and Wittman (2013). Mud logs help confirm that this relationship between chert occurrence and the “zig-zag” pattern between 2-3.5 barns/electron is accurate (Figure 19). Deep resistivity values average below 40 Ohm-m. The Osage has gamma ray values typically between 20-60 API units and generally exhibits a cleaning trend where gamma ray values decreases upward to the top of the formation. Mud logs within the Osage typically mention abundant chert that is tripolitic in the upper portion of the formation (Figure 20). Thickness of the Osage averages 250 feet with a range between less than five feet in the southeastern portion of the study area and over 400 feet in the southwestern portion of the study area (Figure 21).

Following the lowstand within the Northview Formation, an increase in sea level occurred. This sea level rise is attributed to both 2nd and 3rd order transgression superimposed on each other within the Kaskaskia II sequence. As seen in both outcrop and the subsurface, the Osage exhibits abundant amounts of chert. This is most likely the maximum flooding interval that is seen in the lower Boone Formation of the Mississippian outcrop belt. Immediately following the maximum flooding interval, highstand conditions ensued allowing progradation to occur until lowstand conditions prevailed. This regression comprises a 3rd order regressive cycle that reaches maximum regression towards the conclusion of the Osage. Also, the maximum regression marks the end of the first T-R cycle. Within the subsurface there has been a documented minor unconformity at the top of the Osage (Thornton, 1964; Lane and DeKeyser, 1980; Mazzullo *et al.*, 2009; Costello *et al.*, 2013).

A lobate depositional pattern characterizes the Boone Formation in outcrop, similar to what is seen in the Compton Formation (Manger and Evans, 2012) (Figure 22). The lobate geometry is not as pronounced as the Compton Formation, but this could be attributed to much more carbonate being produced or a loss of accommodation space creating the amalgamated lobes. When the Osage goes to thickness below 5 feet, this could be a shadow in deposition. This shadow can somewhat be seen in the Compton Formation due to a tight thickness gradient between thick and thin deposits. It is also apparent that the Pratt Anticline was not active during the Osage, as the strata maintain thickness over the axis of it. This could mean that depositional patterns for the study area were not influenced by the Pratt Anticline during Osage deposition.

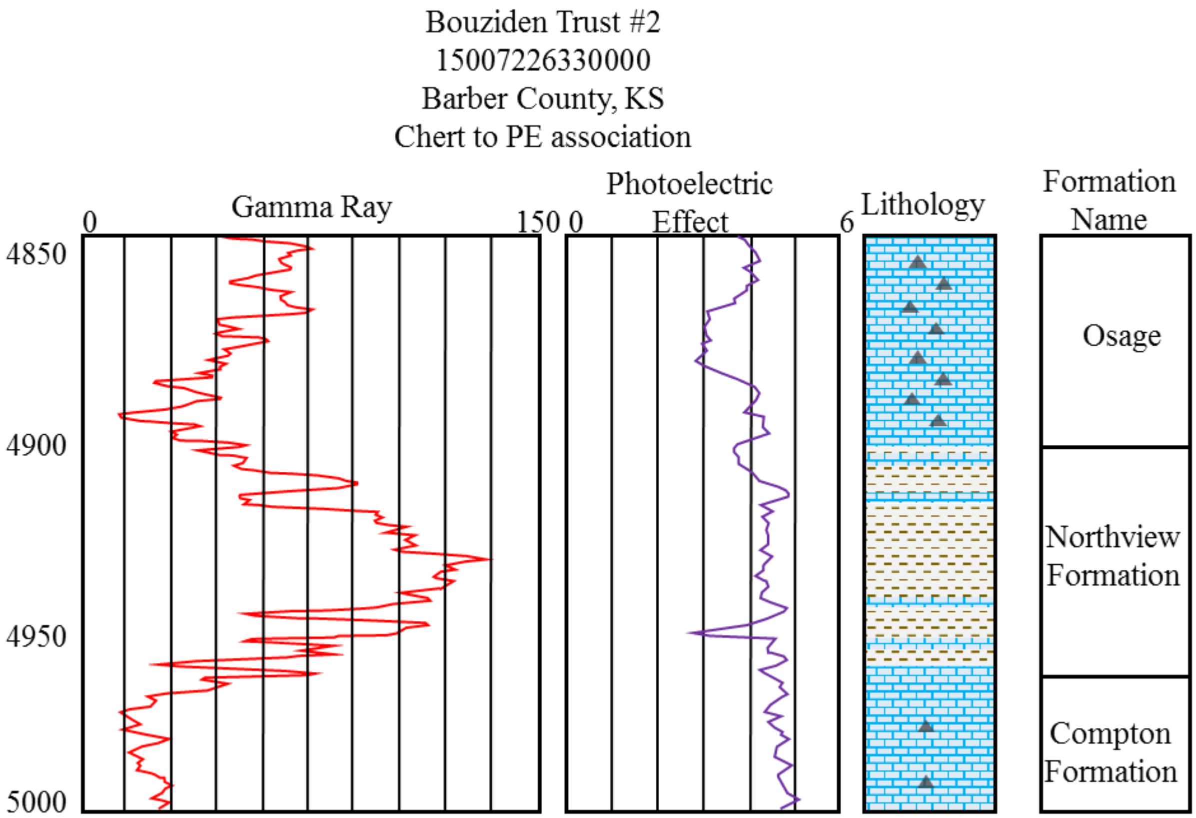

Figure 19: Type log from the Bouziden Trust #2 well in Barber County, Kansas. Gamma ray is on the left in red (0-150 API) and photoelectric effect (0-6 barns/electron) on the right in purple. Within the Osage, there is an abundance of chert, which is reflected on the photoelectric effect log. The lower the photoelectric effect value, the higher the silica content. Thus, when comparing the Compton Formation, a clean limestone with trace chert, to the Osage, which has abundant chert, there is a decreasing trend in the photoelectric effect values.

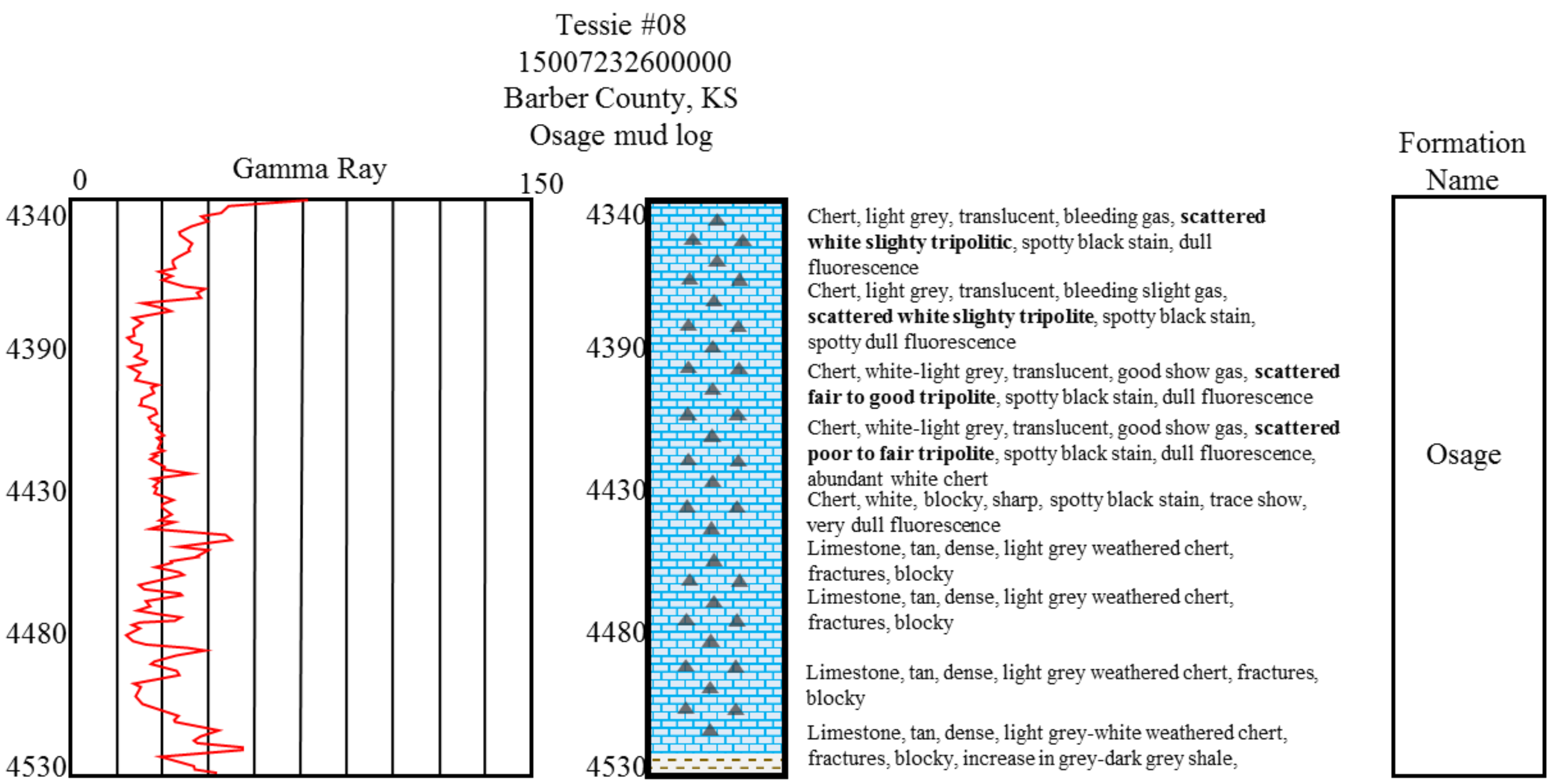

Figure 20: Mud log from the Tessie #08 well in Barber County, Kansas of the Osage. The Osage contains a dense, fractured at times, cherty limestone comprising the lower portion and a tripolitic chert rich limestone comprising the upper portion. Throughout this interval there are many stains and fluorescence, indicating the presence of hydrocarbons.

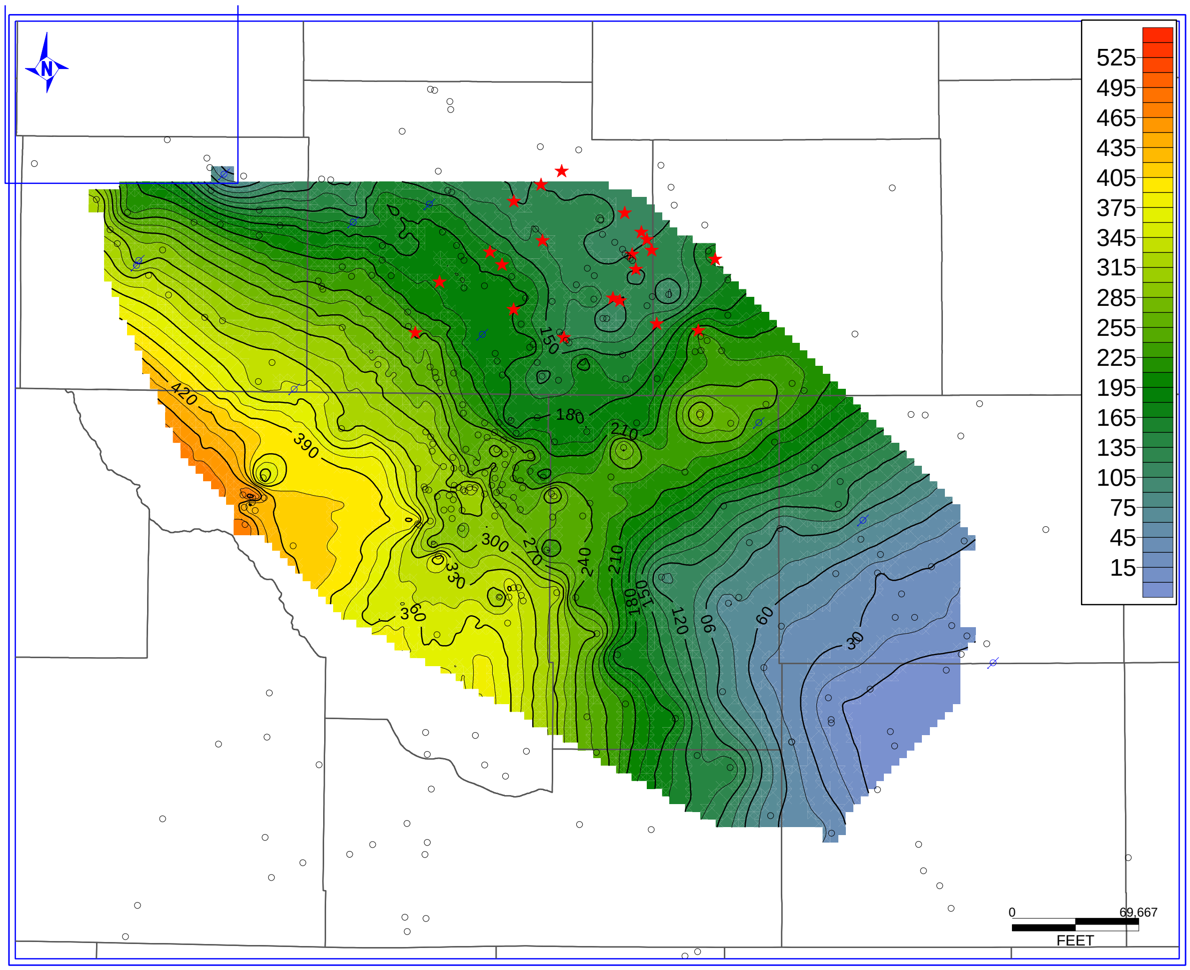

Figure 21: Isopach map of the Osage. Contour interval is 15 feet. A lobate geometry similar to what is seen in the Compton Formation, but more amalgamated. The thin area in the southeastern portion was most likely a shadow of depostion. It also appears that the Pratt Anticline was not active during the Osage, as the Osage maintains thickness over the axis of the Pratt Anticline. The Osage was deposited in a transgression to high stand conditions.

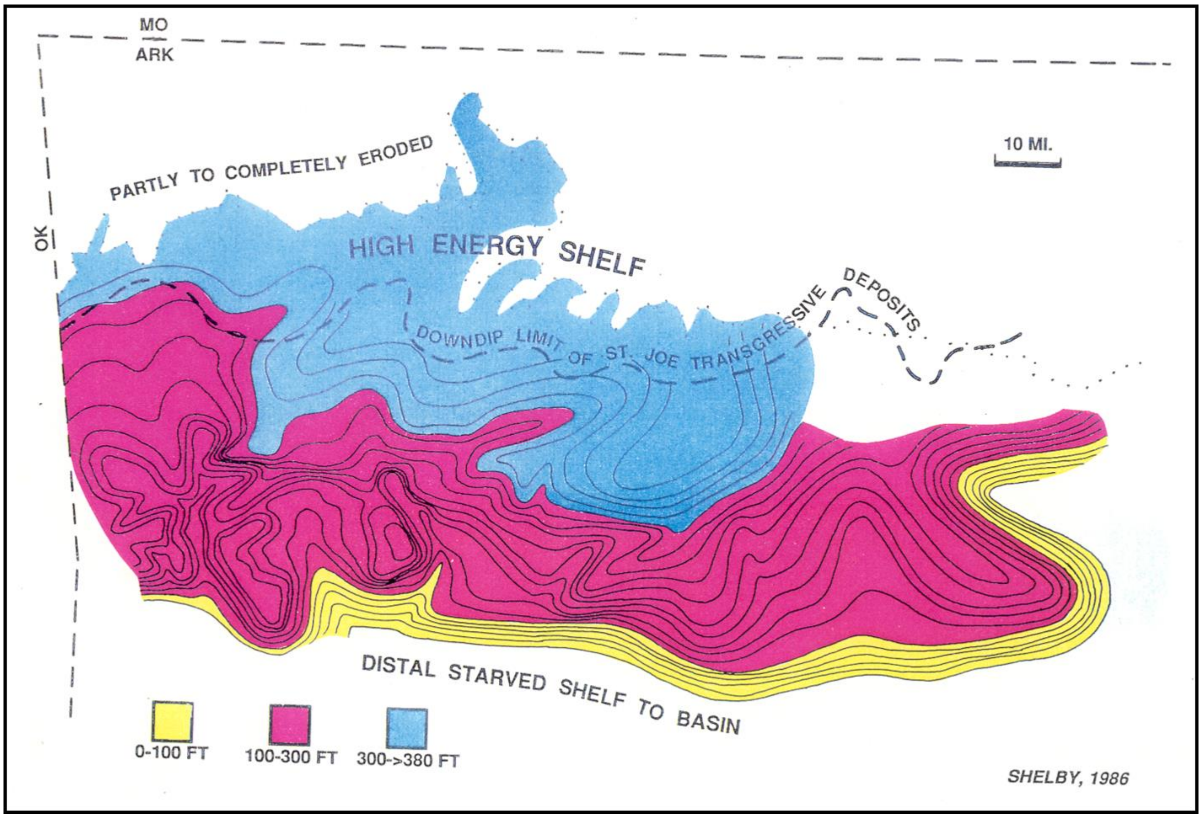

Figure 22: Outcrop isopach map of the Boone Formation (Osage) from Shelby (1986). Notice the amalgamated nature of deposition. Similarities exist in depositional style to what is seen in the subsurface. The amalgamated lobes seen in outcrop are indicative of a large amount of transported carbonates coming off of the Burlington Platform to the north. This same depositional style was most likely occurring within the study area.

4.3.1.1 Lower Boone

The lower Boone Formation is of Osage age and is a calcisiltite with penecontemporaneous chert development (Manger and Evans, 2012). This penecontemporaneous chert formed from silica reorganization from volcanic ash mixing with carbonate sediment, and reorginization immediately below the sediment-water interface shortly after deposition (Manger and Evans, 2012). Its occurrence is limited to only the lower Boone and is associated with maximum flooding (Manger and Evans, 2012) (Figure 23). Calcium content within the chert is low, as silica is not a replacement product (Manger and Evans, 2012; Minor, 2013; Johnson, 2014).

Based on paleogeographic reconstructions of the Mississippian outcrop belt, there is a change in depositional environment from southern Missouri to northwest Arkansas. Environments change from a shallow platform environment to a deeper, ramp (Manger and Evans, 2012). In the shallower platform environment in southern Missouri, the lower Boone is a thin succession of interbedded calcisiltites and dark chert, and is identified as the Reeds Spring Formation. Based on conodont data, the Reeds Spring Formation is of age and lateral equivalence to the thicker Lower Boone to the south in northwest Arkansas (Manger and Evans, 2012). This relationship shows that the maximum flooding interval thins towards the shallower platform environment in effective wave-base and thickens towards the deeper ramp environment below effective wave-base (Manger and Evans, 2012).

Figure 23: Picture taken from Manger (2014) of the lower Boone Formation within the Mississippi outcrop belt. Darker beds above the clean, white St. Joe limestones are penecomtemporaneous chert deposited in deep water during the maximum flooding interval during the Osage.

4.3.1.2 Upper Boone

The upper Boone is of Osage age and is composed of crinozoan detritus that experienced later diagenetic chert replacement (Manger and Evans, 2012). In southern Missouri, succeeding the Reeds Spring Formation is the Elsey Formation. Based on conodont data, the Elsey is equivalent to the upper Boone in northwest Arkansas. Later diagenetic chert present within the upper Boone differs from penecontemporaneous, as it is interpreted to be a groundwater phenomenon that developed after lithification (Manger and Evans, 2012). Lithified carbonate was replaced due to silica-bearing groundwater moving along bedding planes (Manger and Evans, 2012).

Within the upper Boone, there is the occurrence of tripolitic chert (Figure 24). Tripolite is granular, microcrystalline and porous that has been derived from the alteration of chert, or by the leaching of highly siliceous limestones (Tarr, 1938). In order for tripolite to form, it must have had a “chert precursor”. Due to tripolitic chert occurring exclusively in the upper Boone, the precursor had to be later diagenetic chert (Manger and Evans, 2012; Minor, 2013). Study of the tripolitic chert by Minor (2013) and Johnson (in preporation) have shown that in the lower Boone Formation (Reeds Spring Formation) penecontemporaneous chert lacks a sufficient amount of calcite to be decalcitized. Conversely, the upper Boone Formation (Elsey, Burlington-Keokuk) does have enough calcite for decalcification for silica replacement, thus, allowing the opportunity for tripolitic chert to develop.

Figure 24: Lower to upper Boone transition in southwestern Missouri, taken from Manger (2014). Darker limestones are lower Boone Formation and tan colored limestones are upper Boone Formation. The tan color represents the later diagenetic chert, which is different from the penecontemporaneous chert formed during maximum flooding interval. The later diagenetic chert was formed by to an influx of ground water after deposition causing silica replacement of the carbonate.

4.3.1.3 Subsurface Occurence

Using just the standard triple-combo well logs, lithologic correlation is very difficult to do without knowing the actual lithology of the rock. Mud logs were relied on heavily while making such correlations. Mud logs are created based on descriptions of rock fragments brought up to the surface by the drilling mud during drilling. Mud logs were only available for Kansas wells and core descriptions from Costello *et al*, 2013 that were confined to Woods County, Oklahoma, which limited the area where lithologic correlations could be made with confidence.

Both mud logs and core mention the occurrence of tripolitic chert, so presumably observations from the outcrop can be extrapolated down into the subsurface. The tripolitic chert is usually described as white to off-white weathered tripolite with oil staining and good porosity development (Figure 25). The descriptions of the rocks below the tripolitic chert interval are usually white to grey chert within a dense limestone of varying color (Figure 25).

In the previous section, it was explained that tripolitic chert only occurs within the upper Boone. Combining observations from outcrop and the subsurface, there are similarities to where tripolitic chert develops stratigraphically. The first similarity is that below the tripolitic chert development, there is a dense, cherty limestone of a different character. This could be equivalent to the lower Boone (Reeds Spring Formation) Formation that is seen in outcrop. The second is that the tripolitic chert always occurs above the dense cherty limestone, reflecting the relationship seen in outcrop where tripolitic chert does not occur within the lower Boone (Reeds Spring Formation) Formation, but always above. The third is that in the cross-section through eastern Barber County, Kansas, the southern well (Schmidt 1-36) has tripolitic chert development with dense cherty limestone below (Figure 26).

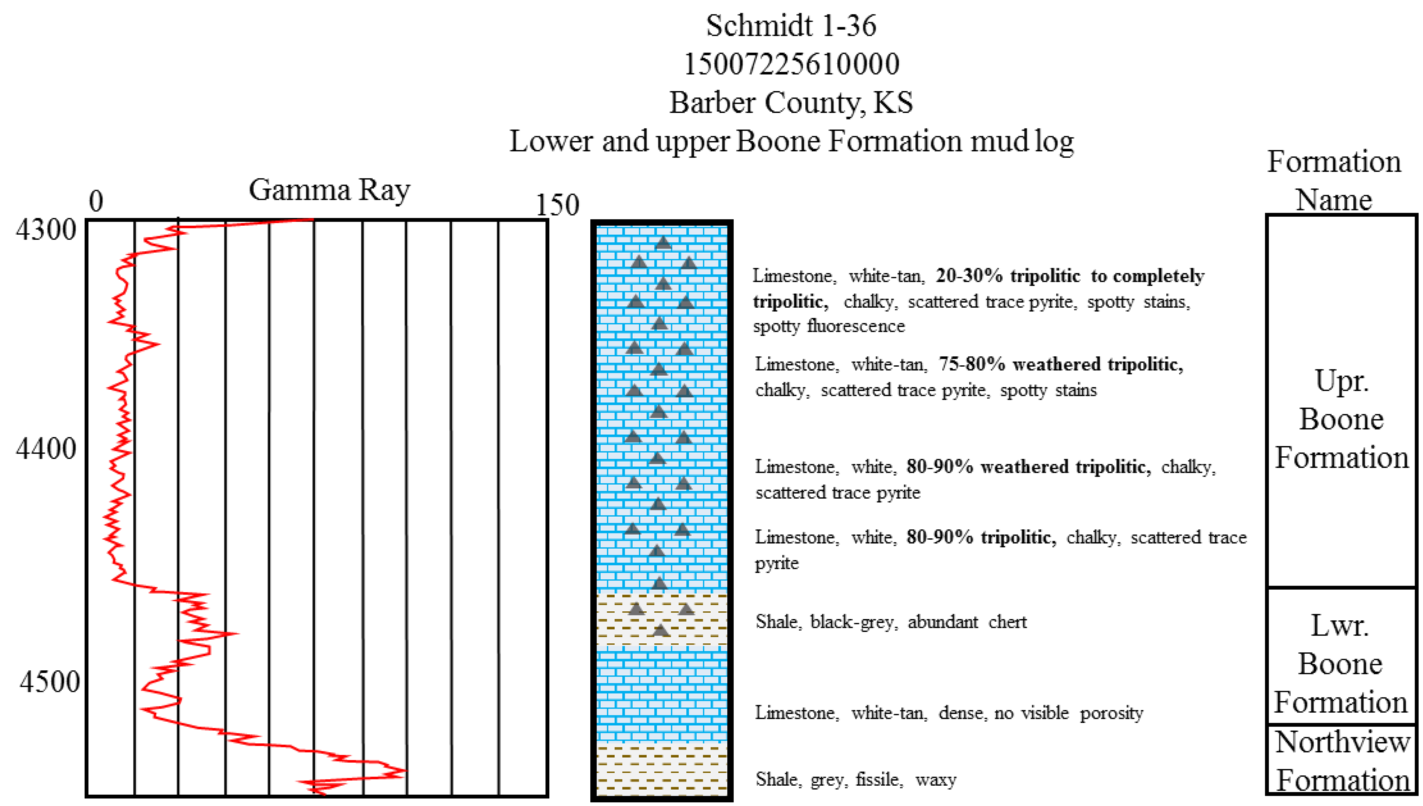

Figure 25: Mud log from the Schmidt 1-36 well in Barber County, Kansas of the Osage. Based on the mud log descriptions, lower and upper Boone Formation have been identified. The lower Boone Formation represents the lower portion of the Osage, where there is a dense, cherty limestone. A transition to tripolitic chert limestones in the upper portion of the Osage could represent upper Boone Formation.

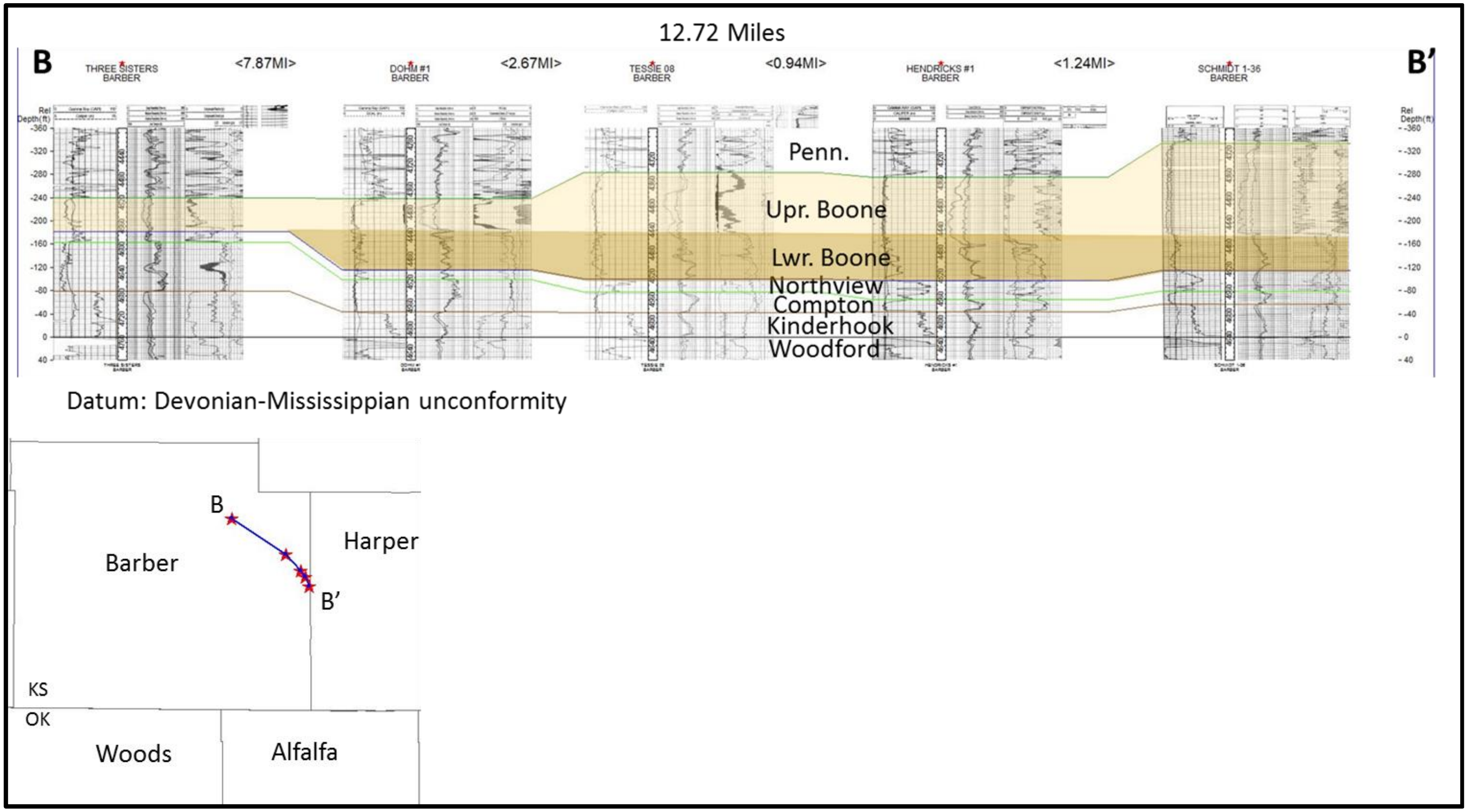

Figure 26: Cross section in eastern Barber County, Kansas. Boundaries for the lower and upper Boone Formation were based on the occurrence of tripolitic chert as mentioned in mud log description.

Moving northward, this dense cherty limestone interval inferred to be the lower Boone (Reeds Spring Formation), begins to thin. In the northern well (Three Sisters), the lower Boone (Reeds Spring Formation) is absent, so upper Boone is directly above the Northview Formation. This is more than likely a facies transition from deeper ramp facies to shallow platform facies occurring between the Three Sisters well and Dohm #1 well. Such a facies transition characterizes the lower and upper Boone as illustrated in the section before from southern Missouri south to northwest Arkansas (Figure 27).

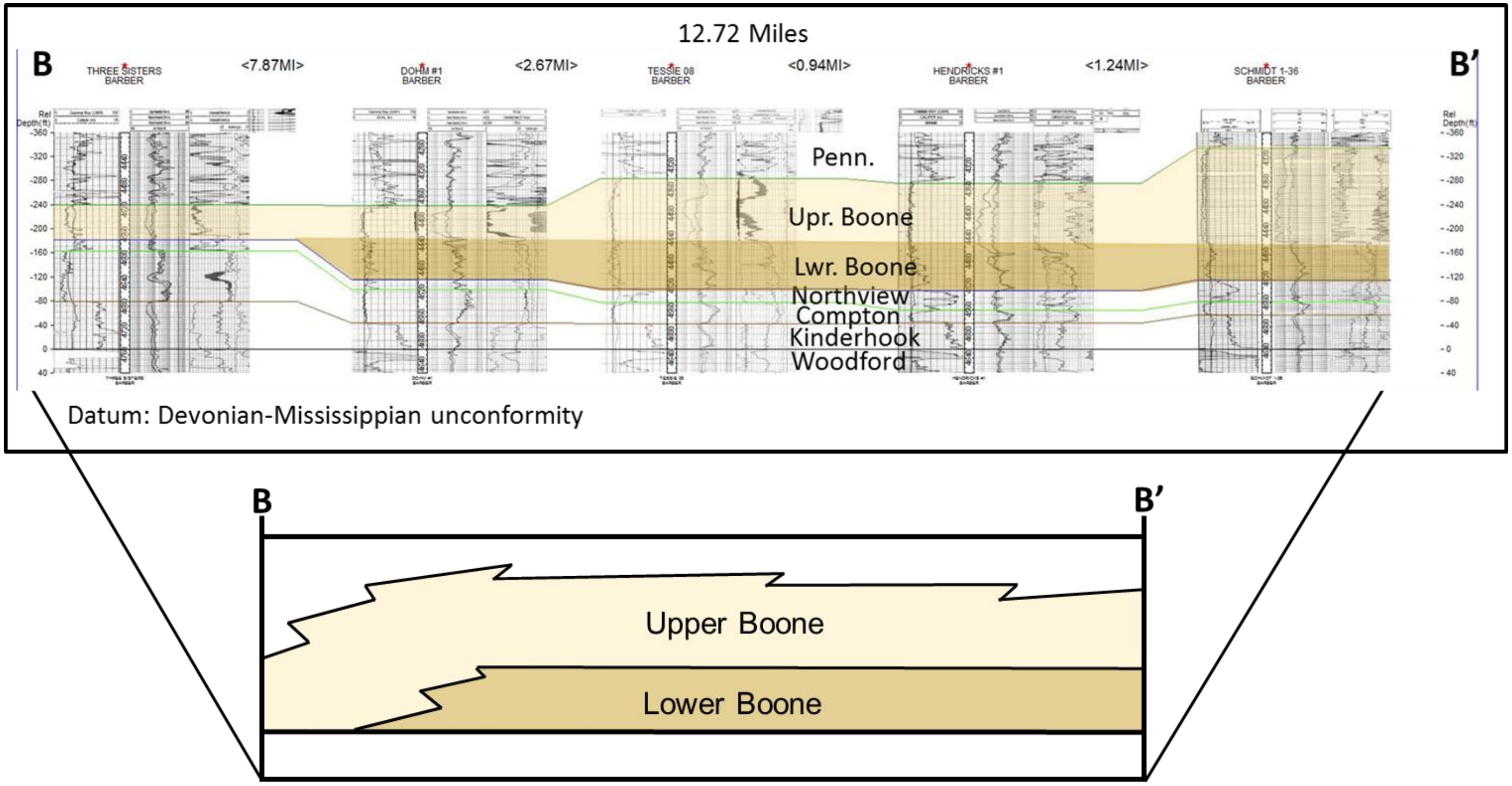

Figure 27: Depositional model based on the Thompson (1986) schematic showing stratigraphic relationships. What is seen in the subsurface reflects the same lithostratigraphic relationships as what is seen in the Mississippian outcrop belt. The lower Boone Formation in the subsurface has a facies transition to upper Boone Formation, suggesting a transition from deeper water facies to shallower water facies. This could also reflect a platform to ramp transition zone.

4.3.1.4 Tripolitic Chert Development

Outcrops of the Mississippian provide depositional implications that can be correlated to the subsurface. The timing of the tripolitic chert formation is unknown, but in order for tripolitic chert to form it must first have carbonate to remove. In the case of the Mississippian, later diagenetic chert would have to be formed before it became tripolitic chert. This principal is taken into the subsurface and there are two scenarios that could have happened to explain this:

Scenario 1) (Figure 28) First, dense, deeper water penecontemporaneous chert is formed by silica reorganization from ash below sediment-water interface during transgression and maximum flooding in the lower Boone. Following the deposition of the penecontemporaneous chert, sea level began to drop depositing the upper Boone limestones. Once sea level reached its maximum regression and the lithification of the upper Boone had taken place, a groundwater network of plumbing allowed for silica replacement and development of chert. This alteration process for the development of chert is analogous to what has been described in the outcrop (Manger and Evans 2012; Minor 2013, Johnson in preporation). Most of the alterations occur along bedding planes, with the silica replacement replacing the smaller grains (Minor 2013). After the maximum regression during the upper Boone, transgression is renewed and the Meramec limestones are deposited. The Mississippian-Pennsylvanian unconformity occurs and subaerial exposure and erodes portions of Meramecian strata. During the subaerial exposure, a water table is perched on the dense cherty limestone of the lower Boone. The overlying later diagenetic chert within the upper Boone is then subjected to this perched water table and tripolitic chert development occurs.

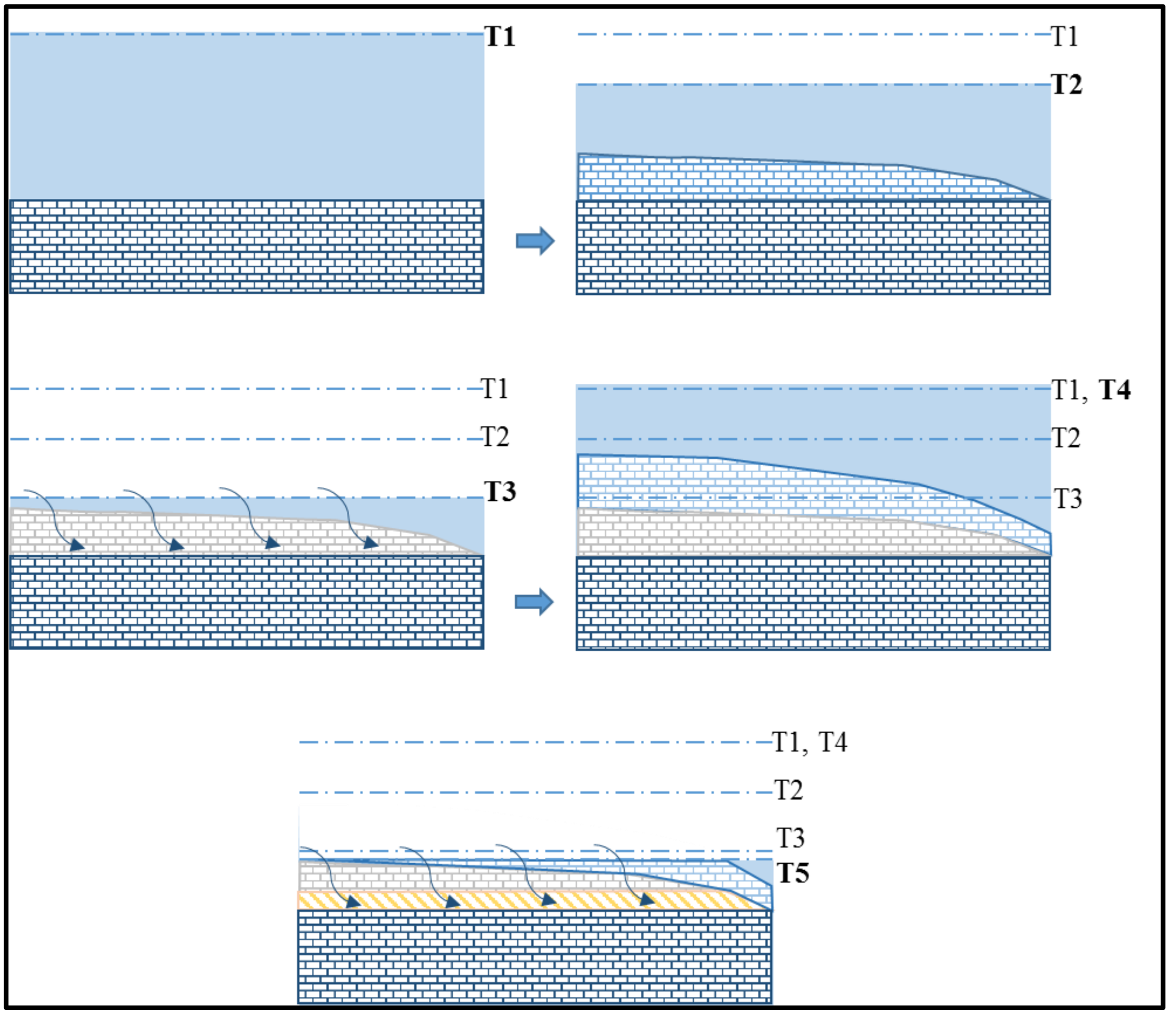

Figure 28: Scenario one for the development of tripolitic chert within the subsurface. T1 represents the deposition of lower Boone Formation penecontemporaneous chert during the maximum flooding interval of the early Osage. T2 represents highstand and a gradual lowering of sea level causing progradation southward of the upper Boone Formation during the upper Osage. T3 represents lowstand at which sea level gets shallow enough for meteoric water influx and the formation of later diagenetic chert via perched water table during the late Osage. The meteoric water influx then gets perched on the penecontemporaneous chert of the lower Boone, causing later diagenetic chert (light brown blocks) to form in the upper Boone Formation. T4 represents renewed transgression and deposition of the Meramec during the Meramec. T5 represents lowstand at the Mississippian-Pennsylvanian unconformity, where another influx of meteoric water causes the decalcification of remaining carbonate within later diagenetic chert to form tripolitic (yellow diagonal lines) chert via another perched water table. The subaerially exposed Meramec could represent Mississippian "chat" development.

In conclusion, this scenario takes two stratigraphically separate water influx events to form the tripolitic chert: 1) The first influx allows for the precipitation of the diagenetic chert during the end of the Osage, 2) After deposition of Meramecian strata, during the Mississippian-Pennsylvanian unconformity, a perched water table atop the penecontemoraneous chert causes decalcification of remaining chert and silica replacement of the carbonate results in tripolitic chert. It is important to note that in areas where the Meramecian strata were not fully eroded (i.e. north-central Oklahoma) there is still tripolitic chert, showing that the presence of it atop the upper Boone had almost no effect on the tripolitic chert creation process (Costello *et al.,* 2013).

Scenario 2) (Figure 29) After deposition of the dense deeper penecontemporaneous chert during transgression and maximum flooding in the lower Boone, sea level began to drop. During this regression, the upper Boone limestones were deposited and lithified. Sea level continued to drop and a groundwater network of plumbing developed. The fluid enabled silica replacement and development of later diagenetic chert. Soon after the formation of the diagenetic chert, another influx of water occurs causing decalcification of the remaining carbonate in the later diagenetic chert into silica, creating tripolitic chert. The tripolitic chert development is limited to a window before deposition of the Meramec.

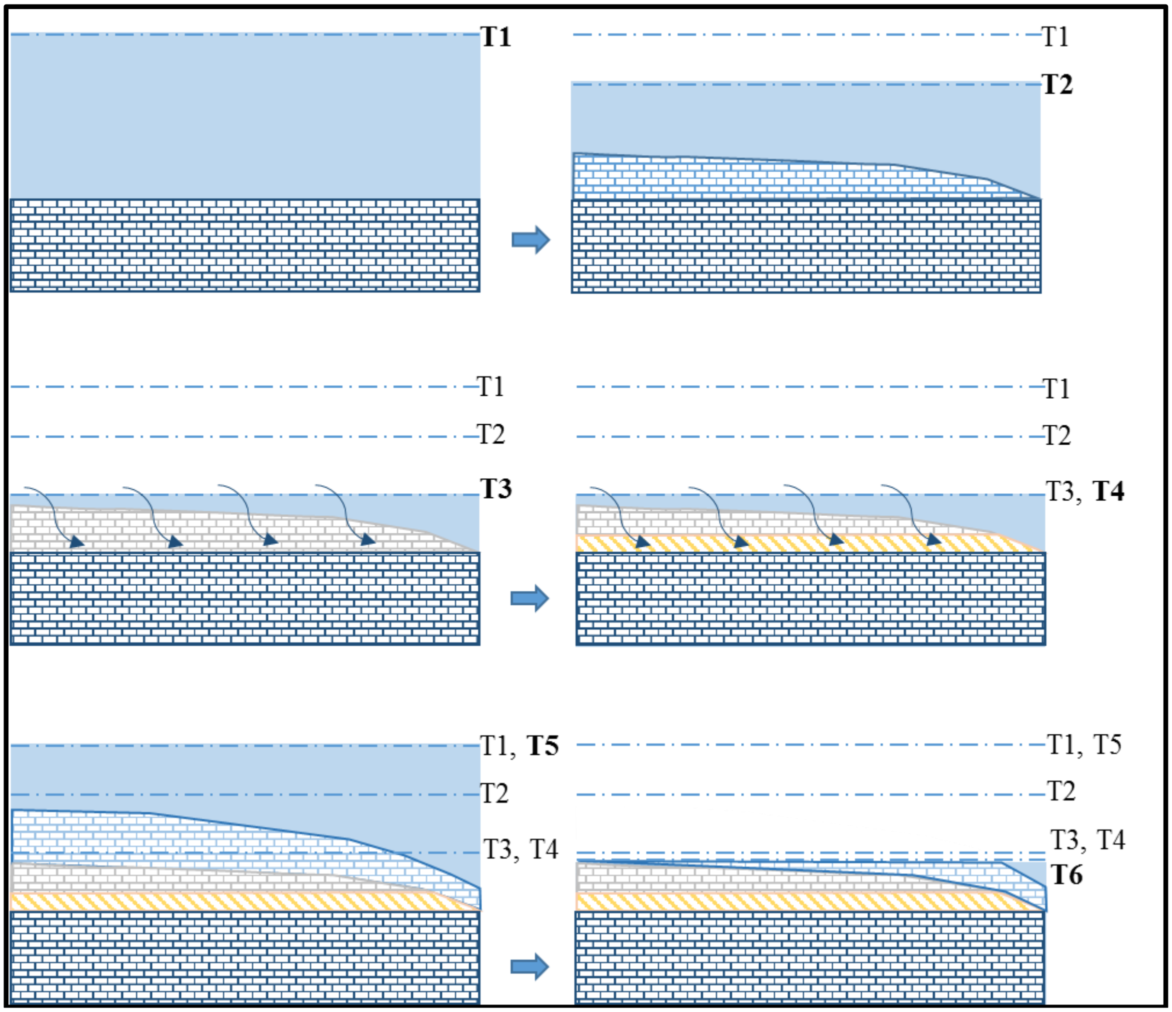

Figure 29: Scenario two for the development of tripolitic chert within the subsurface. T1 represents the deposition of lower Boone Formation penecontemporaneous chert during the maximum flooding interval of the early Osage. T2 represents highstand and a gradual lowering of sea level causing progradation southward of the upper Boone Formation during the upper Osage. T3 represents lowstand at which sea level gets shallow enough for meteoric water influx and the formation of later diagenetic chert (light brown blocks) via perched water table during the late Osage. The meteoric water influx then gets perched on the penecontemporaneous chert of the lower Boone, causing later diagenetic chert to form in the upper Boone Formation. T4 represents another influx of meteoric water after the formation of the later diagenetic chert, causing decalcification of carbonate remaining within the later diagenetic chert into tripolitic chert (yellow diagonal lines) to form before the Meramec is deposited. T5 represents the transgression during the deposition of the Meramec during the Meramec. T6 represents lowstand at the Mississippian-Pennsylvanian unconformity, and the Meramec could represent Mississippian "chat" development.

4.4 Meramecian

The Meramecian series comprises the Meramec deposition. This chronostratigraphic interval in the upper Mississippian occurs after the Osagean. It encompasses 3rd order transgression after the unconformity at the end of the Osagean.

4.4.1 Meramec

Overlying unconformably above the Osage is the Meramec. This boundary does not exist in most of the Mississippian outcrop belt, as there Meramec strata have been eroded away. In the subsurface, finding the contact is not possible with solely gamma ray, so PE and deep resistivity were used. The PE log is the main log used for finding the boundary between the Osage and Meramec due to the Meramec having less quantities of chert, giving a higher PE reading. Deep resistivity is the secondary method for finding the boundary, as the Osage rarely has a greater than 40 Ohm-m value. Due to deep resistivity not being lithology dependent, it was coupled with the PE curve. When the PE curve went above the 3.5 cut off and the deep resistivity went over the 40 Ohm-m cut off, it was assumed this was the boundary between the Osage and Meramec. Gamma ray values in the Meramec are similar to those of the Osage and range from 15-40 API units.

Meramec strata are characterized as a dolomitic crinoidal wackestone and packstone with less abundant chert (Thornton, 1964; Costello *et al.*, 2013). Mud logs within the Meramec describe an abundance of dolomite with little chert (Figure 30). The average thickness of the Meramec is 300 feet, and ranges from zero in the north-central portion of the study area to greater than 400 feet in the southeast and southwest portion of the study area (Figure 31). The lack of Meramec strata in the north central portion of the study area suggests that the Pratt Anticline was active during the Meramec. Activity along the Pratt Anticline also created enough relief to potentially affect depositional patterns, as the Meramec strata thicken dramatically moving to the south.

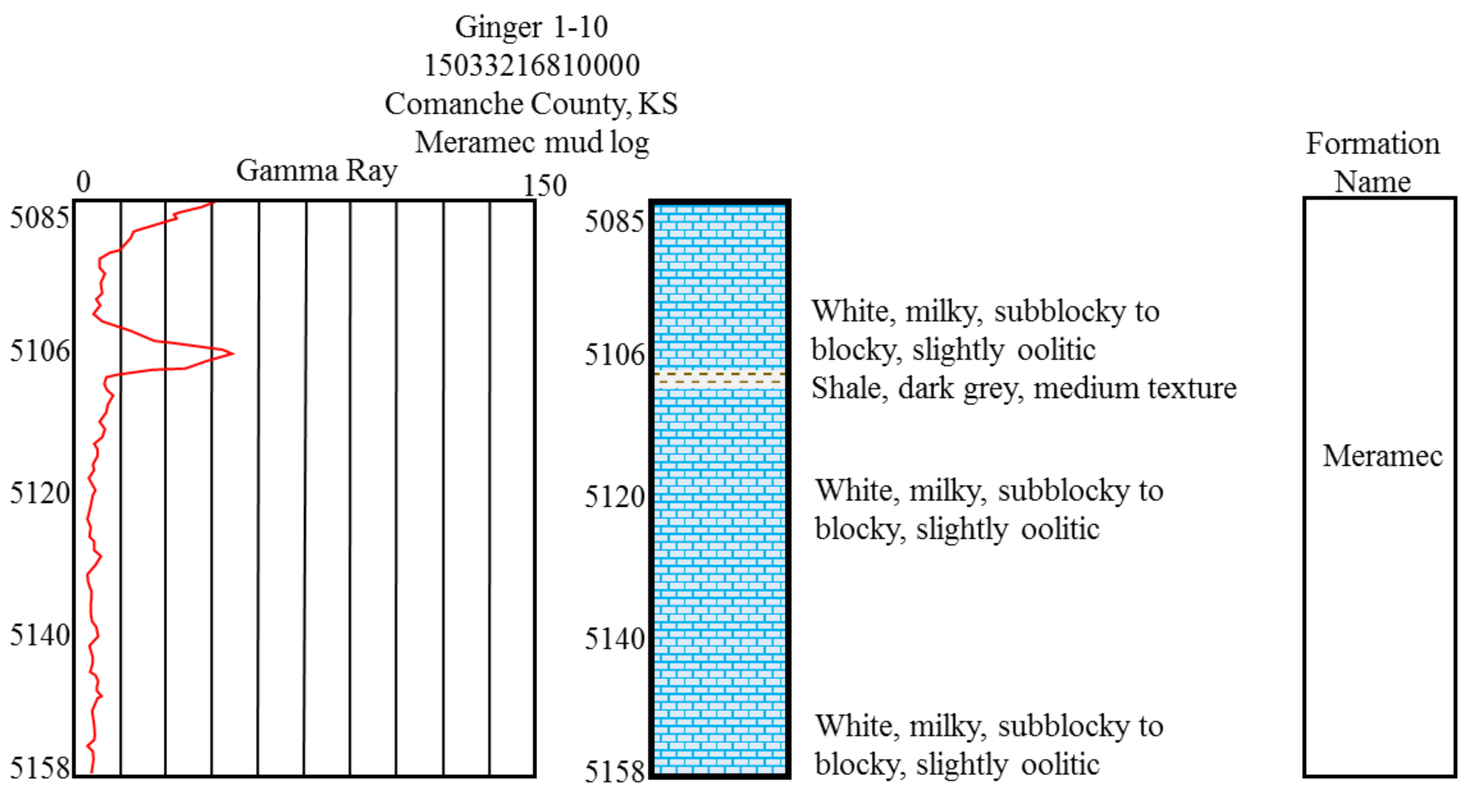

Figure 30: Mud log from the Ginger 1-10 well in Comanche County, Kansas. The Meramec is a much cleaner limestone with respect to chert content than the Osage; mainly a dolomitic, dense limestone.

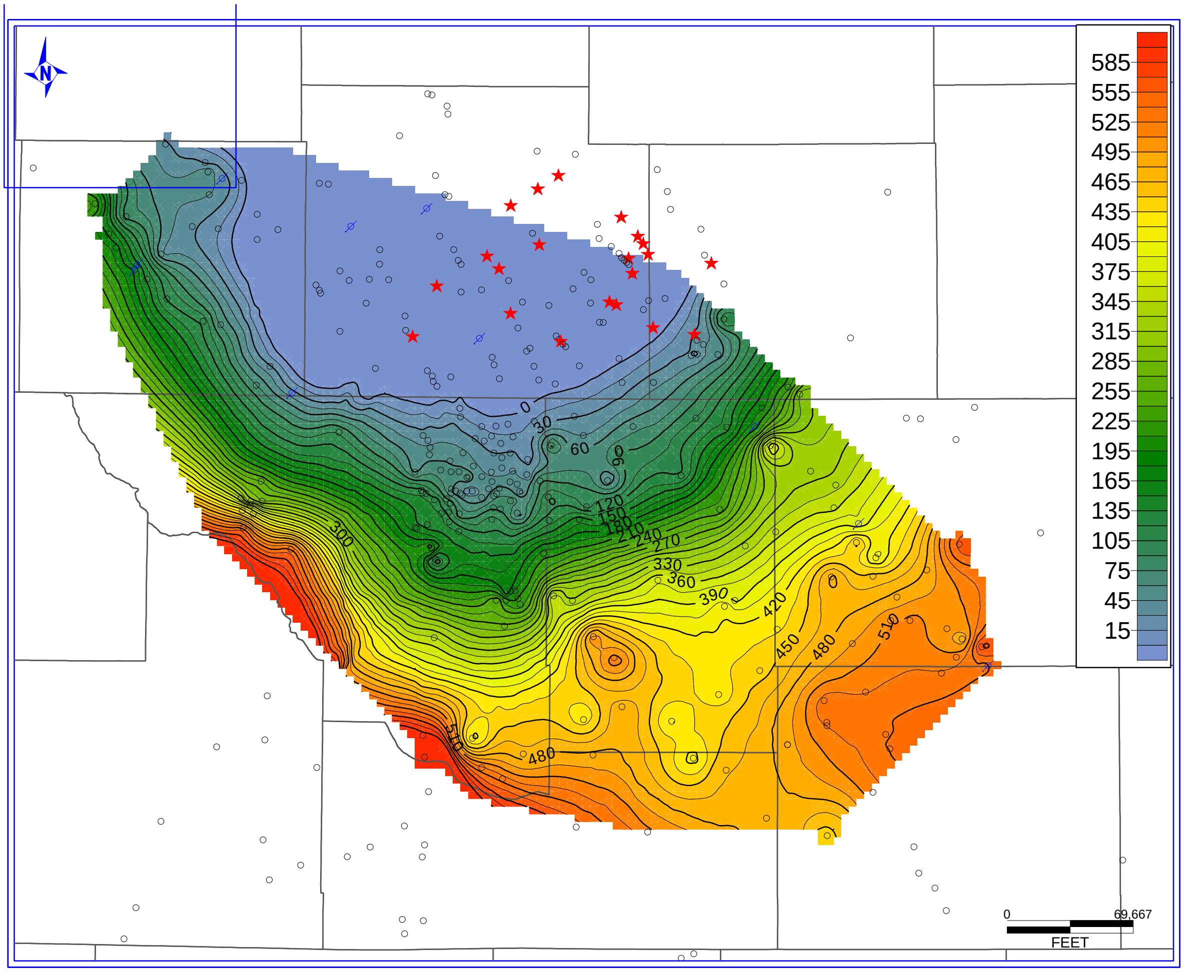

Figure 31: Isopach map of the Meramec. Contour interval is 15 feet. Thickest areas are to the southwest and southeast. There is a large area where the Meramec has been eroded away, suggesting the Pratt Anticline was a post-Osage feature. The Meramec is also heavily eroded along the axis of the Pratt Anticline. The depositional style was similar to Osage. The Meramec was deposited during transgressive to highstand conditions.

After the lowstand and unconformity at the end of the Osage, the second 3rd order T-R cycle began with transgression. This allowed transgression to highstand conditions to prevail. Abundant accommodation space was created yielding the significantly thicker deposits towards the south. Depositional patterns were also similar to Osage, as down-ramp movement of sediment created a lobate geometry. Highstand persisted until sea level drop associated with the Mississippian-Pennsylvanian unconformity took over. At this time, the carbonate factory within the study area was ultimately shut down and Pennsylvanian siliciclastics encroached after the Mississippian-Pennsylvanian unconformity.

5. RESERVOIR CHARACTERIZATION

5.1 Oklahoma

Reservoir intervals within the Mississippian strata are found primarily in two different stratigraphic positions in Oklahoma. The porosity development occurs beneath the Osage-Meramec boundary and beneath the Mississippian-Pennsylvanian unconformity. The porosity averages range from county to county with no real systematic fluctuations. Within western portions of Grant County, Oklahoma, porosity values range from 15-35%. This has the highest porosity average within the three Oklahoma counties of the study area. The highest porosity values are also below the Osage-Meramec boundary. In Alfalfa County, Oklahoma, porosity values range from 10-30%. Again, most of the porosity is developed at the Osage-Meramec boundary. There are at times high porosity intervals beneath the Mississippian-Pennsylvanian unconformity, but the occurrence is not as consistent as porosity beneath the Osage-Meramec boundary. In Woods County, Oklahoma, porosity values range from 5-15%, making this the lowest porosity average within Oklahoma. Intervals within Woods County, Oklahoma, that have up to 15% porosity are located beneath the Osage-Meramec boundary. This seems to have the most consistent porosity development of the reservoir intervals seen within Oklahoma. All of the porosity intervals are accompanied by rather low restivity, less than 60 Ohm-m, and also have low PE values that are less than 3 barns/electron. Oklahoma, particularly in Alfalfa and Woods Counties, exhibit thicker intervals of dense, low porosity cherty limestones. The dense, low porosity nature of these limestones should enable the exploitation of hydrocarbons by unconventional means.

5.2 Kansas

Reservoir intervals within the Mississippian strata are found primarily in one stratigraphic position in Kansas. The porosity development is below the Mississippian-Pennsylvanian unconformity, but within Osage strata. Again, like Oklahoma, the porosity averages range from county to county with no real predictability. In eastern Barber County, Kansas, porosity values range from 20-35%. This has the highest porosity within the three Kansas counties of the study area. This particular area has the thickest intervals of high porosity strata. Based on the lithostratigraphic interpretation for this region of Barber, it can be inferred that tripolitic chert development can explain the high porosity. In western Barber County, Kansas, the porosity values range from 10-20%. Again, the lithostratigraphic interpretation done in this region can attribute the rather high porosity to tripolitic chert development. In Comanche County, Kansas, the porosity values range from 10-15%. Comanche County has porosity development that is similar to Woods County, Oklahoma, but there are much thicker sections of Meramec strata. Barber County has the thickest intervals of porosity greater than 20%. All of the porosity intervals are accompanied by low resistivity, below 60 Ohm-m, and also have PE values less than 3 barns/electron.

6. CONCLUSIONS

6.1 Stratigraphy

- Osage strata maintain thickness over the axis of the Pratt Anticline, suggesting that it was not active during the Osage. Most Meramec strata have been eroded along the axis of the Pratt Anticline, which could imply that it was more active in the Meramec. The Pratt Anticline also could have affected Meramec deposition, due to thicker limestone deposits that prograded further south than Osage strata.
- Deeper ramp conditions could explain thicker intervals of shale (Kinderhook, Northview) and higher occurrence of chert than what is seen typically in the Mississippian outcrop belt. Also, the lack of a Pierson Formation facies above the Northview Formation could be attributed to this setting.
- Mud logs provide a way of separating the Osage in the subsurface to reflect what is seen in outcrop by assigning formation names of lower Boone and upper Boone where similar lithologies exist. This shows that the Thomspon, 1986 schematic of the lithostratigraphic relationship seen in outcrop is applicable to the subsurface.
- Based on previous outcrop studies, tripolite development occurs where there is enough calcite left over for decalcification to occur after replacement by silica. This only occurs within upper Boone Formation in the Mississippian outcrop belt.
- When tripolite develops immediately above the Northview Member, there is more than likely a facies change from lower Boone to upper Boone facies reflecting a change from ramp to platform conditions and shallower water. This could indicate that a platform to ramp transition zone likely existed within northwestern Barber County, Kansas between

Three Sisters well and Dohm #1 well. This relationship is similar to the Thompson (1986) outcrop depositional model for southern Missouri to northwest Arkansas where deeper lower Boone Formation ramp facies thin and transition to shallower upper Boone platform facies.

- Two scenarios for tripolitic chert development based on the perched aquifer system that is seen in outcrop can be applied for the subsurface. The first scenario has two stratigraphically separate pulses of water influx, one at the end of the Osage, where the dense cherty penecontemporaneous limestones of the lower Osage perch a water table causing later diagenetic chert to be created and then a second influx at the Mississippian-Pennsylvanian unconformity further alters yielding tripolitic chert. The second scenario has two stratigraphically related pulses of water influx, one at the end of the Osage causing later diagenetic chert formation and then shortly after another influx of water yields tripolitic chert. The tripolitic chert development in the second scenario is created before Meramec deposition.

6.2 Reservoir Characterization

- In Oklahoma, there are two intervals where porosity development exists; the first is beneath the Osage-Meramec boundary and the second is the Mississippian-Pennsylvanian unconformity. Highest porosity values occur at the Osage-Meramec boundary and are more consistent than the high porosity intervals at the Mississippian-Pennsylvanian unconformity. Typically, Grant County exhibited the highest porosity at greater than 25%. Resistivity values were 60 Ohm-m and PE values were less than 3 barns/electron. High porosity intervals are generally less than 60 feet thick. However, there are also thicker, less porous, cherty limestone that have unconventional potential.

- In Kansas, there is one interval where porosity development exists and it is beneath the Mississippian-Pennsylvanian unconformity. Highest porosity values occur in Barber County where the porosity values are greater than 30%. Resistivity were 60 Ohm-m and PE values were less than 3 barns/electron. High porosity intervals are generally less than 100 feet thick and can be linked to tripolitic chert development.

REFERENCES

Catuneanu, Octavian, 2006. Chapter 5: System Tracts, *in* Catuneanu, Octavian, *Principles of Sequence Stratigraphy*. Elsevier, Amsterdam, p. 165-234.

Costello, Daniel, Dubois, M. K., and Dayton, Ryan, 2013. Core to Characterization and Modeling of Mississippian, North Alva Area, Woods and Alfalfa Counties, Oklahoma, *in* Tollefson, Julie (ed.), 2013, Midcontinent Core Workshop: From Source to Reservoir to Seal. Mid-continent Section, American Association of Petroleum Geologists, joint publication by Kansas Geological Survey and Kansas Geological Society, p. 165-174.

Dolton, G. L., and Finn, T. M., 1989. Petroleum Geology of the Nemaha Uplift, Central Mid-Continent. U. S. Geological Survey, Open-File Report 88-450D, p. 1-18.

Friesenhahn, T. C., 2012. Reservoir Characterization and Outcrop Analog: The Osagean Reeds Spring Formation (Lower Boone), Western Osage and Eastern Kay County, Oklahoma. Unpublished Master of Science thesis, University of Arkansas, 86 p.

Fritz, R. D., and Medlock, P. L., 1995. Recognition of Unconformities and Sequences in Mid-Continent Carbonates, *in Sequence Stratigraphy of the Mid-Continent*, Tulsa Geological Survey, p. 49-80.

Gutschick, R. C., and Sandberg, C. A., 1983. Mississippian Continental Margins of the Conterminous United States, *in* Stanley, D. J., and Moore, G. T., (eds.), *The Shelfbreak: Critical Interface on Continental Margins*. Society of Economic Paleontologists and Mineralogists, Special Publication 33, p. 79-86.

Hanford, R. C., 2013. Carbonate Ramps, Clastic Lowstands and Organic-Rich Transgressive Shales - Hallmarks of Mississippian Sequences in North Arkansas and Southern Missouri. American Association of Petroleum Geologists Forum, Mississippi Lime Play, Abstracts.

Hanford, R. C., and Loucks, G. L., 1993. Carbonate Depositional Sequences and Systems Tracts-Responses of Carbonate Platforms to Relative Sea-Level Changes, *in* Loucks, R. G., and Sarg, J. F., (eds.), *Carbonate Sequence Stratigraphy*. American Association of Petroleum Geologists, Memoir 57, p. 3-14.

Handford, C. R., and Manger, W. L., 1990. Sequence stratigraphy and sedimentology of the Mississippian System in northern Arkansas. Society of Economic Paleontologists and Mineralogists, Midcontinent Section, Guidebook, 64 p., pages unnumbered.

Johnson, Benjamin, in preparation, Diagenesis and Development of Chert and Dolomite in the Mississippian Boone Formation, Northwest Arkansas.

Johnson, K. S., 2008. Geological History of Oklahoma. Educational Publication 9, Oklahoma Geological Survey, 6 p.

Kreman, D. M., 2011. Characterization of Kinderhookian and Osagean Strata of Northeast Oklahoma. Unpublished Master of Science thesis, University of Arkansas, 158 p.

Lambert, M. W., 1993. Internal Stratigraphy and organic facies of the Devonian-Mississippian Chattanooga (Woodford) Shale in Oklahoma and Kansas, *in* Katz, B. J., and Pratt, L. M., (eds.), Source Rocks in a Sequence Stratigraphic Framework. American Association of Petroleum Geologists, Studies in Geology 37, p. 163-176.

Lane, H. R., and DeKeyser, T. L., 1980. Paleogeography of the Late Early Mississippian (Tournaisian 3) in the central and southwestern United States, *in* Fouch, T. D., and Magathan, E. R., (eds.), Paleozoic Paleogeography of west-central United States, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Paleontology Symposium 1, p. 149-162.

Laudon, L. R., 1939. Stratigraphy of Osage Subseries of northeastern Oklahoma. American Association of Petroleum Geologists Bulletin, v. 23, p. 325-338.

Lee, Wallace, 1940. Subsurface Mississippian Rocks of Kansas. Kansas Geological Survey, Bulletin 33, 114 p.

Manger, W. L., 2014. Tripolitic Chert Development in the Mississippian Lime: New Insights from SEM. American Association of Petroleum Geologists, Forum, Oklahoma City, abstract.

Manger, W. L., and Evans, K. R., 2012. An Introduction to the Lower Mississippian (Kinderhookian to Osagean) Geology of the Tri-State region, Southern Ozarks, Atlas Field Trip Guidebook, 82 p.

Mazzullo, S. J., Wilhite, B. W., and Woolsey, I. W., 2009. Petroleum Reservoirs within a Spiculite-dominated Depositional Sequence – Crowley Formation (Mississippian: Lower Carboniferous) South-central Kansas. American Association of Petroleum Geologists Bulletin, v. 93, p. 1649-1689; reprinted with an additional abstract *in* Tollefson, Julie (ed.), 2013, Midcontinent Core Workshop: From Source to Reservoir to Seal. Mid-continent Section, American Association of Petroleum Geologists, joint publication by Kansas Geological Survey and Kansas Geological Society, p. 124-164.

Mazzullo, S. J., Wilhite, B. W., and Woolsey, I. W., 2010. Subsurface Mississippian Lithostratigraphy Based on Cores from South-Central Kansas and Their Comparison to Outcrops. Abstracts with Programs, Geological Society of America, v. 42, no. 2, p. 42.

McBee, William, Jr., 2003. The Nemaha and Other Strike-Slip Faults in the Midcontinent U.S.A. American Association of Petroleum Geologists, Midcontinent Section Meeting, Tulsa, Search and Discovery Article #10055 (2003).

Merriam, D. F., and Goebel, E. D., 1959. Structure of Mississippian Rocks in Southeastern Kansas. Tulsa Geological Society Digest, v. 27, p. 137-158.

Minor, P. M., 2013. Analysis of tripolitic chert in the Boone Formation (lower Mississippian, Osagean), Northwest Arkansas and Southwestern Missouri. Unpublished Master of Science thesis, University of Arkansas, 80 p.

Montgomery, S. L., Mullarkey, J. C., Longman, M. W., Colleary, W. M., and Rogers, J. P., 1998. Mississippian Chat reservoirs, South Kansas: Low resistivity Pay in a Complex Chert reservoir. American Association of Petroleum Geologists Bulletin, v. 82, no. 2, p. 187-205.

Perry, W. J., Jr., 1989. Tectonic Evolution of the Anadrako Basin Region, Oklahoma, *in* Hester, T. C., Schmoker, J. W., and Sahl, H. L. (eds.), Evolution of Sedimentary Basins - Anadarko Basin, U. S. Geological Survey, Bulletin 1866-A, p. A1-A17.

Rogers, J. P., Longman, M. W., and Lloyd, R. M., 1995. Spiculitic Chert Reservoir in Glick Field, South Central Kansas. The Mountain Geologist, v. 32, no. 1, p. 1-22.

Rogers, S. M., 2001. Deposition and Diagenesis of Mississippian chat reservoirs, north central Oklahoma. American Association of Petroleum Geologists Bulletin, v. 85, p. 115-129.

Rottman, Kurt, 2011. Stratigraphic Architecture of the the Kinderhookian to Meramecian Series, *in* Mississippian Play Workshop, Oklahoma Geological Survey, May 18, 2011, p. 22-28.

Shelby, P. R., 1986a. Depositional History of the St. Joe and Boone Formations in Northern Arkansas. Unpublished Master of Science thesis, University of Arkansas, 92 p.

Shelby, P. R., 1986b. Depositional History of the St. Joe and Boone Formations in Northern Arkansas. Arkansas Academy of Science Proceedings, v. 40, p. 67-71.

Sloss, L. L., 1963. Sequences in the Cratonic Interior of North America. Geological Society of America Bulletin, v. 74, no. 2, p. 93-114.

Tarr, W. A., 1938. Terminology of the Chemical Siliceous Sediments. National research Council, Division of Geology and Geography, Committee on Sedimentation, Annual Report for 1937-1938, Appendix A, Exhibit A., p. 8-27.

Thompson, T. L., 1986. Paleozoic Succession in Missouri, Part 4 Mississippian System. Missouri Department of Natural Resources, Division of Geology and Land Survey, Report of Investigations 70, 182 p.

Thornton, W. D., 1964. Mississippian Rocks in the Subsurface of Alfalfa and Parts of Woods and Grant Counties. The Shale Shaker Digest IV, Volumes XII-XIV, p. 117-128.

Watney, W. L., Guy, W. J., and Byrnes, A. P., 2001. Characterization of the Mississippian Chat in south-central Kansas. American Association of Petroleum Geologists Bulletin, v. 85, p. 85-113.

Wittman, B. R., 2013. Subsurface Stratigraphy and Characterization of Mississippian (Osagean to Meramecian) Carbonate Reservoirs of the Northern Anadarko Shelf, North-Central Oklahoma. Unpublished Master of Science thesis, University of Arkansas, 76 p