High Resolution Sequence Stratigraphic Architecture and Reservoir Characterization of the Mississippian Bentonville Formation, Northwestern Arkansas

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Master of Science Thesis Proposal: Buddy Price

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Abstract

Formerly known as the Burlington/Keokuk Formation, the Bentonville Formation comprises the uppermost Osagean Section in the mid-continent. It is a known producer of hydrocarbons in the subsurface of Oklahoma and Kansas. There is a high level of complexity associated with the Bentonville and other Mississippian formations resulting in inadequate correlations and poor well performance in some cases. This stems from the use of oversimplified depositional models and limited understanding of how the Mississippian System responded and evolved over time as a result of sea level variation at various frequencies. Biostratigraphic zonation with a maximum resolution of one million years has provided the most precise dataset for interpretation of the Mississippian. While useful, it does not fully explain the heterogeneity inherent in carbonate systems as a result of 4^{th} and 5^{th} order sea level variation on the order of 40k-400k years.

The primary goal of this research is to identify the impact of high frequency sea level fluctuation on the distribution of facies and reservoir properties within the Bentonville Formation. Outcrop studies will be done in order to provide a two-dimension understanding of the unit. Thin section analysis will aid in the identification of facies stacking patterns and cyclicity in the outcrop. High resolution imaging will allow for mapping the geometries of beds and facies as well as the lateral correlation of cycles. Spectral gamma ray logging will be used to help identify potential cycle-bounding flooding surfaces, and to potentially tie rock characteristics from the outcrop to the subsurface. Together, the datasets can be used in interpretation of the depositional environment of the Bentonville Formation. Modern analogs will then be integrated into the depositional model to provide constraints on the spatial distribution of facies in the z-plane not offered by outcrop studies alone.

Results of this study are expected to produce a sound sequence stratigraphic model that will provide insight and explanation for the heterogeneity occurring in the Bentonville Formation. This will aid in hydrocarbon exploration and development, as well as provide guidelines for development of similar reservoirs in the Mississippian.

I. INTRODUCTION

1.1 Summary of the Problem

The Lower to Middle Mississippian System of the southern mid-continent contains major hydrocarbon reservoirs in the states of Oklahoma and Kansas. The Mississippian rocks in the region are comprised of a mixed carbonate and siliciclastic system of limestone, dolomite, shale, and chert. Within the system limestone, dolomite, and chert are potential reservoir rocks, with chert being the primary key to reservoir development. Previous studies have focused on describing depositional systems, trends, and sea level variation within the Lower to Middle Mississippian in order to explain reservoir distribution. Prior work ranged from regional scale paleodepositional modeling (Lane, 1978; Lane and DeKyser, 1980; Gutschick and Sandberg, 1983) to localized outcrop investigations in northwest Arkansas, southwest Missouri, northeast Oklahoma, and southeast Kansas (Mazzullo, 2011; Mazzullo et al., 2011a; Wilhite et al., 2011). Most work has described macro-scale variations in lithofacies, rock fabric, and biostratigraphic zonation within the system. While prior work was done in an effort to better understand the depositional history of the Lower to Middle Mississippian in the southern mid-continent, it does not explain the heterogeneity that is observed in the subsurface and outcrop.

Carbonate depositional systems are intimately tied to variations in sea level (Goldhammer et al., 1990; Read, 1995). Previous work on the Lower to Middle Mississippian of the mid-continent can be tied to deposition related to fluctuation in sea level on the order of one to six million years (Haq and Schutter, 2008). Sea level fluctuations on the order of one to ten million years are typically responsible for deposition of sequences tens to hundreds of meters thick (Read, 1995). Superimposed within these intervals, there is a great amount of variability as a result of sea level fluctuation on the order of 40k-400k years (Read, 1995). These high frequency fluctuations are important in that they can control facies stacking patterns, the lateral distribution of facies, and potential reservoir distribution on a much finer scale. Analyses of the depositional packages related to the longer duration sea level fluctuation is too all encompassing and does not adequately describe the complexity of the unit. To date, no studies have addressed the finer scale facies heterogeneity and resulting reservoir scale architecture in the rocks resulting from higher frequency sea level changes, or how this variability governs key reservoir parameters within the mid-continent Mississippian carbonate system.

1.2 Fundamental Questions and Hypotheses

The main hypothesis of this work is that higher frequency cyclicity is responsible for finer scale facies variations within the Middle Mississippian rocks in the southern mid-continent than has previously been reported. High frequency changes in sea level would greatly alter carbonate depositional systems over 40k-400k year periods. Migration of depositional systems in response to sea level change would result in fine scale variations in the rocks both laterally and vertically. In addition to this, it is believed that the resulting primary rock fabric and facies geometries controlled subsequent diagenetic alteration and pore system development responsible for the formation of potential reservoir intervals.

The fundamental questions that are to be answered by this research are as follows:

1.) What is the hierarchy of depositional sequences or cycles found within the Middle to Upper Mississippian rocks?

2.) Did higher frequency sea level variation result in fine scale changes in the facies and rock fabric?

3.) Do potential reservoir intervals show fine scale variation as a response to high frequency sea level fluctuation?

1.3 Objectives

The primary objective of this research is to better understand the complex depositional history of the Middle Mississippian Bentonville Formation within the tri-state area of Arkansas, Oklahoma, and

Missouri. The goal of this project is to define a hierarchy of depositional sequences and in turn see how those sequences can control facies variability and stacking patterns. This is to be done by performing detailed outcrop studies in order to create a high resolution sequence stratigraphic framework for the formation. Analysis of samples taken from outcrop will be done in order to define vertical stacking patterns of facies present within the unit. Facies data along with identification of key sequence stratigraphic surfaces in outcrop will be used to understand the lateral and vertical variability and extent of the units as exposed in outcrop. By incorporating knowledge of 2-D facies distribution from outcrop and spatial variability obtained from modern analogs of a similar depositional system, a three dimensional static model can then be made in order to understand facies geometries and the magnitude of heterogeneity in multiple dimensions. Understanding the spatial variability of facies and potential reservoir intervals can significantly increase the predictability of reservoir distribution of the Bentonville Formation in the subsurface

II. GEOLOGIC BACKGROUND

2.1 Regional Geology

During the Mississippian Period, relatively shallow water seas covered much of the mid-continent. The paleo-latitude of present day Oklahoma, Missouri, and Arkansas was located between approximately 20-30° south of the paleo-equator (Gutschick and Sandberg, 1983, Witzke, 1990). The global positioning resulted in warm-temperate to subtropical climatic conditions over the region (Curtis and Champlin, 1959). Dominant prevailing winds and surface currents are believed to have come from a present-day east-northeast direction (Witzke, 1990). The combination of climatic variables and water conditions provided a large area adequate for carbonate production in the mid-continent (Fig. 1).

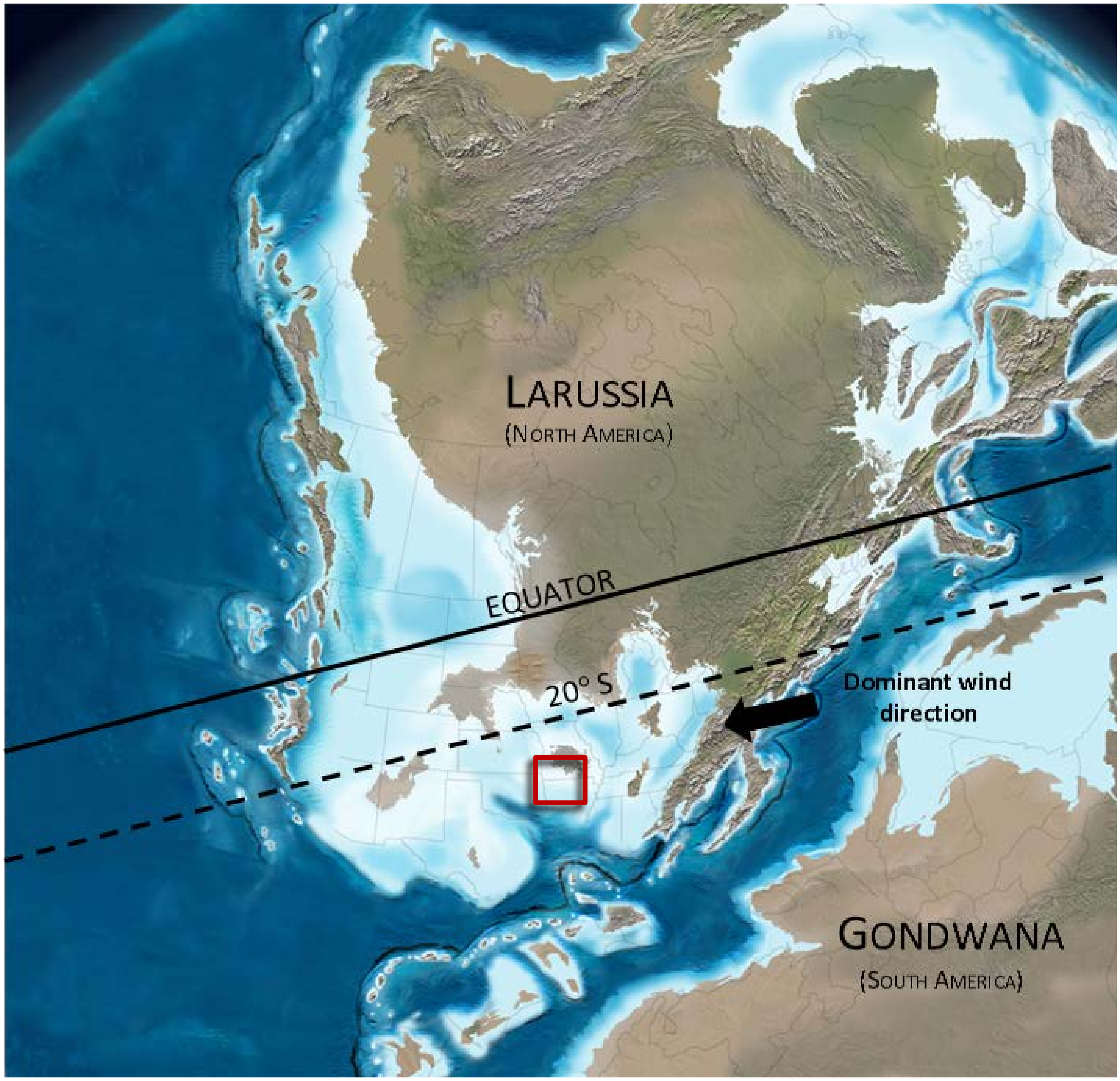

Figure 1: Early Mississippian paleogeography (345 MYA). The Tri-state area of Arkansas, Missouri, and Oklahoma are located between approximately 20-30°S. The study area is outlined in red. Water depth is indicated by color contrast. Light blue indicate shallow water while dark blue indicates deeper water setting. Shallow marine conditions were present in the study area during deposition while deeper waters were located to the south. Paleo-wind direction is interpreted to have come from east-northeast. Paleo-geographic reconstruction shows a number of topographic highs and vast shallow-water conditions to the east. The geography present at the time of deposition in combination with wind direction could potentially affect facies distribution in the study area (Modified from Blakey (www2.nau.edu/rcb/nam.html) and Witzke, 1990).

Mississippian carbonate deposition was aerially extensive over hundreds of square miles in the mid-continent. Carbonate production and deposition were bounded to the north and northwest by the Transcontinental Arch, to the east by the Ozark Uplift, and to the south by the ancestral Anadarko and Arkoma Basins (Fig. 2). The depositional strike of the system was approximately east-west with shallower water settings being found to the north grading into increasingly deeper water to the south (Lane and DeKyser, 1980).

Even with abundant research of the mid-continent Mississippian rocks in both outcrop and subsurface, the type of carbonate depositional system (ramp, shelf etc.) is not well defined. Lane (1978) initially described the Mississippian depositional system as a shelf-type environment referred to as the Burlington Shelf. Later work identified a number of sub-environments/magnafacies on the shelf including the inner shelf, main shelf, shelf margin, and deeper water sediment starved settings (Lane and DeKyser, 1980). Gutschick and Sandberg (1983) also use the shelf terminology of previous authors, but identified that unlike the pronounced margin of the Burlington Shelf present in the western Illinois Basin, in the mid-continent the system was characterized by a broad gentle foreslope present at the margin that graded into deeper water starved facies (Fig. 3).

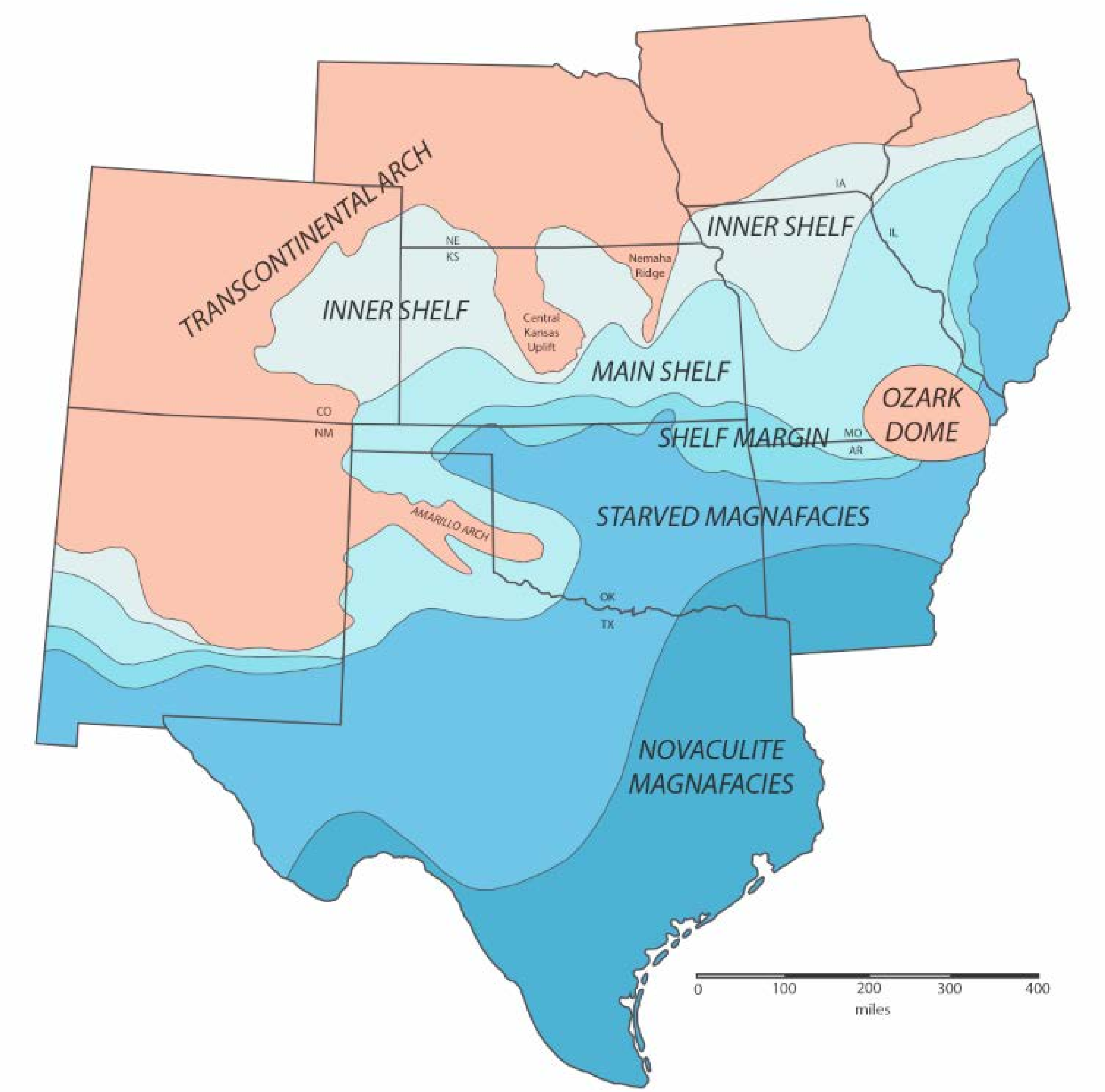

Figure 2: Paleo-depositional model of the late Tournasian (Early Mississippian) Stage in the mid-continent. The system was bounded to the west and north by the Transcontinental Arch, to the east by the Ozark Dome, and to the south by the ancestral Anadarko and Arkoma Basins. The figure shows the depositional system trending east-west with shallower water settings to the north and deeper conditions to the south. This is the most commonly used depositional model for the Mississippian in the region. This model represents one generalized time slice during the period. Carbonate systems migrate and change morphology over short periods of geologic time due to sea level variation. Over the entire period of Mississippian deposition, the system could change drastically. While the image is useful, it may not be an accurate representation of the Mississippian System at any given time in the geologic past (Modified from Lane and DeKyser, 1980).

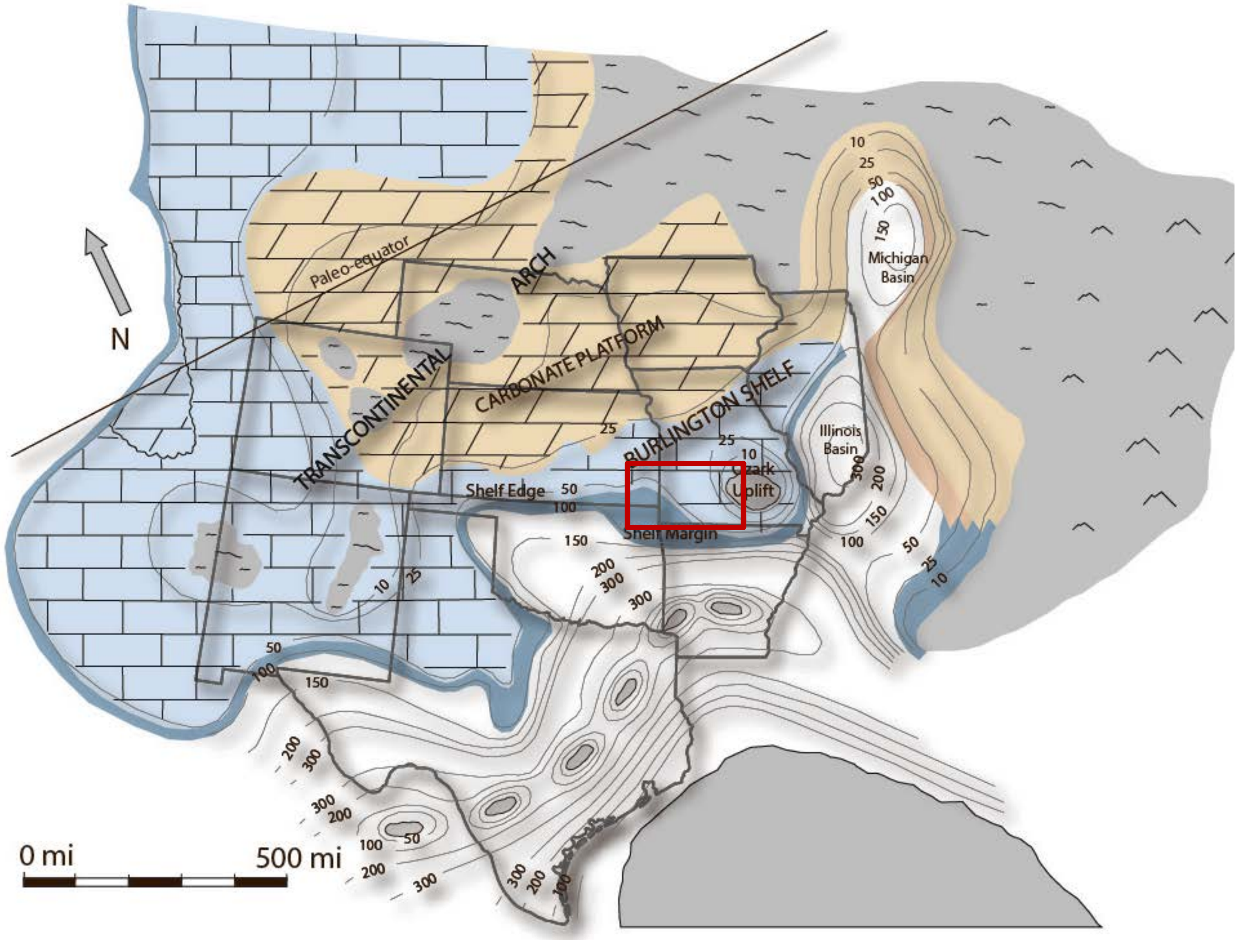

Figure 3: Paleo-geographic map of the US during deposition of the *anchoralis-latus* conodont biozone (Early Mississippian). The study area is outlined in red. The Burlington Shelf covers a large portion of the central US in Kansas, Oklahoma, Arkansas, Missouri, and Iowa. Variations in the width of the shelf edge exist across its extent. The shelf exhibits a relatively narrow zone of margin sediments as it grades into the Illinois Basin, indicative of a steep marginal slope. The shelf margin grading into the Ouachita trough is much wider, indicating a shallow slope grading into deeper water settings. Paleo-bathymetric contours also show a dramatic difference between the eastern and southern margins of the shelf. According to the model, as the shelf grades into the Illinois Basin water depths increase from 50m to 100m in as little as 15-20 miles and to 200m in 40 miles. The southern margin of the shelf deepens from 50m to 100m in as much as 150 miles and becomes relatively steeper as you move farther basinward. In this model the study area is interpreted to have been deposited in a shelf margin setting in water depths between 50-100m (Modified from Gutschick and Sandberg, 1983).

More recent interpretations describe the Mississippian system of Kansas and Oklahoma as a shallow- to deep-water, unrimmed ramp-type environment (Mazzullo et al., 2009, Mazzullo et al., 2011a). It was shown by conodont biostratigraphic zonation that diachronous prograding wedges built out across the ramp-type setting during the Lower to Middle Mississippian, resulting in time-trangressive facies associations (Boardman et al., 2010). The geometry of prograding wedges resulted in a morphologic change from a near homoclinal ramp during the early Mississippian to a distally steepened ramp during the middle Mississippian (Wilhite et al., 2011). While it is commonly accepted that Mississippian sediments were deposited on a distally steepened ramp-type environment, terminology specific to shelf-type settings are still used pervasively, leading to some confusion when interpreting the published literature.

2.2 Sea Level

Sea level is an important controlling factor in the majority of carbonate depositional environments. Shallow water carbonate depositional systems and facies are intimately tied to water depth, leading to sea level fluctuations having pronounced effects on the characteristics of the deposits. Changes in eustatic sea level are controlled by a combination of autogenic (internally derived) and allogenic (externally derived) factors including sedimentation rates, climate, tectonics, and orbital variability of the earth.

2.2.1. Eustatic Sea Level Cycles

The driving forces responsible for fluctuation in eustatic sea level are changes in ocean basin volume as a result of mid ocean ridge spreading or convergence of continents, and variations in global ice volumes resulting in fluctuations in the total amount of ocean water. The combination of the two mechanisms creates a temporal hierarchy of sea level fluctuations referred to as “cycles”. Each sea level cycle is defined by its length or duration, the magnitude change in sea level over that duration, and the processes responsible for the change in sea level. First order cycles are generally 200-300 million years in length and are associated with rearrangement of tectonic plates, and opening and closing of ocean basins (Read, 1995). The resulting sedimentary features are large scale cratonic onlap and offlap (Read, 1995). Second order cycles are approximately 10-50 million years in length. They are controlled by tectonics, changes in ocean basin volume, and to a lesser extent by variation in global ice volumes (Read, 1995). These cycles are responsible for widespread, regionally correlative sequences of rocks commonly hundreds to a few thousand meters thick (Read, 1995). Superimposed upon the 2nd order are third order cycles. These cycles span a range of 1 to 10 million years, while most researchers believe they are generally less than 3 million years in length (Plint, et al., 1992; Haq and Schutter, 2008). The reason for the debate in their duration is due to the enigma of their occurrence. There is no generally accepted idea or hypothesis for the controlling mechanisms or periodicity of the 3rd order cycles. While tectonics and ocean floor spreading have been hypothesized as the driver of sea level fluctuation (Plint et al., 1992), waxing and waning of continental ice sheets is the more probable causal mechanism of 3rd order cyclicity (Read, 1995).

4th and 5th order cycles represent shorter, higher frequency variations in sea level and are controlled primarily by Milankovitch Cyclicity. Milankovitch Cycles are responsible for variations in the intensity of solar radiation that reaches the earth, which in turn has a pronounced effect on climatic variability and glaciation. The hierarchy of these cycles is defined by variations in eccentricity, obliquity, and precession. Eccentricity results in variations in glacial volume, and corresponding sea level fall on a 4th order scale of 100-400 thousand years and is controlled by changes in the shape of earth's orbit around the sun. Movement of the earth closer to and farther from the sun is believed to be a controlling factor on continental glaciation over this time scale (Read, 1995). Obliquity is controlled by change in the tilt of the earth's axis, resulting in seasonal variability. The axial tilt is responsible for 5th order 40 thousand year cycles (Read, 1995). Precession cycles refer to the wobble of the earth's axial orientation. The "wobble" is responsible for 5th order cycles approximately 21 thousand years in length (Read, 1995).

The magnitude of sea level fluctuation experienced during each cycle is correlative to the volume of continental ice present during a given cycle. Greenhouse times are characterized by low volumes of continental ice. These conditions result in low amplitude sea level variations that are commonly less than 10m, and dominated by precession cycles (Read, 1995). Icehouse times are characterized by continental glaciation. The amplitude of sea level change associated with eccentricity during these times can be as much as 100 meters (Read, 1995). During icehouse times sea level rise and transgression is rapid during periods of deglaciation, and sea level fall and regression is gradual during glaciation (Read, 1995). Obliquity cycles of approximately 40k years seem to be more important during the ice-house times as well as during transitional periods from greenhouse to ice-house conditions (Read, 1995).

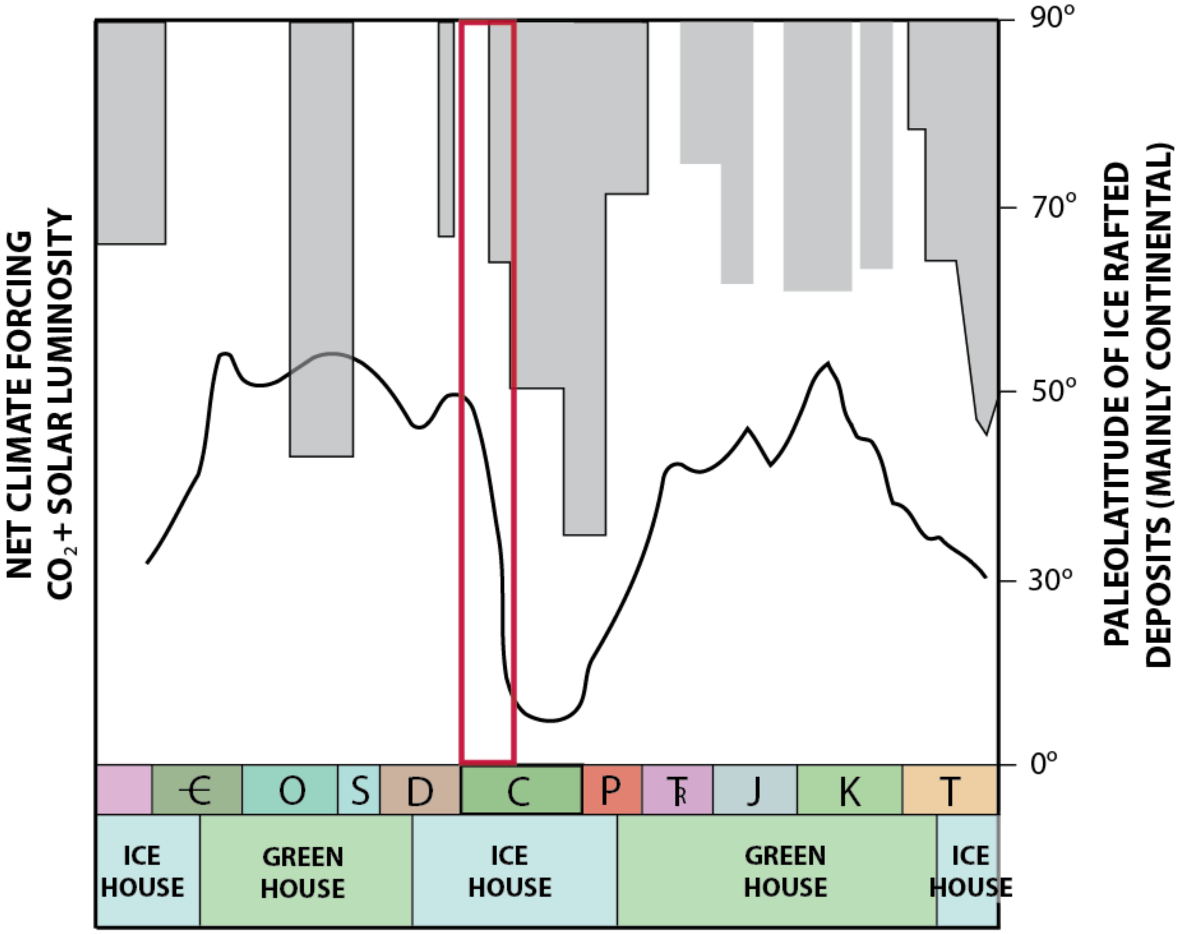

Figure 4: Diagram illustrating long-lived changes from greenhouse to icehouse conditions over geologic time. The Lower to Middle Mississippian (outlined in red) was deposited in general icehouse times. Viewing the paleo-latitudes of ice-rafted glacial deposits (Gray with black outline) and marine ice-rafted deposits (gray with no outline) in combination with climatic change due to variation in CO^2 and solar intensity (solid line), it can be seen that Lower to Middle Mississippian deposition occurred during a transitional period from greenhouse to dominant icehouse conditions during the Pennsylvanian and Permian (Modified from Read, 1995).

2.2.2 Mississippian Sea Level

The Mississippian comprises the upper portion of the Kaskaskia Sequence as defined by Sloss (1963), and represents a transitional period from greenhouse conditions present during the Devonian to icehouse conditions that were present during the Pennsylvanian and Permian (Fig. 4). Long term first-order eustatic sea level was positioned between 50-100m above present day levels (Haq and Schutter, 2008). Ross and Ross (1988) identified 14-15 transgressive-regressive cycles within the Mississippian on the order of 1-3 million years (possibly 3^{rd} order) that can be correlated globally. Haq and Schutter (2008) recognize 21 transgressive-regressive cycles within the same time frame that can be correlated world-wide as well. They also note that during the Tournasian and Visean Stages the 3^{rd} order sequences are anomalously long, spanning up to six million years (Fig. 5)

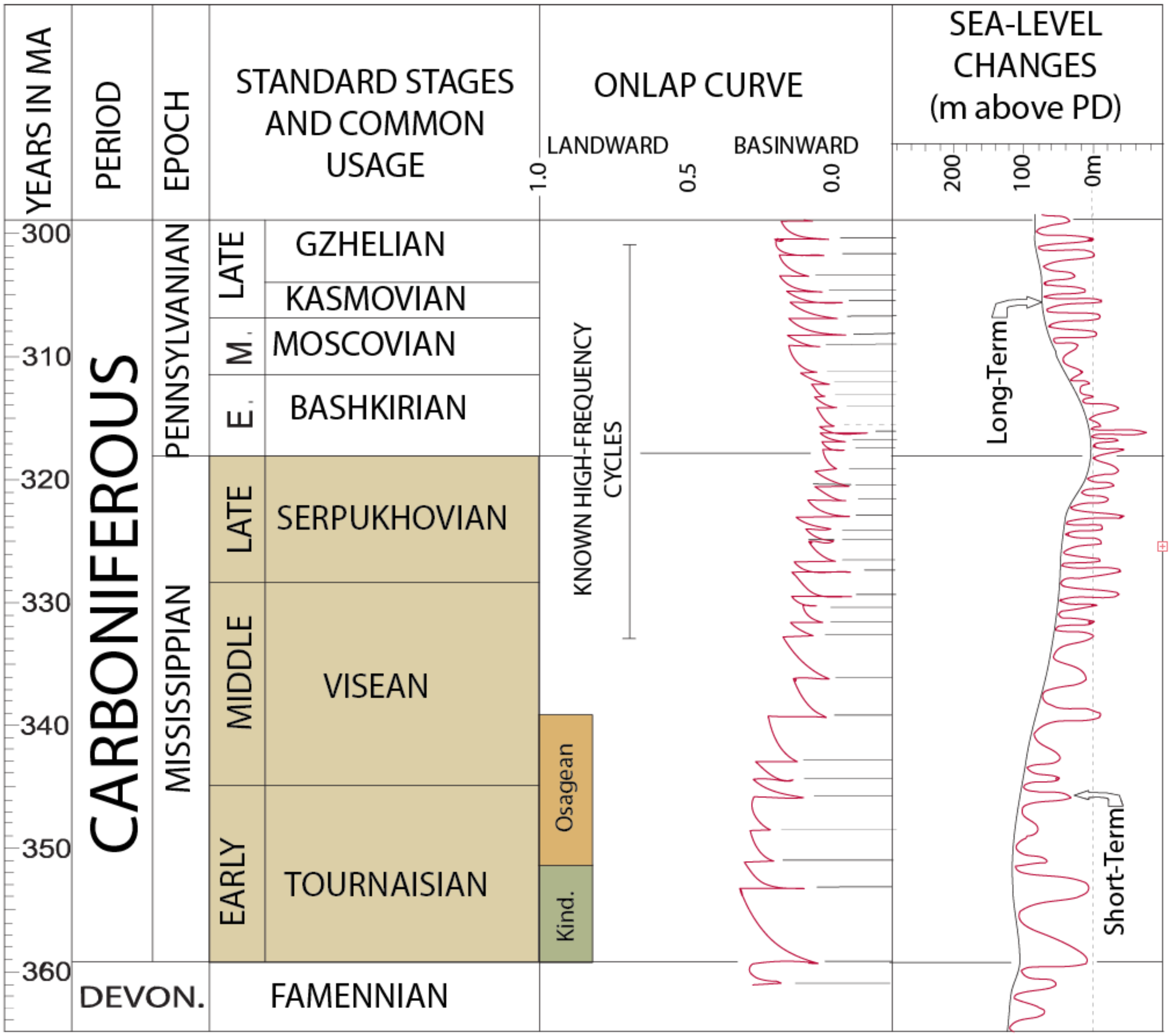

Figure 5: Global sea level and onlap curve for the Carboniferous Period. Stages of the Mississippian are highlighted in brown. Kinderhookian and Osagean strata correspond to the Tournasian through Middle Visean Stages over approximately 20 MY. Six to eight cycles between one and six million years in length have been identified globally during this time frame. The length of correlative cycles can be seen to decrease into the later Mississippian and into the Pennsylvanian. The decrease possibly can be attributed to more prominent icehouse conditions and larger fluctuations in sea level, resulting in more distinct cycle boundaries (Modified from Haq and Schutter, 2008).

The Kinderhookian through Osagean rocks correspond to the Tournasian through Middle Visean Stages over approximately twenty million years (Fig. 5). Six to eight cycles (potentially 3rd order) were identified within this period ranging from one to six million years (Ross and Ross, 1988; Haq and Schutter, 2008). Outcrop studies within the Mississippian of the mid-continent have identified key exposure surfaces and sequences of rocks indicative of cycles, but no research in the area has delineated the potential signals of higher frequency cyclicity, or the hierarchy of cycles that could play a role in the formation of complex stacking patterns and lateral variability within the carbonates.

2.2.3. Potential Problems in Delineating High Frequency Cyclicity

While there is a known relationship between sea level fluctuation and the resulting changes in carbonate sedimentary systems, a number of variables can inhibit the identification of high frequency cyclicity. Subsidence, rate of sedimentation, and sediment body migration among other things have been shown to produce meter scale packages of rocks similar to those ascribed to higher frequency 4th and 5th order cycles, free from the influence of eustatic sea level change (Drummond and Wilkinson, 1993; Cowan and James, 1996). One can easily misinterpret the hierarchy of cycles without understanding the system responsible for its formation. While both allocyclic and autocyclic processes can cloud the signal of sea level fluctuation, by understanding how facies are distributed within a system, how facies can migrate within the system, and tectonics/subsidence, changes in the system as a result of higher frequency variations in sea level can be assessed (Drummond and Wilkinson, 1993; Rankey, 2002).

2.3 Stratigraphy

Identification of formal stratigraphic units within the Lower to Middle Mississippian of the mid-continent is problematic. In much of the region the terms Mississippian or Miss are used in reference to the entire system. In subsurface interpretations the terms Miss Lime, Miss Solid, and Miss Chat are used pervasively throughout literature and industry. The use of such terms suggests a great oversimplification of the system and in many instances leads to erroneous correlations. The use of formation nomenclature from the Mississippian Type sections in the tri-state area of Oklahoma, Arkansas, and Missouri can be much more useful, given constraints by rock data. The use of outcrop nomenclature provides its own set of problems as formation names are highly variable between state lines (Fig. 6). Work by Mazzullo et al. (2013) provided standardized formation names for the tri-state area that will be referred to in this work.

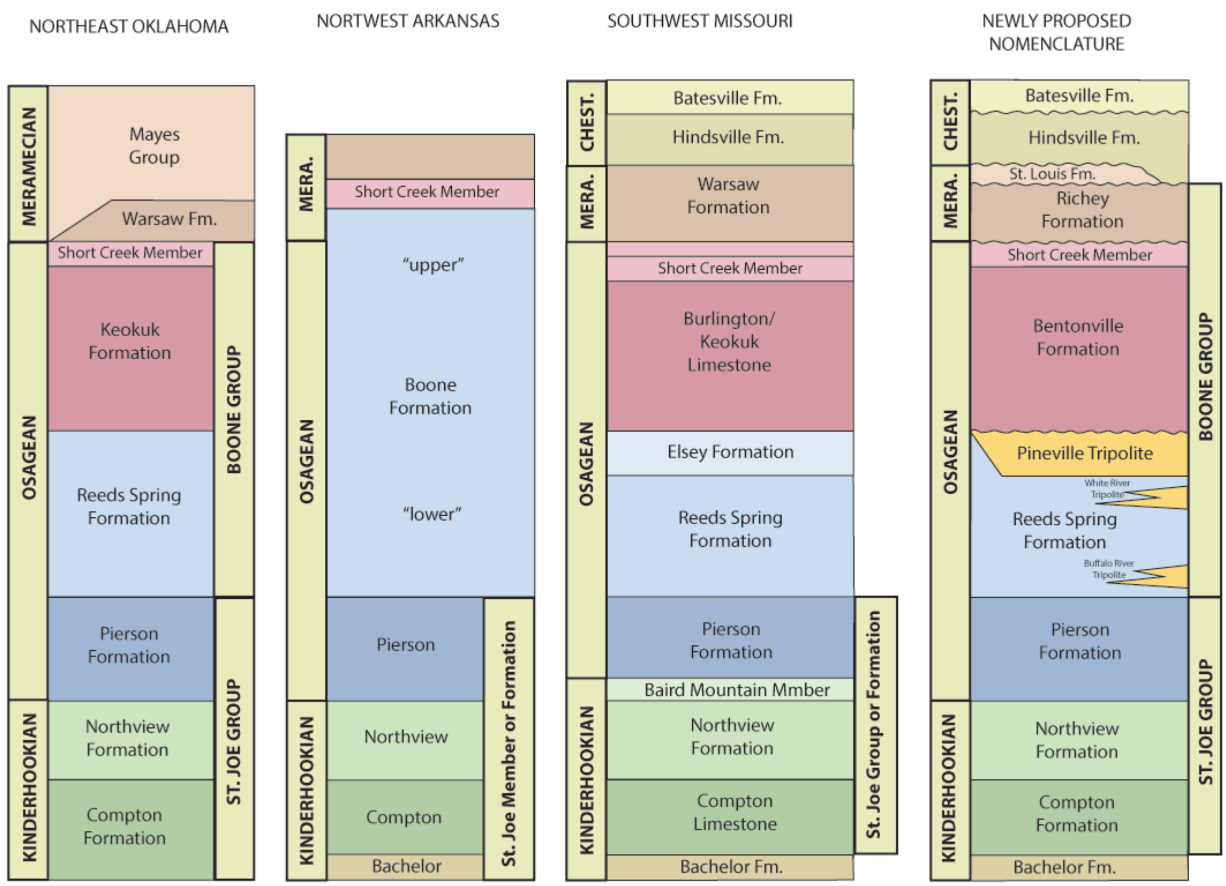

Figure 6: Previous stratigraphic nomenclature for the Kinderhookian through Meramec in northeastern Oklahoma, northwestern Arkansas, and southwestern Missouri. There were multiple names for many of the formations that changed once you crossed a state line, which was problematic in outcrop and in subsurface investigations. Work was done to propose a new standardized stratigraphic nomenclature for the formations present in the Tri-state area (Modified from Mazzullo et al., 2013).

In the mid-continent, Lower to Middle Mississippian generally refers to Kinderhookian through Osagean-aged strata. The Late Devonian to Earliest Mississippian Woodford Shale provides the lower boundary for the section while the uppermost units are overlain by Meramecian-age strata. Middle to Upper Mississippian rocks were subject to extensive erosion at the Mississippian-Pennsylvanian Unconformity (Rogers, 2001). In some instances the entire Chesterian and Meramecian sections have been removed (Rogers, 2001). Between the Woodford Shale and Meramecian section are a number of formations that have been identified in outcrop. While this study focuses on Upper Osagean rocks, understanding the formations, facies, and depositional trends above and below the unit can provide a starting point for interpretation and help to ground truth potential hypotheses about the formations.

2.3.1 Kinderhookian Strata

The Kinderhookian comprises the lowermost section of the Mississippian, and is composed of dark gray to green-gray silty shale and limestone. Sections of the Kinderhook may exhibit high gamma ray readings, resulting in the misinterpretation of the unit as the Woodford shale in subsurface logs (Jordan and Rowland, 1959). It is noteworthy that the Kinkerhook strata contain far less chert than the overlying Osagean strata. The Bachelor, Compton, and Northview Formations are all housed within the Kinderhookian section.

Bachelor Formation

The Bachelor Formation is the basal member of the Mississippian Section in the Tri-State outcrop belt. The unit consists of thin quartzose sandstone and green silty shale, the source most likely being clastic material shed from the Ozark Uplift (Thompson and Fellows, 1970; Shoeia, 2012). The Bachelor is typically less than .7 meters (2 ft.) thick in outcrop (Mazzullo et al., 2013). Kremen (2011) notes that the formation is not developed in northeastern Oklahoma, which brings into question its extent farther west into the subsurface. It has been interpreted as the initial flooding phase of the system due to the presence of glauconite (Evans et al., 2010).

Compton Formation

Conformably overlaying the Bachelor is the Compton Formation (Thompson and Fellows, 1970). Based on work by Lane (1978) and Lane and DeKyser (1980) the Compton was interpreted to have been deposited in a shelf margin environment. It is predominantly a limestone unit of crinoid-bryozoan mudstone to packstone with interbedded dark green clay-rich shales (Manger and Shanks, 1976; Shoeia, 2012). It has been noted that allochem content increases from the bottom of the formation to the top (Manger and Shanks, 1976). The Compton may range in thickness from 1.5 meters (5 ft.) to greater than 15 meters (50 ft.) throughout the outcrop belt (Manger and Shanks, 1976; Kruger, 1965). The Compton also contains asymmetrical mud mounds 1-6 meters (3-20 ft) tall and up to 12 meters (40 ft.) in length (Morris et al., 2013). The mounds are generally composed of bryozoan-rich wackestone with accessory crinoids, brachiopods, rugose corals, pelecypods, red algae, ostracodes, and spicules (Morris et al., 2013). The occurrence of the mounds as constructional bioherms resulting from *in situ* growth, transported blocks, or a combination of the two is equivocal (Morris et al., 2013; Unrast, 2013).

Northview Formation

Directly above the Compton is the Northview Formation. It is typically described as a green-gray to red-gray shaley limestone that locally contains glauconite (Mazzullo et al., 2009; Kreman, 2011). Shoeia (2012) describes the formation as a laminated siltstone with a wackestone to packstone texture. The Northview has been interpreted to have been deposited in a range of settings from shallow near-shore to offshore settings (Mazzullo et al., 2011b).The formation obtains a maximum thickness of 24 meters (80 ft.) in southwest Missouri and thins to less than 1.5 meters (5 ft.) north and south of Springfield, MO (Kruger, 1965). Conodont biostratigraphy shows that deposition of the Northview was continuous with no significant hiatuses, indicating that the thickness variations must have been controlled by modification in accommodation or by varying rates of sedimentation (Shoeia, 2012).

2.3.2 Osagean Strata

Pierson Limestone

Above the Northview sits the Pierson Formation. A glauconitic interval at the bottom of the Pierson marks the base of the Osagean section (Heinselmann, 1964; Kruger, 1965). The interpreted depositional environment of the Pierson is near-shore shallow open-marine conditions (Mazzullo et al., 2011b). The Pierson Formation is primarily a limestone unit dominated by packstone and grainstone facies with micritic cements (Kreman, 2011; Wilhite et al., 2011). Dark gray to black cherts are present throughout much of the formation (Thornton, 1961-1964). It can be observed that chert content increases up section into younger strata. Brown dolomitic intervals have also been found in the lower sections of the Pierson. The formation has an average thickness of 1.2-5 meters (4-18 ft.), but extends to 9 meters (30 ft.) near the Ozark Uplift and up to 23 meters (75 ft.) paralleling the Kanoka Ridge in Kansas (Huffman, 1960; Kreman, 2011; Krueger, 1965; Wilhite et al. 2011). Like the Compton Formation, the Pierson contains mud mounds or blocks larger than those in the underlying formation (Morris et al., 2013).

Reeds Spring Formation

The Reeds Spring Formation conformably to unconformably overlies the Pierson without a (Mazzullo et al., 2011a). The Reeds Spring marks a change from conditions conducive to deposition of grain-rich faces in the Pierson to a mud dominated system representing what has been interpreted to be deeper water conditions (Mazzullo et al., 2011a). In outcrop the unit ranges from 23-55 meters (75-185 ft.) of medium to dark gray mudstone to wackestone interbedded with dark gray to blue-gray chert

(Huffman, 1960; Mazzullo et al., 2011a; Kreman, 2011). The chert occurs in both continuous and discontinuous beds, lenses, and anastomosing nodules a few inches to a few feet in thickness (Mazzullo et al., 2011a). Up-section the Reeds Spring becomes increasingly more chert-rich and may even be composed of nearly one hundred percent chert (Mazzullo et al., 2011a). The Reeds Spring Formation has been interpreted to have formed in quiet water conditions, distal ramp-type setting with the mud comprising the formation being transported from more proximal up-dip locations (Mazzullo et al. 2011a).

Interesting features found in the formation are the tripolitic chert zones. Tripolitic chert, or tripolite, is weathered, de-vitrified chert that is hypothesized to have formed during periods of subaerial exposure (Mazzullo et al., 2013). The most prominent tripolitic interval within the Reeds Spring is the Pineville Tripolite facies that occurs locally at the top of the formation. Less widespread tripolitic intervals such as the Buffalo River and White River Tripolites are also observed within lower units of the Reeds Spring Formation (Fig. 6). In outcrop, a gradational change can be seen from unaltered chert upward into increasingly higher percentages of tripolite, while the uppermost tripolitic intervals show a relatively sharp contact with overlying lithologies (Mazzullo et al., 2011a). The tripolitic zones are of interest in subsurface exploration, as they contain abundant micro- to nano-scale scale pores as well as fractures, enhancing the porosity and permeability of the rocks.

Bentonville Formation

The Bentonville Formation comprises the uppermost unit of the Osagean-age strata in the outcrop region. The new nomenclature includes renaming of the Upper Boone Formation of northern Arkansas as well as grouping of the previously named Burlington and Keokuk Formations. The Burlington Formation was named by Hall (1857) in reference to Osagean crinoidal limestones found in outcrop bluffs along the Mississippi River in Burlington, Iowa. Thickness of the Burlington Formation ranges from

16-24 meters (55-80 ft.) at its type locality and thickens westward (Witzke et al., 1990). The overlying Keokuk Formation was named by Owen (1852) in reference to cherty crinoidal limestone found in bluffs in Keokuk, Iowa. The formation ranges in thickness from 14-27 meters (45-90 ft.) and averages approximately 20 meters (65 ft) at its type locality (Witzke et al., 1990). The two formations generally have a gradational contact making it difficult to recognize, often resulting in the formations being grouped together as the Burlington/Keokuk Formation (Choquette et al., 1992).

Research of the Burlington/Keokuk Formation in northeastern Missouri, Iowa, and western Illinois shows that the rocks consists of crinoidal grainstones/packstones with interbedded dolomitic wackestones/mudstones with nodular chert and green to black shales in the uppermost beds (Choquette et al., 1992). Dolomite that is predominantly found in the mudstone/wackestone facies has been reported to comprise as much as 70% of the Burlington/Keokuk in southeast Iowa (Fig. 7). Abundance decreases as you move through northern and central Missouri until it is absent in southwestern Missouri and northern Arkansas (Choquette et al., 1992).

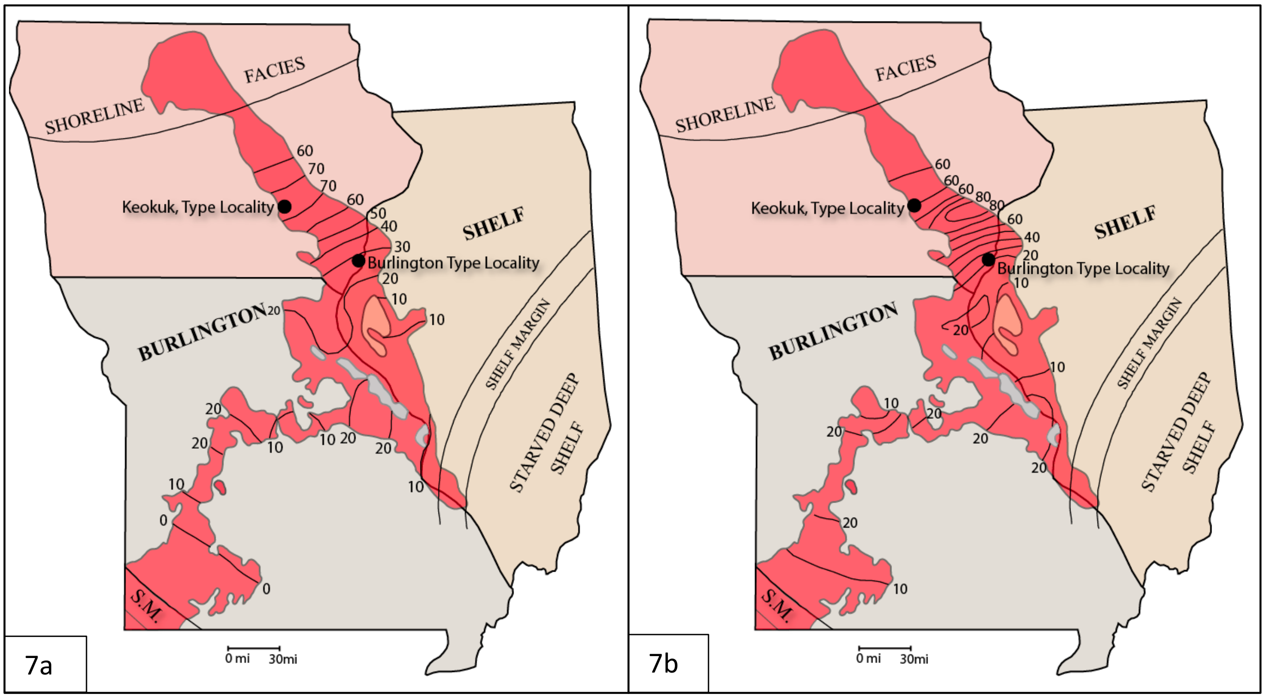

Figure 7: Map showing the outcrop occurrence (red) and paleo-depositional setting during the time of Burlington/Keokuk deposition. The type localities in Iowa of the Burlington and Keokuk Formations are indicated. It is important to note that the shelf margin during this time was oriented northwest-southeast as opposed to directly east-west. Figure 7A shows the abundance of dolomite by percentage contours. Dolomite volume reaches a maximum in southeastern Iowa of 70% and decreases to the south where it is minimal or absent. Figure 7B indicates the total abundance of mudstone and wackestone within the Burlington/Keokuk. The formation is comprised of up to 80% percent mud-dominated rocks in southeastern Iowa and becomes increasingly more mud lean to the south. There is a near one-to-one correlation between dolomite and mudstone/wackestone occurrence (Modified from Choquette et al., 1992).

There are a number of lithologic variations within the Burlington/Keokuk Formation between its type localities in the Mississippi Valley region and the outcrop belt in Arkansas, Missouri, and Oklahoma. Due to this, a new name was proposed for the formation and new reference sections were chosen that more accurately represent the formation throughout the tri-state area (Mazzullo et al., 2013). The Bentonville Formation now encompasses strata that were previously defined as Burlington/Keokuk. The depositional setting of the Bentonville Formation within the Tri-State region is interpreted in shallow, moderate to high energy settings (Mazzullo et al., 2011b). The formation has a composite type locality composed of two outcrop locations since the formation is not completely exposed in any single location (Mazzullo et al., 2013). The lower section of the Bentonville is represented by the Highway 71-US 540 outcrop approximately 5 km (3 mi.) north of Bentonville, Arkansas in Benton County. The upper portion of the formation is represented by an outcrop along the eastern side of Highway 65 approximately 2km (1.3 miles) north of Burlington, Arkansas in Boone County. In these outcrops and throughout the region, observations of the Bentonville Formation show that it is dominated by fine to coarse-grained packstones to grainstones with interbedded lenses of mudstone to wackestones, nodular to bedded chert and little to no dolomite (Mazzullo et al., 2013).

Short Creek Member

In localized spots at the top of the Bentonville Formation, an oolitic interval can be observed, known as the Short Creek Member or Short Creek Oolite. This facies consists of a chalky white to light brown cross-bedded oolitic grainstone with a recessive weathering profile in outcrop (McKnight and Fischer, 1970).The unit is relatively thin, with an average range in thickness of 0.3-2.5 meters (1-8 ft.) (Mazzullo et al., 2013) while it reaches a maximum thickness of 7.5 meters (25 ft.) (Lisle, 1983). Portions of the oolite exhibit cross-bedding indicative of deposition in high energy environments in probable water depths of 0m to 3m (Ritter and Goldstein, 2012). Structureless oolitic intervals have also been identified, lacking the cross-bedding of higher energy shoal environments. Structureless oolite may also contain high percentages of mud or cement while total percentages of ooids in varying locations may range from 5-59% (Lisle, 1983). These oolitic intervals are interpreted to have been transported by storms down-ramp into relatively deeper water of approximately 2m to 10m (Ritter and Goldstein, 2012).

Above the Bentonville and Short Creek, a glauconitic limestone marks the top of the Osagean and the base of the Meramecian sections. Overlying Meramecian rocks are generally similar in character to the Bentonville Formation, indicating similar environmental conditions during its deposition.

2.4 Structure and Tectonics

The Mississippian outcrop belt is present on the western flank of the Ozark Uplift (Fig. 8). Paleogeographic reconstructions as well as depositional models of the Mississippian indicate that the uplift was a topographic high at that time of carbonate deposition (Fig. 1, Fig. 2). Rock ages decrease westward as Mississippian strata dip into the subsurface and become increasingly older to the east as strata onlap and are truncated by the uplift.

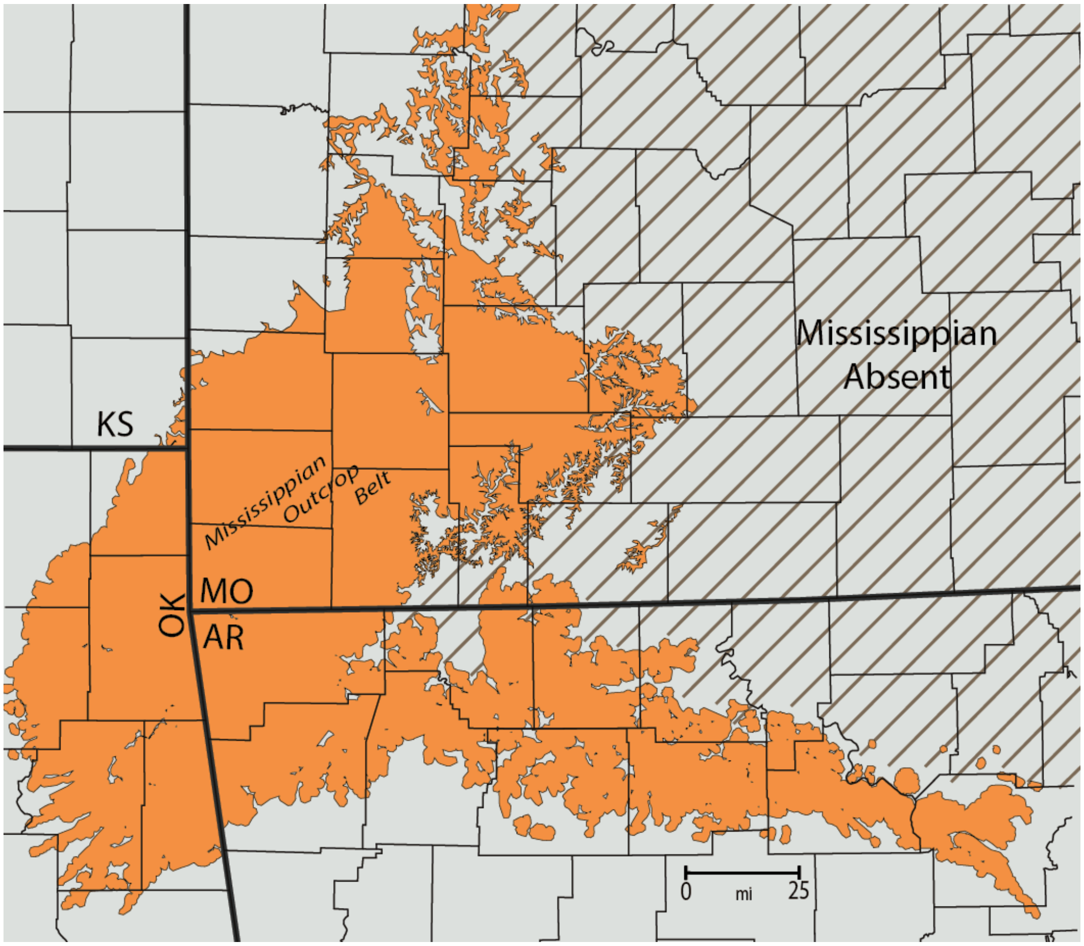

Figure 8: Map of the Tri-State area showing the aerial extent of the Mississippian outcrops. The outcrop belt extends in a somewhat ring-like fashion around the Ozark Uplift. As you move to the east the Mississippian section is absent due to uplift and erosion. Rock ages become younger to the west and south as the Mississippian-age rocks dip into the subsurface (Modified from Mazzullo et al., 2011a).

While the outcrop belt is structurally simple, anomalies exist within the region that are difficult to explain solely by deposition. Both the Compton and the Pierson Formations are characterized by progradation to the north, opposite of the regional paleo-dip to the south during the Mississippian. Anomalously thick, elongate successions of Compton, Northview, and Pierson Formations are viewed in the outcrop region trending east-west, parallel to depositional strike (Beveridge and Clark, 1952; Wilhite et al., 2011). There is also evidence of subaerial exposure in the Reeds Spring Formation, which is interpreted to be the most basinal and deepest water facies present in the Lower to Middle Mississippian of the region (Wilhite et al., 2011).

Syndepositional tectonics has been hypothesized as a driving mechanism for the occurrence of these anomalies. While the onset of the Ouachita-Marathon Orogeny occurred during latest Mississippian to earliest Pennsylvanian, it is proposed that compressional forces resulted in the formation of a fore-bulge and subsequent back-bulge basin that was present in the outcrop region from Kinderhookian through Osagean time (Wilhite et al, 2011). The presence of a fore-bulge and back-bulge could potentially create a sub-basin with a paleo-dip to the north. This can explain the occurrence of northward progradation as well as the anomalously thick successions of formations due to the increased accommodation. The uplift of the fore-bulge has also been used to explain the occurrence of tripolitic intervals within the Reeds Spring Formation, as it has been hypothesized that they formed from subaerial exposure (Wilhite et al., 2011).

III. DATA AND METHODS

3.1 Outcrop

Subsurface data in the Mississippian many times does not differentiate between formations. When formations are identified, they are generally chosen based on log shapes that are not tied to rock data. Therefore, in order to analyze the Bentonville Formation, detailed outcrop studies will be done in order to identify the depositional environment, the effects of high frequency cyclicity, potential reservoir heterogeneity, and possible correlations to subsurface data. The type locality of the Bentonville Formation in northwestern Arkansas is the primary study site (Fig. 9a).The outcrop occurs in a road cut on Highway 71-US 540 approximately three miles north of Bentonville, Arkansas (Fig. 9b). The total outcrop exposure is approximately 1500’ long and 78’ tall at its thickest section (Fig. 9c). At this locality the Bentonville Formation overlies the Pineville Tripolite Facies of the Reeds Spring Formation while the uppermost section is exposed to present-day subaerial conditions, resulting in removal of a portion of the upper section. The capping Short Creek Oolite Member is not present at this location, either due to non-deposition or erosional processes. The trend of the roadcut is from the northwest to the southeast, which roughly parallels the shelf margin during deposition of the Bentonville as proposed by Choquette et al. (1992).

This outcrop was selected for research for multiple reasons. Based on average thicknesses of the Bentonville throughout the Mississippian outcrop belt it is believed that the Highway 71 location represents a large percentage of the formation. The lateral extent of the roadcut can allow for tracing of beds, surfaces, and facies over a great distance. The extent of the exposure also allows for identification of potential reservoir heterogeneity on the production-scale. The roadcut has multiple ledges along its entire length that allow easy access for sampling and data collection. Lastly, due to the Highway 71 outcrop being the type-locality for the Bentonville, it provides a good representation of the environment present during deposition and subsequent facies distribution throughout the formation.

Figure 9: Location of the outcrop study. The outcrop to be examined represents the lower part of the composite type section for the Bentonville Formation. Figure 9b presents the study area's geographic location. The outcrop is approximately 5km (3 mi.) north of Bentonville, AR and 10km (6 mi.) south of the Missouri state line on Highway 71-US 540. Figure 9c illustrates the orientation and length of the type section. It trends northwest-southeast oblique to the shelf margin as defined by Lane and DeKyser (1980), and parallel to the margin defined by Choquette et al. (1992) (Modified from Mazzullo et al., 2011a and www.bing/maps/).

Figure 10: Image showing the lateral extent of the outcrop study location. The photo is taken with northeast oriented to the left. The outcrop is approximately 500m in total length (1600-1700 ft.) and 24m (78 ft.) tall at its thickest point. Multiple ledges exist on the outcrop allowing for relatively easy vertical sampling and collection of data.

3.2 Thin Section Analysis

A detailed understanding of the facies distribution in the outcrop is critical in interpretation of depositional environments as well as understanding the stacking patterns and potential cyclicity within the Bentonville Formation. Previous descriptions of the rocks in the outcrop have been made from hand specimen. However, in order to accurately describe these carbonate rocks, thin sections must be analyzed. Thin section analysis allows for more accurate identification of facies composition as well as recognition of subtle variations in facies that may be key in understanding changes in environmental setting due to high frequency cyclicity.

Samples are to be collected from three vertical sections of the outcrop. Sections will be spaced 100-150m (330-500 ft.) apart in order to provide control points when interpolating and extrapolation facies and cycles across the outcrop. Samples from the vertical sections will be taken between 0.5-1m (1.5-3 ft.) apart, and sample locations within the sections are to be chosen based on identifiable changes in the rock fabric. Once samples are collected, they are to be cut and prepared for thin sections.

Thin sections will be described using the classification system defined by Dunham (1962), for grain size, allochems, and mineralogy. Pore types and overall abundance of porosity will be defined using the terminology of Choquette and Pray (1970), and visual estimation of porosity in thin section. The facies present will be analyzed to identify repeatable vertical patterns or cycles within the outcrop. Cycles can then be interpreted to create an idealized facies succession for the Bentonville Formation. Relationships between porosity development, facies, and mineralogy will be examined in order to determine if higher frequency cyclicity plays a role in the heterogeneity of the carbonate and chert reservoirs. Understanding the porosity distribution within a given facies and the position of that facies within the idealized facies succession can aid in explaining a large portion of the reservoir heterogeneity present in the Mississippian.

3.3 Photography

When working in the subsurface, logs are the most commonly used type of data. A log provides one-dimensional data for a single location. It is common practice to correlate logs based on gamma ray or resistivity measurements, sometimes over distances of a mile or more. This method is not adequate in the Mississippian System of the mid-continent. There is a large degree of uncertainty in this method due to the inherent complexity of the Mississippian in the region which can lead to poor correlations and poor well performance. The benefit of using outcrops is that they help to explain potential heterogeneity of the rocks by providing a second dimension to be studied (Grammer et al.,2004). Vertically sampled sections of the outcrop act as one dimensional constrained data sets. The use of high-resolution photography over the extent of the outcrop can provide a two-dimensional data set that further constrains interpolation and extrapolation away from sample locations.

High-resolution images of the outcrop are to be taken with a GigaPan® Epic Pro, Nikon® D7000 DSLR camera, and Nikon® AF-S Nikkor 300mm lens setup (Fig. 11). The GigaPan® is an automated device that captures approximately one thousand images at preset intervals in a large photo montage. GigaPan Stitch™ software seamlessly merges the photos into one gigapixel image. The resulting outcrop photo is capable of capturing fine details of the rocks and also allows provides a holistic view of the outcrop that can't be examined or analyzed in the field or by traditional photography.

Figure 11: GigaPan® Epic Pro setup used for creation of high resolution giga-pixel images. The GigaPan® is an automated device that positions the camera at equally spaced user defined intervals while remotely capturing a picture at each interval. The output is a large number of overlapping images within a grid of rows and columns. GigaPan Stitch™ software is then used to piece together the photographs. The program first aligns the pixels of each image to identify how they overlap. It then stretches and rotates each image to make them align. The program then blends the images into one seamless high resolution panorama (www.gigapan.com).

Using the constraints from vertically sampled sections along with the images, data can be interpolated over the entire length of the outcrop. Use of photography can allow for recognition of depositional geometries which aids in the interpretation of depositional environment. Images can be used to map bedding features and to trace potential flooding surfaces, allowing for a two dimensional view of depositional cycles. Observations of facies distribution from control sections can also be made, allowing for a better understanding of reservoir distribution within a sequence stratigraphic framework.

3.4 Spectral Gamma Ray

Standard gamma ray logs measure the total amount of gamma ray emission from a source, most being emitted by potassium-40 as well as uranium and thorium isotopes (Doveton, 1994). While standard gamma ray measurements don't differentiate between the sources of emission, spectral gamma ray measures the contribution of K-40, Th, and U individually. Typically used for analysis of shale and clay rich formations, spectral gamma ray logs can be very useful in the interpretation of carbonate rocks. In carbonate systems thorium and potassium are mutually correlative and are direct indicators of siliciclastic content (Ehrenberg and Sva°na, 2001). Uranium is uncorrelated to thorium and potassium and may or may not be present in the system depending on the conditions under which the carbonates were formed (Ehrenberg and Sva°na, 2001). The absence of uranium indicates carbonate formation in an oxidizing environment while its presence indicates probable formation in a reduced setting (Doveton, 1994). Therefore, the thorium-uranium ratio (Th/U) can be used as an indicator of environmental conditions present at the time of carbonate deposition (Doveton, 1994).

Spectral gamma ray measurements will be taken on the outcrop using the Exploranium® GR-320 enviSPEC scintillometer. Readings will be collected at six inch intervals from vertical sections constrained by facies data. Collected data will then be compiled to create a gamma ray API log for potential subsurface ties. A Th/U log will also be calculated and viewed in relation to facies data from the outcrop. Low value spikes may indicate reduced deeper water conditions that may correlate to higher frequency flooding surfaces.

Using rock data in combination with the spectral gamma ray can help to adjust and constrain 4^{th} order sequence and 5^{th} order cycle boundaries, aid in the delineation of the sequence stratigraphic framework of the formation, and allow for outcrop to subsurface correlations.

It is important to note that pressure dissolution and formation of stylolites can concentrate insoluble minerals such as clays along seams in the rock (Glover, 2012). If measured, these zones may potentially be high in uranium, generating data not accurately representing conditions present during carbonate deposition. Viewing the stylolites in outcrop and thin section for mineralogic differences can validate or disprove that environmental conditions were responsible for variations in abundance of radioactive mineral as opposed to later diagenetic alteration. Clays may also be more abundant in zones of karstic weathering due to the input of terrigenous soils. The uppermost units of the outcrop therefore may provide erroneous data and need to be viewed with caution when used for interpretation and correlation.

3.5 Modern Analog Analysis

Outcrops are invaluable datasets that can explain a great deal of complexity associated with carbonates. Very rarely do they provide a three-dimensional view of the facies geometries present in the system, and when they do it is often in a limited aerial extent due to the orientation of the outcrop (Grammer et al., 2004). Modern analogs are useful in that they allow for an understanding of the facies geometries in plan-view (Fig. 12). Analyses of modern environments can provide insight on the facies distribution of a single time slice for obtaining an approximation of the geometrical attributes of a given facies (Grammer et al., 2004). Plan-view data from modern analogs can further be enhanced by incorporation of sediment coring. This allows for an understanding of the depositional system's response to autocyclic and allocyclic processes, as well the resulting facies distribution. Therefore, the incorporation of modern analogs is critical in that it gives a quantitative view into the third dimension not provided by the outcrop, as well as an understanding of the controls on sedimentation. Combining constrained two dimensional rock data from outcrop with spatial data from modern analogs will allow for much more confined predictions when interpreting facies and reservoir distribution in the third dimension.

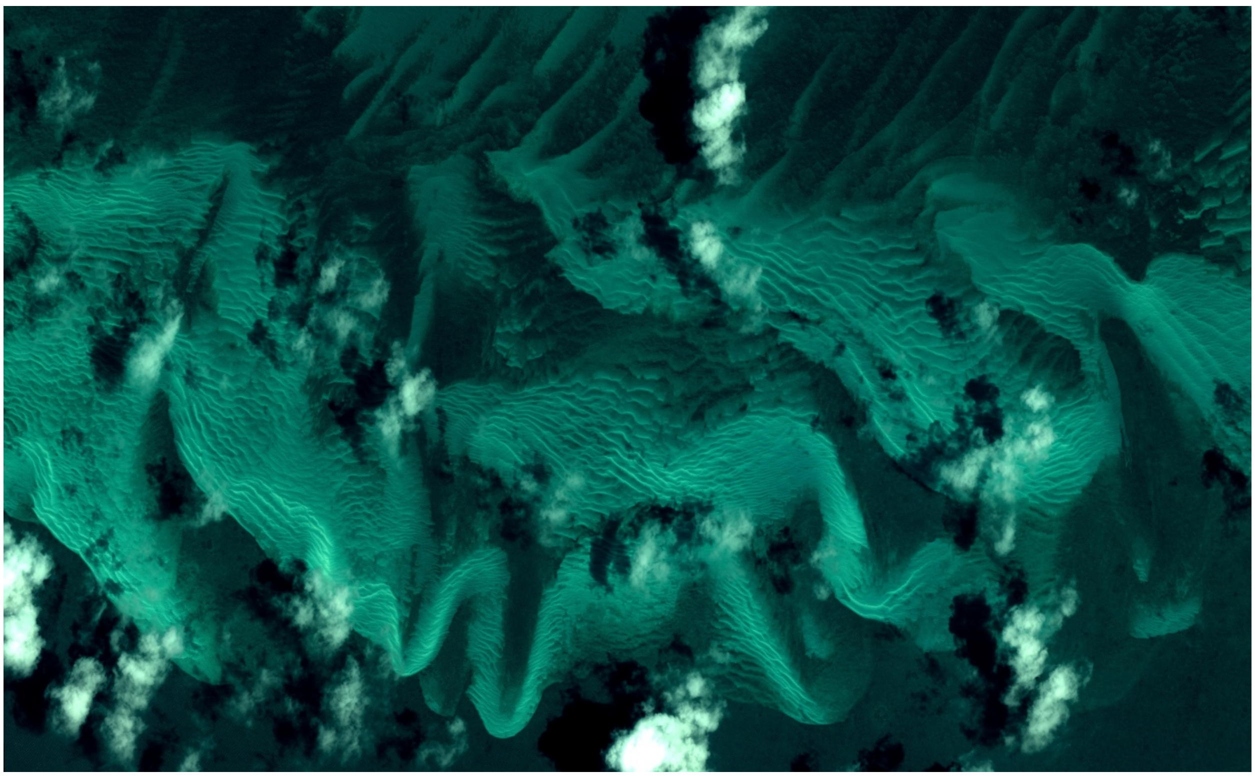

Figure 12: Remote sensing image of Lily Bank Ooid Shoal Complex on Little Bahama Bank. The photograph is approximately 9.2km from east to west. The image illustrates numerous geometries present within a high energy shoal complex viewed in the Z-plane. The high degree of variability in plan-view is inherent in most carbonate depositional environments. Outcrops provide one slice through a depositional system, but cannot fully explain the complexity of the environment responsible for its formation. The use of modern analogs not only helps to explain the facies geometries in plan-view, but can also provide a predictive tool when mapping facies and reservoir distribution away from control sections (Image from Rankey and Reeder, 2011).

IV. References Cited

Beveridge, T. R. and Clark, E. L., 1952, A revision of the early Mississippian nomenclature in western Missouri, West-Central and Southwestern Missouri: Guidebook, 16th Regional Field Conference, p. 71-79.

Blakey, R., 2011, North American paleogeography, Northern Arizona University. <http://www2.nau.edu/rcb7/nam.html> , Accessed March 28, 2013.

Boardman, D.R. II, Mazzullo, S.J.,Wilhite, B.W., Puckette, J.O., Thompson, T.L., and Woolsey, I.W., 2010, Diachronous prograding carbonate wedges from the Burlington Shelf to the southern distal shelf/basin in the southern flanks of the Ozarks: Abstracts with Programs, Joint North-Central and South-Central Meeting, Geological Society of America, v. 42, no. 2, p. 41.

Curtis, Doris M. and Champlin, Stephen C., 1959, Depositional Environments of Mississippian Limestones of Oklahoma, Tulsa Geological Society Digest, v. 27, no. 1, p. 90-103.

Cowan, C.A., and James, N. P., 1996, Autogenic dynamics in carbonate sedimentation: meter-scale shallowing upward cycles, Upper Cambrian, Western Newfoundland, Canada, American Journal of Science, v. 296, p. 1175-1207

Choquette, P. W., Cox, A., and Meyers, W. J., 1992, Characteristics, distribution and origin of porosity in shelf dolostones: Burlington-Keokuk Formation (Mississippian), U.S. Mid-continent, Journal of Sedimentary Petrology, v. 62, p. 167-189.

Choquette, P. W. and Pray, L. C., 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates, AAPG Bulletin, V. 54, No. 2, p. 207-250.

Doveton, J. H., 1994, Geologic Log Interpretation: reading the rocks from wireline logs, SEPM Short Course 29, 169 p.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture, *in* Ham, W.E., ed., Classification of Carbonate Rocks: AAPG Memoir, V. 1, p. 108-121.

Drummond, C. N., and Wilkinson, B H., 1993, Carbonate cycle stacking patterns and hierarchies of orbitally-forced eustatic sealevel change, Journal of Sedimentary Petrology, v. 63, p. 369-37.

Ehrenberg, S. N. and Sva°na, T. A., 2001, Use of spectral gamma-ray signature to interpret stratigraphic surfaces in carbonate strata: An example from the Finnmark carbonate platform (Carboniferous-Permian) Barents Sea, AAPG Bulletin, V. 85, No. 2, p. 295-308.

Evans, K. R., Mickus, K. L., and Jackson, J. S., 2010, Geology of the Branson area, Southwestern Missouri: AIPG Missouri Section Annual Meeting Field Trip Guidebook, 40p.

Glover, P., 2012, The spectral gamma ray log, *in* Petrophysics MSc Course Notes, p. 111-120.

Grammer, G. M., Harris, P. M., and Eberli, G. P., 2004, Integration of outcrop and modern analogs in reservoir modeling: Overview with examples from the Bahamas, *in* Integration of outcrop and modern analogs in reservoir modeling, AAPG Memoir 80, p. 1-22.

Goldhammer, R. K., Dunn, P. A., and Hardie, L. A., 1990, Depositional cycles, composite sea-level changes, cycle stacking patterns, and the hierarchy of stratigraphic forcing: Examples from Alpine Triassic platform carbonates, Geological Society of America Bulletin, v. 102, p. 535-562.

Gutschick, R. C., and Sandberg, C. A., 1983, Mississippian Continental Margins of the Conterminous United States, SEPM Special Publication, no. 33, p. 79-96.

Hall, J., 1857, Observations upon the Carboniferous limestones of the Mississippi Valley, American Journal of Science, V. 23, p. 187-203.

Haq, B. U., and Schutter, S. R., 2008, A chronology of Paleozoic sea-level changes, Science, v. 322, October 2008, p. 64-68.

Huffman, G. G., 1960, Geology of the Oklahoma Ozark Region, North-eastern Oklahoma: Guidebook, 25th Field Conference, p. 82-109.

Jordan, L. and Rowland, T.L., 1959, Mississippian Rocks in Northern Oklahoma, TGS, Tulsa Geological Society Digest, v. 27, p. 124-136.

Kreman, D. M., 2011, Characterization of Kinderhookian and Osagean Strata of Northeast Oklahoma, Master of Science Thesis, ProQuest, UMI Dissertation Publishing. 160 p.

Krueger, R. C., 1965, Subsurface Study of Mississippian Rocks in the Tulsa Area, OCGS, The Shale Shaker Digest V, v. XV-XVII, p. 217-239.

Lane, H. R., 1978, The Burlington Shelf (Mississippian, north-central United States): Geologica et Palaeontologica, v. 12, p. 165-175.

Lane, H. R., and DeKyser, T. L., 1980, Paleogeography of the Late Early Mississippian (Tournasian 3) in the central and southwestern United States, Paleozoic Paleogeography of West-Central United States: Rocky Mountain Paleogeography Symposium 1, p. 149-162.

Lisle, B. A., 1983, Short Creek Oolite (Lower Mississippian) deposition, War Eagle Quarry, Madison County, Arkansas, Arkansas Academy of Science Proceedings, v. 38, p. 47-49.

Manger, W.L., and Shanks, J.L., 1976, Lower Mississippian lithostratigraphy, Northern Arkansas: Arkansas Academy of Science Proceedings, v. 30, p. 78-80.

Mazzullo, S. J., 2011, Mississippian Oil Reservoirs in the Southern Midcontinent: New Exploration Concepts for a mature reservoir objective, AAPG Search and Discovery Article #10373.

Mazzullo, S. J., Boardman, D. R., Wilhite, B. W.,Godwin, C., Morris, B. T., 2013, Revisions of outcrop lithostratigraphic nomenclature in the lower to middle Mississippian subsystem (Kinderhookian to basal Meramecian series) along the shelf-edge in southwest Missouri, northwest Arkansas, and northeast Oklahoma, Shale Shaker, v. 63, no. 6, p. 414-452.

Mazzullo, S. J., Wilhite, B. W., and Boardman, D. R., 2011a, Lithostratigraphic Architecture of the Mississippian Reeds Spring Formation (Middle Osagean) In Southwest Missouri, Northwest Arkansas, and Northeast Oklahoma: Outcrop Analog of Subsurface Petroleum Reservoirs, Shale Shaker, V. 61, No. 5, p. 254-269.

Mazzullo, S. J., Wilhite, B. W., Boardman, D. R., Morris, B., Turner, R., and Godwin, C., 2011b, Lithostratigraphy and conodont biostratigraphy of the Kinderhookian to Osagean series on the western flank of the Ozark Uplift, Tulsa Geological Society Field Trip Guide Book, 48 p.

Mazzullo, S.J., Wilhite, Brian W., and Woolsey, I. Wayne, 2009, Petroleum reservoirs within a spiculite-dominated depositional sequence: Cowley Formation (Mississippian: Lower Carboniferous), south-central Kansas, AAPG Bulletin, v.93, p. 1649-1689.

Morris, B. T., Mazzullo, S. J., and Wilhite, B. W., 2013, Sedimentology, biota, and diagenesis of 'Reefs" in lower Mississippian (Kinderhookian to basal Osagean: Lower Carboniferous) strata in the St. Joe Group in the western Ozark area, Shale Shaker, V. 64, No. 3, p. 194-227.

Owen, D. D., 1852, Report of a Geological Survey of Wisconsin, Iowa, and Minnesota; and incidentally of a portion of Nebraska territory: Lippincott, Gambo and Co., 638 p.

Plint, A. G., Eyles, N., Eyles, C. H., and Walker, R. G., 1992, Controls on sea-level changes. *In:* Walker, R. J. and James, N. P. (eds.), *Facies Models: Response to Sea-Level Change*, Geological Association of Canada, St. John's Newfoundland, p. 15-25.

Rankey, E. C., 2002, Spatial patterns of sediment accumulation on a Holocene carbonate tidal flat, northwest Andros Island, Bahamas, Journal of Sedimentary Research, v. 72, p. 591-601.

Rankey, E. C., and Reeder, S. L., 2011, Holocene oolitic marine sand complexes of the Bahamas, Journal of Sedimentary Research, v. 81, p. 97-117.

Read, J. F., 1995, Overview of carbonate platform sequences, cycle stratigraphy and reservoirs in greenhouse and icehouse worlds. *In:* Read, J. F., Kearns, C., Weber, L. J., Sarg, J. F., and Wright, F. M., (eds.) *Milankovitch sea level changes, cycles, and reservoirs on carbonate platforms in greenhouse and ice-house worlds: SEPM Short Course* 35, p. 1-102.

Ritter, M. E., and Goldstein, R. H., 2012, Diagenetic controls on porosity preservation in lowstand oolitic and crinoidal carbonate, Mississippian, Kansas and Missouri, USA, International Association of Sedimentologists, Special Publication 45, p. 379-406.

Rogers, S. M., 2001, Deposition and diagenesis of Mississippian chat reservoirs, north-central Oklahoma, AAPG Bulletin, v. 85, no. 1, p. 115-129,

Ross, C. A., and Ross, J. R., 1988, Late Paleozoic transgressive-regressive deposits, *In: Sea-Level Changes-An Integrated Approach, SEPM Special Publication* no. 42, p. 227-247.

Shoeia, O. O., 2012, High resolution stratigraphy of Lower Mississippian strata near Jane, Missouri, Master of Science Thesis, Oklahoma State University, unpublished.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America. Geological Society of America Bulletin, 74: 93-114.

Thompson, T. L., and Fellows, L. D., 1970, Stratigraphy and conodont biostratigraphy of Kinderhookian and Osagean (Lower Mississippian) rocks of southwestern Missouri and adjacent areas, Missouri Geological Survey and Water Resources Report of Investigation 45, 263 p.

Unrast, M., 2013, Composition and classification of Mississippian carbonate mounds in the Ozark region, North America, Shale Shaker, v. 63, p. 629-664.

Wilhite, B. W., Mazzullo, S. J., Morris, B. T., and Boardman, D. R., 2011, Syndepositional Tectonism and its effects on Mississippian (Kinderhookian to Osagean) lithostratigraphic architecture: Part 1- based on exposures in the Midcontinent USA, AAPG Search and Discovery Article # 30207.

Witzke, B. J., 1990, Paleoclimatic constraints for Paleozoic paleolatitudes of Laurentia and Euramerica, W. S. McKerrow and C. R. Scotese, eds. Paleogeography and biogeography: Geological Society (London) Memoir 12, p. 57-73.

Witzke, B.J., R.M. McKay, B.J. Bunker, B.J., and F.J. Woodson, 1990, Stratigraphy and environments of Mississippian strata in Keokuk and Washington Counties, southeast Iowa: Iowa Department of Natural Resources, Geological Survey Bureau Guidebook Series No. 10, 105 p.