8-2012

Reservoir Characterization and Outcrop Analog: The Osagean Reeds Spring Formation (Lower Boone), Western Osage and Eastern Kay County, Oklahoma

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Recommended Citation

Friesenhahn, Taylor, "Reservoir Characterization and Outcrop Analog: The Osagean Reeds Spring Formation (Lower Boone), Western Osage and Eastern Kay County, Oklahoma" (2012). *Theses and Dissertations*. 543.
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RESERVOIR CHARACTERIZATION AND OUTCROP ANALOG: THE OSAGEAN REEDS SPRING FORMATION (LOWER BOONE), WESTERN OSAGE AND EASTERN KAY COUNTY, OKLAHOMA

RESERVOIR CHARACTERIZATION AND OUTCROP ANALOG: THE OSAGEAN REEDS SPRING FORMATION (LOWER BOONE), WESTERN OSAGE AND EASTERN KAY COUNTY, OKLAHOMA

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

By

Taylor Cole Friesenhahn
University of Arkansas
Bachelor of Science in Geology, 2010

August 2012
University of Arkansas

ABSTRACT

The Reeds Spring Formation (Osagean) is a member of the Lower Mississippian carbonate series developed on the Cherokee Platform Province of northeastern Oklahoma. On the western flank of the Ozark Dome, these rocks dip in a west-southwest direction into the subsurface where they are oil and gas reservoirs. A series of road cuts and surface exposures are cropped out in the tri-state area of northwest Arkansas, northeastern Oklahoma, and southwestern Missouri. Outcrop characteristics, including an abundant amount of nodular, anastomosing chert, generally finer-grained carbonate texture, and stratigraphic relationships provide an analog for its subsurface counterpart. Based on core description and well log correlation, the Reeds Spring Formation developed in the Cherokee Platform in western Osage and eastern Kay County, Oklahoma reflect transportation of crinozoan detritus, spicules, and carbonate mud off the Burlington shelf, passing downslope from the north, northwest, and northeast, into deeper waters of the deep shelf margin setting. As the result, its subsurface lithologies are characterized by shaly fine-grained spiculitic crinoid wackestone.

Subdivision of the formation, which exceeds 200 feet in the subsurface, offers more control on determining reservoir quality across a large study area (approx. 840 square miles). Criteria used to examine reservoir quality include clean carbonate content, true porosity, and high resistivity signatures. Additionally, Formation Micro-Image (FMI) log evaluation shows that the chert content does not develop in the Reeds Spring Formation where low gamma ray (< 40 API) and high resistivity (+90 ohm-m) signatures are absent. An anomalous amount of silt and clay content, identified by thin section and petrophysical analysis, reveals that the Reeds Spring Formation lacks vertically and laterally continuous reservoir grade rocks across a large area. Across western Osage and eastern Kay County, Oklahoma the lower member of the Reeds

Spring offers the poorest reservoir quality, the middle member the best, and the upper member moderate quality.

This thesis is approved for recommendation
to the Graduate Council.

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ACKNOWLEDGEMENTS

I would like to thank all who aided in the completion of this thesis project and the graduate program. Dr. Xiangyang “Cheyenne” Xie, thesis advisor, for his mentoring, time, and sincere efforts through the entire thesis process. Dr. Walter Manger, for his expertise and directing outcrop discussions. Dr. Doy Zachry, for his support, advising, and guidance through my academic career and thesis project.

I am greatly indebted to the University of Arkansas’ Department of Geosciences for helping me to develop my love for geology. I want express my deepest appreciation to the faculty, staff, alumni, and fellow students for the education and memorable moments during my stay at the University. The department will always remain a special place to me.

A great deal of thanks goes to Shane Matson and Spyglass Energy Group for presenting me with the opportunity and data to carry out this project.

Last and most important, I would like to extend the most sincere gratitude to my parents, brother, and sister for always being so supportive and encouraging through my life and academic career.

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INTRODUCTION

Through most of the early Paleozoic Era, shallow seas covered present-day Oklahoma. Submerged periods were followed by phases of partially inundated or emergent as sea level fluctuations continued over time (Johnson, 2008). These depositional sequences developed marine and coastal marine shales, limestones and sandstones. Limestone and dolomite development extended across Oklahoma area during sea level highstands, initiating as early as the Late Cambrian Arbuckle Group (Johnson, 2008). Carbonate intervals, such as the Lower Mississippian-age limestones, have been exploited as hydrocarbon reservoirs in the Cherokee Platform Province of northeastern Oklahoma since the late nineteenth century. With the first discovery occurring in 1873, over 200,000 wells have been drilled. The Mississippi Lime Play of Osage and Kay County, Oklahoma is among the different petroleum plays discovered in the province (Charpentier, 1995). The Mississippi Lime Play encompasses multiple reservoir units that all belong to Lower Mississippian carbonate formations. The thickness of the Lower Mississippian carbonates in Osage County ranges from over 300 feet in three-fourths of the county to less than 100 feet in the southern portion (Bass, 1942). The Reeds Spring Formation, one of the Lower Mississippian reservoir rocks, is a major hydrocarbon exploration objective in northeastern Oklahoma (Mazzullo et al., 2011). The Reeds Spring section crops out in the tri-state area of northwest Arkansas, northeastern Oklahoma, and southwestern Missouri. On the western flank of the Ozark Dome, these rocks dip in a west-southwest direction into the subsurface, where they are oil and gas reservoirs (Mazzullo et al., 2010).

With the support of Spyglass Energy Group in Tulsa, Oklahoma and the Department Of Geosciences, University Of Arkansas, this study focuses on characterizing the reservoir quality and attributes of the Reeds Spring Formation in western Osage and eastern Kay County, northeastern Oklahoma while utilizing surface exposures as an analog. All results can be directly applied to the hydrocarbon exploration and production in this area.

Purpose and Scope

As previously stated, the Reeds Spring Formation is a significant oil and gas producer in the Midcontinent but also proves to be one of the most complex reservoirs (Watney et al., 2001). The purpose of this study is to understand the stratigraphic framework and reservoir characteristics of the complex carbonate hydrocarbon reservoir.

Previous depositional models of the Lower Mississippian strata were created on a regional scale. These models focus on an extreme amount of land area that covers much of the southern midcontinent (Lane and De Keyser, 1980; Gutschick and Sandberg, 1983). Primary subsurface correlation shows that the Lower Mississippian carbonate sedimentology in the midcontinent is not a simple carbonate ramp deposit suggested by previous studies (Lane, 1978; Lane and De Keyser, 1980; Gutschick and Sandberg, 1983; Shelby, 1986). In order to adequately characterize the sedimentation, texture, and quality of the Reeds Spring as a reservoir, it is necessary to propose a localized and more detailed depositional model and compartmentalize the geographic extent of the reservoir.

Study Area

The subsurface study area is focused in western Osage County, Oklahoma and includes a portion of eastern Kay County, Oklahoma (Figure 1). The geographic extent of the study area encompasses twenty-five townships. Townships included in this study are T25N through T29N and ranges R3E through R7E, which generates approximately 840 square miles (Figure 1). Western Osage and eastern Kay County, Oklahoma are located in the middle of the Cherokee Platform Province, which extends from southeastern Kansas and southwestern Missouri into northeastern Oklahoma. Physiographically, the Cherokee Platform is situated between the Ozark Dome to the east and the subsurface Nemaha Uplift to the west. ` The major geologic provinces located to the south are the Anadarko Basin to the southwest, and Arkoma Basin to the south and southeast (Figure 2).

Reeds Spring outcrop geology and stratigraphic relationships of northwest Arkansas acted as a subsurface analog for this project. An outcrop to core comparative study done by Mazzullo et al. (2011) suggests that the outcrop is not totally representative of the subsurface, but acts as a reference point for evaluating the subsurface counterpart. Figure 3 identifies the subsurface study area in relation to the surface exposures that were used to examine the Reeds Spring.

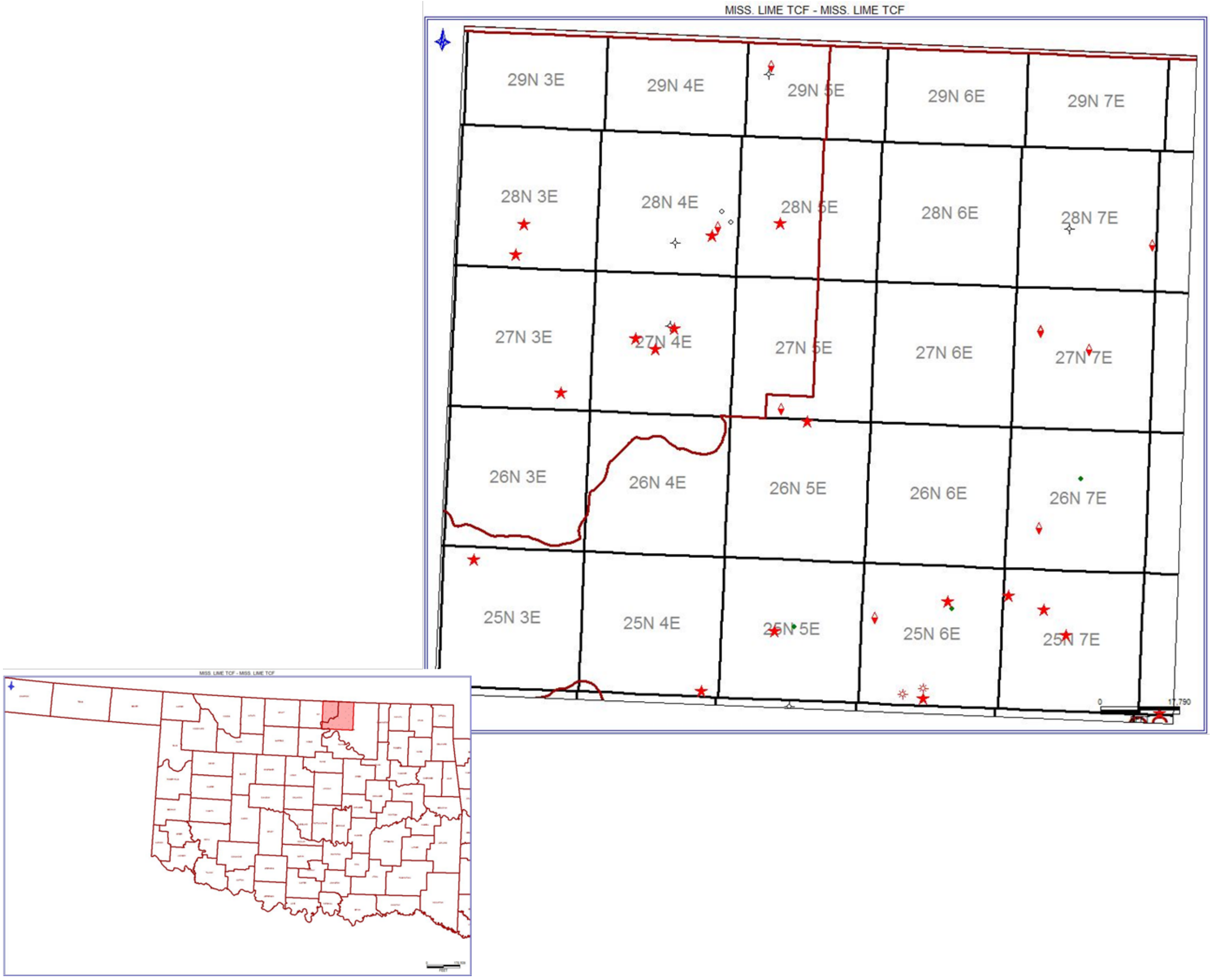

Figure 1 – Study area location. The study area is found in western Osage county and eastern Kay County, Oklahoma, as shown in the inset map in the lower left hand corner of the figure. The top image shows the dimensions of the study area and the well spots used in the project. The north arrow is found in the top left corner of the larger image and the map scale is found at the lower right hand corner.

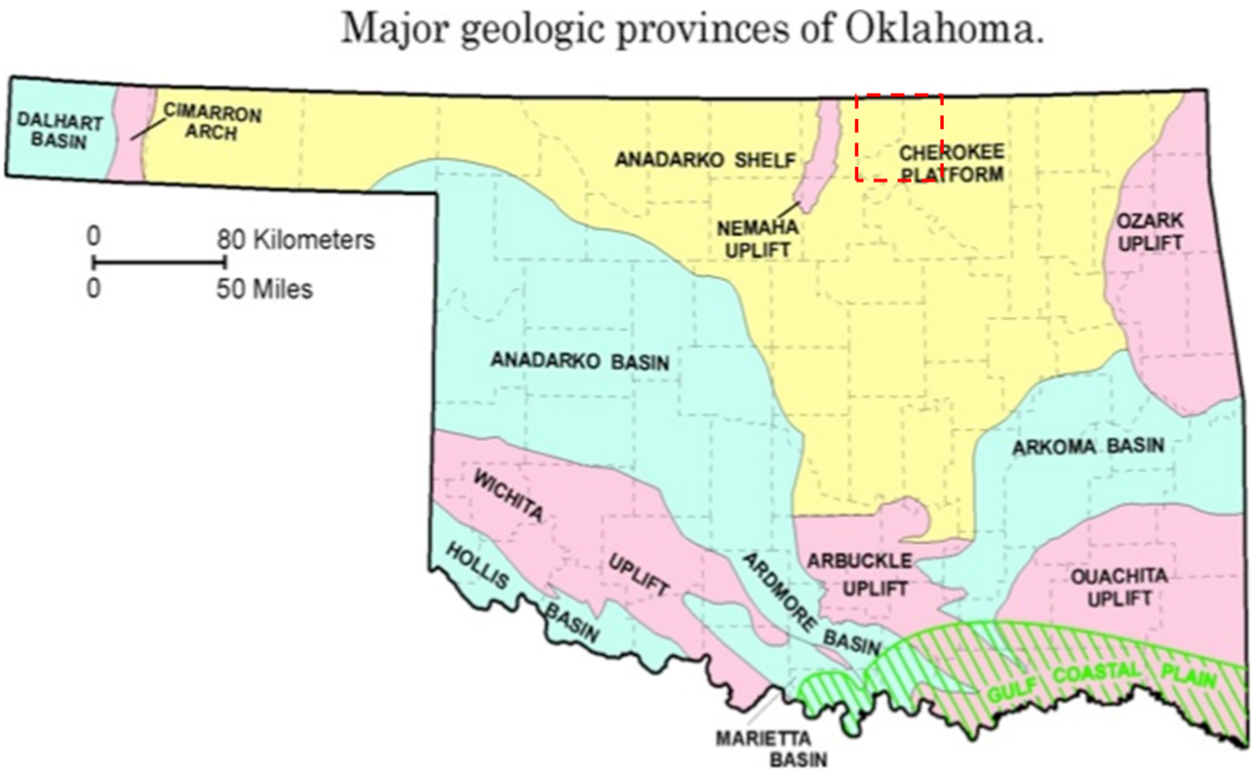

Figure 2 – The state of Oklahoma and the major geological provinces. The study area is highlighted in the red dashed box east of the Nemaha Uplift. Taken from Johnson (2008).

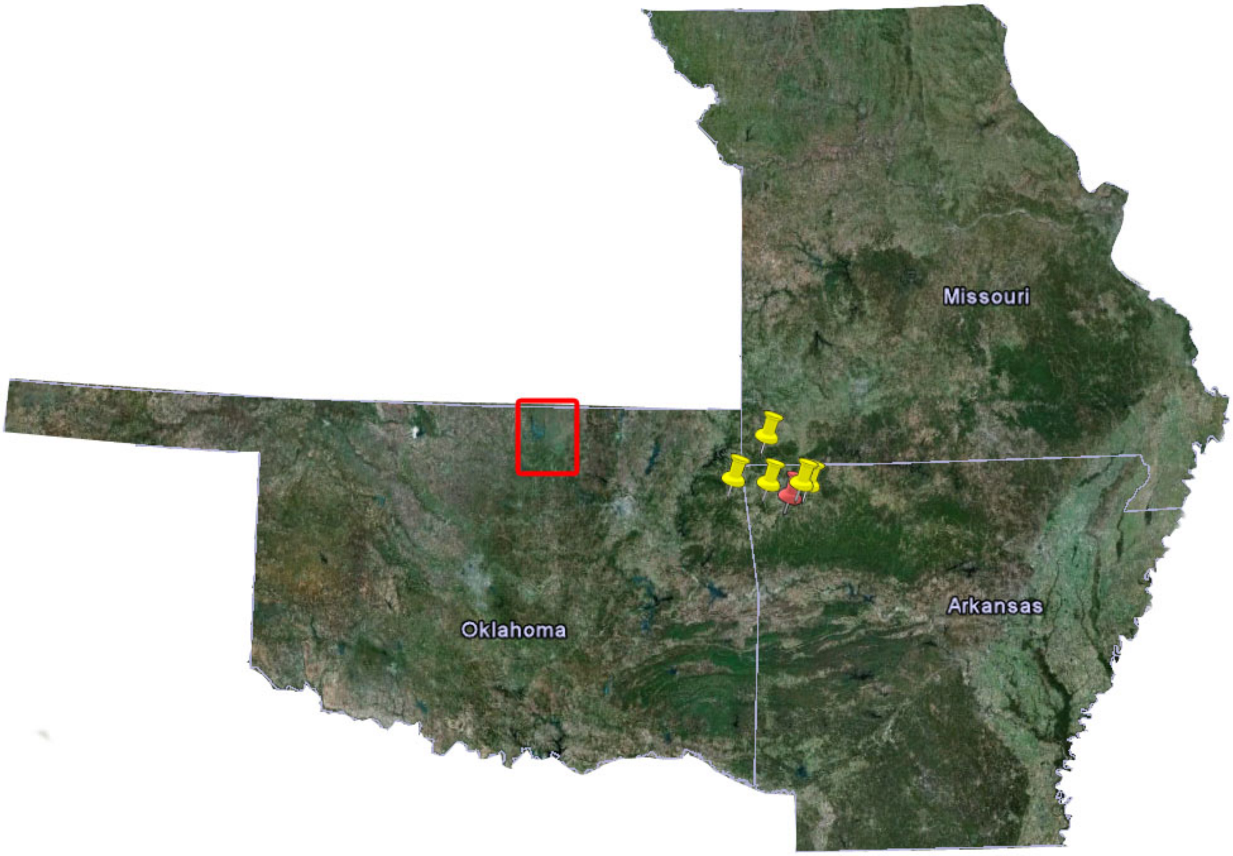

Figure 3 – Map showing locations of Reeds Spring exposures in Oklahoma, Arkansas, and Missouri used during the project in relation to the subsurface study area. The yellow pins are Reeds Spring outcrop and the red pin is the location of Fayetteville, AR. In Oklahoma, the study area is outlined in the red box. There are approximately 150 miles between the group of outcrops and the subsurface study area.

General Statement

Lower Mississippian rocks are exposed in the tri-state area (Arkansas, Oklahoma, and Missouri), but the states combined do not follow the same system of nomenclature for the units of the Lower Mississippian interval. Time and lithologically equivalent rocks are referred formally to different names in each state (Figure 4). The lithostratigraphic relationships observed and described from outcrop in this study are based on mostly northwestern Arkansas geology. The Reeds Spring formation is not usually recognized as a formal stratigraphic unit in northeastern Oklahoma or northwestern Arkansas (Kreman, 2011). The name Reeds Spring is a Missouri unit, but has gained popularity in the petroleum industry in the tri-state area. Consequently, the Reeds Spring Formation is utilized for this study. In all aspects, this study considers the Reeds Spring Formation as lithologically and chronologically equivalent to the lower member of the Boone Formation in northern Arkansas. Due to lack of uniform nomenclature in these states, an informal stratigraphic column was composed for this project in order to relate subsurface terminology to that of the equivalent outcrop geology (Figure 5).

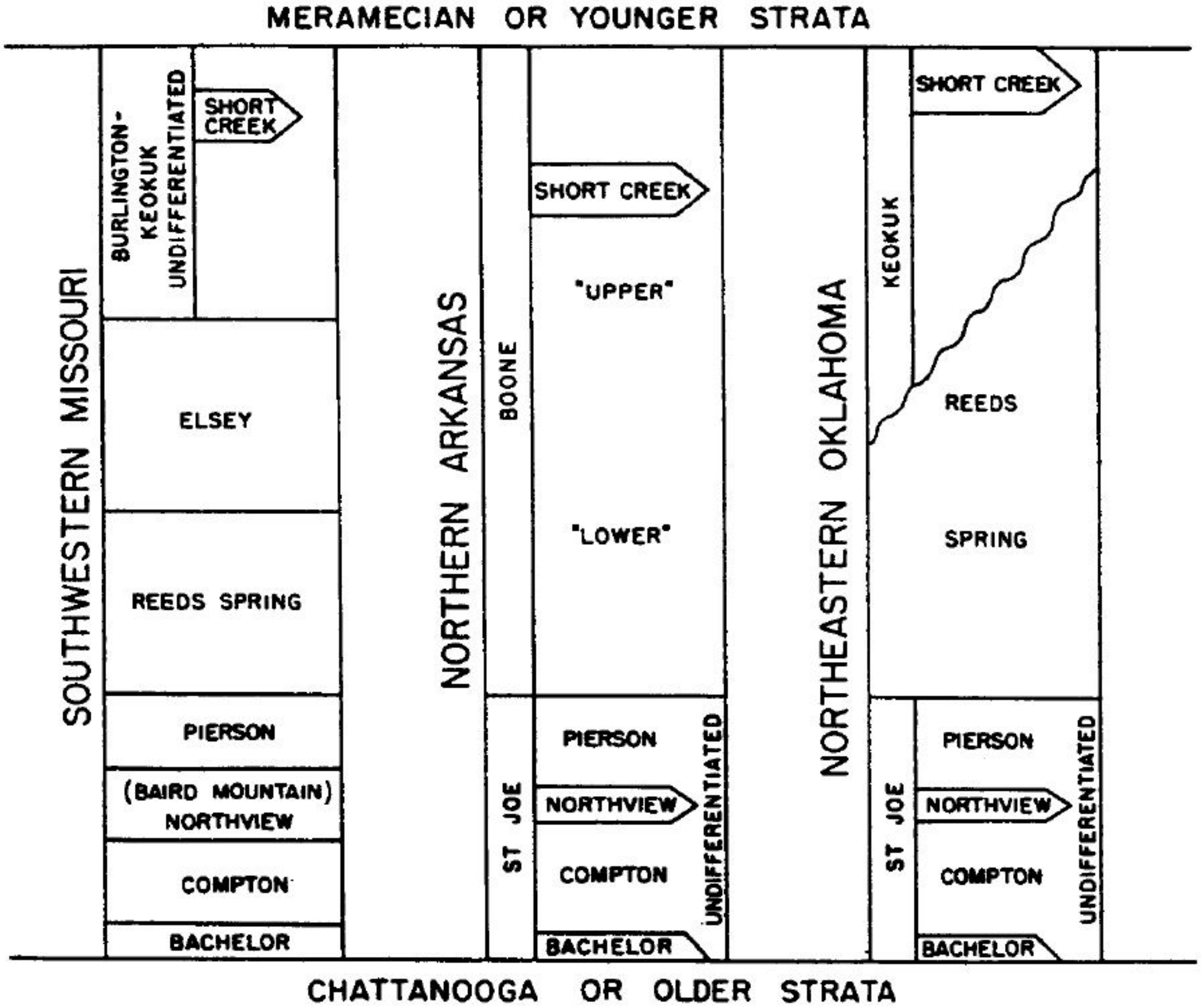

Figure 4 – Stratigraphic columns comparing the nomenclature differences between the tri-state outcrop belt (southwestern Missouri, northern Arkansas, northeastern Oklahoma). Taken from Manger and others (1988).

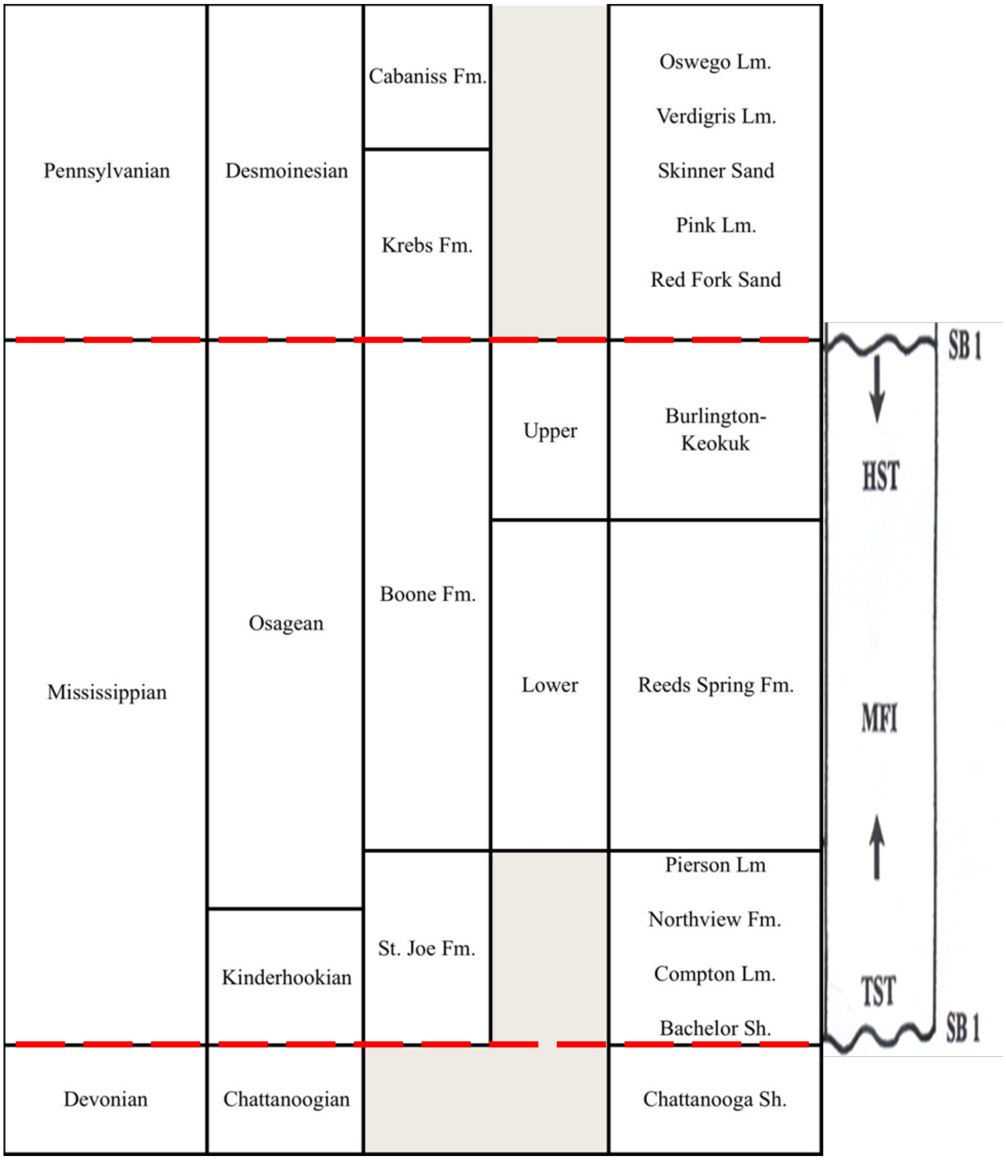

Figure 5 – Stratigraphic column constructed for the project. The right hand column illustrates the sequence stratigraphic positions of each formation. HST – high systems tract; MFI – maximum flooding interval; TST – transgressive systems tract. Red dashed lines represent unconformities. Modified from Handford and Manger (1993).

Lithostratigraphy

Mississippian System

St. Joe

The St. Joe Formation, seen in the tri-state Mississippian outcrop belt, is comprised of carbonate lithologies, which are separated by terrigenous units (Shelby, 1986). Average thickness of the St. Joe is approximately 110 feet in the Ozark Plateaus, where it is seen on the surface (Kreman, 2011). Units that make up the St. Joe Formation, in ascending order, include the Bachelor, Compton, Northview, and Pierson members. All members of the St. Joe are not recognized in the study area, but should be noted as they are observed in outcrops and reflect deposition of the transgressive sequence.

Overlying the Chattanooga/Woodford shale, the Bachelor member of the St. Joe Formation rests unconformably on either Devonian or Ordovician age rock and has been described as having two lithic characters: green fissile shale and a phosphoric quartzarenite conglomerate (Thompson and Fellows, 1970; Shanks, 1976). McFarland (1975) subdivided the rest of the St. Joe based on lithostatigraphy. These units may be described as follows: Compton member – a fine grained calcarenite, Northview member – a calcareous silty shale or an interbedded shale and calcarenite, Pierson member – a fine grained calcarenite (Shanks, 1976). Because the Pierson is overlain by a carbonate unit, as a generalization, the upper contact between the St. Joe Formation and its succeeding formation is marked by the change from grain-supported lithology to mud-supported and the presence of chert in the rock (Shelby, 1986).

Boone

The Boone Formation, Osagean in age, is a gray, fine to coarse-grained, fossilifereous limestone with an abundant amount of chert (Davis, 2005). In exposures and in the subsurface, the Boone Formation overlies the St. Joe Formation conformably with an angular relationship and is bounded above by a prominent unconformity (Van Dan Huevel, 1979). In the subsurface study area, shales of the Cherokee Group unconformably overlie the Boone. Thickness of the Boone in outcrop have been reported to range from 100 feet in eastern Oklahoma, 485 feet in southern Missouri and 300 feet in northern Arkansas (Van Den Huevel, 1979).

Chert, a major constituent of the Boone Formation, is quite variable throughout the outcrop belt with respect to quantity, mode of occurrence, and color (Van Den Huevel, 1979). The chert content of the Boone provides criteria to informally subdivide the interval into lower and upper members, which are equivalent to the Reeds Spring and Burlington-Keokuk from the project stratigraphic column. Two types of chert have been described in outcrop, penecontemperaneous and later diagenetic chert. The lower member, or Reeds Spring (Lower Boone), is characterized by the development of penecontemperaneous chert. Penecontemperaneous chert is described as dark colored, nodular, anastomosing and disruptive to bedding planes (Figure 6). Van Den Huevel (1979) noted that penecontemperaneous chert contributes 45-65% of the Lower Boone and exhibits nodules that range from a few inches to one foot in diameter and up to three to four feet in length. The Upper Boone is defined by the presence of later diagenetic cherts, which occur in discontinuous bands parallel to limestone bedding in a light grey to white color and also makes up 60-70% of the Upper Boone (Figure 7) (Van Den Huevel, 1979). Giles (1935) described later diagenetic chert as soluble with the application of acid and the penecontemperaneous chert had no reaction. The terminology used to describe the two chert types is indicative of their inferred origin.

In addition to a difference in chert type, the Burlington-Keokuk and Reeds Spring (Upper and Lower Boone) members are also differentiated by lithofacies. By and large the Reeds Spring Formation exhibits two distinct mud-supported facies: Mudstone and Wackestone (Liner, 1979). In a sequence stratigraphic framework, the mud-supported facies represented in the Reeds Spring are products of the maximum-flooding interval of the Lower Mississippian carbonate sequence (Figure 5) (Manger and Shelby, 2000; Handford and Manger, 1993). The Burlington-Keokuk (Upper Boone) is characterized by the return of grain-supported facies: Packstone and Grainstone (Liner, 1979). Burlington-Keokuk deposition is the highstand and regressive sequence of the Lower Mississippian carbonates in the southern midcontinent (Figure 5) (Manger and Shelby, 2000).

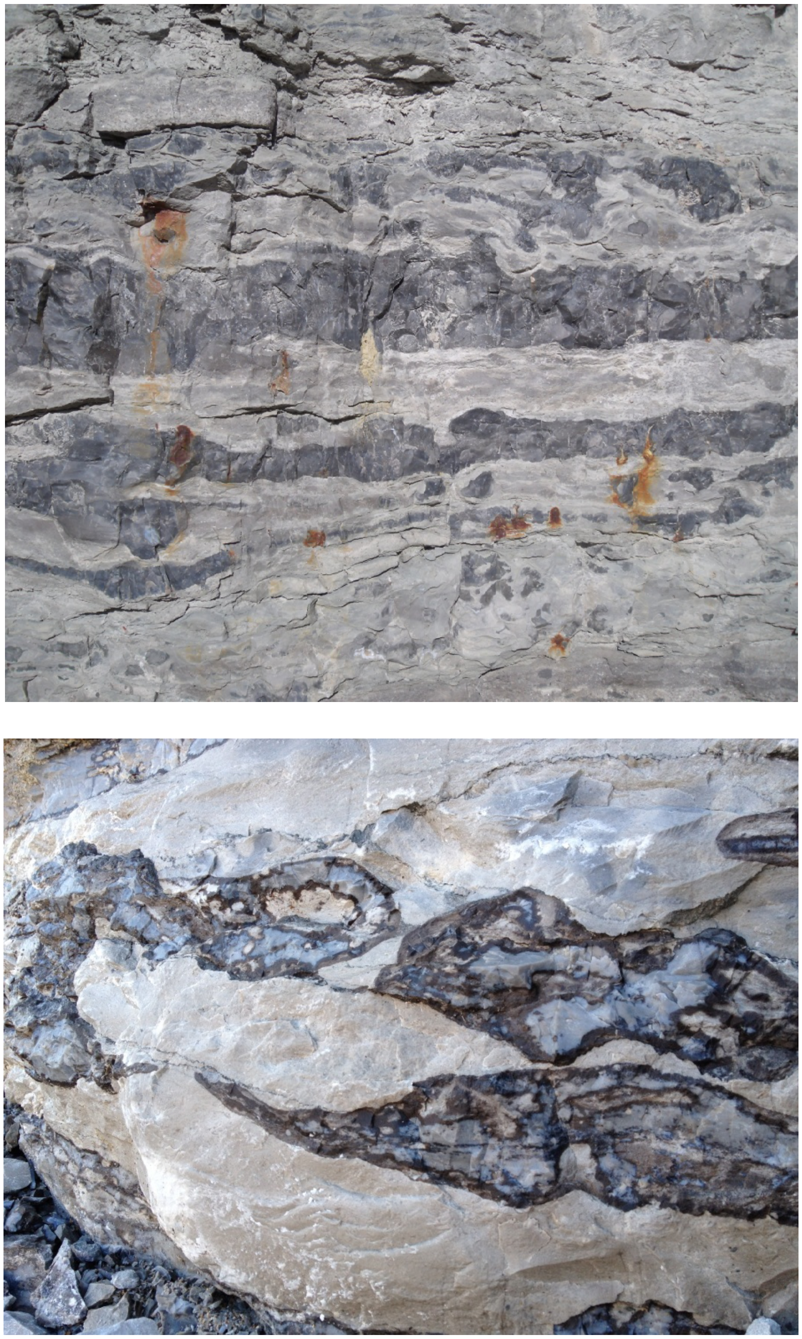

Figure 6 – Reeds Spring (Lower Boone) outcrop photos. Reeds Spring texture is fine-grained mud-dominated lithology. Generally occurring as a mudstone or packstone. Note the nodular, anastomosing, and dark blue to black character of the penecontemperaneous chert. Top photo taken from Kreman (2011).

Figure 7 – Burlington-Keokuk (Upper Boone) outcrop photos. Burlington-Keokuk texture is dominated by grain-supported lithologies. Generally occurs as wackestone to grainstone. Note the occurrence and arrangement according to bedding planes of the later diagenetic chert referred to in the Burlington-Keokuk. Photos taken by Dr. Walter Manger, Department of Geosciences, University of Arkansas.

METHODS OF INVESTIGATION

General Statement

The workflow to further characterize the Reeds Spring reservoir in the study area incorporated the combination of digital and physical studies (Figure 8). Physical studies refer to all supplemental knowledge gained from outcrop exposures of the Lower Mississippian carbonates and all previous academic studies done in and around northwest Arkansas. A large portion of the rock descriptions found in the Lithostatigraphy section of this work were generated from previous studies done at the outcrop level. Additionally, digital geophysical well log data was utilized in order to assess the Reeds Spring Formation in the subsurface in the study area. Obtaining all the digital data used in this study was made possible through donation by Spyglass Energy Group based in Tulsa, Oklahoma.

Geophysical Well Log Correlation

In total, 35 well spots with associated geophysical well log data were correlated across the study area. The well log dataset for this project was housed in a project created in the geological software IHS Petra. The Petra workstation was used to correlate sections from well to well and generate maps illustrating reservoir properties of the Reeds Spring Formation in the study area.

The suites of geophysical well logs available varied from well to well, but the typed logs available for a well in the study area were gamma ray, resistivity, porosity, and photoelectric effect (PE). Only wells that contained at least the first three logs were used in the correlation process. The gamma ray and resistivity logs were used together to correlate each formation/units; porosity log signatures were identified and used to constrain the correlation.

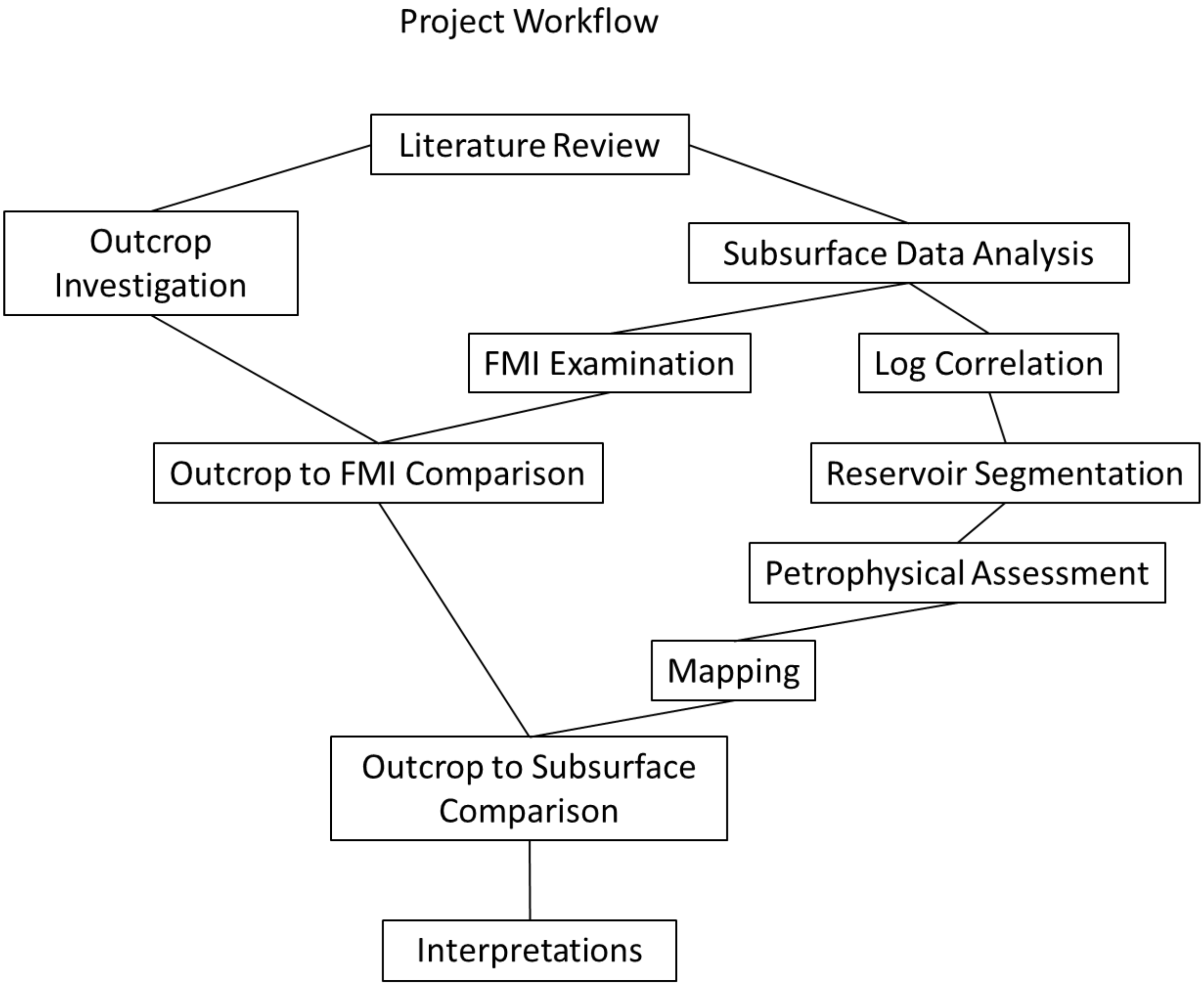

Figure 8 – Work flow diagram illustrating the overall work flow of the project.

Wireline Log Response

Log signatures of the Reeds Spring were not very consistent and difficult to correlate across a large area, even over a few miles. The gamma ray log signature could not be solely utilized to identify the Reeds Spring because it is underlain and overlain by carbonate rocks. Due to this stratigraphic relationship, the Lower Mississippian carbonates appear as one large unit approximately 400 feet in thickness with minor clay/silt development to act as stratigraphic markers. Figure 9 is the type log used for this project and an example of the stratigraphic setup can be seen in this figure. With a low gamma ray baseline through the whole Lower Mississippian section, the resistivity curve was used to identify the Reeds Spring in wireline logs. As chert is a major constituent to the reservoir, identifying the Reeds Spring through the resistivity curve was marked by a large increase in resistivity (+100ohm-m). In general, the baseline of the resistivity curve is deflected right when a section bears a dense amount of chert. Similarly, the PE curve demonstrates a very condensed zig-zag pattern, alternating from 2 to 5 when passing through the alternating beds, e.g. limestone with interbedded chert (Figure 9). Because chert's chemical formula (SiO_2) is the same as quartz, the PE curve demonstrates the same value for quartz and chert. Limestone has a PE value of 5 because its calcite mineralogy. Although the resistivity varies to some degree, the Reeds Spring was identified through its high resistivity and PE signatures.

The Reeds Spring overlays the Pierson Limestone, a member of the St. Joe Formation previously mentioned in the Lithostatigraphy section. A basal shale, ranging from less than one to thirty feet in thickness, marks the Reeds Spring-Pierson contact. The log signatures of the Pierson Limestone denote a true limestone unit with a PE value of 5, low gamma ray, high resistivity, and low neutron-density values that mirror each other. This contact was typically easier to identify and proved to be a very good stratigraphic marker in the study area. In this project, five stratigraphic markers—the Pennsylvanian-Mississippian boundary, and tops of the Reeds Spring, Pierson Limestone, Woodford shale, and Arbuckle Formation— were identified in each well. In addition to its top and base, the Reeds Spring Formation was further subdivided into three informal layers/members (upper, middle, and lower). Outcrop stratigraphy does not formally divide the Reeds Spring into separate members. The type log, Figure 9, presents these divisions. Separating the formation into three correlatable layers offered more control on characterizing the reservoir that reached thicknesses of 200 feet in the study area.

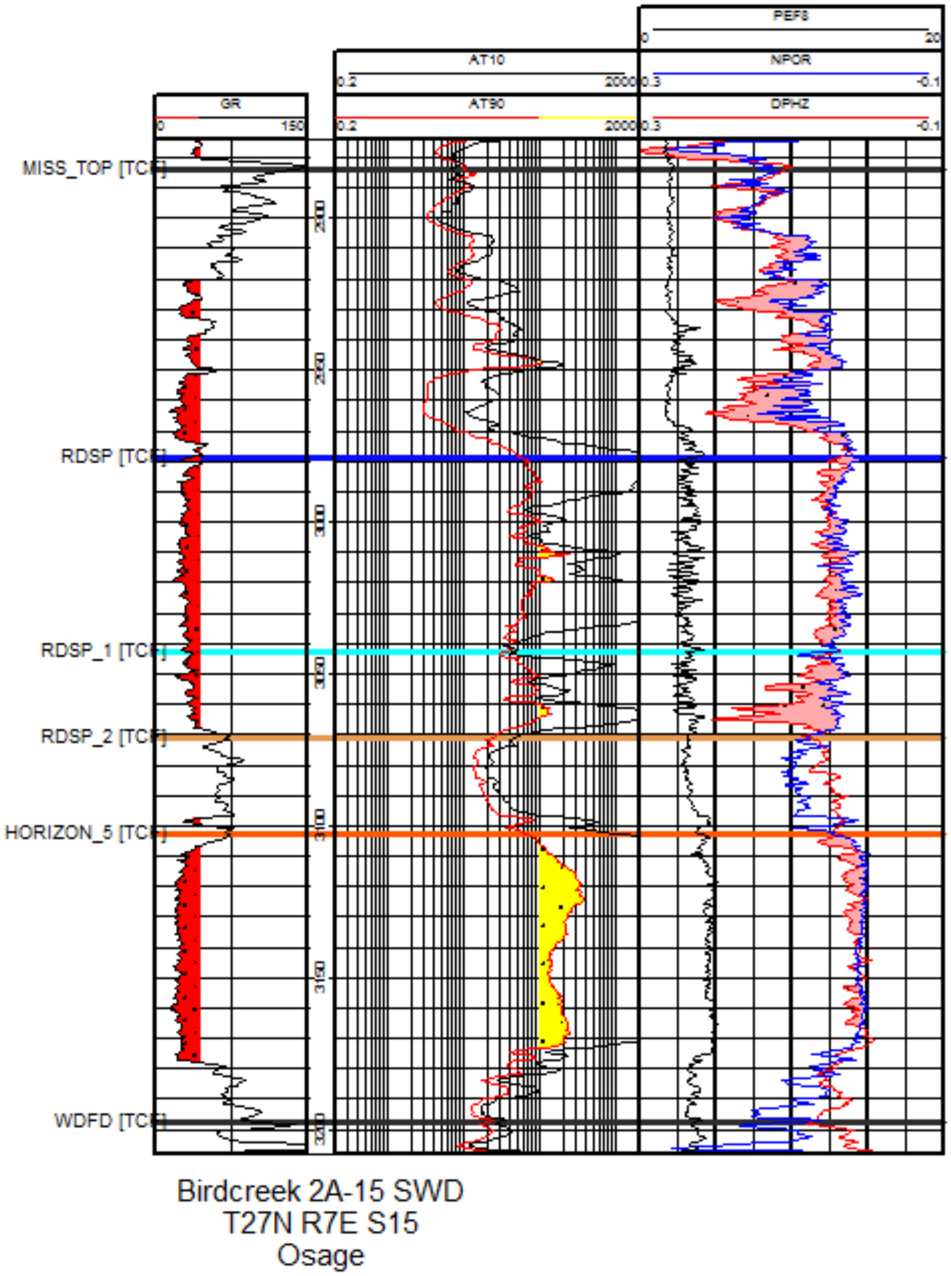

Figure 9 – Type log for the project. Gamma ray is in Track 1, Resistivity in Track 2, PE and Porosity in Track 3. The dark blue horizon (RDSP) is the top of the Reeds Spring, the black (RDSP_1) top of the Reeds Spring Middle member, dull orange horizon (RDSP_2) top of the Lower member, and dark orange (HORIZON_5) top of the Pierson. Note the PE zig-zag character, high resistivity, low gamma ray, and low porosity crossover of the Reeds Spring interval.

FMI Analysis

Coupled with traditional gamma ray, resistivity, porosity, and PE geophysical wireline logs, the quality and resolution the Formation Micro-Image (FMI) log was heavily exploited in this project. The FMI tool uses the resistivity properties of the rock to generate an image of the wellbore based on a spectral color display using a black, orange, white color scale (Figure 10). For example, highly resistive features, such as cherts and limestones are displayed in shades of brown, yellow, and white. Low resistivity, or conductive intervals, such as shale or drilling mud-filled bedding planes or factures, is denoted by black and darker colors (Kreman, 2011; Hurley, 2004). Most importantly, the FMI log resolution is adequate enough to investigate the rock composition, chert content, texture, bedding plane variation, fracture patterns, and overall appearance of the Reeds Spring throughout the subsurface study area without the availability of core data. Seven FMI logs were utilized in this project to identify chert-bearing intervals typical of the Reeds Spring. Geophysical log parameters were then identified and used to correlate across the study area where FMI logs were absent. Their geographic positioning provided a gross coverage of the study area. Recognizable rock properties are discussed in a following chapter – Reservoir Properties.

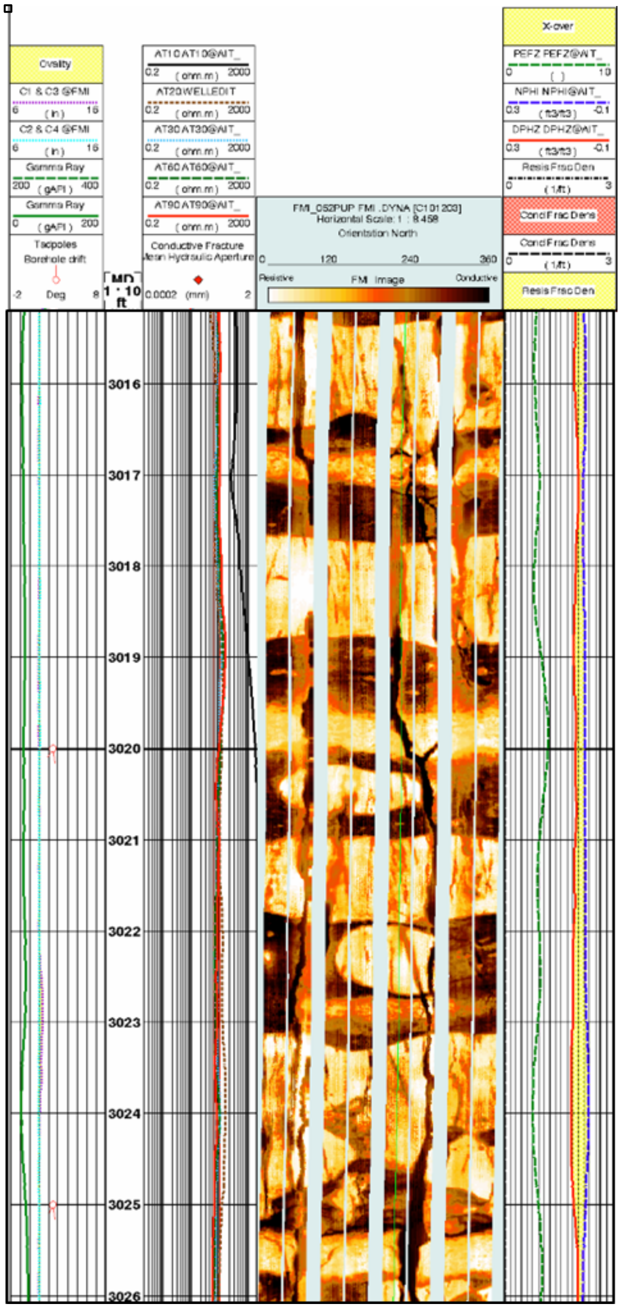

Figure 10 – Example of a FMI log used in the project. The FMI tool uses the resistivity properties of the rock to generate an image of the wellbore based on a spectral color display using a black, orange, white color scale. In this image, the bright whites are cherts and the blacks are limestone fabric. Track 1 is gamma ray, Track 2 resistivity, Track 3 FMI, and Track 4 porosity. In between Track 1 and 2 is the depth scale.

Isopachous and Structure Mapping

Isopachous (isopach) maps were generated using IHS Petra to examine the Reeds Spring true vertical thickness and the variation in thickness of each layer across the study area. Structure maps were created using sub sea-level total vertical depths (SSTVD). Using SSTVD instead of measured depth (MD) allowed each structure map to discount topography at the surface by using sea level as the datum and not elevation. Results and interpretations of these maps are included in the Depositional Setting chapter.

Petrophysical Analysis

The petrophysical properties of the Reeds Spring were investigated throughout the designated project study area in an attempt to further characterize the reservoir from its digital characteristics. True porosity (Φ_t), average resistivity (RESA), clean carbonate volume (V_{cc}), water saturation (S_w), and Net Pay were calculated using the same IHS Petra workstation as the geophysical well log correlations. In addition to evaluating those petrophysical properties of the Reeds Spring reservoir, a subsurface lithology model was created using neutron-density crossplots to compare to outcrop and core lithologies. Furthermore, specific petrophysical properties were mapped over the study area in an attempt to identify reservoir property trends.

True porosity (Φ_t): True porosity is considered to be a more precise porosity calculation than average porosity because it helps to suppress the effects of residual gas in the flushed zone around the wellbore (Chilingarian and Wolf, 1975). The neutron-density crossover effect is present in much of the Reeds Springs reservoir. In turn, true porosity was used to negate that effect on the wireline logs.

$$\Phi_t = \sqrt{\frac{\Phi_n^2 + \Phi_d^2}{2}}$$

where:

Φ_t = true porosity (PHIT)

Φ_n = neutron porosity (NPOR)

Φ_d = density porosity (DPOR)

Average resistivity (RESA): A major constituent to highly productive portions of the Reeds Spring reservoir is chert content. The most productive portions of the reservoir contain an abundant amount of chert. With this in consideration, RESA of the whole Reeds Spring and each separate member (upper, middle, lower) was calculated. Deep resistivity was used in the calculations because it has a deeper zone of investigation into the rocks therefore it discounts the flushed and invaded zone which can often be filled with drilling mud (Asquith and Krygowski, 2004). In theory, due to chert's highly resistive nature, the higher the average resistivity values the more chert is present in the rock.

Clean carbonate volume (V_{cc}): Although the Lower Mississippian section did not contain many shale units to act as stratigraphic markers during correlation, some sections of the interval had more clay/silt content than others, specifically in the Reeds Spring portion of the Lower Mississippian rocks. Higher gamma ray log response is interpreted to have higher clay/silt content. By this fact, clean carbonate volume was calculated in place of shale volume (V_{sh}). Three separate calculations were run using the gamma ray log using an API cut off of 20, 40, and

60. V_{cc} is a reservoir parameter that is partially indicative of reservoir quality in the Reeds Spring.

Water saturation (S_w): Multiple experimental water saturation calculations were done over the Reeds Spring in the study area. The S_w calculation of the uninvaded zone was done using a form of the Archie (1942) equation:

$$S_w = (\frac{R_w}{R_t * \Phi^m})^{\frac{1}{n}}$$

where:

S_w = water saturation of the uninvaded zone

R_w = resistivity of the formation water at formation temperature

R_t = true formation resistivity (taken from deep resistivity log)

Φ = porosity

m = cementation factor

n = saturation exponent

Due to an ongoing water quality study, the R_w value used in the equation was obtained through actual water samples recently taken from the Reeds Spring Formation in the project study area. Water conductivity values were initially acquired and then converted to resistivity values. The value used for R_w was 0.04 ohm-m, which remained constant through the calculations. Water sample conductivity values were made possible through Trenton Rogers of the University of Arkansas, Department of Geosciences and Spyglass Energy Group from Tulsa, Oklahoma. R_t values were taken directly from the deep resistivity log for each well. Porosity values came from the true porosity calculations previously mentioned. The n value was set as a constant of 2, which is the accepted value used for carbonate reservoirs (Asquith, 1980).

Multiple calculations were conducted due to the dynamic nature of the Reeds Spring reservoir. In each derivation of S_w, all variables remained constant except for the cementation factor, m. Values ranging from 1 to greater than 2 are used in the cementation factor to describe the type of porosity present in the reservoir (Asquith, 1985). By the petrographic work of Liner (1979) and Shelby (1986), the Reeds Spring consists of primarily intercrystalline porosity. Also, vugular and fracture porosity are present in the subsurface and will be elaborated upon further in the Reservoir Properties chapter. In turn, m values of 1.5, 1.8, 2, and 2.2 were used in the S_w equation.

Net Pay calculations: Net Pay calculations were done to identify how many feet of potentially good reservoir were present in each interval of the Reeds Spring. The stipulations used to calculate net pay were gamma ray, resistivity, and porosity. Cutoffs chosen were 40 API units of gamma ray, equal to or greater than 100 ohm-m resistivity, and three cutoffs of 2%, 4%, and 6% porosity. Results can be found in the Reservoir Properties chapter. After all petrophysical parameters were assessed, maps were generated to examine the variation in petrophysical properties over the entire study area.

Neutron-Density Crossplot: the neutron-density crossplot technique was used to determine subsurface lithology. Conventional methods of using the crossplot table recognize sandstone as a potential lithology plot. A literature consensus concludes that there are no sandstones present in the Reeds Spring interval in the subsurface of north central and northeastern Oklahoma, or in outcrop. The neutron-density crossplot uses mineral constituents to plot the data points and since chert is a constituent of the Reeds Spring, some data points plotted in the sandstone section of the crossplot table (Figure 11). Similar to the effect on the PE curve, this occurs due to the similar mineral composition of quartz and chert. Data points that fell in this section were treated as a cherty limestone lithology. Additionally, data points that fell in the limestone section were treated as limestone and in the dolomite section, dolomitic limestone. From these crossplots, a lithofacies log curve was generated for correlation and evaluation purposes.

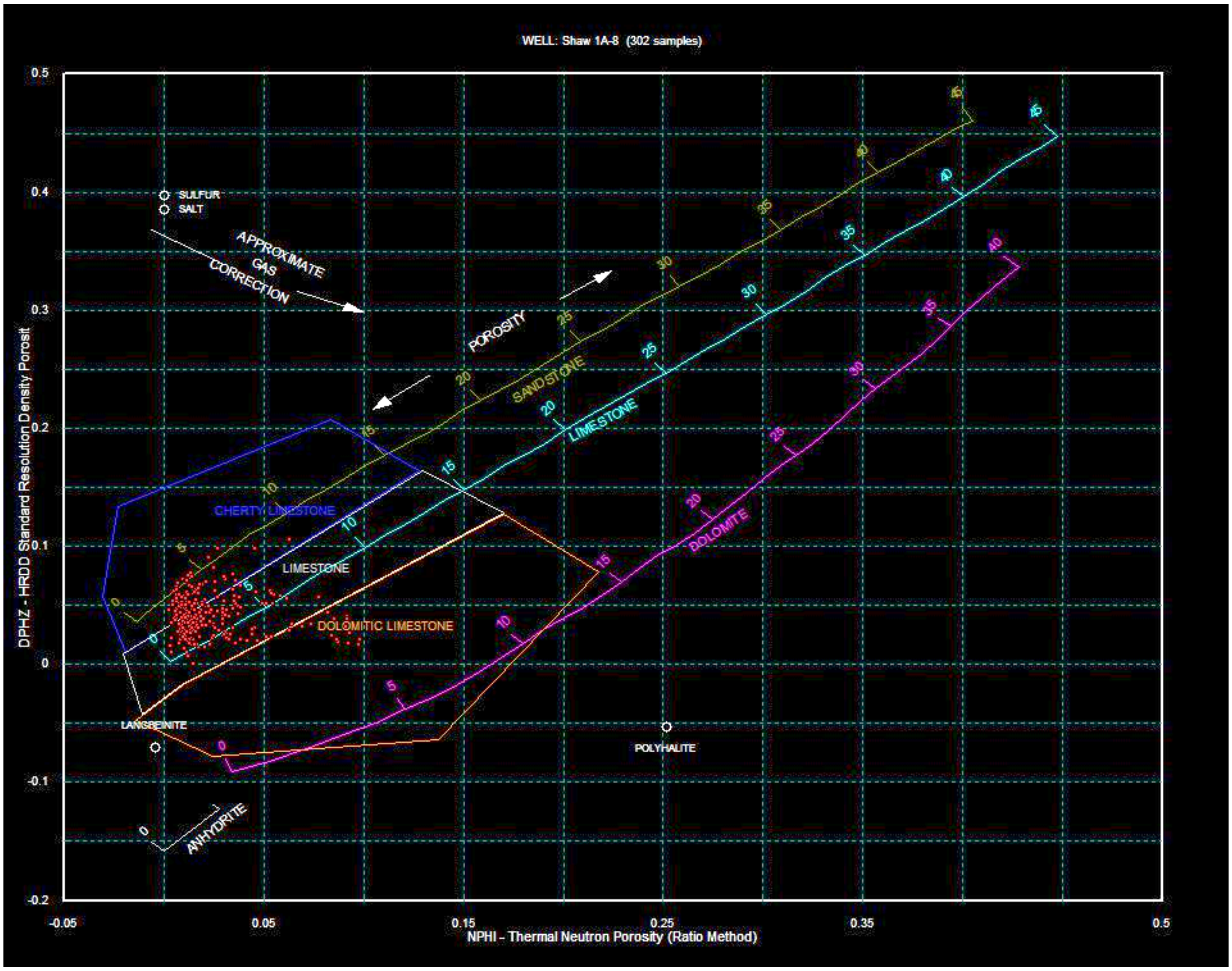

Figure 11 – Neutron-Density crossplot created using Petra Geological software. The density porosity curve (DPHZ) is used for the y-axis and the neutron porosity curve (NPHI) is used for the x-axis. The polygons drawn in the lower left of the screenshot categorize data points into lithology groups: cherty limestone (blue), limestone (grey), and dolomitic limestone (orange).

Petrographic Analysis

A limited petrographic study was conducted for the project through the use of thin sections. Twenty-three Lower Mississippian thin section digital images were created from sidewall core plugs taken from the Shaw 5A-8 SWD well, eight of which were from the Reeds Spring (Appendix D). Although only one set of thin sections was available, the set of thin sections essentially covered the entire reservoir interval. Because petrographic studies have been done on the outcrops of the Reeds Spring, this presented an opportunity to compare the outcrop equivalent rocks to the subsurface reservoir. Industry activity recognizes the outcrop rocks to be an analog to the subsurface, but a petrographic evaluation shows that there are fundamental differences in depositional environment and sedimentation from the outcrop locations to the subsurface. The thin sections were also used to compare to FMI images of the Shaw 5A-8 to assist in delineating the depositional setting of the study area.

DEPOSITIONAL SETTING

Carbonate Shelf Deposition Overview

During the Early Mississippian, a broad carbonate platform (e.g. the Burlington Shelf) developed across much of the southern midcontinent of North America (Lane, 1978; Lane and DeKeyser, 1980; Franseen, 2009). According to paleogeographic reconstructions, the study area was located at approximately 5-15 degrees south latitude at moderate water depths (Figure 12; Gutschick and Sandberg, 1983; Mazzullo et al., 2011). Mississippian carbonates were deposited along the shelf-margin and into basinal environments (Figure 13 (Lane and DeKeyser, 1980; Mazzullo et al., 2009; Kreman, 2011).

Previous Studies

Although midcontinental Lower Mississippian carbonates have not been extensively researched in the last two decades, results from previous investigations do offer noteworthy insights to the overall Mississippian system. Lane and De Keyser (1980) and Gutschick and Sandberg (1983) set the foundation for paleogeography and depositional architecture of central-south-central North American Mississippian carbonates. Lane (1978) conducted a field-based study identifying stratigraphic relationships among the Mississippian carbonates in the tri-state area (Oklahoma, Missouri, Arkansas). His investigations led to the recognition of an extensive carbonate shelf that developed during the early and middle Osagean time, e.g. The Burlington Shelf (Lane, 1978). Based on conodont biostratigraphy, he concluded that there are four carbonate magnafacies present in outcrop: inner shelf, main shelf, shelf margin, and offshelf starved. Lane and De Keyser (1980) extended their study through the southern midcontinent and created the midcontinent magnafacies and depositional setting map (Figure 13).

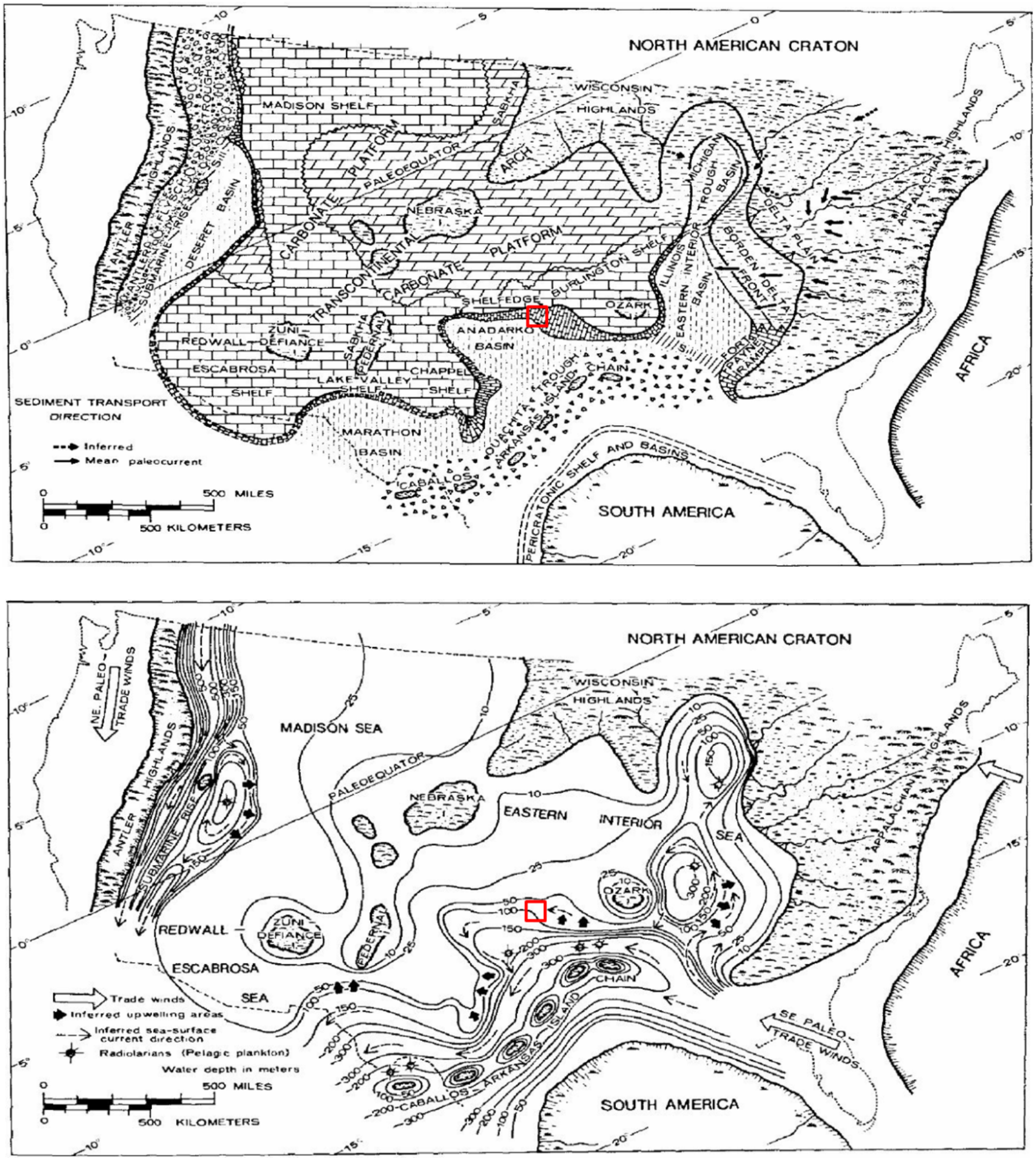

Figure 12 – Paleogeographic, lithofacies distribution, and bathymetric maps of the continental United States during Early Mississippian time. The study area is outlined by a red box in both maps. Taken from Gutschick and Sandberg (1983).

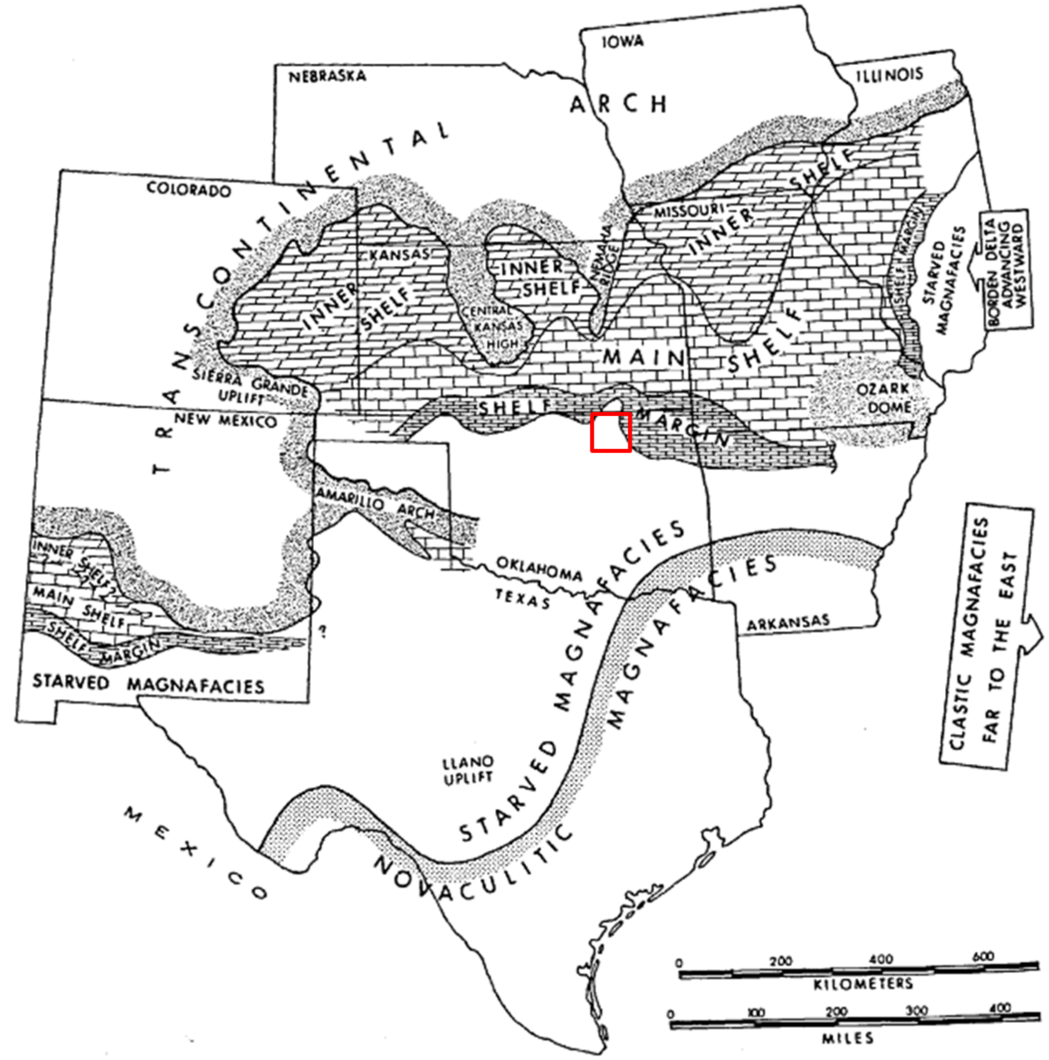

Figure 13 – Osagean paleogeography and magnafacies distribution of the southern midcontinent. The study area is outline by a red box. Taken from Lane and DeKeyser (1980).

Gutschick and Sandberg (1983) produced a body of work that focused more on continental paleogeography and gross lithofacies distribution during the Mississippian period (Figure 12). A map illustrating the marine conditions of the United States during Mississippian time was proposed (Figure 12). Similar to that of Lane and De Keyser (1980), Gutschick and Sandberg (1983) identified three suites of rocks in their lithofacies model: basinal or deep-water facies, foreslope or shelf-to-basin facies, and platform or shallow-water facies (Figure 14). On a regional basis, these works provide the framework and broad overview of the Mississippian depositional system.

Shelby (1986) investigated the sequence stratigraphy of the Lower Mississippian rocks of northwest Arkansas (St. Joe and Boone Formations). His study deduced that the Lower Mississippian section was an unconformity bounded transgressive-regressive deposit based on the stratigraphic framework. Shelby (1986) contended that the grainstones and packstones of the St. Joe, which underlie the Boone (Figure 5), represented the initiation of transgression. As sea level continued to rise, the lower Boone mainly developed in deeper waters, represented through the mudstone and wackestone facies. Later on it was overlain by the regressive sequence of the Upper Boone (Figure 5). In addition, Shelby (1986) provided a schematic diagram inferring the depositional style of the ramp setting in Lower Mississippian carbonates (Figure 15). From the Burlington Shelf, down to deeper water settings, Figure 15 suggests that crinozoan, bryozoan, and algae located on a higher position of the ramp are the source of down-ramp transported carbonate grains.

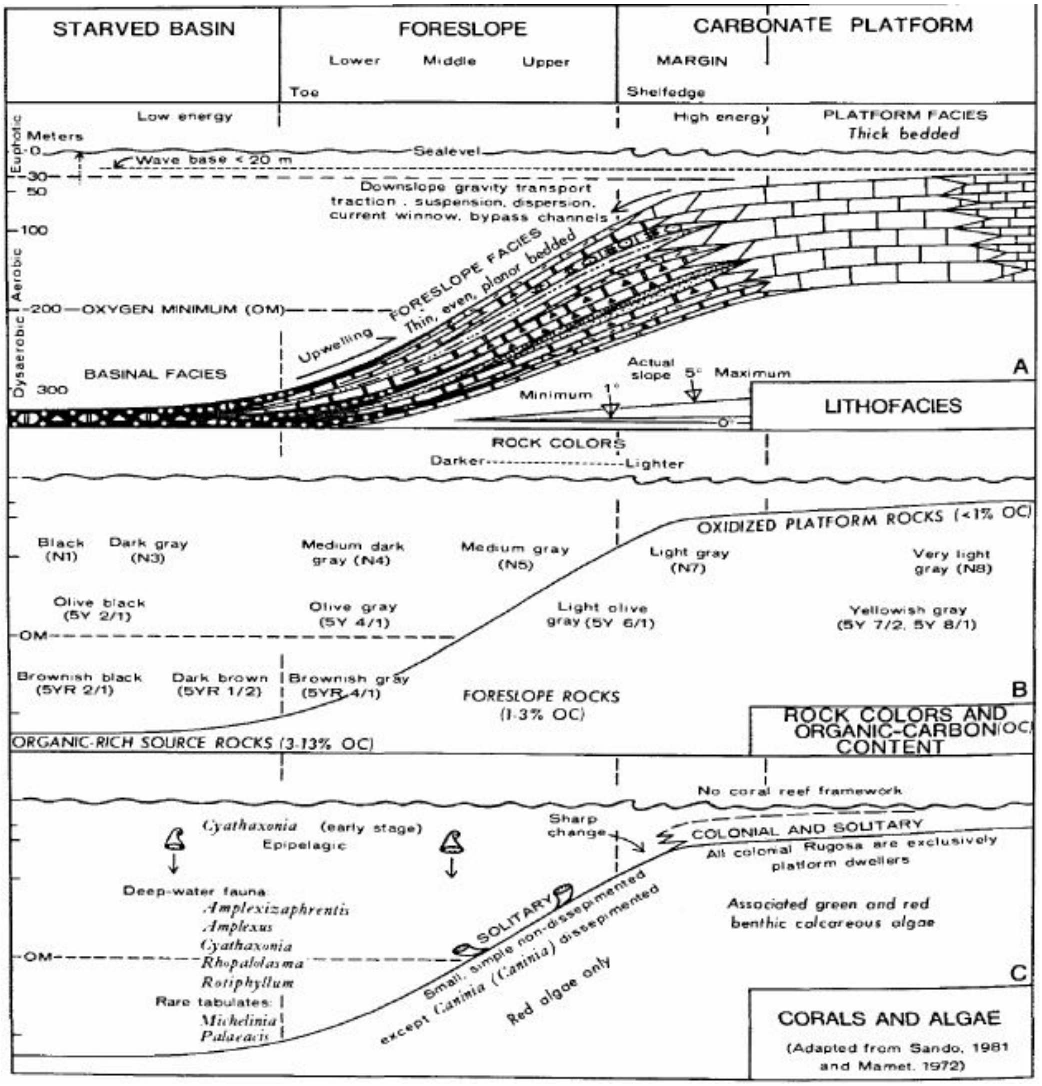

Figure 14 – Schematic cross-sections illustrating three depositional facies belts represented during the Early Mississippian carbonate deposition. Taken from Gutschick and Sandberg (1983).

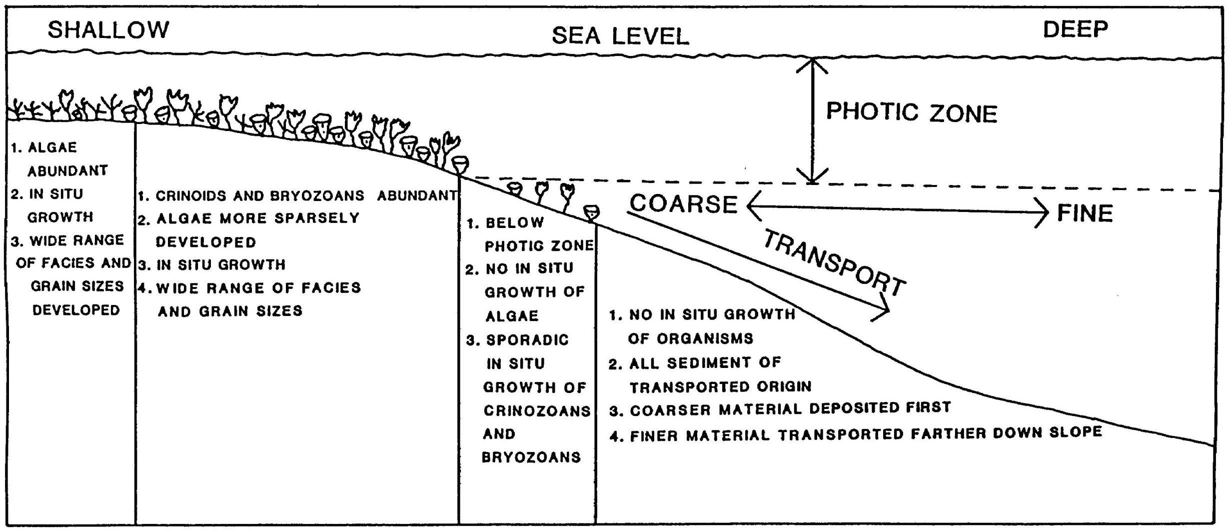

Figure 15 – Schematic cross-section illustrating the depositional style of the Reeds Spring in the ramp setting. Taken from Shelby (1986).

Furthermore, Liner (1979) determined that the Boone Formation was deposited on the southern margin of the Burlington Shelf with progradation of the shelf during late Osagean time resulting in the vertical succession of the lithofacies found in his study: lime mudstone, crinozoan-bryozoan lime wackestone, crinozoan-bryozoan lime packstone, crinozoan lime grainstone and oolitic facies.

More recently, an onset of academic and professional studies have been conducted mostly due to the resurrection of an active oil and gas play by Mazzullo and others (2011) and Kreman (2011). Kreman (2011) performed a subsurface study on the Lower Mississippian carbonates in northeastern Oklahoma. Kreman subdivided the thick carbonate section into five intervals based on geophysical well log parameters. The study examined the average porosity associated with each interval and concluded that an increase or decrease in porosity values was dependent on the type of silica (chert) present in the interval. Additionally, Mazzullo and others (2011) recognized the complexity of the Reeds Spring in terms of lithostratigraphic architecture, multiple component progradational wedges, and structural history based on an outcrop study in the tri state area. They believed that the outcrop relationships had subsurface counterparts throughout southern Kansas and northern Oklahoma.

Reeds Spring Depositional Environment

Mazzullo and others (2011) state that the Reeds Spring was deposited on a moderate-depth ramp (i.e. slope facies) during the maximum flooding interval, or high stand, of Osagean seas based on their outcrop observations. This may be correct for the timing and deposits found in outcrop, but subsurface correlations and thin sections present a contrasting environment. Instead, evidence from this study supports the depictions of the Mississippian depositional environment of the Reeds Spring Formation proposed by Lane and DeKeyser (1980).

The depositional style of the Reeds Spring Formation in the study area is comparable to the models inferred by previous studies based on outcrop evaluations (Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983; Shelby, 1986). The Reeds Spring deposits reflect transportation of crinozoan detritus, spicules, and carbonate mud off the Burlington shelf passing downslope into deeper waters of the deep shelf margin (Figure 15; Gutschick and Sandberg, 1983; Shelby, 1986; Manger and Shelby, 2000; Kreman, 2011).

Based on the Wilson (1975) study of the three major types of shelf margin profiles, this type of carbonate deposition belongs to downslope mud accumulation (type 1). Slope angles associated with this type deposition may be as gentle as a few degrees or as steep as 25 degrees and variations in angle are generally tectonically controlled. The carbonate grains are transported from high energy environments, up on the platform, down to low energy environments of deeper water. Overall carbonate grain-size distribution (bioclastic calcisiltites and wackestones) of the reservoir (Figures 16, 17) support this low energy depositional model. Furthermore, the stratigraphic thickness of the Reeds Spring through the area demonstrates a configuration that represents the infilling of the shelf margin shown by Figure 13 (Figure 18). Isopach maps of the ascending Reeds Spring members reveal the sedimentation stages in the study area (Appendix A). This character is constant with the midcontinent magnafacies illustration by Lane and DeKeyser (1980; Figure 13). Increasing accommodation space would have centralized the sedimentation in this area and the triangular thickness appearance is likely caused by the presence of shelf margins to the east and west, respectively.

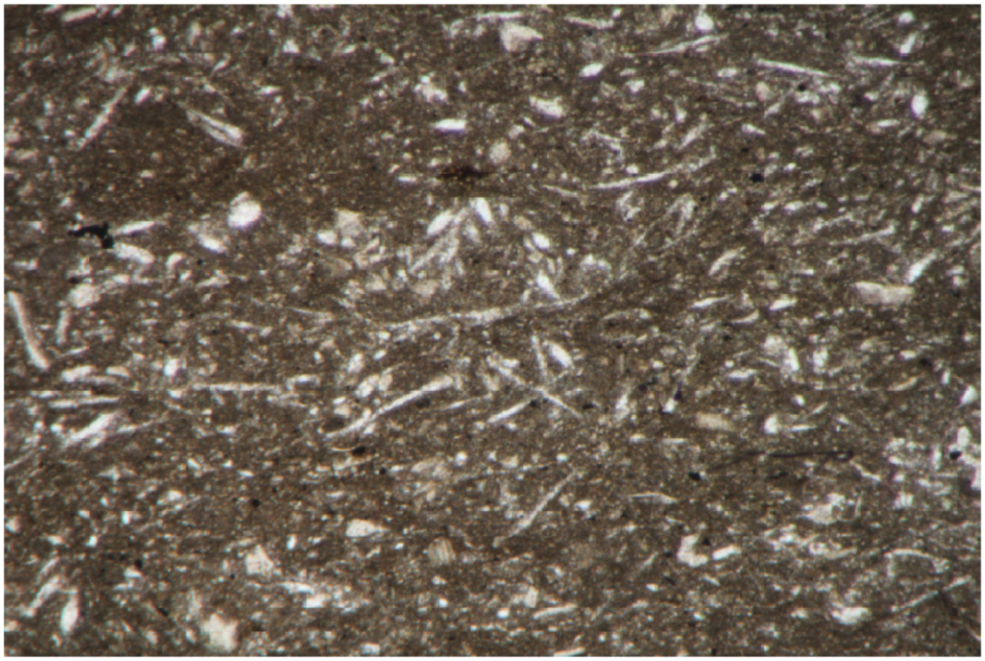

Figure 16 – Thin section demonstrating the overall bioclastic constituents of the Reeds Spring from down-ramp transport. Description: spiculitic, shaly, fine-grained crinoid wackestone, non-porous. 20x, plane light.

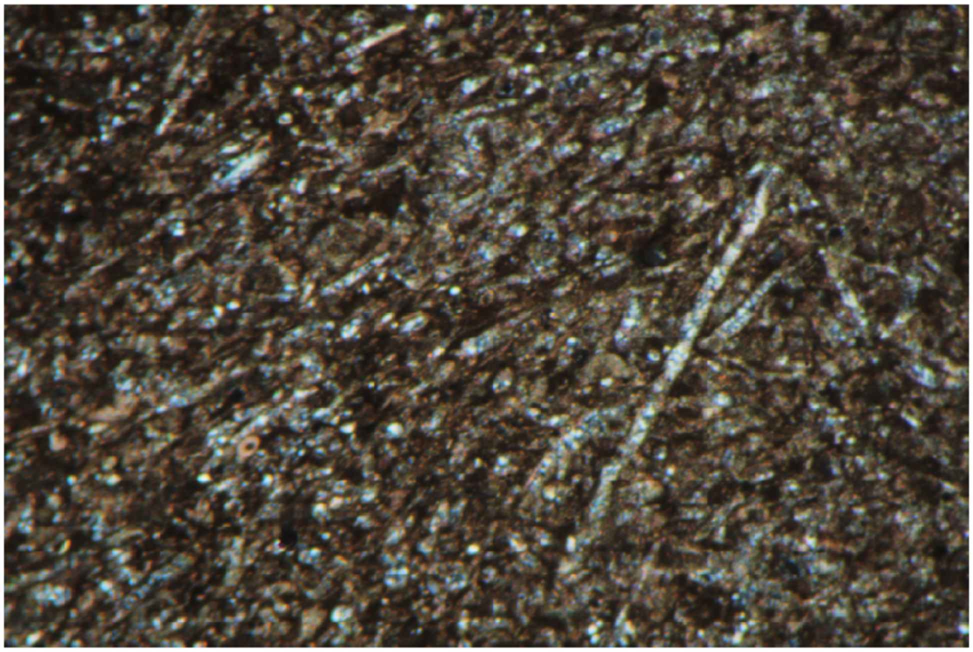

Figure 17 – Thin section demonstrating the abundant amount of spicules found in intervals of the Reeds Spring. Description: very spiculitic, shaly, fine-grained crinoid wackestone, non-porous, some angular quartzose silt. 20x, crossed polars.

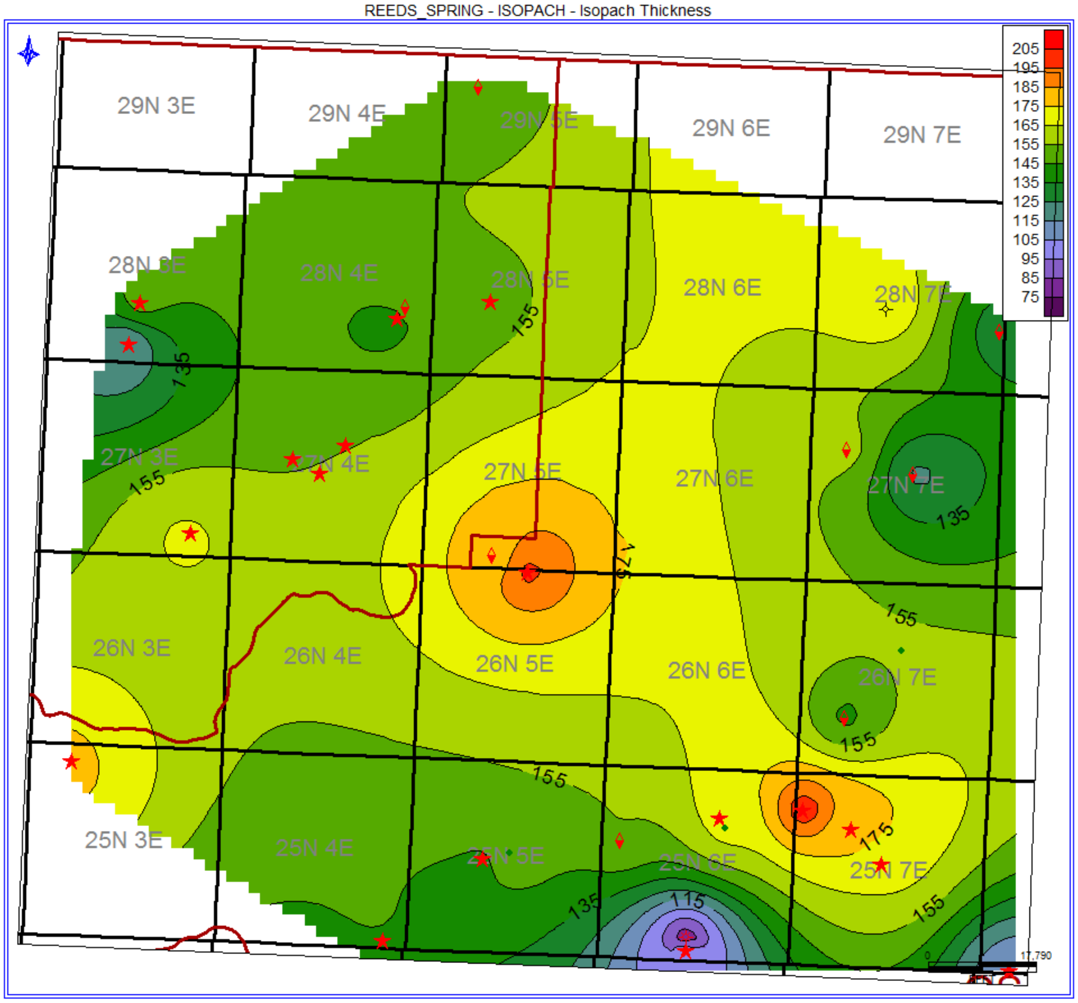

Figure 18 – Isopach map of the entire Reeds Spring interval. The figure demonstrates a lobate geometry as a product of the depositional style of the reservoir. The color bar is found in the top right of the map, north arrow in the top left, and map scale in the lower right hand corner. Red color indicates thick portions and purple indicates thinner portions of the Reeds Spring. Data points can be seen as red starts, red diamonds, and green circles. CI = 10ft.

Moreover, subsurface correlations show that the Reeds Spring stratigraphic architecture exhibits progradational sedimentation in the study area. Basinward progradation to the south and southwest has been readily recognized (Liner, 1979; Shelby, 1986; Boardman et al., 2010; Mazzullo et al., 2011). These progradational wedges thin basinward and pass up dip to the coeval facies in more energetic shallow water environments of the upper shelf and platform (Mazzullo et al., 2001). The subsurface Reeds Spring exhibits progradation to the south and southwest, similar to the outcrop, but contrary to its outcrop counterpart, it is seen to prograde to the southeast (Figure 19).

Liner (1979) recognized a progradation in the shelf structure during a period of stable sea level by the succession of coarsening upward facies in the Boone Formation. His petrographic investigation focused on the whole Boone Formation (Burlington-Keokuk and Reeds Spring), but a similar trend is noticeable in the Reeds Spring in the subsurface. Detailed petrographic studies done by Spyglass Energy Group show that there is a coarsening upward trend in the Reed Spring but on a smaller grain-size scale. The lower member of the Reeds Spring is characterized by fine-grained crinoid-spicule wackestone. The middle member belongs to fine-grained crinoid-spicule wackestone with some packstone. The upper member is described as fine-grained crinoid-spicule packstone with some wackestone. It should note that crinoid packstone to grainstone with rare spicules is also found in the upper portion of the upper member.

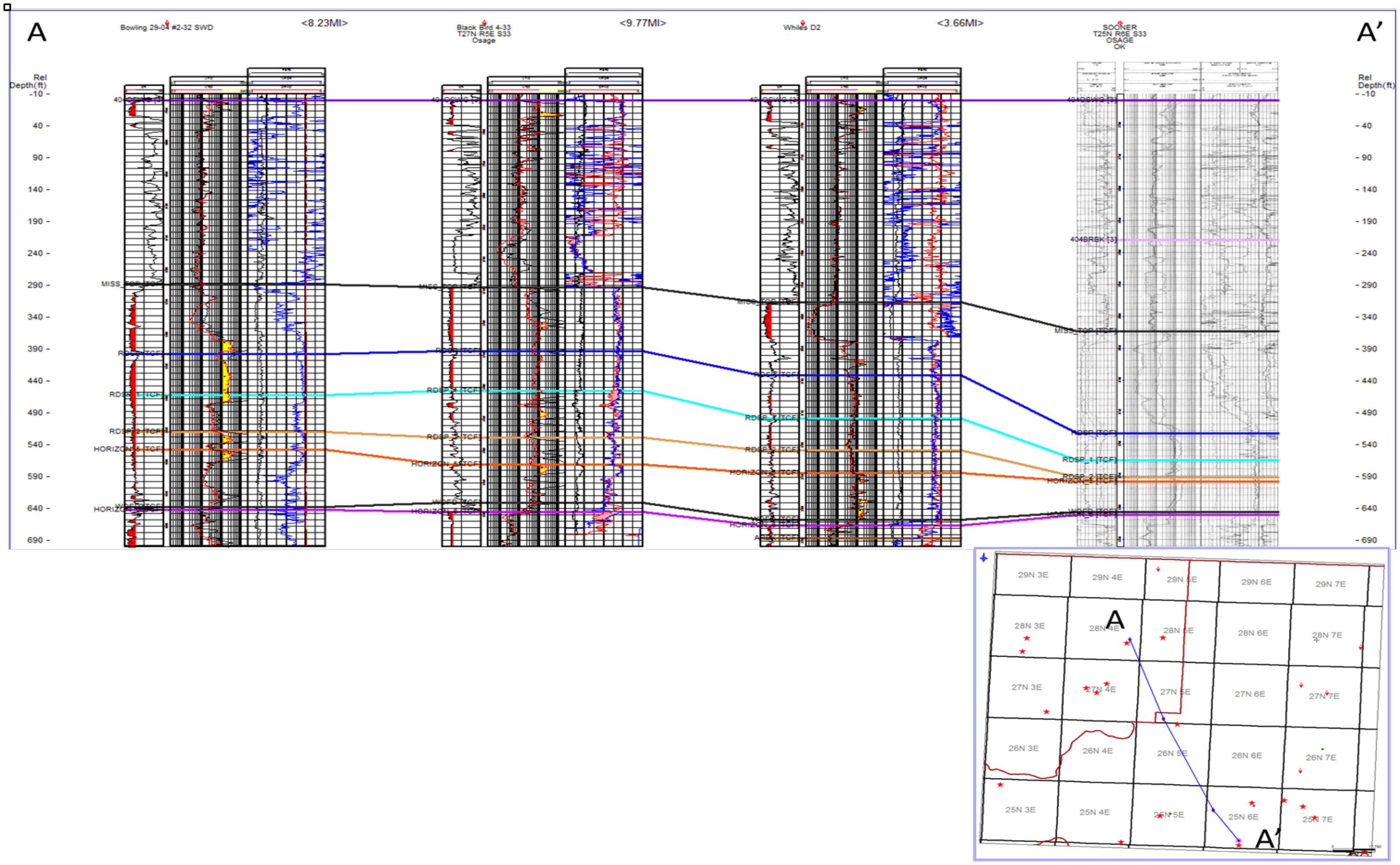

Figure 19 – Northwest-Southeast stratigraphic cross-section hung on the Oswego limestone. An inset map is located in the lower right hand corner. This cross-section demonstrates the progradation and thinning of the Reeds Spring in a southeast direction which is not previously recognized. The dark blue horizon (RDSP) is the top of the Reeds Spring, the baby blue (RDSP_1) top of the Reeds Spring Middle member, dull orange horizon (RDSP_2) top of the Lower member, and dark orange (HORIZON_5) top of the Pierson.

Depositional Model

Based on previous regional scale studies and results from this project, a synthesized depositional model of the Reeds Spring in the study area is as follows: First, the study area reflects a deep water setting, but the sediment type and rate of deposition is not typical of a basinal or deep water environment; secondly, the sediments consist of predominately transported bioclastic carbonate grains (crinozoan and spicules), but also an abnormal amount of terrigenous material which is more typical of the basinal setting; thirdly, characteristics of both moderate and deep water settings of the Mississippian system prevail through rocks in the study area. Moreover, thin sections reveal an anomalous amount of silt and rarely quartz sand, up to 50%, in the carbonate dominated rock fabrics. The apparent grain-size presents a similar disparity since a deep-water setting is mostly conducive to very fine-grained material such as clay or mudstone rather than wackestones and packstones, which occur. The explanation of co-existing depositional settings is because of the study area's unique location, e.g. adjacent to two shelf margins and the depositional style of the carbonate complex. Finally, petrophysical evidence of a significant carbonate to silt ratio. Subsurface geophysical data suggests that terrigenous material influx was at its peak during the early stages of the Reeds Spring deposition. The volume clean carbonate maps (40 API cutoff) show that the least amount of clean carbonate by volume is mainly found at the base of the Reeds Spring (lower member) while the most is present in the upper portion (upper member) (Appendix B).

To sum up, during the Mississippian, carbonate material was produced, transported, and then redeposited in the study area from the northwest, north, and northeast (Figure 20). The absence of shelf margins in the study creates an asymmetrical sub-basin by the broad extensions of the encompassing, adjacent shelf margins, which created accommodation space for the transported carbonate sediment. This promotes progradation to the south, southwest, and southeast, which is different than what is seen in the outcrops areas. The absence of shelf margin in the study area refines the sedimentation and depositional setting.

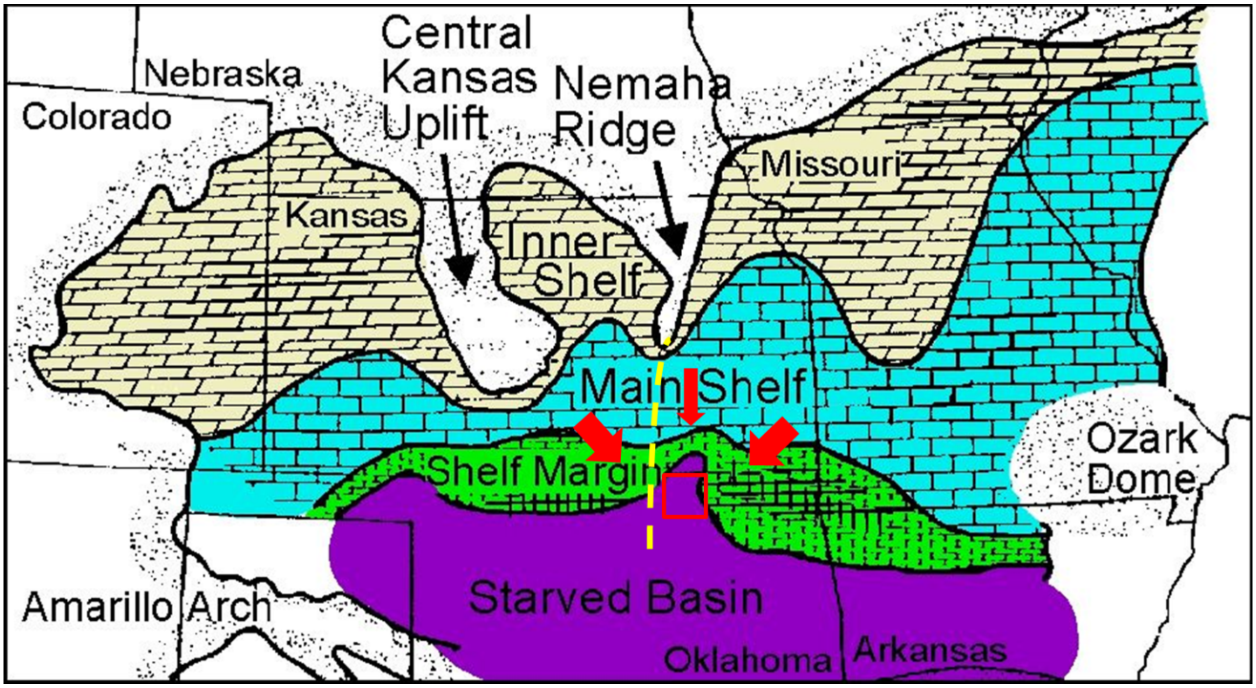

Figure 20 – Paleogeographic map of the Midcontinent during the Early Mississippian. Red arrows indicate carbonate sediment transport direction. The study area is outlined by a red box. The yellow dashed line represents the present day position of the Nemaha Ridge. Modified from Kansas Geological Survey; Lane and DeKeyser (1980)

RESERVOIR PROPERTIES

FMI Analysis

Chert Occurrence & Arrangement

The chert content of the Reeds Spring at exposures has been well documented by works as early as Giles (1935) and more recently Mazzullo and others (2011). Similar to outcrop, the Reeds Spring contains a copious amount of chert in the subsurface study area. The chert content observed in the Reeds Spring is dark blue to black penecontemporaneous chert, having a nodular and anastomosing character (Mazzullo and others, 2011). By this study, subsurface estimated percentage of chert volume is 50-80% in the study area. These values rival those of the outcrop estimate of 40-65% (Liner, 1979).

The width and orientation of the anastomosing chert described in outcrop is comparable to that in the subsurface. FMI logs reveal that the horizontal bands of chert range from a few inches to almost a foot in thickness, which resembles the descriptions found by Giles (1935) and Van Den Huevel (1979). Nodules from one to three inches in width are present also. The diameter of a borehole image is not an adequate width to be able to describe the lateral extent of the chert bands, although the lengths of the chert bands are most likely similar to that of outcrop descriptions due to other parameters of chert occurrence being similar. Consistency in chert density is quite variable through the section. Giles (1935) adequately addressed the fact that although chert percentage can range up to 65%, vertical variation in the limestone-chert ratio is inconsistent (Giles, 1935).

Moreover, chert is not developed in sections of the Reeds Spring that have a higher gamma ray baseline and a separation in the neutron and density porosity curves (Figure 21). This log response can be interpreted to be a shaly limestone lithology. The shale, or clay content, of the section causes the lowering in gamma ray baseline and separation in neutron and density curves. The increasing neutron porosity value is caused by the effect of bound water on the clay particles, which increases the amount of hydrogen atoms; this record is called the "shale effect" (Asquith and Krygowski, 2004). In turn, a control on chert development in the Reeds Spring reservoir is the presence of a clean carbonate matrix. Based on a Reeds Spring core from northeastern Oklahoma, Mazzullo and others (2011) acknowledged that chert was absent in shaly sections of the carbonate interval and would probably not be a good reservoir (Mazzullo and others, 2011). When present, the clay-rich sections occur in one of two stratigraphic positions, either at the base of the Reeds Spring or in the middle. When the reservoir is bisected by the clay segment, the lower half may be a better drilling target as the clay-rich section may serve as an impermeable, or less permeable, trap becoming a potentially favorable stratigraphic setting for petroleum accumulation.

Subsequently, zones of low gamma ray baseline and low porosity values (2-6%) that exhibit the crossover effect coincide with an abundant amount chert (Figure 22). Further evidence of this is seen in the neutron-density porosity plots. In intervals with low value crossover, they display an interbedded limestone and cherty limestone stratigraphic framework (Figure 22). Using FMI logs, constraints have been established to reasonably predict chert content in wells lacking borehole image logs. Zones that lack the crossover effect in the neutron and density curves did not contain, or contained inadequate amounts of, the penecontemperaneous chert typical of the Reeds Spring

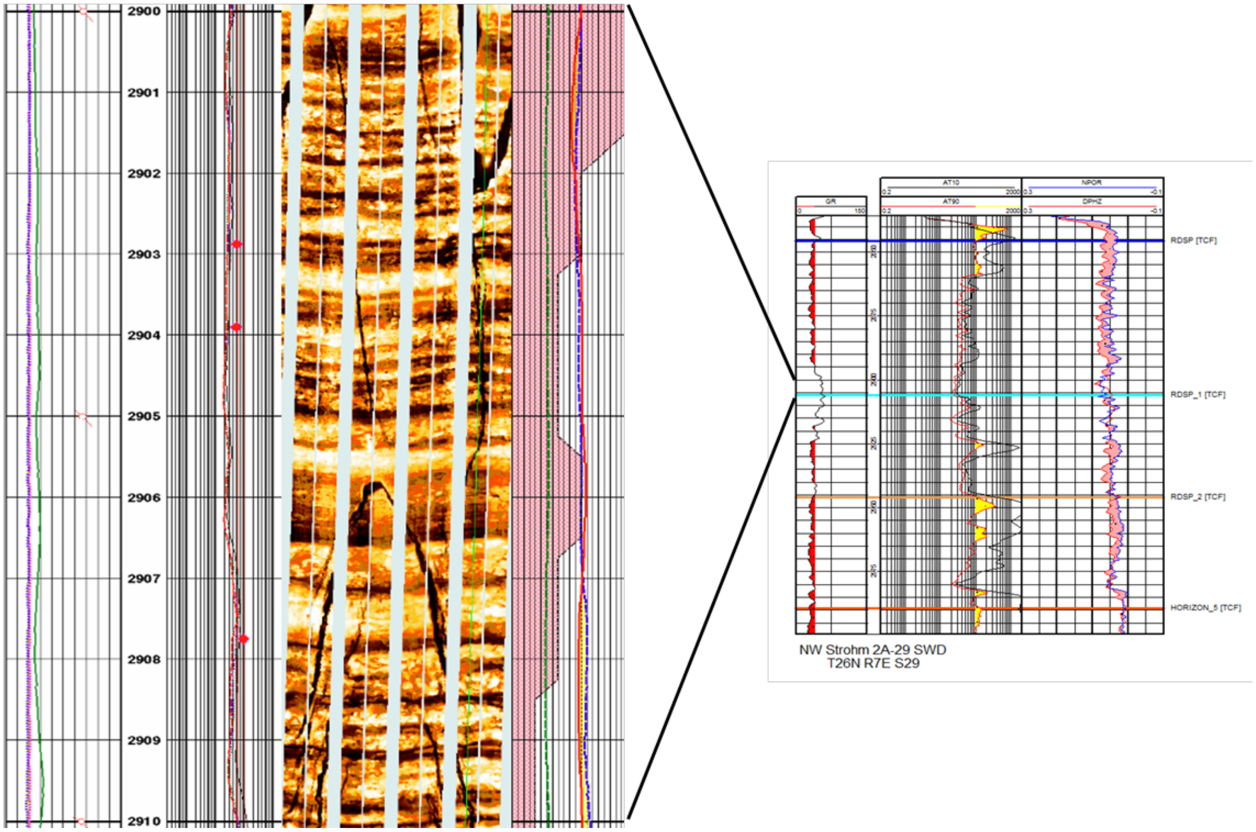

Figure 21 – FMI image on the left demonstrates that no chert is developed in a silty interval. Laminated silt layers are represented in the FMI image instead. Image on the right is a reference log to show the geophysical log signatures at that same interval. Note higher gamma ray baseline, lower resistivity, and no crossover in porosity curves. The dark blue horizon (RDSP) is the top of the Reeds Spring, the baby blue (RDSP_1) top of the Reeds Spring Middle member, dull orange horizon (RDSP_2) top of the Lower member, and dark orange (HORIZON_5) top of the Pierson.

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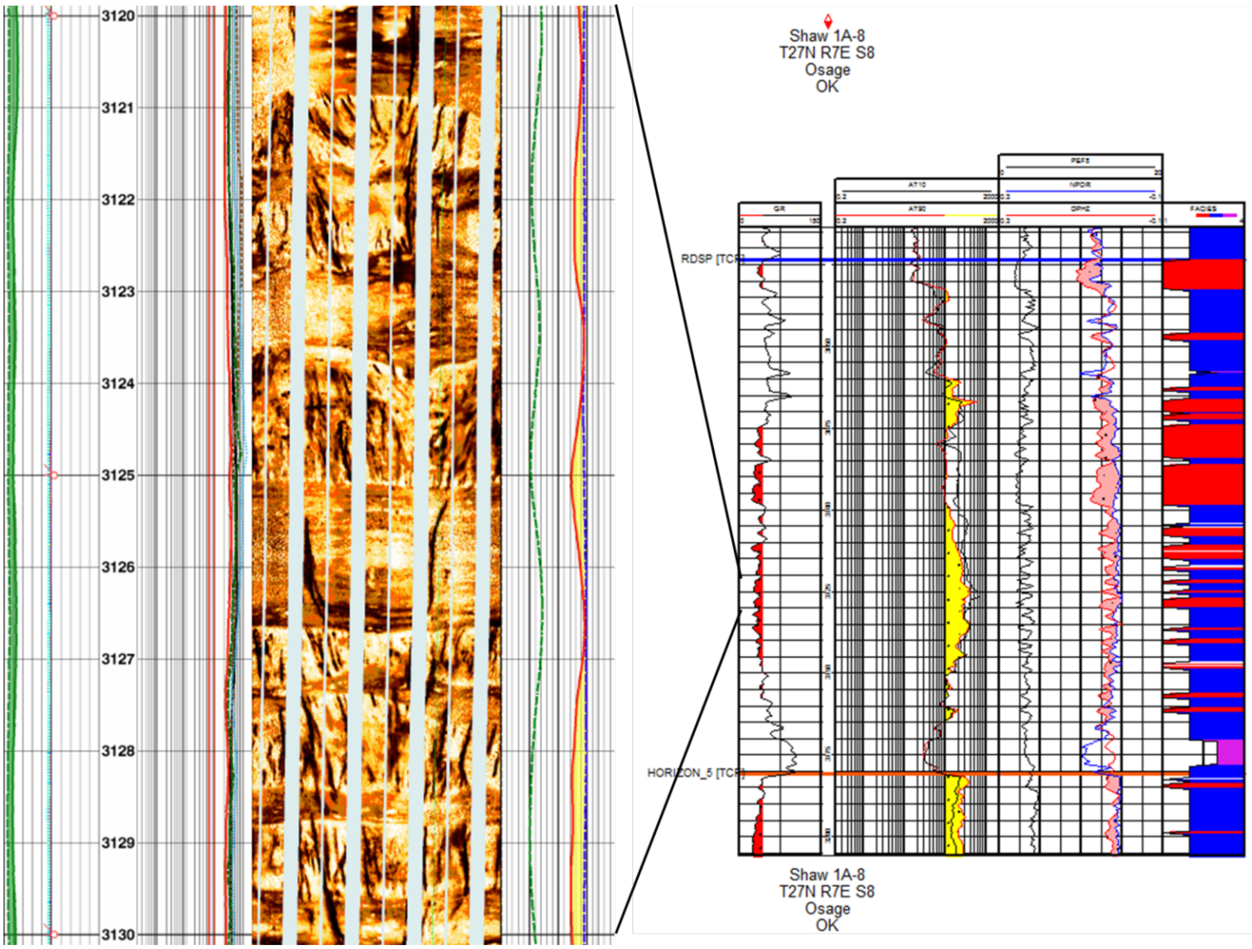

Figure 22 – FMI image on the left demonstrates the abundant chert content of the Reeds Spring. The chert is seen as the white nodules in the image. The image on the left is a geophysical log to provide reference. Note the low gamma ray value, high resistivity, zig-zag PE pattern, and low value porosity crossover which is highlighted by the pink color in track 3. Track 4 is a lithofacies curve generated from neutron-density crossplots. The alteration of blue and red signifies interbedded limestone and cherty limestone. The dark blue horizon (RDSP) is the top of the Reeds Spring and the orange horizon (HORIZON_5) is the top of the Pierson.

Fractures

Analogous to outcrop appearance, the chert nodules and bedding in the subsurface contain conductive and resistive natural fractures. Drilling induced, or tensile, fractures are also identified, but not evaluated in this study. Healed and semi-healed resistive fractures are found in the chert of the Reeds Spring reservoir. The healed resistive fractures found in the FMI logs were delineated by a glowing halo appearance (Figure 23). The mineralogical fill of the subsurface resistive fractures are not distinguishable through FMI log, but thin sections from the Shaw 5A-8 SWD well reveal that calcite is present in healed fractures in the chert of the subsurface (Figure 24). Samples from outcrop exposures show fractures that are most often filled with calcite and occasionally silica (Figure 25). Davis (2007) conducted a subsurface evaluation of the Reeds Spring in northern Arkansas in Batson and Ozone fields of the Arkoma basin where the reservoir produces dry methane gas. His petrographic analysis stated that fractures found in the Reeds Spring chert were in filled with authigenic quartz and sparry calcite (Davis, 2007). Similar to the conclusions of Davis (2007), natural fracture development is most likely a geomechanical response to major regional syn- and post-depositional tectonics, such as the Ouachita orogeny and further maturation of the Anadarko basin. Additionally, advancement in other tectonic structures close to the study area, such as the Ozark Uplift, Transcontinental Arch, and Nemaha Uplift likely complimented the wrenching of the rocks. Evidence of multiple fracturing episodes is present through the existence of two types of mineralogical infillings, but sparse thin section data in the study prohibits further investigation into the prevalence of silica-healed fractures (Davis, 2007).

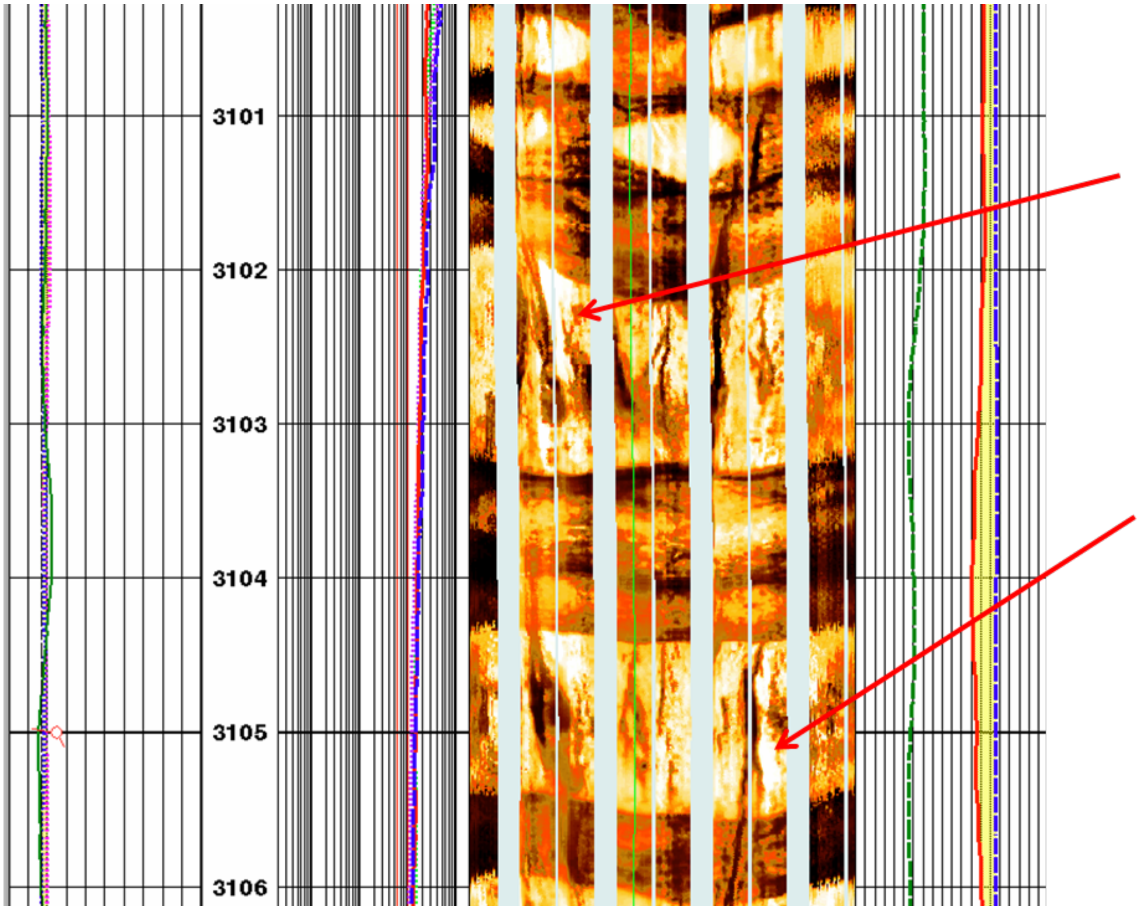

Figure 23 – FMI image exhibiting the occurrence of resistive fractures in the chert of the subsurface Reeds Spring. The red arrows show the FMI appearance of the resistive fractures.

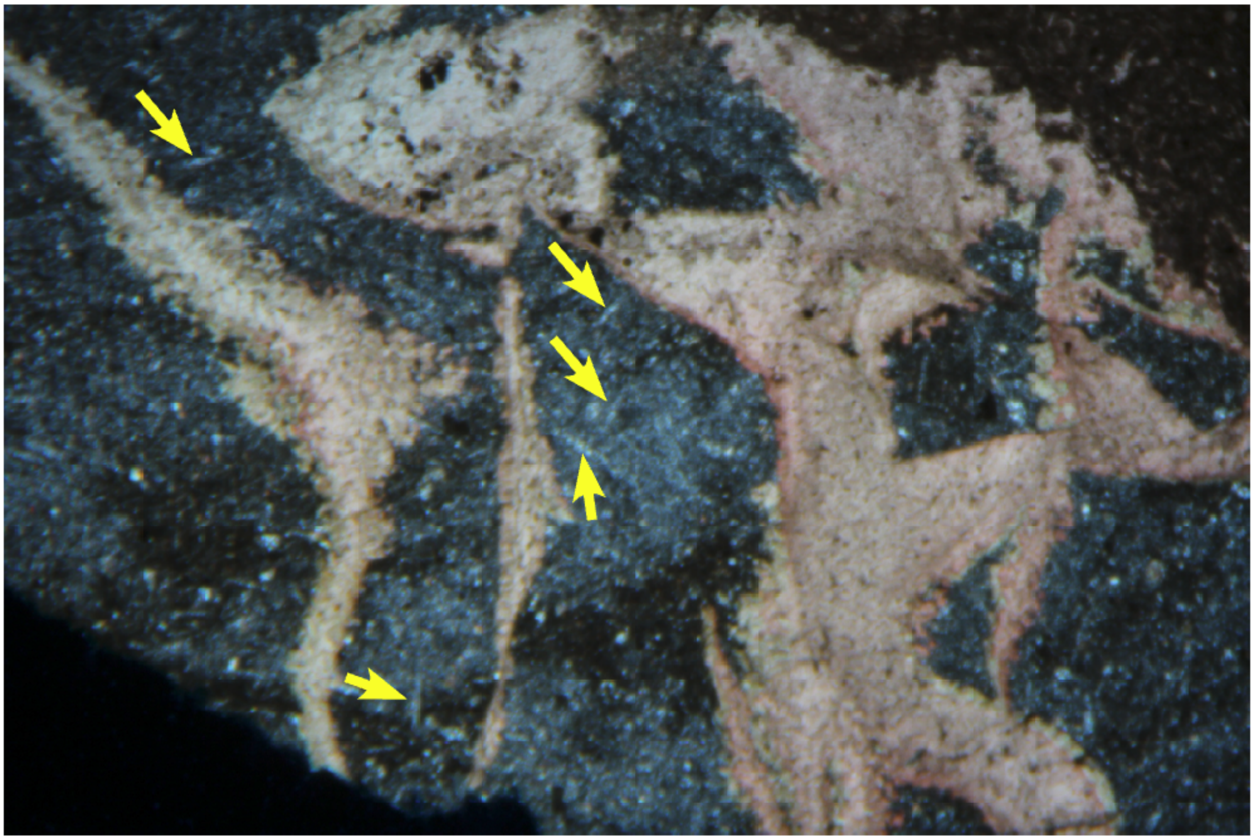

Figure 24 – Thin section demonstrating resistive fractures on the petrographic level. The resistive factures are calcite-filled and denoted by the pink appearance in the image. The yellow areas point out spicule occurrence in the chert. 8x, crossed polars.

Figure 25 – Outcrop samples revealing the presence of resistive fractures. The top photo shows calcite filled fractures pointed out by the yellow arrows. The bottom shows silica filled fractures indicated by the yellow arrows.

Additionally, conductive fractures are present in the Reeds Spring reservoir and are seen as a sinusoid across the wellbore in a FMI log (Figure 26). Conductive fractures within the reservoir unit are not unidirectional in strike. The fractures demonstrate multi-directional strike in a perpendicular, or orthogonal pattern. For example, the NW Strohm 2A-29 SWD showed conductive fracture strikes in East-West, WSW-ENE, WNW-ESE, N-S, and NNW-SSE directions. Density of fractures varied from well to well with some wells exhibiting swarms of conductive fractures and others only baring a few through the entire thickness of the reservoir. The pervasiveness of continuous conductive fractures warrants investigation. The reoccurrence of continuous conductive and resistive fractures through the Reeds Spring interval provides supporting evidence to Mazzullo and others (2011) ideology that production from this reservoir must be associated with permeability pathways created by a fracture system due to the lack of matrix porosity seen in outcrop (Mazzullo and others, 2011). The Reeds Spring is a naturally fractured reservoir that contains a range of different fracture types and networks. A study focused on the connection between the fracture systems should be undertaken in an attempt to understand the fracture patterns present in the subsurface. Insight to fracture patterns can reveal concentrations of petroleum accumulation and therefore more productive wells.

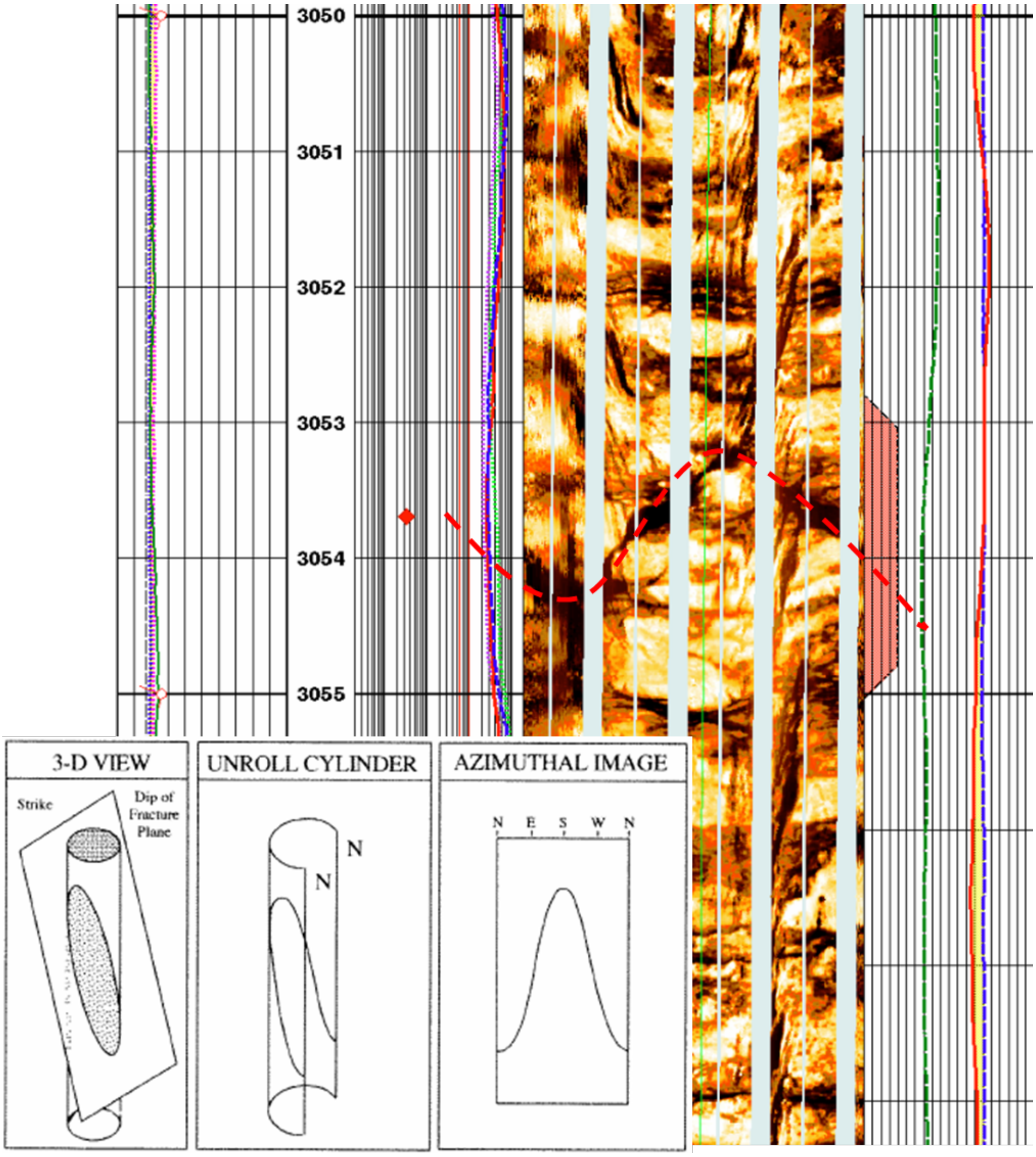

Figure 26 – FMI image showing the occurrence of conductive fractures. Conductive fractures appear as a sinusoid in the FMI log and is traced by the red dashed line in the image. The smaller image in the lower left corner is a three-part diagram illustrating how the sinusoid appearances of conductive fractures appear in FMI logs. Lower left image was taken from Hurley (2004).

Porosity Types

As carbonate rocks are generally subject to diagenetic processes, the Reeds Spring reservoir exhibits multiple porosity types. Although Reeds Spring matrix porosity is rather underdeveloped, primary and secondary porosity types exist in the subsurface. Based on the carbonate porosity classification scheme by Choquette and Pray (1970), vugular, and fracture porosity types are present in the study area along with intercrystalline porosity. Intercrystalline pore space development is typical of the Reeds Spring tight lime mudstone matrix. It is the most dominant porosity system in the reservoir.

As previously discussed, natural fractures are a major component to the reservoir unit. Extensive fracture systems assist in creating permeability pathways, but also contribute to the overall porosity development in the reservoir as it adds void space for petroleum accumulation. From a petroleum systems aspect, the natural fractures greatly contribute to the development of a petroleum reservoir through providing both porosity and permeability. Therefore, fracture porosity is to be considered a porosity type of the Reeds Spring and should be taken into consideration during petrophysical analysis (e.g. S_w).

Secondary solution of pores and fractures by meteoric waters is indicated by vugular porosity occurrence in the Reeds Spring. In the FMI log, singular and discontinuous clusters of irregular vug pores are developed, but also zones of vugular porosity are identified (Figure 27). Zones of vugular porosity are less widespread and could not be correlated from well to well. The PE curve response to developed zones of Reeds Spring vugular porosity is a 2. Siliceous intervals of rock may be more resistant to vug development than silica-free sections. The character, occurrence, and size of the vugs are somewhat random, but they generally occur in a chert free, clean carbonate matrix. In addition to pore space vugs, evidence of bedding plane and fracture enhancement by dissolution is present (Figure 28). Dissolution along bedding planes was further indicated by an increase in spectral gamma ray.

The limited amount of thin sections available for this project did not display vugs, but works of Mazzullo and others (2011) and Davis (2007) denote vug presence in the Reeds Spring at surface exposure and subsurface. Outcrop exposure resembles the same porosity interval succession as the subsurface (Figure 29). Vugular porosity is a secondary porosity type that makes a minor contribution to the overall porosity system due to the inconsistency and lack of size. Although it was not interpreted in the subsurface, it should be noted that the probability of some sort of moldic porosity being present is relatively high, but like vugular porosity only contributes a small amount to the total porosity present. The resolution of the FMI logs very high, but moldic porosity could have been mistaken for vugular porosity in some instances. The multiple porosity types of the Reeds Spring complement each other to provide adequate porosity and permeability to enable petroleum accumulation, exploitation, and production.

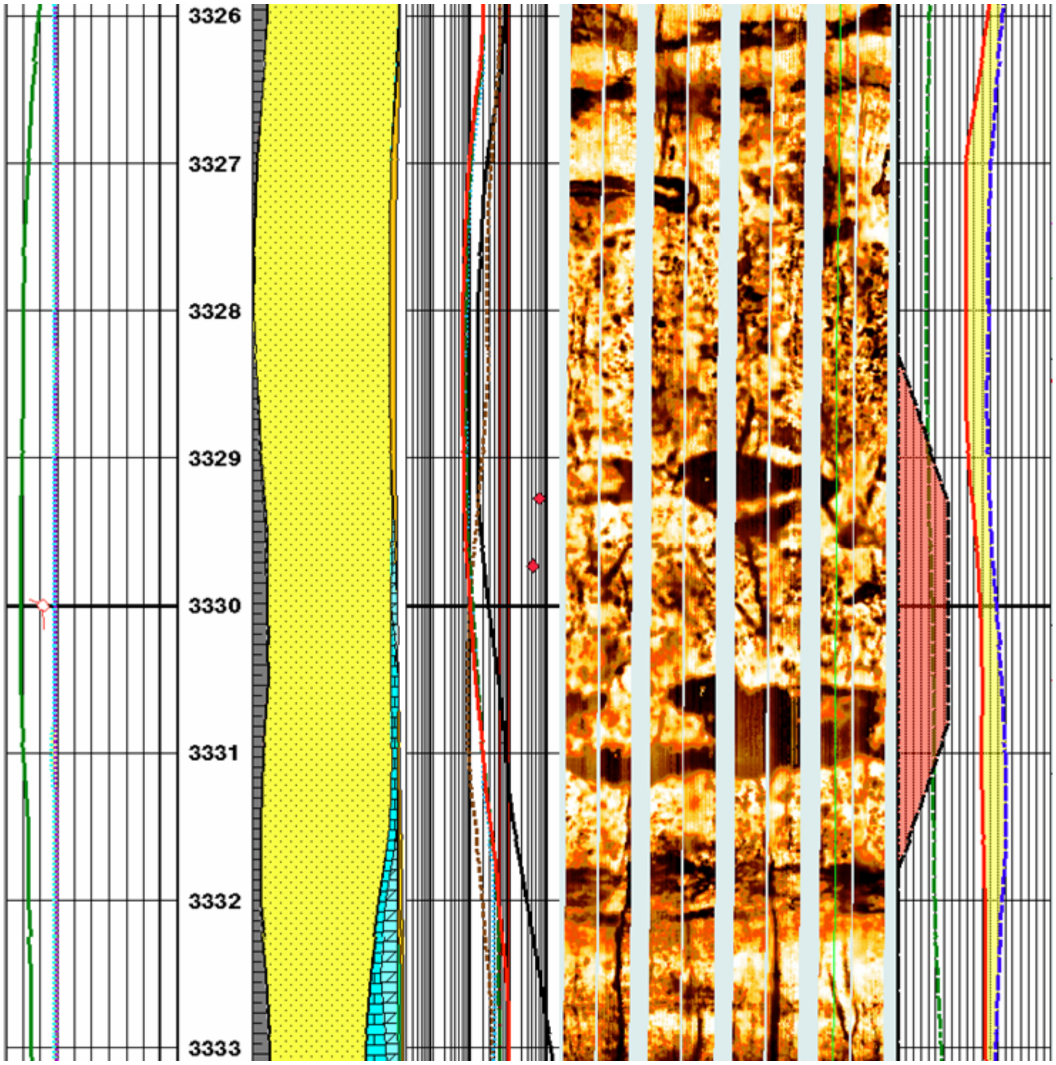

Figure 27 – FMI image showing the occurrence and appearance of vuggular porosity in the subsurface. The vug porosity exists between the depths 3327'MD and 3332'MD. Note the dissolution micropores created.

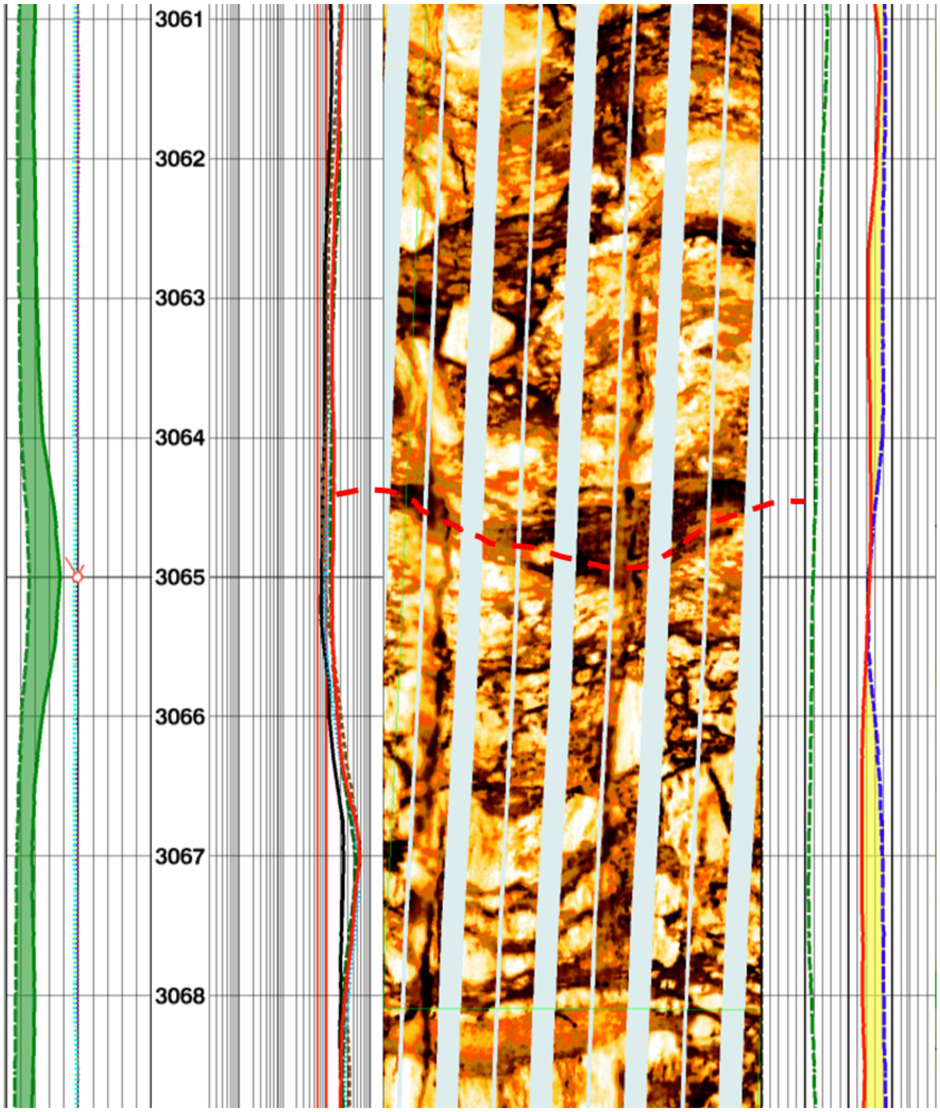

Figure 28 – FMI image showing dissolution enhanced bedding planes. The bedding plane is highlighted by the red dashed arrow. In track 1, the normal gamma ray is the dotted green line and the spectral gamma ray is the solid green line. At the occurrence of the dissolution enhanced bedding plane note the clear separation in curves (3065'MD).

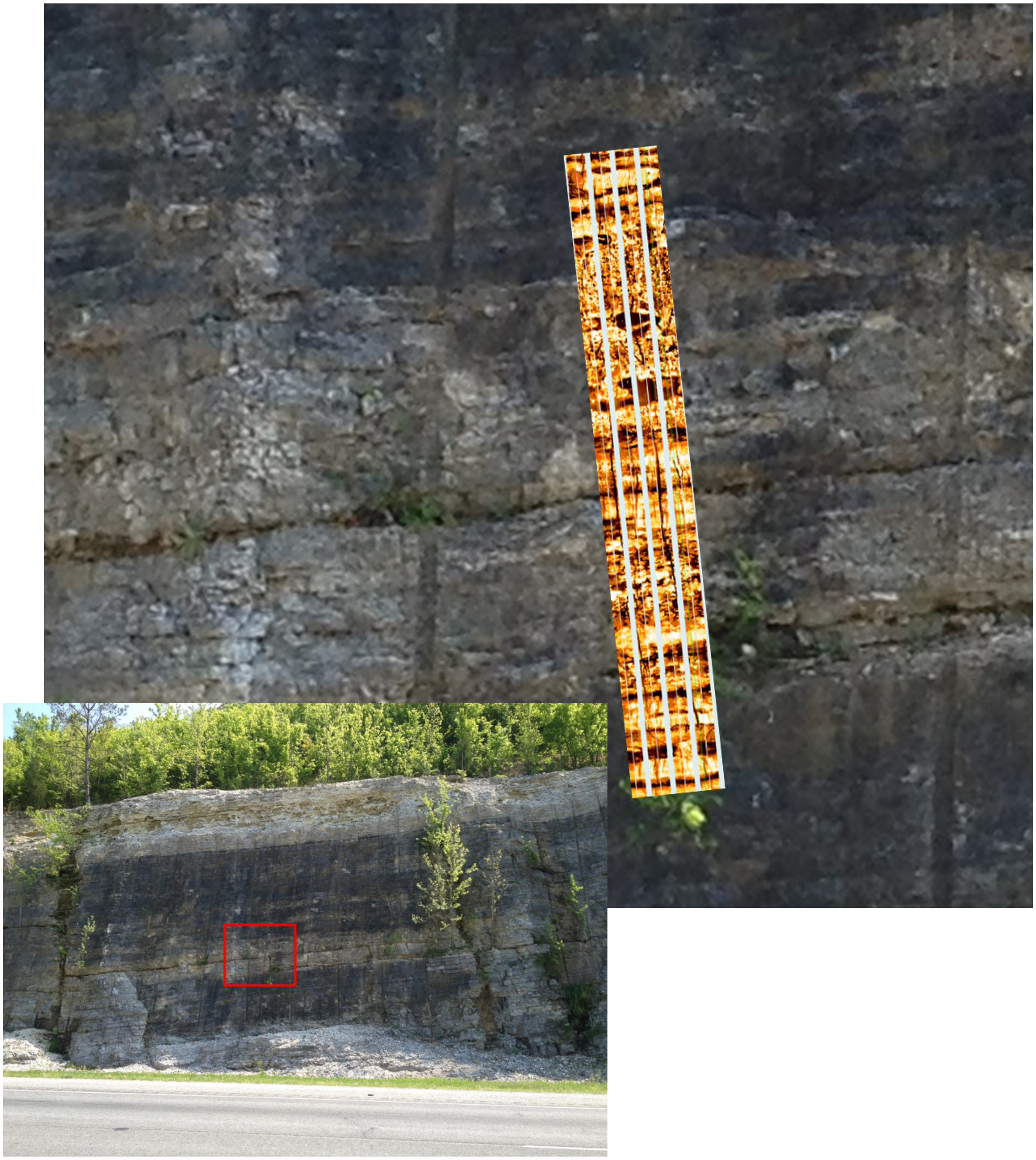

Figure 29 – This figure demonstrates the relationship between subsurface vug porosity and outcrop occurrence. The outcrop is on Hwy 412 outside Pedro, AR. The lower left photo provides reference to the segment of outcrop that is emphasized and compared. Similarities in porosity development occur between outcrop and subsurface Reeds Spring.

Structure

Regional dip of basement rock overprints the local structural nature of the Reeds Spring. Structural variability may be in place, but sparse data density over a large study area suggests that the dip of the reservoir unit is due west in the eastern portion of the study area and turns to the northwest in the western portion (Figure 30). An increase in data density would help delineate the subtle structural changes. This predictable structure of the Reeds Spring is most likely attributed to gently westward dipping regional homocline that covers much of eastern Kansas and Oklahoma (McBee, 2006) (Figure 31). The positive structural influence of Ozark dome to the east and the negative Anadarko basin to the south and west also may have had an influence at time of deposition and post-depositional deformation. Approximate magnitude of regional dip for these rocks has been cited as 25 to 50 feet per mile (Huffman, 1951). From a petroleum system perspective, this is an important feature to acknowledge because it relieves dependency on structure to be an integral trapping mechanism for the reservoir. Moreover, identifying faults perpendicular to dip may provide traps for major petroleum accumulation. Structure maps of the upper, middle, and lower members all demonstrated the same dipping character.

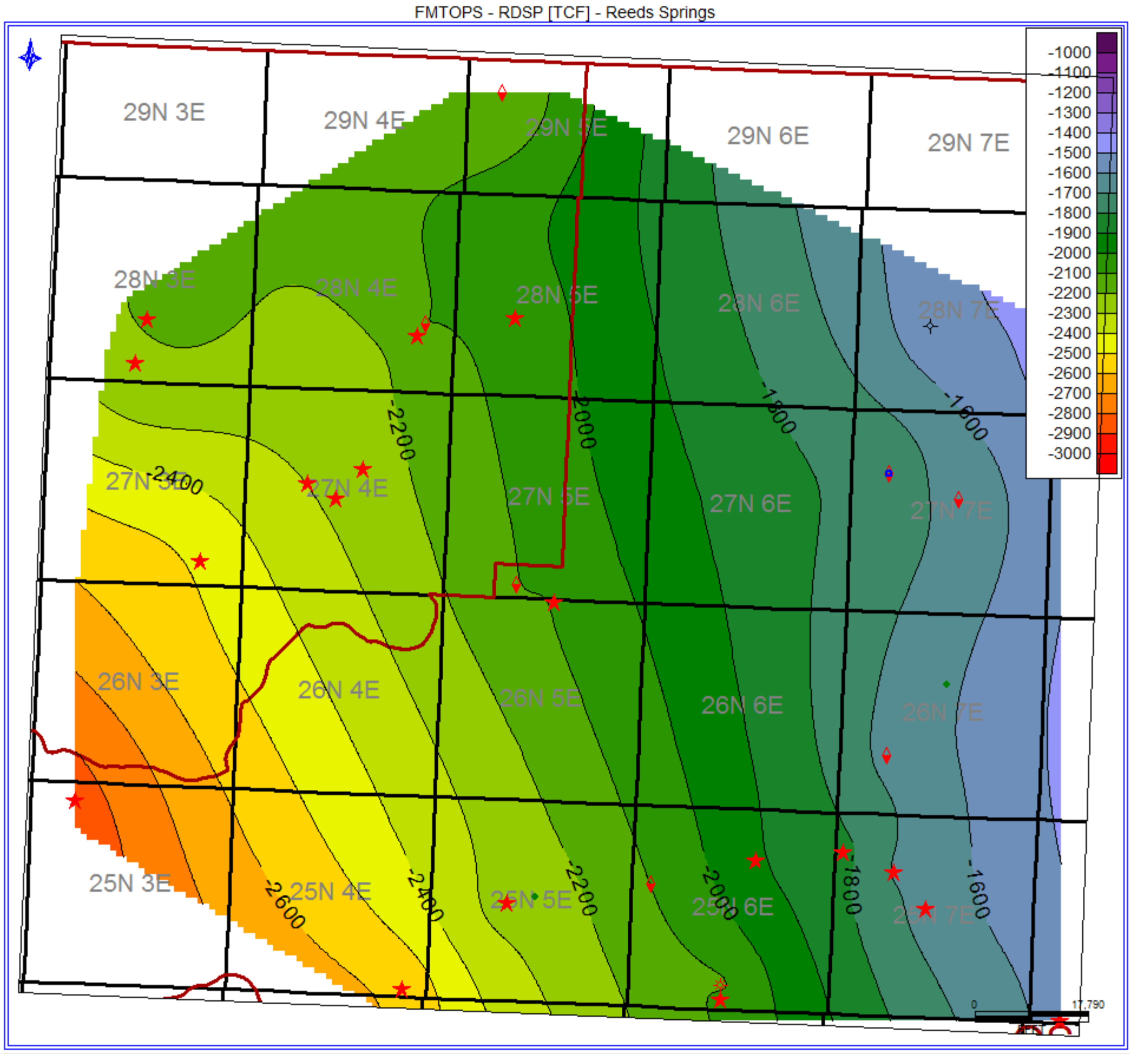

Figure 30 – Structure map of the top of the Reeds Spring reservoir in the study area. The depths are calculated with respect to sea level not elevation. Structural character of the Reeds Spring follows regional dip to the south and southwest. The color bar in the top right hand corner of the map indicates that red colors signify deep and purple signifies shallow. The map scale is found in the lower right hand corner and the north arrow in the top left.

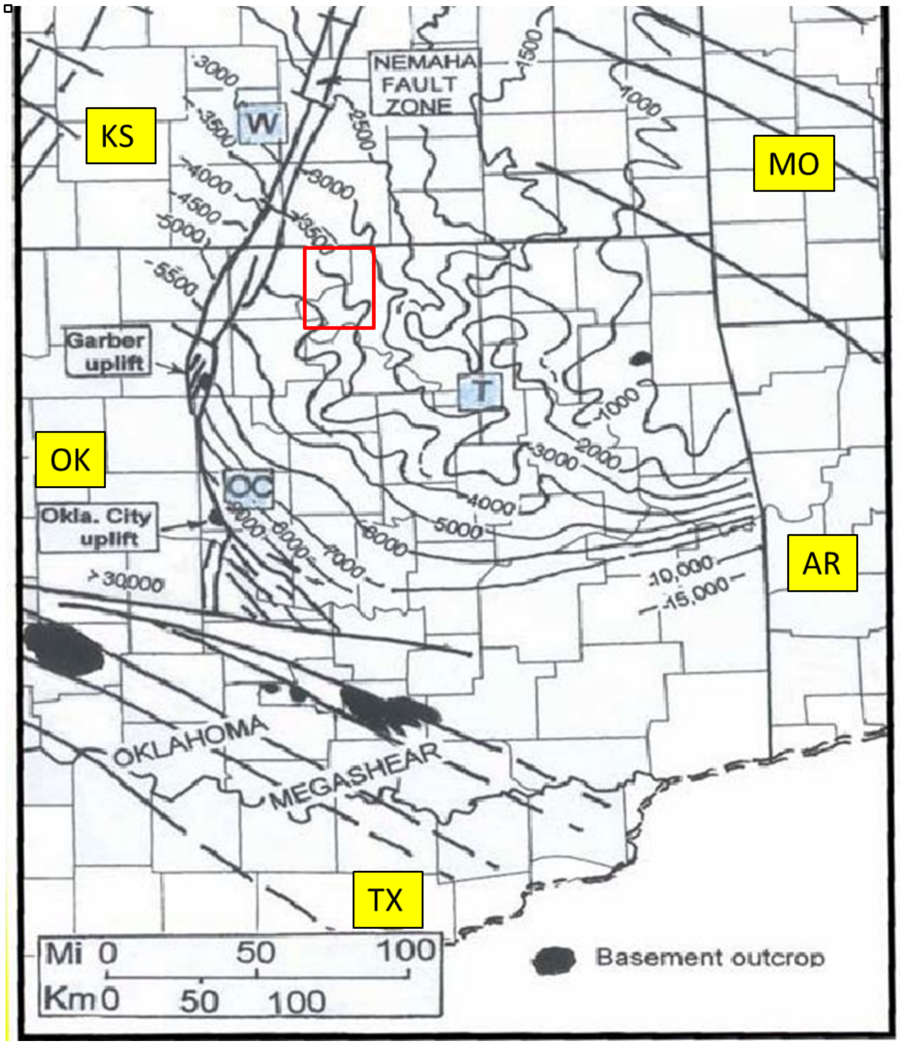

Figure 31 – Contour map of the basement structure of northeastern Oklahoma and southeastern Kansas. The project study area is outlined by the red box in northern Oklahoma. Note the resemblance between the basement rock dipping trend and the Reeds Spring from Figure 25. Taken from McBee (2006).

Water Saturation

Water saturation calculations of the Reeds Spring using the Archie equation yielded widely variable results. The cementation factor (*m*) 2 generated the highest and most realistic saturation percentages, generally averaging 50% or greater. Water saturation increased steadily as *m* values increased from 1 to 2.2. *M* values of 2.2 did yield percentages that were highly unreasonable with many values exceeding 100% (Figure 32).

Based on communication with industry professionals, the Reeds Spring is a very wet reservoir; a large amount of water is produced with the petroleum production. Enough water is produced that one saltwater disposal (SWD) well is needed for every four to five producing wells. Consequently, the water saturation percentages calculated when using any *m* lower than 2 are not realistic. In fact, the percentages produced by 2 are most likely conservative and without detailed production data there is no way to test the saturation calculations. Accurate water saturation values are difficult to generate because the porosity system in the Reeds Spring is not uniform, therefore certain zones should be defined by different *m* values. Although, focusing on water saturation analysis may be futile due to the naturally high amount of produced water, the middle member of the Reeds Spring exhibited the lowest average water saturation across the study area. Furthermore, it is observed that when higher porosity is coupled with high resistivity, water saturation percentages are calculated to be less than 25% regardless of the *m* value used (Figure 32). In the Reeds Spring reservoir, water saturation calculations are inversely proportional to the deep resistivity curve. In zones of high resistivity, saturation is low and zones of lower resistivity zones exhibit higher saturation.

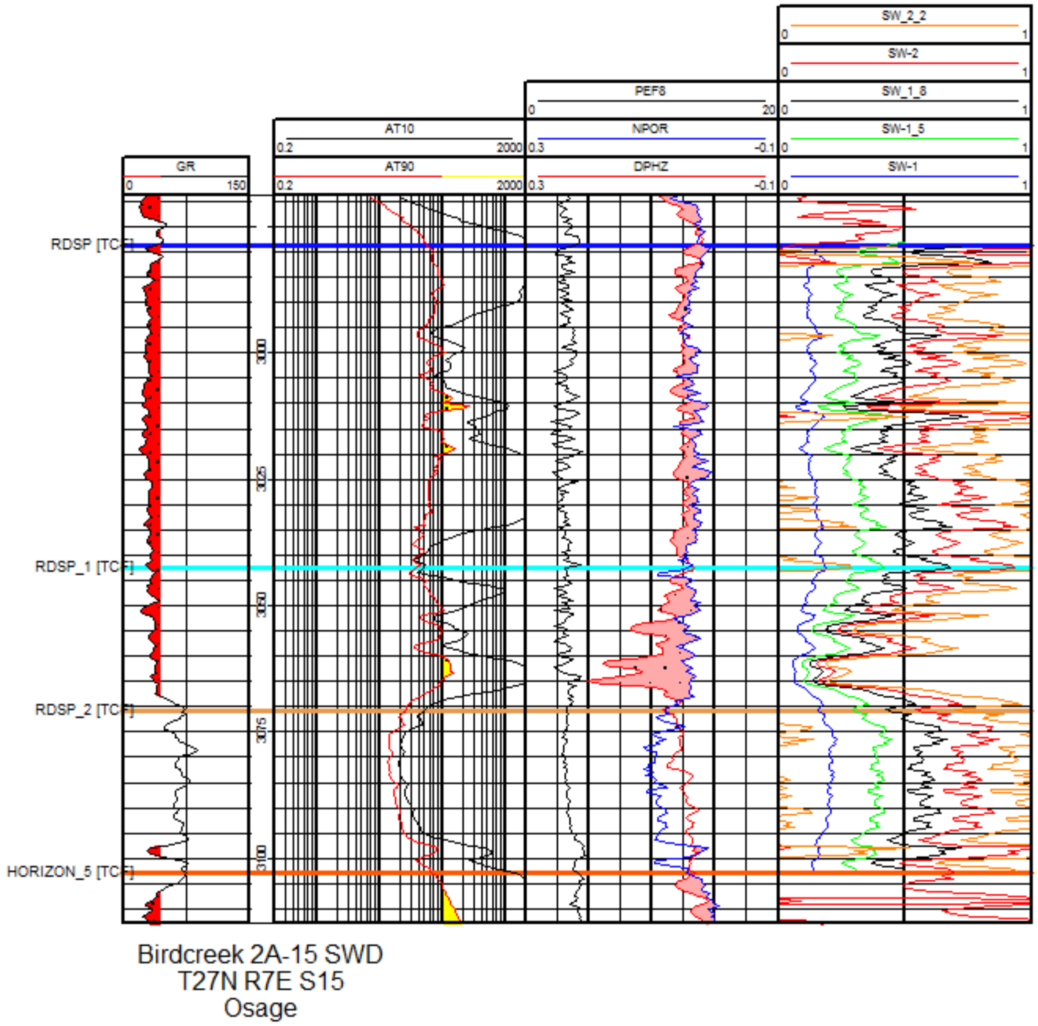

Figure 32 – Calculated water saturation values of the Reeds Spring. Track 4 shows the water saturation values from 0 to 100% with respect to each of the different *m* values used. The blue curve in Track 4 is *m* value of 1, lime green 1.5, black 1.8, red 2, and orange 2.2. The dark blue horizon (RDSP) is the top of the Reeds Spring, the baby blue (RDSP_1) top of the Reeds Spring middle member, dull orange horizon (RDSP_2) top of the lower member, and dark orange (HORIZON_5) top of the Pierson. The Reeds Spring middle member shows a zone of high porosity with crossover, note the character of the water saturation curves; they all demonstrate low saturation values not matter what *m* value used.

Reservoir Pay Qualities

Criteria for the Reeds Spring pay zones were established through the overall workflow of this project and communication with industry professionals actively drilling the Reeds Spring play. In conventional reservoir geology, porosity is generally one of the main controlling factors in determining pay zones. This is true for the Reeds Spring, but the degree of porosity development required to produce petroleum is significantly reduced due to horizontal drilling practices and hydraulic fracturing techniques. In this, more emphasis and importance is applied to resistivity and gamma ray properties of the unit. Economically productive zones of the Reeds Springs exhibit high resistivity (+100ohm-m), clean carbonate gamma ray (20-45 API), zig-zag PE curve appearance between 2 and 4-5, when available, and relatively low porosity values with crossover (2-10%) (Figure 33).

The different pay criteria were established to ultimately identify chert baring, clay free zones. From FMI analysis, it was established that chert does not develop in clay rich intervals, therefore clean carbonate matrix is an important reservoir characteristic of the Reed Spring. Additionally, during the hydraulic fracturing completion process, clay content decreases the extent of induced fracture propagation. The lower member of the Reeds Spring typically contained more clay/silt than the other two members, which decreased its reservoir quality across the study area. Volume clean carbonate maps, which demonstrate the clean carbonate matrix across the study area, can be found in Appendix B.

Moreover, high resistivity zones are indicative of abundant chert content in the Reeds Spring. Average resistivity values of the Reeds Spring members varied throughout the study area. The middle member contained the overall best average resistivity across the area. Average resistivity maps can be found in Appendix C. A low-value crossover in the neutron and density

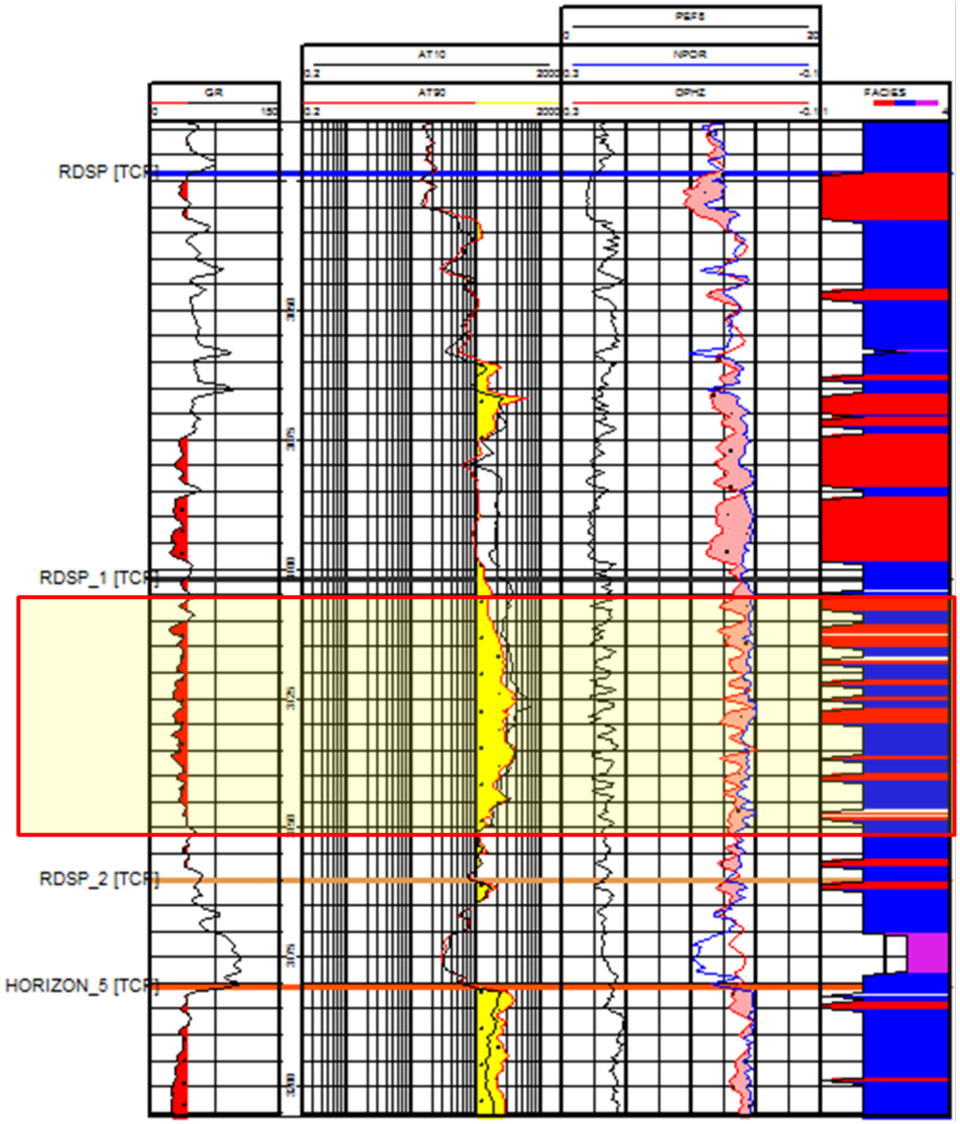

Figure 33 – Log illustrating the Reeds Spring pay criteria. The red box infilled with faint yellow in the middle of the log shows a pay zone found in the Reeds Spring reservoir. Note the gamma ray baseline in Track 1 shows a clean carbonate matrix with an API value of less than 40. Resistivity in Track 2 is shown having high values, over 100 ohm-m. The PE curve in the first half of Track 3 demonstrates a zig-zag pattern indicating interbedded chert and limestone. The porosity curves in Track 3 exhibit low value crossover and the lithofacies curve in Track 4 shows interbedded chert and limestone. The dark blue horizon (RDSP) is the top of the Reeds Spring, the black (RDSP_1) top of the Reeds Spring Middle member, dull orange horizon (RDSP_2) top of the Lower member, and dark orange (HORIZON_5) top of the Pierson.

curves also signifies interbedded chert within a limestone matrix, as seen from FMI analysis. No correlation in productivity trends is seen in the amount of porosity developed, but rather the display of the crossover effect in the neutron-density porosity curves. Based on the methods of investigation, the upper and middle members of the Reeds Spring offered the best reservoir quality across the study area. Net Pay maps can be found in Appendix E. These maps display the amount of reservoir feet for each Reeds Spring member across the study area using the minimal pay qualities established (2% true porosity, 100 ohm-m resistivity, 40 API gamma ray).

These electronic signatures are important to note, but inconsistent production occurs across the play. Production values in the study area have been reported as high as 1,400 barrels of oil per day (BOPD) and as low as 25 BOPD. Variability in production is likely due to lack of understanding of the fracture systems through the play, which is a primary control in migration and trapping. The Reeds Springs is series of stacked compartmentalized reservoirs separated by tight impermeable layers, bedding planes, and fractures. It is not one horizontally continuous reservoir as most unconventional reservoirs are thought to be. Fluid migration through the reservoir has no vertical continuity. Evidence of this interpretation is represented in outcrop after observing water migrate through fractures in the rocks and interact with impermeable layers. Water pours out of different conduits at surface exposure (Figure 34). The writer acknowledges that petroleum migration is generally vertical, but lateral migration could play a larger role in the Reeds Spring petroleum system than in other petroleum system examples. The water movement through the outcrop exposure is representative of the fluid mechanics and migration pathways of the subsurface.

Figure 34 – Outcrop exposure of the Reeds Spring exhibiting an example of fluid permeability pathways and conduits through bedding planes and fractures shortly after rainfall. The red circles highlight a couple areas where fluid outpour can be identified to different scales. This exposure is located on Hwy 412, outside Pedro, AR.

SUMMARY AND CONCLUSIONS

This study has identified multiple reservoir characteristics of the Reeds Spring Formation that are imperative in understanding the Reeds Spring as an economically exploitable petroleum reservoir. Additionally, the outcrop exposures of the Reeds Spring have been previously thought of as an analog for its subsurface counterpart; this work acknowledges key fundamental similarities, but describes some of the differences seen through the use of geophysical wireline logs, formation micro-image logs and thin sections from northeastern-north central Oklahoma.

- The overall depositional style of the outcrop and subsurface Reeds Spring is similar but sediment supply and water depths differ between the locations. The study area is thought to have been deposited in deeper waters than previously published.
- The Reeds Spring represents a deep shelf margin deposit, which filled in accommodation space created by the absence of shelf margin during the Early Mississippian.
- Subdivision of the Reeds Spring reservoir interval offers more control on identifying reservoir properties and quality. Of the three members defined by this project, the lower member offers the poorest reservoir quality, the middle the best, and the upper member moderate quality across the study area in western Osage and eastern Kay County, Oklahoma.
- When core and FMI logs are unavailable, geophysical log signatures have been used to accurately predict chert occurrence typical of the Reeds Spring: clean carbonate matrix (< 40 API gamma ray), high resistivity (+ 90 ohm-m), and low value neutron-density porosity that exhibits the crossover effect (2-10%). Additionally, FMI logs identify three types of porosity systems to exist in the subsurface: intercrystalline, vuggular, and fracture.

- Permeability pathways (fractures and bedding planes) appear to be the control on petroleum migration and accumulation in the Reeds Spring due to the lack of matrix porosity.

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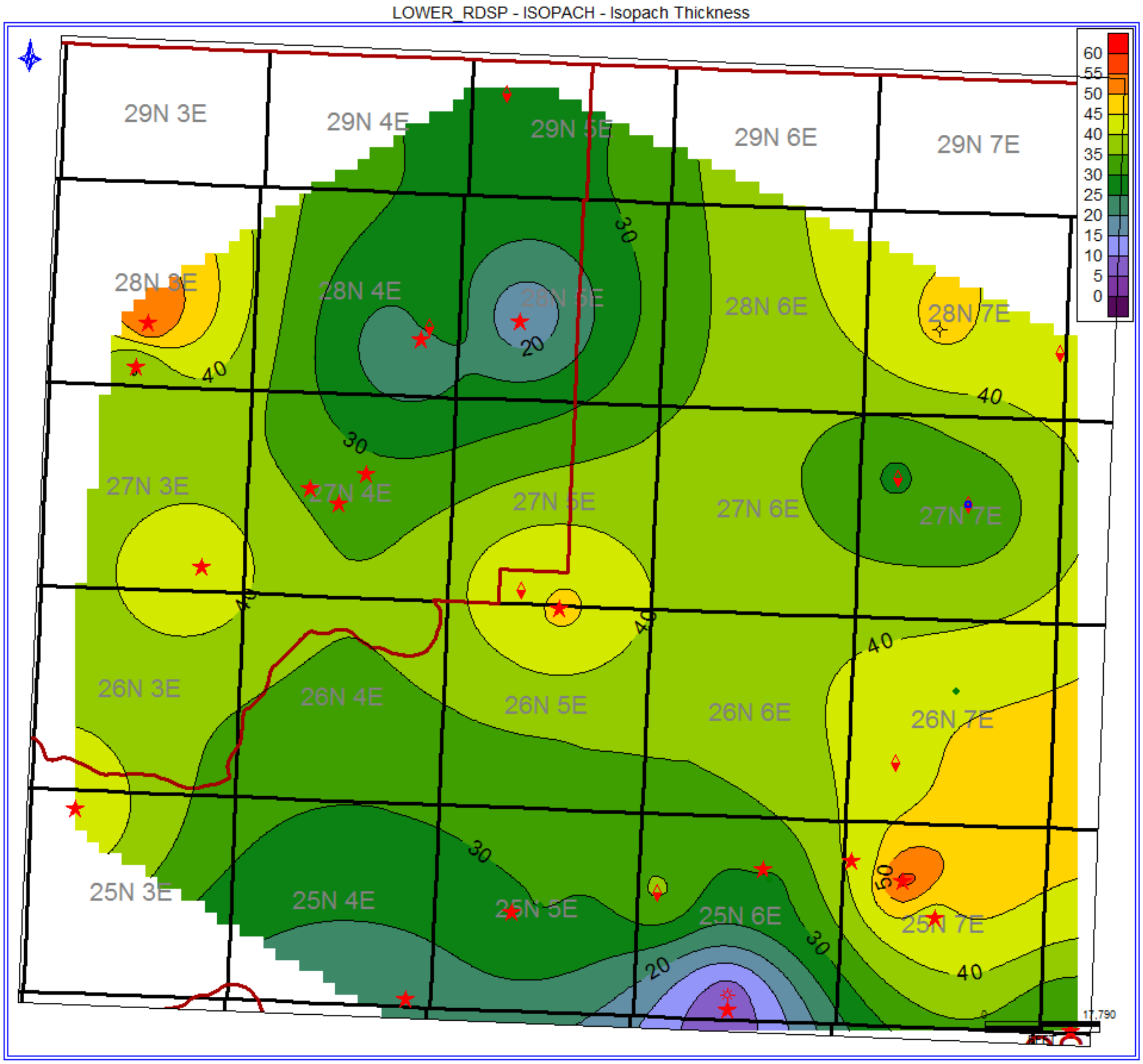
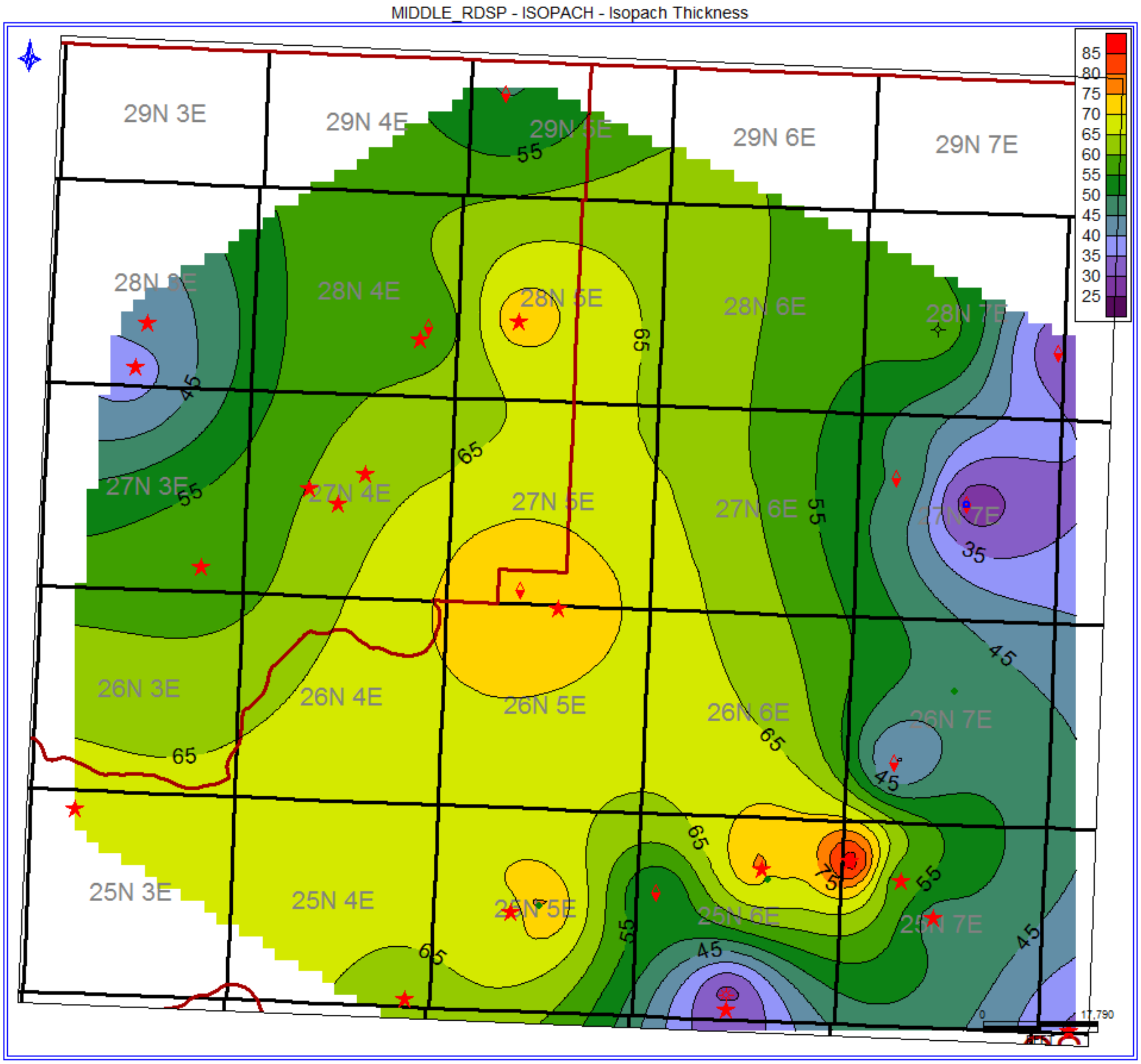
Appendix A – Isopach Maps

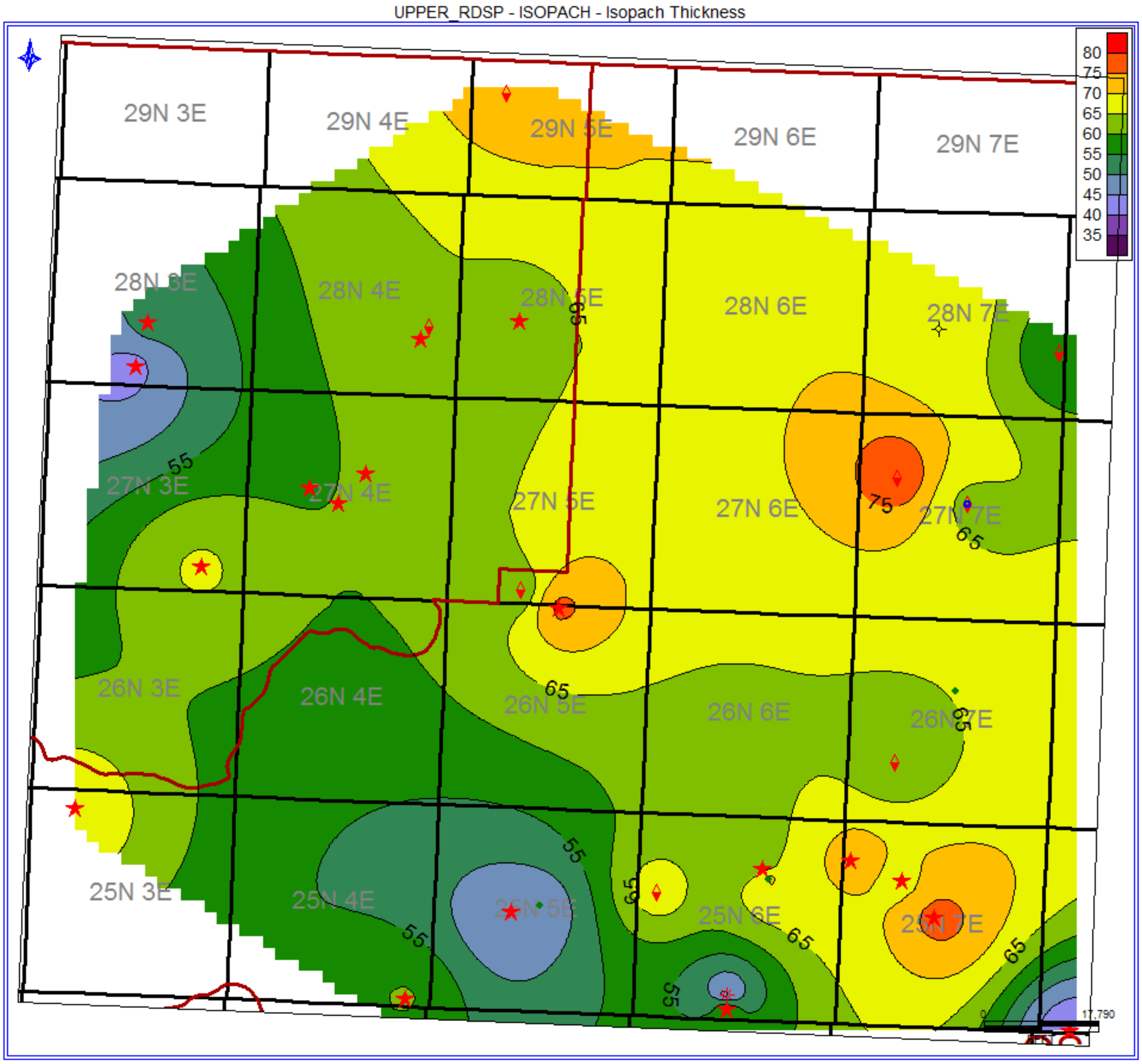
Lower Member – color bar ranges from 0ft (purple) to 60ft (red); CI = 5ft



Middle Member – color bar ranges from 25ft (purple) to 85ft (red); CI = 5ft

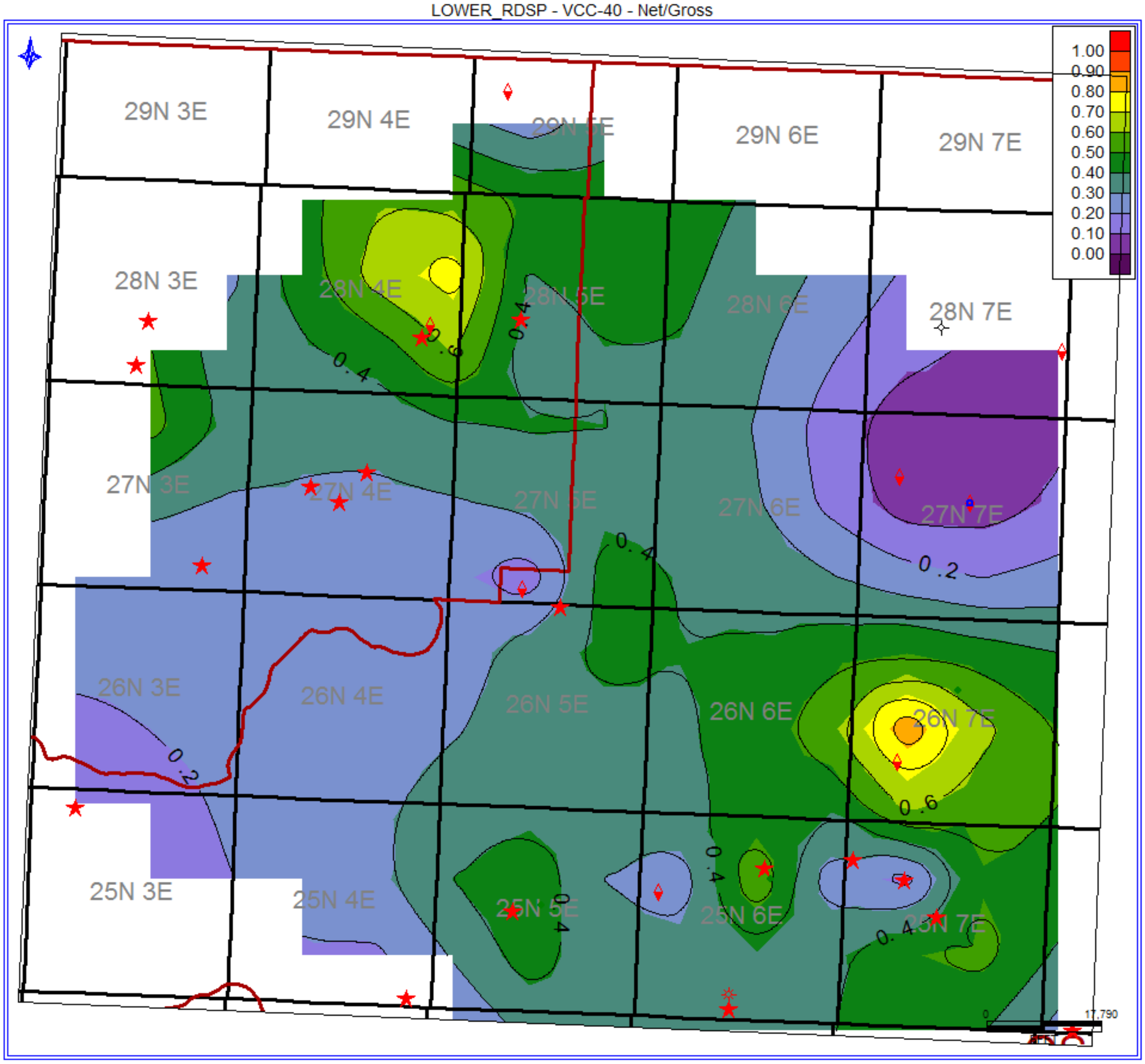


Upper Member – color bar ranges from 35ft (purple) to 80ft (red); CI = 5ft

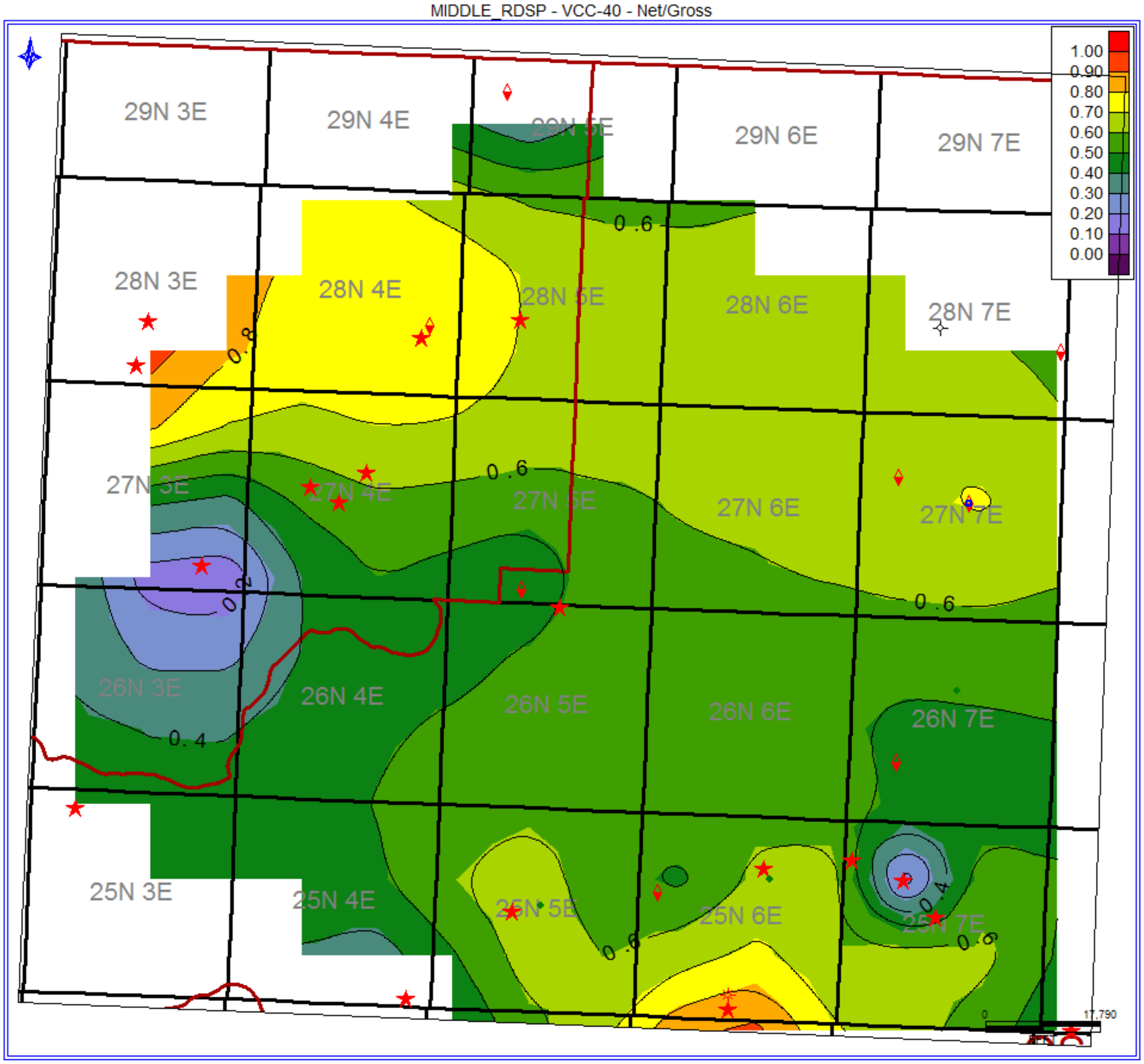


Appendix B – 40 API Cutoff Volume Clean Carbonate Maps

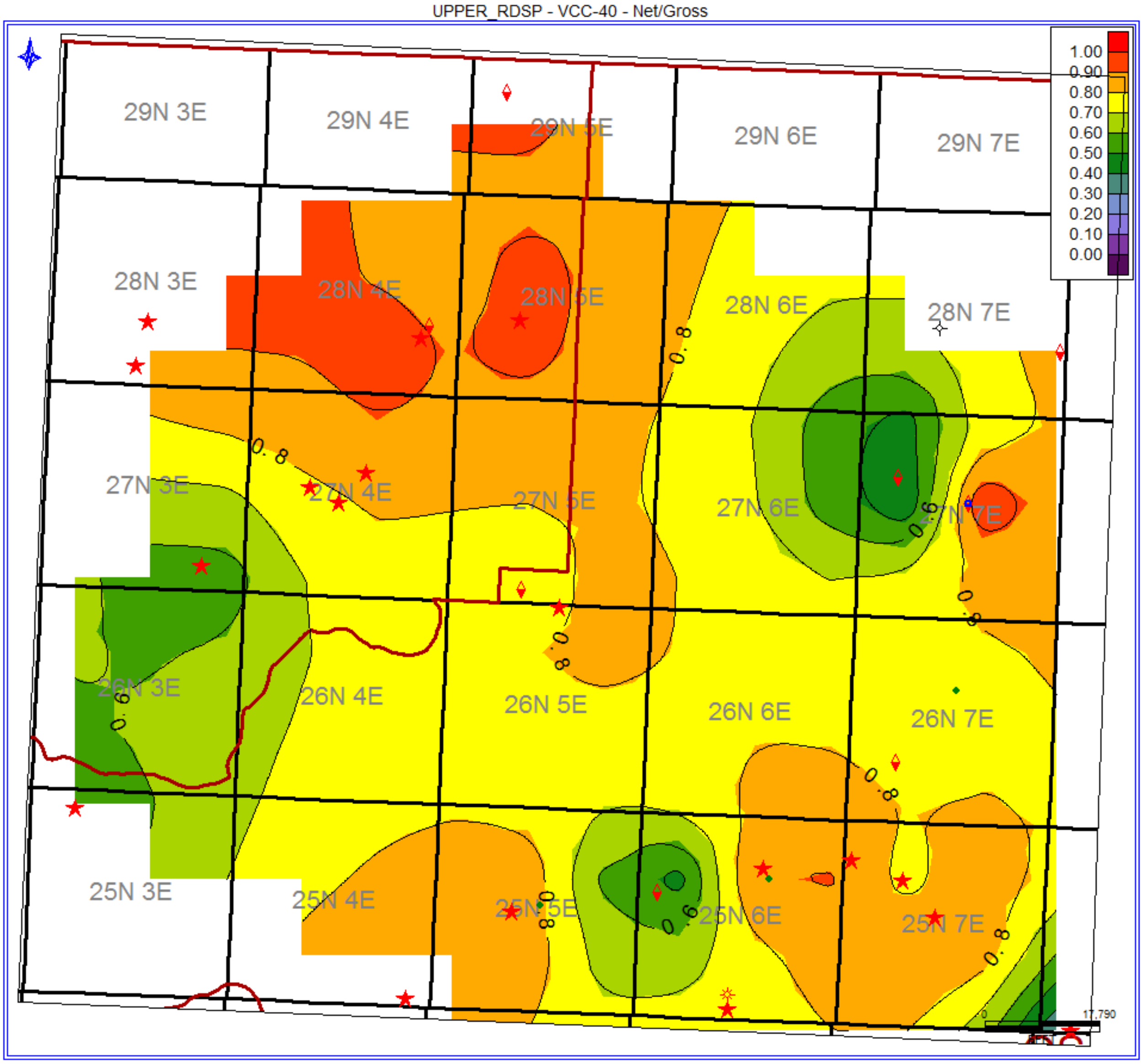
Lower Member – color bar ranges from 0% (purple) to 100% (red); CI = 0.1



Middle Member – color bar ranges from 0% (purple) to 100% (red); CI = 0.1

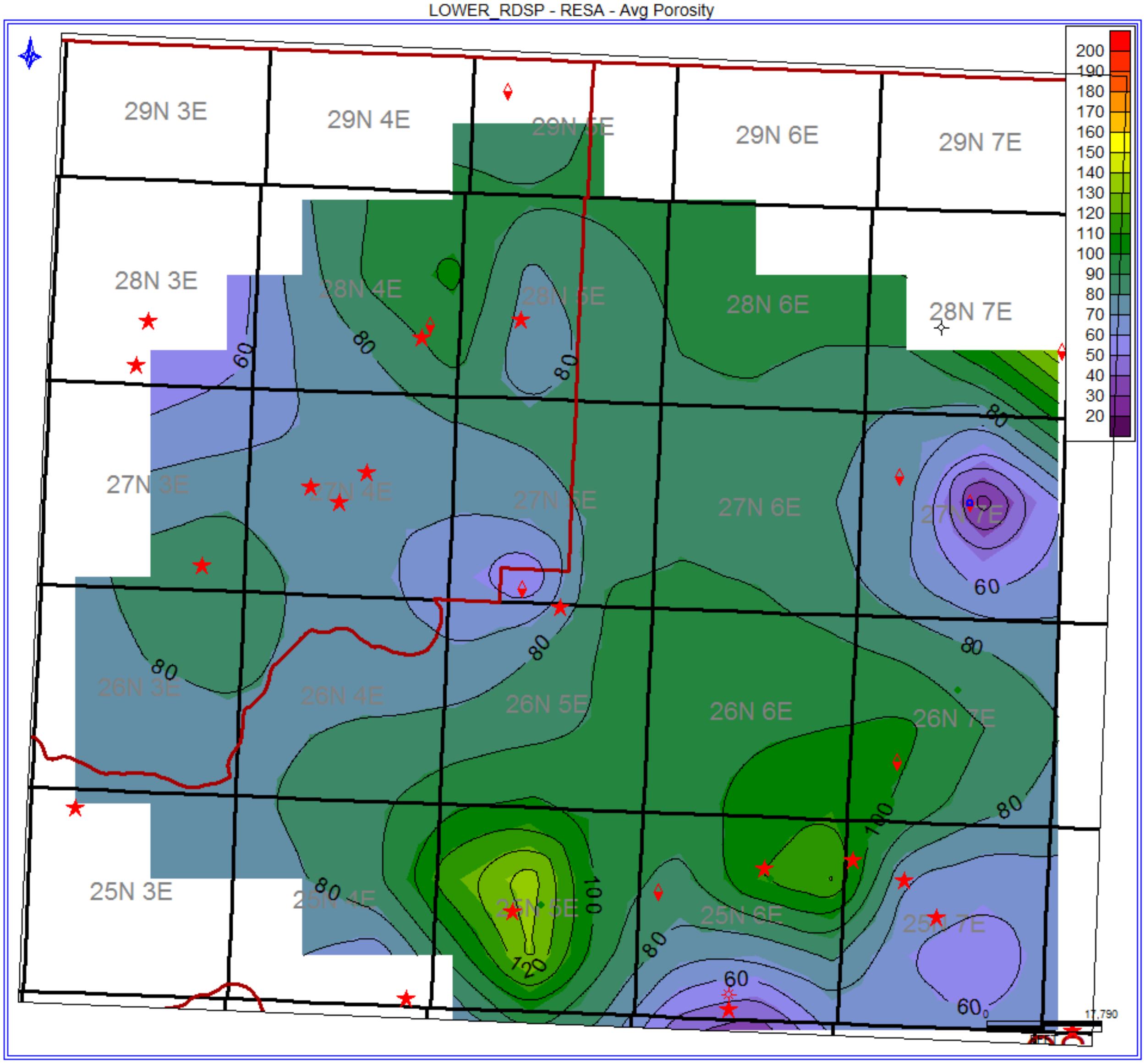


Upper Member – color bar ranges from 0% (purple) to 100% (red); CI= 0.1



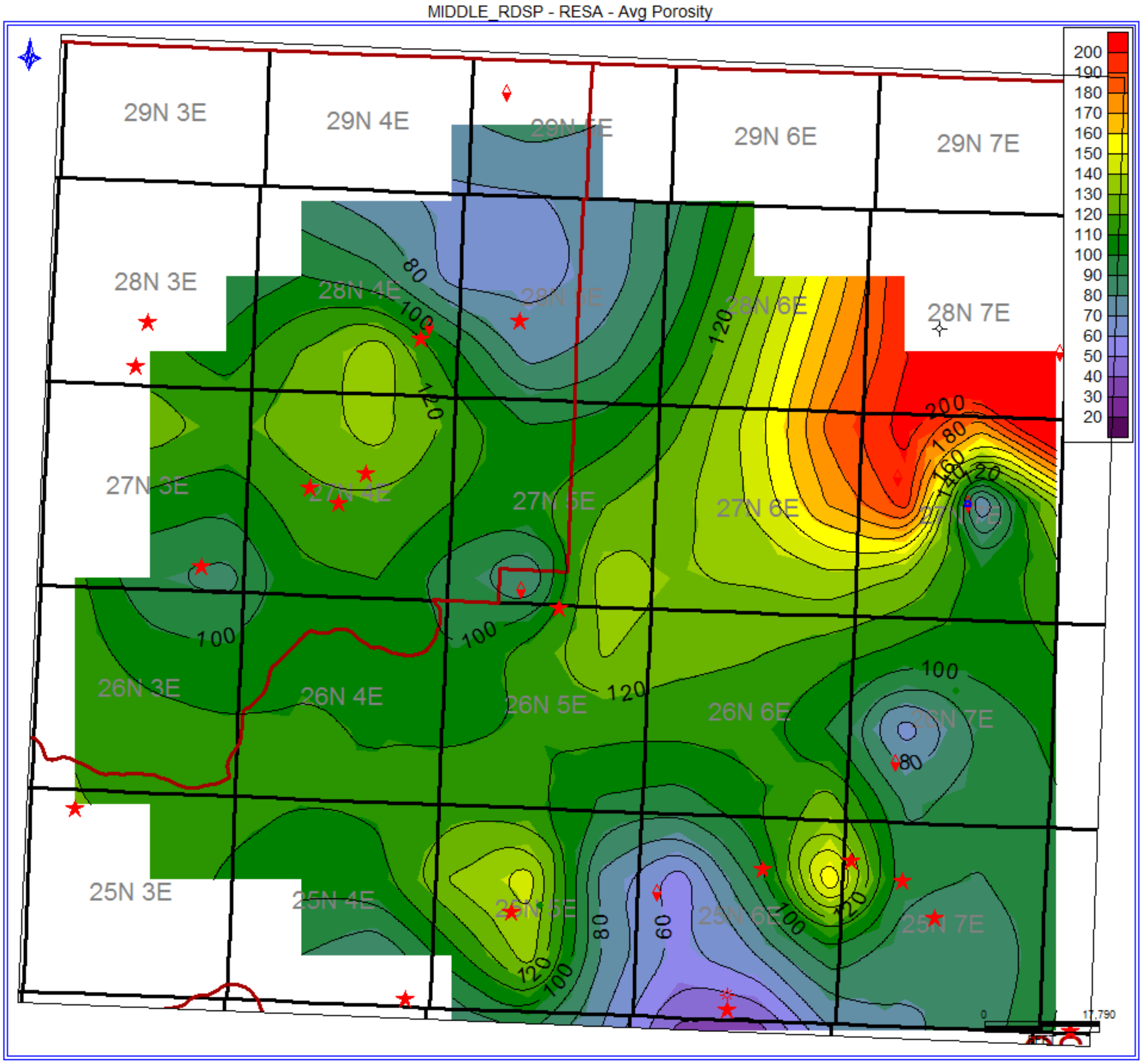
Appendix C – Average Resistivity Maps

Lower Member – color bar ranges from 20ohm-m (purple) to 200ohm-m (red); CI = 10ohm-m

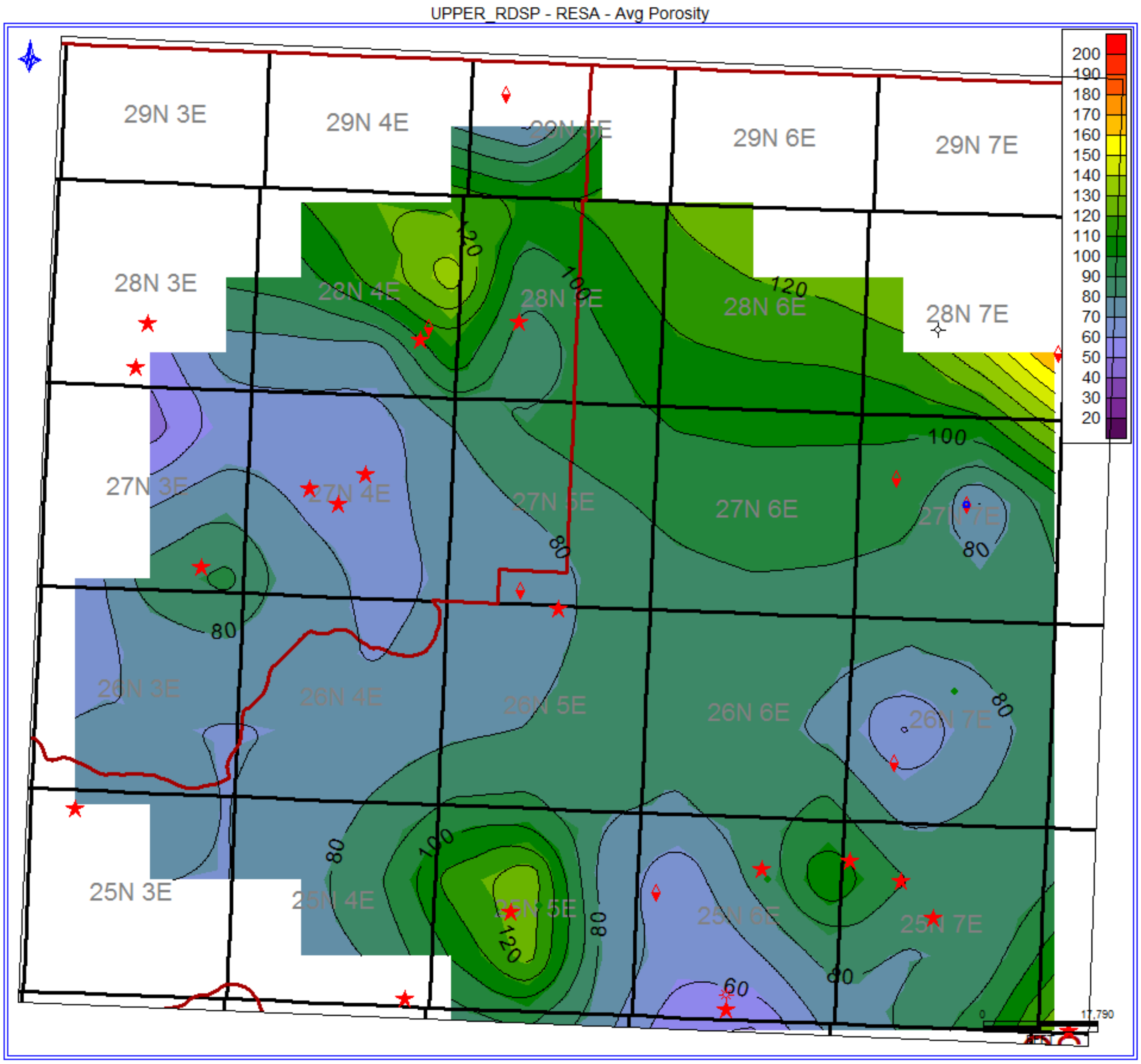


LOWER_RDSP - RESA - Avg Porosity

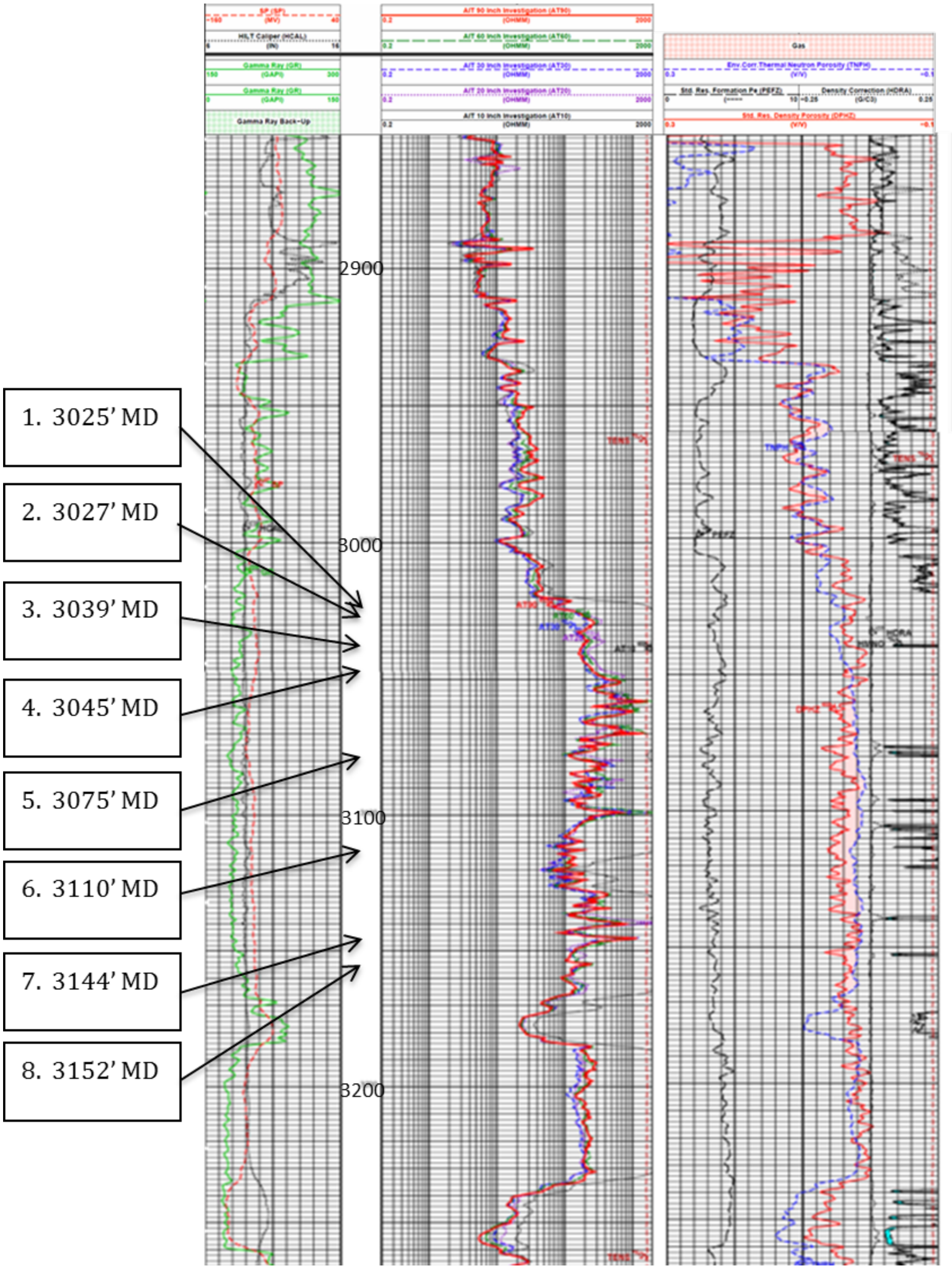
Middle Member – color bar ranges from 20ohm-m (purple) to 200ohm-m (red); CI = 10ohm-m



<u>Upper Member</u> – color bar ranges from 20ohm-m (purple) to 200ohm-m (red); CI = 10ohm-m

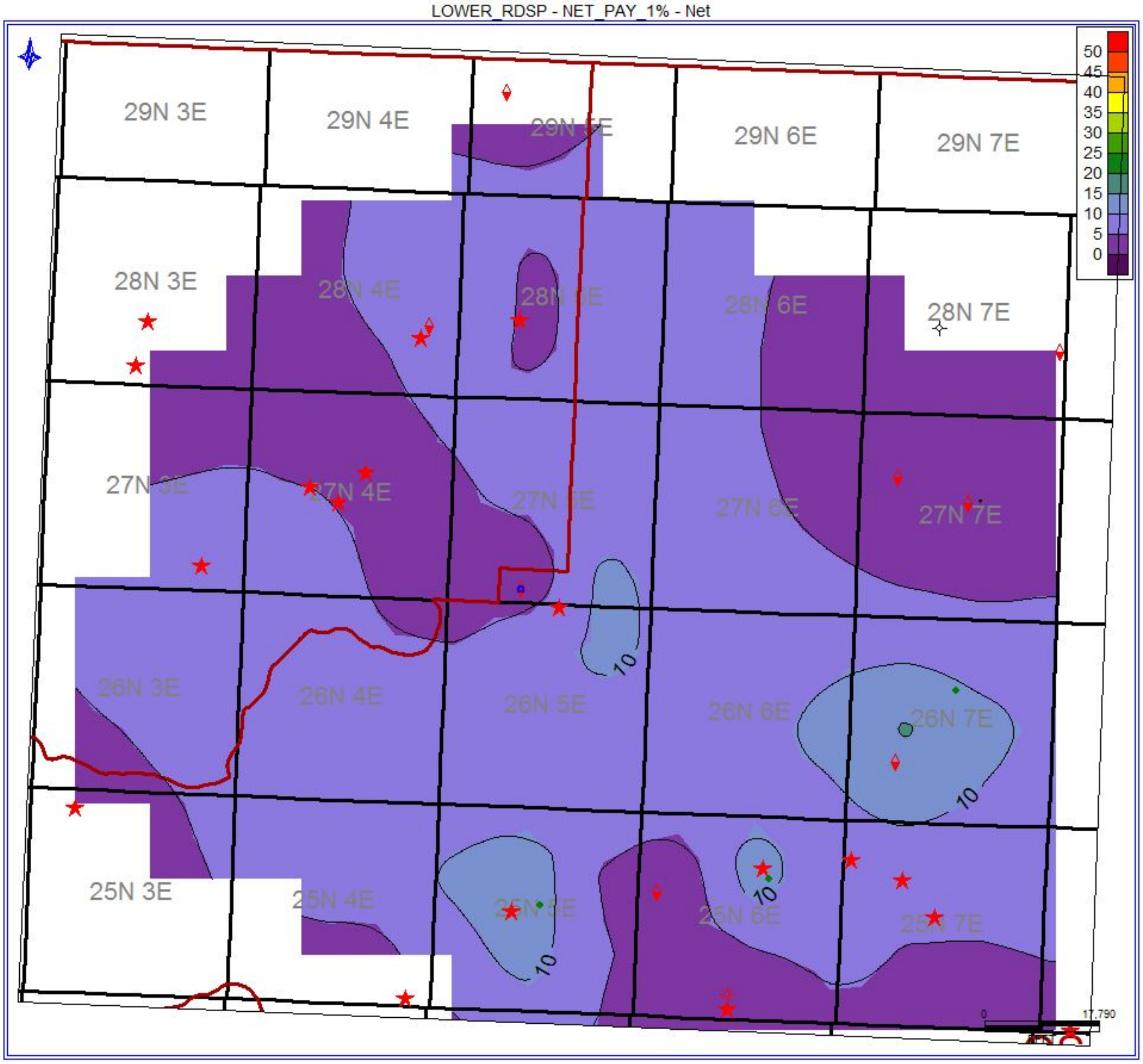


Appendix D – Reeds Spring thin section locations with respect to Shaw 5A-8 geophysical log

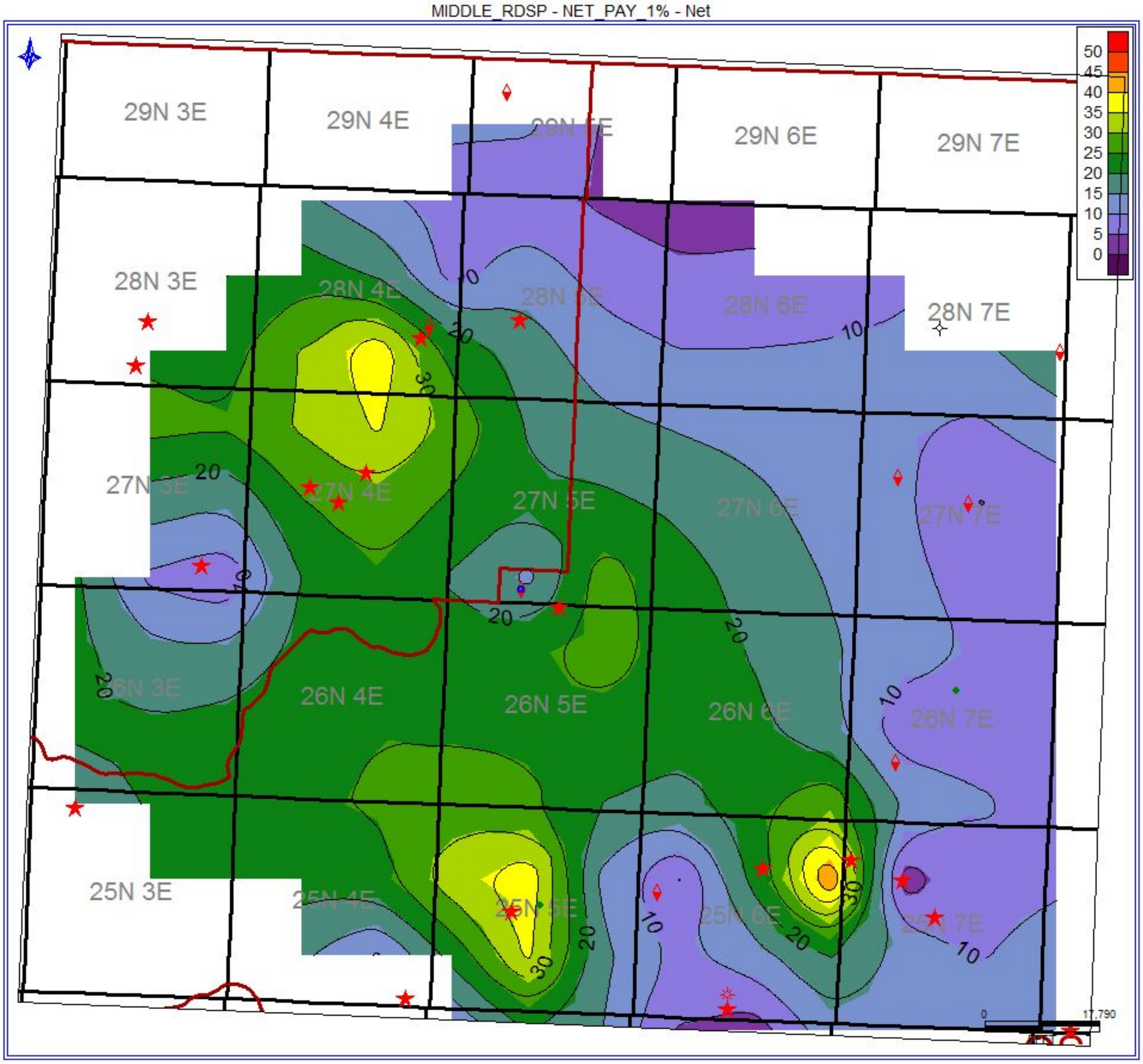


Appendix E – Net Pay Maps. Cutoffs: 2% true porosity, 100 ohm-m resistivity, and 40 API gamma ray

<u>Lower Member –</u> color bar ranges from 0ft (purple) to 50ft (red); CI = 5ft



<u>Middle Member –</u> color bar ranges from 0ft (purple) to 50ft (red); CI = 5ft



<u>Upper Member</u> – color bar ranges from 0ft (purple) to 50ft (red); CI = 5ft