AN ABSTRACT OF THE THESIS OF

Jordan Ann Williams for the Master of Science Degree in the Department of Physical Science – Earth Science presented on April 5, 2017

TITLE: Geologic, Permeability, and Fracture Characterization of the Arbuckle Group in the Cherokee Platform, Oklahoma

THESIS CHAIR: Dr. Richard Sleezer

ABSTRACT APPROVED: ______________________________

Permeability in the Arbuckle Group (Arbuckle) of central- Oklahoma is not well understood and may be key to understanding the relationship between fluids injected into subsurface formations and seismicity in the basement. Seismic activity from 2009 to 2016 far exceeded background seismicity in central-Oklahoma and motivated research in the Arbuckle and Timbered Hills overlying the Precambrian Basement. Movement of fluids in each formation must be understood, beginning with characterizing lithology, fracturing, and rock properties. Properties that help evaluate fluid movement in the Arbuckle and basement rock includes types of fractures, lengths of fractures, fracture aperture, lithology, and primary/secondary mineralogy. The different type of porosity and rock matrices affect fluid movement and can provide conduit for it. This research is important for understanding how and where saltwater disposed into the Arbuckle is migrating and whether individual formations act as fluid conduits, seals, or impermeable barriers.

Arbuckle core was described to understand formation scale variability in rock properties affecting fluid migration. Small-scale permeability measurements from 165 locations within an Arbuckle core ranged from 0.22–387.2 mD. These values represent the smallest scale of the study and likely the lowest reasonable matrix permeability for Arbuckle subsurface materials in the study. Measurements were taken along fractures, but resulting values may underrepresent the upper limits of Arbuckle permeability. Analysis of observed solid earth tides yielded a range of permeabilities from 285.5–1304.7 mD from two wells over an open interval within the Arbuckle. This range is at the largest on the scale for permeabilities measured. By analyzing pressure monitoring data, injection response via a slug test method, drill-stem tests, small-scale permeability from core, describing the fracture pattern, and examining well logs, better hydrogeologic and geomechanical models will be developed to understand fluid or pressure propagation from the Arbuckle and into the underlying Precambrian Basement.

GEOLOGIC, PERMEABILITY, AND FRACTURE CHARACTERIZATION OF

THE ARBUCKLE GROUP IN

THE CHEROKEE PLATFORM, OKLAHOMA

A Thesis

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by

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Chapter 1 Introduction

1.1 Background

The Arbuckle Group is a producing zone for oil and gas in the State of Texas and Kansas, but there is limited production in the State of Oklahoma (Sternbach, 2012). The Arbuckle Group, commonly referred to as the Arbuckle, is a deep brine carbonate reservoir in Oklahoma that is predominately used for saltwater disposal of co-produced water. The Arbuckle has been used for saltwater disposal because it is available in areas of oil and gas production, and it is able to accept large volumes of fluids (Morgan and Murray, 2015). The Arbuckle can accept large volumes of fluid because it is under pressured, and the reservoir contains fluid with exceedingly high total dissolved solids (TDS), greater than 35,000 mg/l, throughout the State of Oklahoma (Murray, 2016). A relationship exists between increased saltwater disposal and increased induced seismicity in Oklahoma. The driving force of an earthquake to occur and failure along a fault occurs when the pore pressure is increased as there is an increase in fluids into the subsurface which decreases the effective stress of the surrounding rock matrix (Kroll et al., 2017-Accepted; Walsh III and Zoback, 2015; Zhang et al., 2013). The hydraulic connections for migration of fluid from the Arbuckle to the underlying basement have yet to be defined since the petrophysical characteristics of the Arbuckle Group are not well understood in the State of Oklahoma. Other unknowns include the limits of saturation, pressure barriers, and the rock properties of the subsurface formations. The focus of this research project is to investigate a few of the petrophysical characteristics of the Arbuckle Group to understand how these properties affect subsurface fluid movement and explain their relationship to the underlying Precambrian Basement where earthquakes originate.

1.2. Salt-water Disposal and Seismicity

In the late 1970s and early 1980s, 128 earthquakes were reported in central and northern Oklahoma (Burchett et al., 1985; Luza and Lawson, 1981). Earthquake activity subsided until the late 2000's. In the mid-2000s, the Mississippi Lime and Hunton oil and gas plays were productive in Oklahoma and led to an increase in co-produced water. A 41.3 % increase in saltwater disposal (SWD) volume into the Arbuckle zone was reported over a five-year period starting in 2009, corresponding to an increase in seismicity recorded in the same region (Kroll et al., 2017-Accepted; Murray, 2014). In 2014, it was reported that 65% of co-produced saltwater was disposed of by injection into the Arbuckle (Murray, 2014). The apparent correlation between the increase in seismicity in recent years and the concurrent increased volumes of waste-water injection into the Arbuckle has increased research interest aimed at characterization of the reservoir properties of the Arbuckle because limited information is currently available (Horton, 2012; Keranen et al., 2013; Kroll et al., 2017-Accepted; Walsh III and Zoback, 2015; Weingarten et al., 2015).

Since late 2015 and continuing into 2017, the Oklahoma Corporation Commission has reduced the volume of saltwater allowed to be injected into the Arbuckle by deducting a percentage of the total amount injected and placing a cap on the amount injected into the Arbuckle (Commission, 2016). Operators have shut in several wells due to the increased regulation or decline in profitability. Shut in or inactive SWD wells were recognized in the past year as potential sites for monitoring pressure in the Arbuckle.

Currently, 14 wells in the Anadarko Shelf and Cherokee Platform are monitored for pressure, temperature, and fluid elevation changes using pressure transducers. Using information from pressure transducers, injection rates and volumes, hydraulic parameters of the Arbuckle can be calculated to better understand the relationship between SWD and seismicity occurring within the Arbuckle and the underlying Precambrian Basement in northern Oklahoma.

1.3. Geologic Background

The Arbuckle in Oklahoma was deposited in the Cambrian–Ordovician Period during the Sauk III (Morgan, 2012), when environmental conditions allowed for widespread deposition of limestone and dolostone with interbedded sandstone, siltstone and mudstone (Donovan and Ragland, 1986; Ham, 1955). The Sauk III was a transgressive period where a warm shallow sea moved onshore in what is present day Oklahoma, depositing shallow water carbonate sediments and interbedded sandstone, silt, and shale. The Arbuckle can be subdivided into six distinct formations that are correlated to units in Arkansas, Kansas and Texas (Carrell, 2014; Williams and Murray, 2016). From youngest to oldest, the Powell, Cotter, Jefferson City, Roubidoux, Gasconade Formations, Gunter Sandstone, and Eminence Dolomite are in northern Oklahoma and can be correlated to central Oklahoma where the formations are more commonly referred to locally as the West Spring Creek, Kindblade, Cool Creek, McKenzie Hill, Signal Mountain, and Fort Sill Formations (Figure 1) (Derby et al., 1991; Ethington et al., 2012; Fritz et al., 2012; Johnson, 1991).

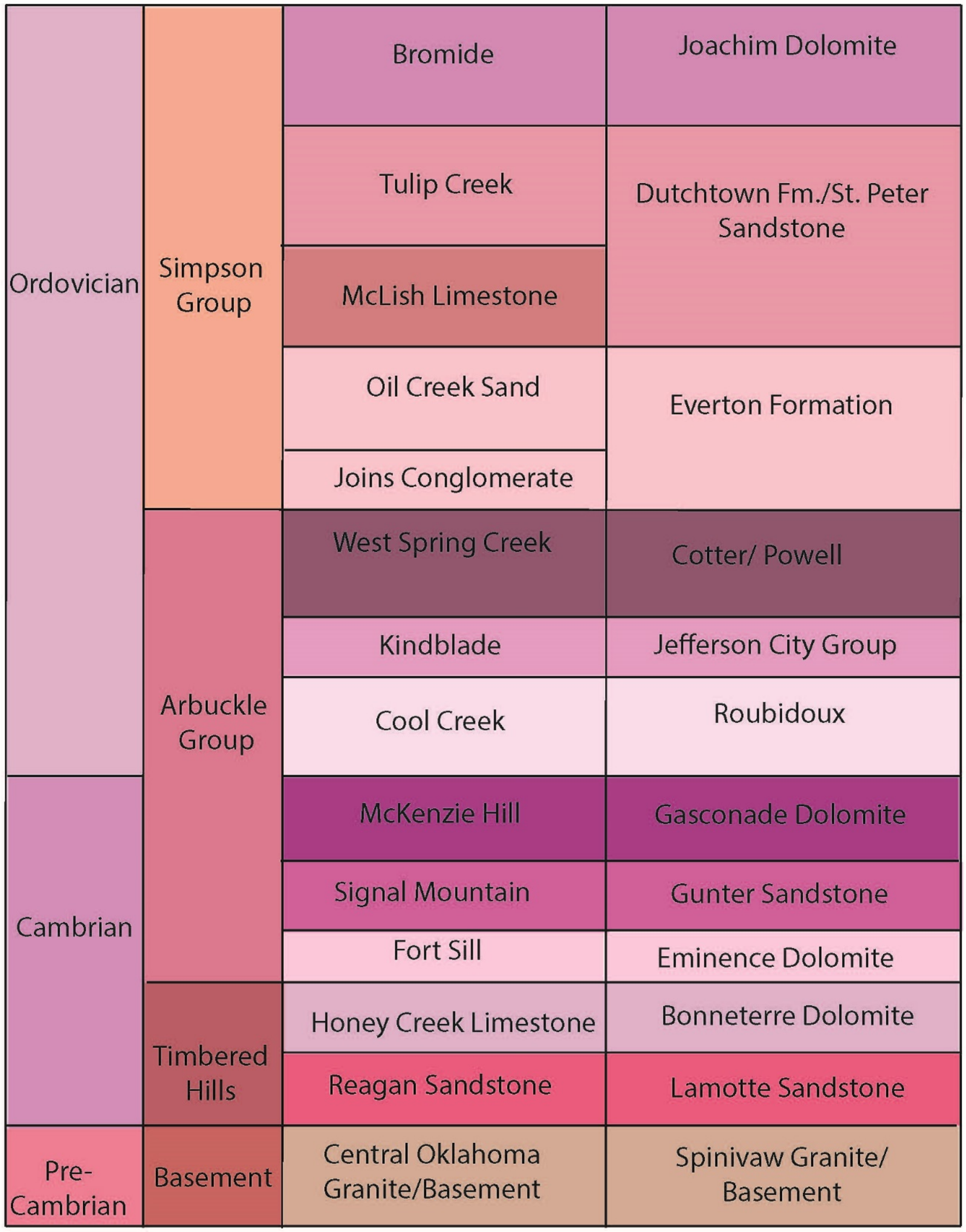

Figure 1 Geologic Timescale of the Arbuckle Group (modified from Carrell, 2014)

The underlying Precambrian Basement rock units are variable in composition but granites, rhyolites, and meta-granites are common. The Arbuckle varies in stratigraphic thickness across Oklahoma, from a few hundred feet to more than 3,000 feet (more than 914 meters) and exhibits heterogeneity in physical characteristics. The greatest stratigraphic thickness of the Arbuckle was the greatest in the Southern Oklahoma Aulacogen (SOA) in south-central and western Oklahoma. The SOA trends from northwest to southeast and was formed during the late Precambrian into the Cambrian, including the Ardmore and Anadarko Basins (Figure 2) (Donovan and Ragland, 1986)

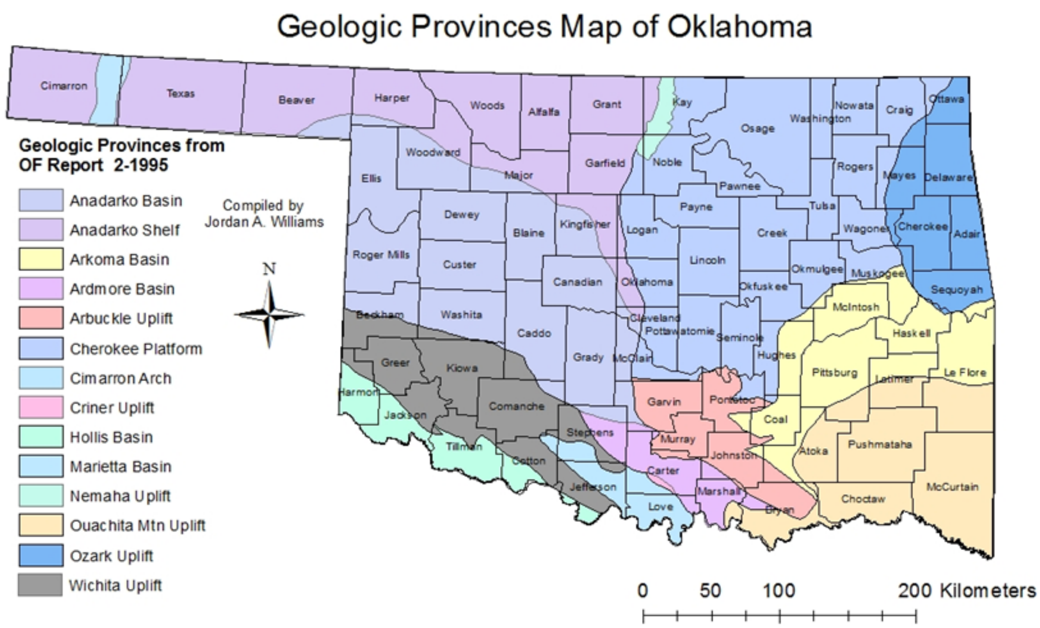

Figure 2 Geologic Provinces (Northcutt and Campbell, 1995) and Counties in Oklahoma

The depth below the land surface to the top of the Arbuckle is more than 30,000 feet (more than 9,144 meters) in the thickest part of the Anadarko Basin and outcrops in southern Oklahoma in the Arbuckle and Wichita Mountains. The study area for this research is the Cherokee Platform where the stratigraphic thickness of the Arbuckle averages about 1500 feet (457 meters). Sharp formation boundaries found in the Arbuckle suggest that the SOA continued to settle (Donovan and Ragland, 1986). A transition between the lowest formations, the Fort Sill and the Signal Mountain, shows an increased abundance of secondary minerals supporting a continued settling hypothesis. Post-depositional faulting and folding occurred as recently as during the Pennsylvanian in the southern part of Oklahoma. Less information on the subsurface characteristics of the Arbuckle are available in central and north-western Oklahoma, but faults are present along the western side of the study area in Cleveland, Logan, and Oklahoma Counties along the Nemaha fault zone.

Chapter 2 Objectives

Hydraulic properties of the Arbuckle have not been sufficiently characterized across the State of Oklahoma to answer pressing questions about the effects of saltwater injection into the Arbuckle. Because the Arbuckle is the primary disposal zone for wastewater from drilling activity and increased seismic activity is likely associated with increased injection volumes into the Arbuckle, it is important to understand the subsurface properties of the Arbuckle and the underlying basement. A variety of methods are available to calculate, estimate, and/or measure the hydraulic and physical properties of the Arbuckle, but a limited amount of such analyses has been completed within the study area. Hydraulic properties can be calculated using a variety of available data and methods, including observed solid earth tides, injection rate measurements, drill stem tests, and small-scale measurements of permeability. Other physical properties of the Arbuckle can be measured using geophysical (well) logs and core descriptions. The main objective of this research is to use a combination of data types and methods to characterize the hydraulic and physical properties of the Arbuckle within the Cherokee Platform region of Oklahoma. Petrophysical properties of the Arbuckle were estimated from the specific objectives listed below:

1. Development of a ‘type log’ for the Arbuckle in central Oklahoma from a concurrent study of core and geophysical logs at the same location, so that the individual formations can be identified from geophysical logs collected in other wells where core was not available;
2. Analyzing small-scale permeability from one core, the Union Texas Idema I, from Cleveland, County (southern Cherokee Platform);

3. Calculating permeability using drill stem tests from various locations throughout the Cherokee Platform;
4. Estimating the specific storage, permeability, porosity, storativity, and transmissivity from observed solid earth tides in Noble County using two inactive SWD wells designated as Noble 13 and Noble14;
5. Calculating permeability from active injection and downhole pressure monitoring using the Hvorslev slug test analysis method. This method was estimated from inactive SWD well in Pawnee, County, designated as Pawnee 11, which was temporarily activated.

The combination of methods, data, calculations and sampling listed above will provide characterization data that can be used to better understand and quantify the heterogeneity in lithology and physical properties, the scale (earth tide to small air permeameter) and range of permeability values measured at various geographic locations within the Arbuckle in the Cherokee Platform. Availability of such data should help geologists, hydrogeologists, and regulators better understand the movements of saltwater disposal injected into the Arbuckle.

2.1 Study Area

A large part of the research was a regional scale comparison of permeability values measured using different methods within the areas of increased seismicity in Oklahoma. The methods had different spatial scales with a range of permeability values. Analysis of injection volumes from Pawnee County, pressure monitoring data from Noble County, laboratory results from Rogers County, and core characterization from Cleveland County are incorporated into this multidimensional analysis of Arbuckle permeability that will focus on the Cherokee Platform (Figure 3). Limited data were available with regards to the subsurface rock properties affecting the permeability of the Arbuckle. Upscaling permeability values from the core scale to a regional scale is challenging but important to develop geomechanical and hydrogeologic models capable of accurately predicting fluid movement through the Arbuckle.

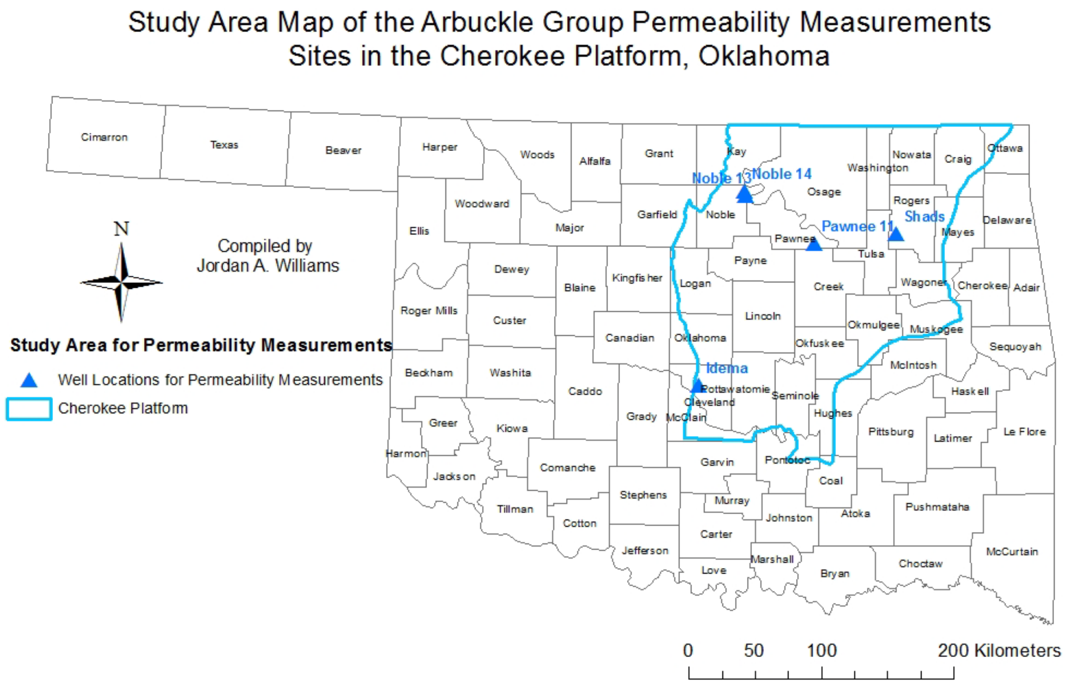

Figure 3 Study Area Map with Permeability Measurement Locations (Northcutt and Campbell, 1995)

Increased earthquake activity has been documented in central and northwestern Oklahoma. Since the 1980's, seismic activity was in quiescence, until activity increased in 2009 (Figure 4). The timing of increased seismic events in central and northwestern Oklahoma corresponds spatially and temporally with areas where increased saltwater disposal into the Arbuckle has occurred. Earthquakes in the 1970's–1980's reportedly corresponded spatially with increased oil and gas production and indicated there might be a relationship between changes in reservoir pressure and tectonic regime settling (Burchett et al., 1985).

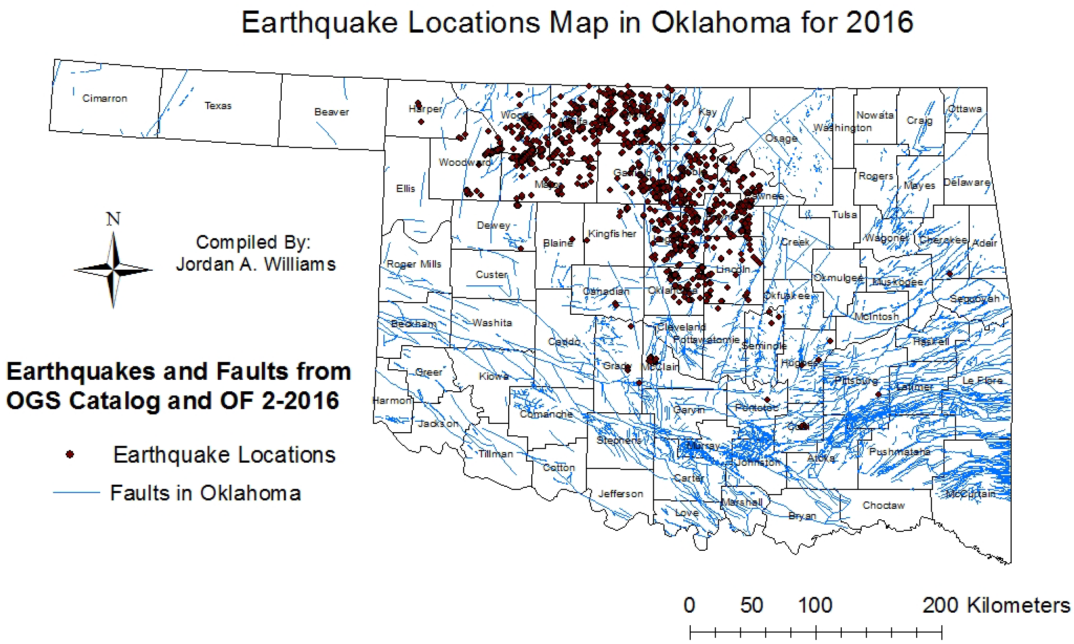

Figure 4 Comprehensive and interpreted surface and subsurface faults located in Oklahoma and seismic events in 2016 (Marsh and Holland, 2016)

Chapter 3 Methods

3.1 Geophysical Log Interpretation and Core Description

Cores extracted from drilling efforts into the Arbuckle across the Anadarko Shelf and Cherokee Platform were viewed at the Oklahoma Petroleum Information Center (OPIC) in Norman, Oklahoma in late May and early June 2016. The Union Texas Idema I (Idema) core along with six additional cores (Table 1) were described at the formation level within the Arbuckle. An additional core was viewed in 2017, the Amoco Shads No.4, that was previously described by Derby et al. (1991) . The descriptions were used to validate and compare the work completed on the Idema core in Cleveland, County. Core plugs were sampled from the Shads No. 4 core for laboratory analysis as well.

Table 1 Core Layout

API	Operator	Well Name	Well Number
35027500230000	Union	Idema	1
35093236460000	Continental	Mary Ellen	1-22
35047204210000	Shenandoah	Miesner	2
35093237190000	Nicor	Chestnut	18-4
35113304470000	Texaco	Osage C	1
35113029090000	Oliphant	Nate	1-A
35071237390000	Wedgewood	Biddle-burke	6
N/A	AMOCO	Shads No. 4	4

The core descriptions aimed to represent core where all known formations of the Arbuckle were present, core that penetrated down to the basement, and where unique stratigraphic markers were visible to correlation with core extracted at other locations. A 'type log' for the Arbuckle in central Oklahoma was developed by concurrently studying core and geophysical logs at the same location so that geophysical logs could be used for correlation to other wells where core was not available.

The Idema core was four-inches (0.11 meters) in diameter and stored in three feet (0.91 meters) sections in core boxes. Core descriptions were recorded on a foot (0.3048 meter) scale following the approach of Lynch and Al- Shaieb (1991) who created a table describing the lithology, texture, grain size, cement, porosity type, permeability, fracture type, and rock descriptions for an Arbuckle core. Data included in rock descriptions were the presence of secondary minerals, evidence for diagenetic alteration, primary and secondary dolomite and limestone, fossils, stromatolites, and facies changes.

Geophysical (well) log interpretations for the Arbuckle were completed by hand from printed copies of logs and using Petra software to analyze digital raster logs. Geophysical log interpretations were used to validate the core descriptions and define the tops of formations for maps of the Arbuckle. The logs were collected from old microfiche, strip logs, and well reports that were downloaded from OPIC, Tulsa Geologic Society (TGS), and IHS reports that included production reports, scout tickets, and well log summaries (IHS, 2010; TGS, 2010). Geophysical log interpretations were used to validate Arbuckle tops for the core and used to infer the individual formations within the Arbuckle subsurface. By identifying the individual formations within the Arbuckle, more accurate information can be calculated for the hydraulic parameters needed for geohydrologic modeling of fluid movements within the Arbuckle.

A study of the Arbuckle-Simpson aquifer in south-eastern Oklahoma (Christenson et al., 2011) provided a type log for reference. An additional type log available for comparison has also been described for the Ozarks region by Fritz et al. (2012). Background research for additional type logs for the Arbuckle in Oklahoma indicated the limited number of logs publicly available for study. Gatewood (1976-1979) correlated logs throughout the State of Oklahoma in the 1970s; however, limited geophysical cross sections and type logs from his collection are available for others to study. Researchers have developed type logs for regions in other geologic provinces in Oklahoma that were used for initial research. Christenson et al. (2011) examined the Arbuckle-Simpson aquifer in south-central Oklahoma, and Fritz et al. (2012) was studying diagenetic properties of the Arbuckle affecting oil and gas occurrence and production in south-eastern Oklahoma. Different depositional environments led to different stratigraphic thicknesses and compositions in these areas compared to the Arbuckle in the Cherokee Platform, exemplifying the heterogeneity observed in the Arbuckle across Oklahoma. Therefore, the use of core, hand samples and permeability measurements was necessary to validate the type log results for the Cherokee Platform.

3.2 Small-scale Permeability

Small-scale permeability measurements were used to capture the lower end member of spatial scale for permeability variability in the Arbuckle that was measurable using the Union Texas Idema core extracted in Cleveland County, Oklahoma. Measurements captured representative values from different orientations for the Idema core. The Idema core displays representative sections for the Arbuckle in the south-central region of the Cherokee Platform of Oklahoma. Each of the individual formations were represented in the core; however, the core is stratigraphically thinner than what has been estimated for the Arbuckle thickness in the Cherokee Platform. Permeability measurements were performed on the apparent horizontal and vertical axes and performed where fractured surfaces were visible. Fracture aperture was calculated from the permeability measurement data.

A hand-held permeameter, *TinyPerm II*, was used to capture permeability readings after timed intervals. All readings were converted to millidarcies (mD) using Equation 1. Timed intervals utilized were up to 300 seconds (five minutes).

$$T = -8.206 \times \log_{10} K + 12.8737 \text{ (Equation 1)}$$

Where,

T= Tiny Perm II Reading (dimensionless)

K= Permeability in millidarcies (mD)

The apparent vertical measurements were taken perpendicular to the face of a selected section of core. The surface, where vertical measurements were performed, was normally rough, weathered, and if fractured had slight offset on the surface. Fractured surfaces were measured along horizontal and vertical surfaces. Fracture apertures were calculated from the Tiny Perm II fracture readings using:

$$T = -1.5022 \times \log_{10} A + 8.2887 \text{ (Equation 2)}$$

Where,

T= Tiny Perm II reading

K= Permeability in millidarcies (mD)

A= Aperture in millimetres (mm)

3.3 Fracture Characterization

The Idema core from Cleveland County, Oklahoma was characterized for the relative volume of fractures, the fracture orientation, and fracture apertures. Fractures were recorded in the Idema well at each depth. The length of vertical fractures was measured if the beginning and termination points were visible on the exterior of the core surfaces. Horizontal and sub-vertical fractures could not be used to calculate fracture characteristics because both fracture end points must be visible for the necessary measurements to be made. Fracture aperture was calculated during permeability measurements using equation (2).

3.4 Laboratory Analysis of Core

The Amoco Shads No. 4 core was extracted from a test site in the northeastern Cherokee Platform in Rogers County, Oklahoma. Derby et al. (1991) previously characterized the core at the formation scale describing the lithology, fractures, and sedimentary structures. The well the core was extracted from was an experiment for Amoco to test drilling equipment. The company preserved core interpreted as Arbuckle (about 1295 feet, about 395 meters), Timbered Hills (about 100 feet, about 31 meters), and Precambrian Basement (about 460 feet, about 140 meters), which was viewed at OPIC before sampling. The Integrated Core Characterizations Center (IC3) and Integrated Poremechanics Institute (iPMI) are the two laboratories where petrophysical analysis was performed on seven plugs drilled from this core. Plug samples were chosen from each formation in the Arbuckle (i.e Cotter, Powell, Jefferson City, Roubidoux, Gasconade, Gunter Sandstone, Eminence Dolomite Formations) and within the underlying Precambrian Basement. Static and dynamic compressibility, porosity, permeability, and mineralogy are the rock properties measured from each two and a half inches in length (on average) by one inch (two and a half centimeters) diameter plugs.

3.5 Drill Stem Tests

Drill stem tests provide information about the rock and fluid properties of an interval within an entire formation. Originally the test was designed for the oil and gas industry to calculate the permeability of a set interval or to provide information about the subsurface fluids (Bredehoeft, 1965). There are hydrogeologic applications to solve similar problems. In central and northern Oklahoma drill stem test results are available and calculations can be performed using methods demonstrated by Bredehoeft (1965) in his paper on groundwater modeling.

The drill stem test measurements were collected from IHS Enerdeq reports online (IHS, 2010) and converted to permeability using Equation (3) from Bredehoeft (1965). Using Equation (3), the permeability for intervals in individual formations of the Arbuckle can be calculated.

$$P_w = P_o - 162.6 \frac{q_a \mu}{kh} \log(\frac{t_o + \Delta t}{\Delta t}) \text{ (Equation 3)}$$

Where,

P_w = Final shut in pressure in pounds per square inch (psi)

P_o = Initial shut in pressure in pounds per square inch (psi)

q_a= Rate of production barrels per day (BPD)

μ= Viscosity in centipoise (cp)

k= Permeability in millidarcies (mD)

h= Thickness of DST interval in feet (ft)

t_o= Time final open

Δt = Time final shut in

Drill-stem tests are not economically feasible to provide hydrogeologic information through the entire Arbuckle. Drill stem test data are limited to the 1944–2006 timeframe in Oklahoma because the technology has been superseded by the repeat formation tester (RFT), Modular Formation Dynamics Tester (MFDT), Wireline Formation Tester (WFT), or Multiprobe Formation Tester (MFT) methods. Drill stem tests are more abundant in units that are high producers for oil and gas across the State of Oklahoma, so there are limited drill stem test data from the Arbuckle, which has traditionally not been a major oil and gas producer within the State.

3.6 Solid Earth Tides

Pressure, temperature, rates of fluid movement, and depth affect subsurface studies of the Arbuckle and its hydraulic properties. Solid earth tides are the interactions between the sun, earth, and moon. The interactions create strain in the subsurface rock matrix, pressure and temperature changes that result in fluid fluctuation in confined and unconfined aquifers or reservoirs (Cutillo and Bredehoeft, 2011; Merritt, 2004). The solid earth tide method was appropriate for use in the Arbuckle of Oklahoma, because it calculates the earth tides intercontinentally and ignores ocean-tide patterns. Solid earth tide analysis was conducted using 35 days of data from two wells in northern Oklahoma: Noble 13, and Noble 14. Noble 13 and 14 are inactive SWD wells that previously disposed fluid into the Arbuckle (Figure 5).

Monitored Wells with Pressure Transducers Location Map

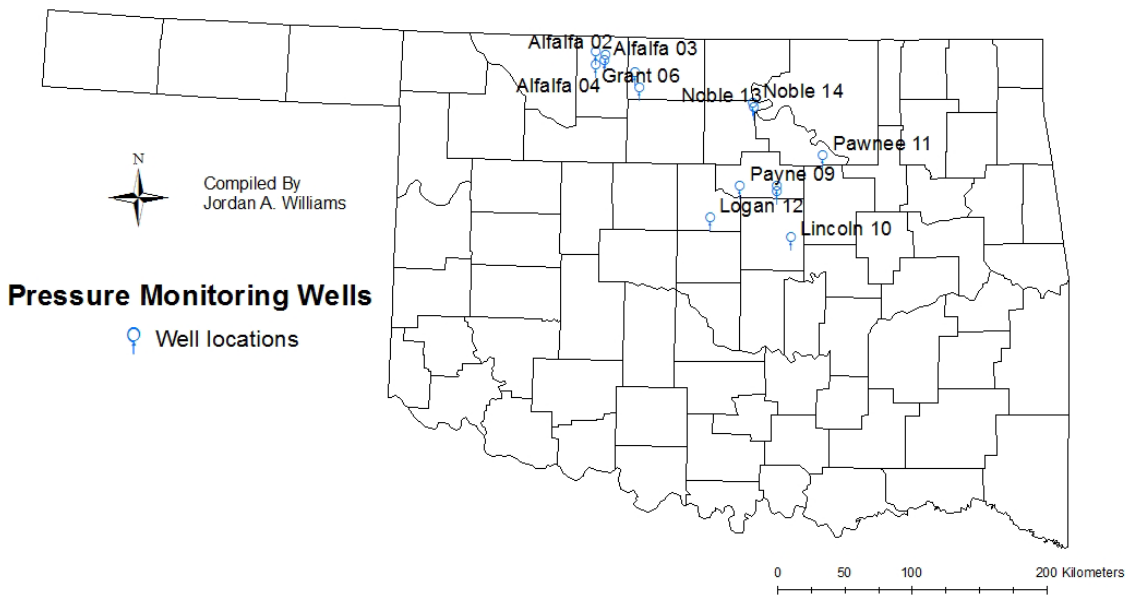

Figure 5 Pressure Monitored Well Locations

At each monitoring well, a water/oil interface probe measured the initial water levels in the borehole. L.R. McBride Inc. performed static pressure tests as baseline measurements to use for comparison and calibration. Solinst Leveloggers® were then deployed to measure downhole pressures and Solinst Barologgers® were deployed within ten feet of the wellheads to measure barometric pressure. Pressure transducers monitored the pressure, temperature, and water level changes every 30 seconds from the day of installation to present.

Calculations were made to estimate the permeability, porosity, specific storage, storativity, and transmissivity of the rock using Noble 13 and Noble 14 pressure monitoring data. The tidal analysis was performed using T-soft software, which is publicly available from the Royal Observatory of Belgium (Van Camp and Vauterin, 2005), and following procedures similar to those used by Cutillo and Bredehoeft (2011) to calculate the amplitude, frequency, and the phase shift of the tidal components. The tidal components $\mathbf{O_1}$ (lunar tidal diurnal), $\mathbf{K_1}$ (lunar-solar tide diurnal), $\mathbf{M_2}$ and $\mathbf{N_2}$ (semi-diurnal lunar tides), and $\mathbf{S_2}$ (semi-diurnal solar) (Cutillo and Bredehoeft, 2011; Hortle et al., 2012; Merritt, 2004) are the most common tidal components used in earth tidal analysis to calculate hydraulic properties. The $\mathbf{O_1}$ and $\mathbf{M_2}$ tidal components were used to calculate the specific storage, storativity, and transmissivity, porosity and permeability in Noble 13 and Noble 14, because the lunar tides ($\mathbf{O_1}$ and $\mathbf{M_2}$) are less affected by atmospheric pressure changes and the effects were not observed (Cutillo and Bredehoeft, 2011; Merritt, 2004). Limitations are placed on calculations using K_1, S_2 and $N_{2.}$ Most research involving tidal methods has not used these components when barometric efficiency and porosity has been calculated (Cutillo and Bredehoeft, 2011; Merritt, 2004).

The raw data from the pressure monitoring wells documented changes in pressure, measured in psi, and temperature measured in Fahrenheit every 30 seconds from February 2, 2017 to March 14, 2017. These data comprised the raw data set that was converted to metric units before calculations. The raw data was uncompensated for barometric pressure because barometric efficiency calculations showed that the reservoir was confined and not affected by barometric pressure changes. Water level measurements were analyzed by importing fluid level (normalized to elevation from pressure readings) into T-Soft. The water level recordings were filtered using a fast Fourier transform filter at a cut-off frequency of 1.5 and 1.0 at band pass for cycles per day (cpd). The spectrum was fit to the model to calculate the amplitude (m), frequency (cpd), and phase shift (degrees).

Table 2 Tidal components used to calculate hydraulic properties from observed solid Earth tide Analysis from Noble 14 (Van Camp and Vauterin, 2005)

Minimum Frequency	Maximum Frequency	Amplitude (m)	Phase Shift (degrees)	Name
0.921941	0.940016	0.00006	89.5602	O1
1.001972	1.003504	2.17786	-44.5194	K1
1.888387	1.906462	0.00005	160.0846	N2
1.924679	1.942753	0.00003	177.5164	M2
1.994524	2.002738	0.00004	126.9871	S2

Calculations of specific storage were based on methods used by Merritt (2004) and Cutillo and Bredehoeft (2011). Merritt (2004) followed the formula developed by Bredehoeft (1967), which was later modified by Kamp and Gale (1983) and Hsieh et al. (1988), which added compressibility of grains to the equation. The compressibility of grains is unknown in the Arbuckle for the specific wells measured at this time; therefore, we used the equation by Merritt (2004) to calculate specific storage of the Arbuckle.

$$S_s = -\left[\left(\frac{1-2v}{1-v}\right)\left(\frac{2\bar{h}-6\bar{l}}{ag}\right)\right]\frac{dW_2}{dh} \quad (Equation\ 4)$$

Where,

v= Poisson's Ratio is 0.25 (dimensionless)

$\bar{h}$= Love number, elastic property is 0.60 (dimensionless)

$\bar{l}$= Love number, elastic property is 0.07 (dimensionless)

a= Radius of the Earth is 6.3709×10^7 m

g=Gravity 9.8 m/s^2

The calculation in brackets remains constant. The negative in front of the brackets is explained by Merritt (2004) as "the head in the aquifer decreases as the tide-generating potential increases.” To complete the calculation in Equation (4) for $\frac{dW_2}{dh}$ Equation (5) and Equation (6) were used. Equation (5) calculated the amplitude of the tidal potential (Cutillo and Bredehoeft, 2011).

$$A_2 = gK_m bf(\theta) \quad Equation\ (5)$$

Where,

A_2= Amplitude of the tidal potential in squared meters per squared seconds(m^2/s^2)

K_m= Lunar coefficient in meters(m)

b= Amplitude factor (dimensionless)

$f(\theta)$=Latitude function (dimensionless)

The tidal components used to calculate A_2 were found in a chart provided by Cutillo and Bredehoeft (2011) and Merritt (2004). Equation (6) can be calculated with the final product of A_2 solved by dividing by the amplitude of the tidal component found in Tsoft (Van Camp and Vauterin, 2005).

$$-\frac{\Delta W_2}{\Delta h} = \frac{A_2}{A_w} \quad Equation\ (6)$$

Where,

ΔW_2= Theoretical tide generating potential

Δh = Change in height

A_w = Amplitude of the head change

There are two solutions: one for O1 and M2 tidal wave components. The two specific storage solutions are used for the rest of the calculations, including porosity, permeability, storativity, and transmissivity. The storativity (S), referred to as the storage coefficient, was calculated in Equation (7), using an estimate of the specific storage used above and the thickness of the unit (Cutillo and Bredehoeft, 2011).

$$S = S_s \times l \quad Equation\ (7)$$

Where,

S= Storativity (dimensionless)

S_s = Specific storage in inverse meters(m^{-1})

l= Thickness of the reservior in meters(m)

The total thickness of the Arbuckle reservoir is unknown across most of the State of Oklahoma, excluding that portion referred to as Arbuckle-Simpson aquifer. Formation tops within the Arbuckle are not well constrained over an entire study area, nor is the depth to the basement rock at the base of the Arbuckle over much of its areal extent well constrained. For the interpretation of the thickness of the Arbuckle, the thickness of the open interval from well completion reports (Commisssion, 2017) were used as the saturated unit thickness. If no open interval was listed, interpreted thickness of the Arbuckle was the top of the Arbuckle listed for the well drilled or the top of the production casing if it was listed below the top of the Arbuckle. From the 1002A reports, the top of production casing to total depth (TD) was commonly interpreted as the open interval (Commisssion, 2017). The reservoir could theoretically be the entire thickness of the Arbuckle and even extending into the Timbered Hills or Precambrian Basement; therefore; the values calculated using a smaller interval were more conservative and can be used as the lower range of values. Calculating a thicker unit would indicate values on the upper range of values for storativity and transmissivity. Equation (8) was used to calculate the transmissivity of the well in such cases (Cutillo and Bredehoeft, 2011) by using charts provided in Merritt (2004), which plot the dimensionless transmissivity versus the phase lag.

$$\frac{T\tau}{r_c^2} \quad Equation\ (8)$$

Where,

T=Transmissivity in squared meters per day (m^2 /d)

τ= Period (1/frequency,T)

r_c^2=Radius of the well casing in meters(m)

The storativity was not calculated using equation (9) due to limitations in the well production data, but storativity was demonstrated by (Cutillo and Bredehoeft, 2011) to calculate transmissivity using curve matching techniques from (Merritt, 2004) where the information was well known. The radius of open interval was unknown for most of the Arbuckle wells in Oklahoma. It was assumed they would be equal or less than the well casing, or the casing of the tubing could be used. By using equation (7) more information was provided about the subsurface formation.

$$\frac{Sr_w^2}{r_c^2} \quad Equation\ (9)$$

Where,

S= Storativity (dimensionless)

r_w^2= Radius of the screened or open portion of the well in meters (m)

r_c^2=Radius of the well casing in meters(m)

The hydraulic conductivity at each well location was then be computed using equation (10).

$$K = \frac{T}{b} \quad Equation\ (10)$$

Where,

K= Hydraulic conductivity in meters per day (m/d)

T=Transmissivity in squared meters per day (m^2/d)

b= Reservoir thickness in meters (m)

The permeability was calculated from the hydraulic conductivity using equation (11) (Fetter, 2001).

$$K = k\left(\frac{\rho g}{\mu}\right) \quad Equation\ (11)$$

Where,

K = Hydraulic conductivity in meters per day(m/d)

k = Permeability in millidarcies (mD)

p= Density in parts per million or kilograms per cubic meter (ppm, kg/m^3)

g= Gravity in meter per squared second (m/s^2)

μ=Kinematic viscosity in centipoise (cp)

The kinematic viscosity was found from the methods from Carrell (2014), using the density and temperature curves to estimate the viscosity values. Density values were used from a chart of total dissolved solids per county for each county in the State of Oklahoma by (Murray, 2016). Barometric efficiency was calculated using the amplitudes of the M_2 and S_2 tidal components to measure the atmospheric pressure effects (Acworth et al., 2015; Jacob, 1940). To calculate the barometric efficiency, the ratio of the tidal components S_2 and M_2 was found and then multiplied by M_2. This number was then subtracted from S_2 to provide the S_{h-2} value, which provides the value of the atmospheric pressure changes with the solid earth tides subtracted (Acworth et al., 2015). Barometric efficiency was also calculated using equation (12).

$$BE = \frac{S_{2h-earth}}{S_{2h}} \; Equation\ 12$$

Where,

BE = Barometric Efficiency (dimensionless)

$S_{2h-earth}$ = Hydraulic head response without earth tides in meters (m)

S_{2h} = Hydraulic head, solid earth tide amplitude response S_2 in meters (m)

The porosity was calculated using equation (13) (Cutillo and Bredehoeft, 2011). The compressibility of water used was 2.0×10^{-6}Pascals^{-1} from a chart of brine compressibility versus depth.

$$n = \frac{S_s * BE}{\rho g \beta_f} \; Equation\ 13$$

Where,

n = Porosity (dimensionless)

S_s = Specific storage in inverse meters (m^{-1})

BE = Barometric efficiency (dimensonless)

β_f = Compressibility of water in inverse Pascals (Pa^{-1})

ρ = Density in parts per million or kilograms per cubic meter (ppm, kg/m^3)

g = Gravity in meters per squared second(m/s^2)

The value was then multiplied by 100 to get a percentage.

3.7 Slug Test

An inactive saltwater disposal well in Pawnee County, Pawnee 11, started injection for a period of time while data was collected. The level logger and barologger stayed in the wellbore during this time. Using the injection time periods and the water level recorded with the pressure monitoring equipment, the Hvorslev slug test method was applied to measure the permeability at Pawnee 11 using equation (14) (Fetter, 2001). Only one injection period was measured at this time.

$$K = \frac{r^2 \ln(L_e/R)}{2Lt_{37}} \quad Equation\ (14)$$

K= Hydraulic conductivity in feet per day (ft/d)

L_e = The length of the open interval in feet (ft)

R= Radius of the well screen/open interval in feet (ft)

r= Radius of the well casing in feet (ft)

The hydraulic conductivity was found using this equation and then converted to permeability using equation (11).

Chapter 4 Results

4.1 Geophysical Well Logs and Interpretation

In Cleveland County, Oklahoma 232 feet (71 meters) of core were described in detail from the Idema well. The list of descriptions included: the depth, lithology, porosity type, permeability, and general notes. The core description's model used by Lynch and Al- Shaieb (1991)'s table found in the "Arbuckle Group Core Workshop and Field Trip" was used in this analysis. The core was described and compared to hand samples William Ham collected and identified from the specific formations described from outcrops in south-central Oklahoma in the Arbuckle and Wichita Mountains. From Ham's samples and literature (Ham, 1955), there appeared to be more karst processes and dolomitization in south-central Oklahoma (Johnson, 2003; Lynch and Al- Shaieb, 1991; Ragland and Donovan, 1991) compared to the study area in central Oklahoma. From Ham's work, there were additional formations described in southern Oklahoma which were identified as formations that formed from dolomitization and karst (Carrell, 2014; Ham, 1955). The formations were found regionally in southern Oklahoma and are not noted to be found within the present study area. The results from Ham (1955) showed the importance of comparing strata from different regions across Oklahoma and the heterogeneity and limited spatial extent of some of the Arbuckle formations.

The core was divided into facies zones A-E based on transitions identified on the geophysical well log for the Idema core and based on the described lithology, where natural transitions in the core were visible indicating different depositional environments. Based on core observations, geophysical well logs, and previous literature, missing sections of core were indicated; however, the sections remaining represent most facies found within the Arbuckle.

From central Oklahoma, the top zone (zone A) was a sandy-limestone with interbedded shale and sandstone. Stromatolites were the main sedimentary structure observed, along with secondary minerals i.e., anhydrite, glauconite and pyrite. The upper contact of the core was missing and the total stratigraphic thickness of this zone was unknown. The dark grey argillaceous brittle shale was broken, and it appeared that core was missing. It also appeared that there may have been significant compaction in the shale layers as they were well consolidated and had low permeabilities.

Zone B was only about 30 feet (about 9 meters) thick and was compositionally a limestone with bands of iron staining with peloids. The limestone was lighter in color, more of a grey-brown with iron band staining in areas, and transitions to a lighter grey. As before in zone A, the sandy limestone was a medium to dark grey.

The third major facies zone (zone C) was limestone and dolomite with areas of vuggy porosity, brecciated chert, and glauconite. Glauconite was abundant along broken planes and fractured surfaces within a brecciated zone of chert and dolomite. All the fractures in the brecciated chert were filled with calcite. Carbonate-mud, brecciated zones, and dolomitized limestone and dolostone were present. Core was suggested to be missing from this interval because there were smooth transitions at the top and base of zone C, but throughout the facies there were abrupt facies changes and broken core which cannot be oriented or placed back together in proper sequence with confidence. Zone C had large vertical fractures that extended through multiple pieces of core. The fractures were filled with calcite.

Zone D had large clasts of chert and dolomite as well as dessication features that suggested large vugs were infilled and replaced. Tidally influenced soft-sediment deformation and rip-up clasts were common in zone D. Fractures could be found on a small-scale off-setting beds planes. Glauconite was present at the top of the formation between eroded and broken beds. Glauconite could be secondary from subaerial exposure or formed during a diagenetic process (Donovan and Ragland, 1986). This facies was predominately a limestone with interbedded lime mud and shale which had been dolomitized. Dolomitization of the limestone and dolomite was found throughout the Arbuckle with increased volumes of dolomite in northern Oklahoma. There was a sharp contact between the lower two contacts of zone D and E, similarly found on the well log, where the shale and lime mud interbedded in limestone transition sharply to zone E.

Zone E was an algal boundstone with large deposits of fossils, glauconite and lime mud. This contact marked a change in environment and Donovan and Ragland (1986) stated the change in lithology and environment may indicate movement in the faults along the Southern Oklahoma Aulocogen. There were many small-scale fractures as it transitions from the facies in zone E up in stratigraphic section to the facies in zone D. Most of the fractures were vertical to sub-vertical. The timing of the fractures was unknown, but was post-deposition. It was most likely a compilation of fractures.

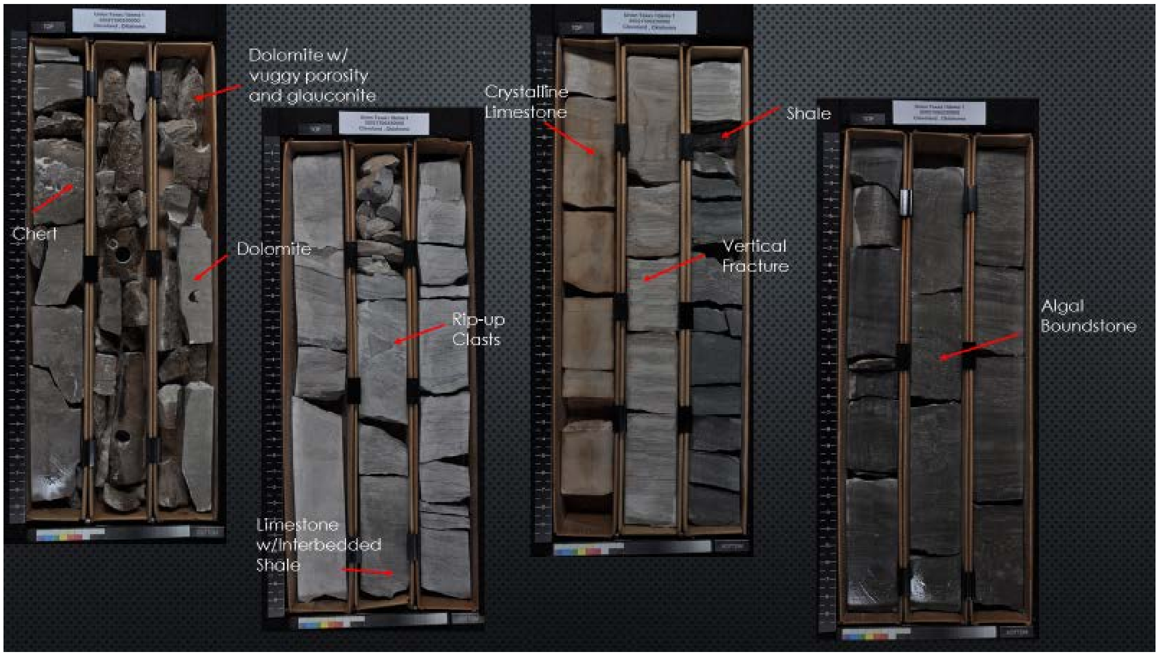

Figure 6 Examples of features commonly found in Idema core of the Arbuckle Group

Fractures developed in zone E, after zone E (algal boundstone) and zone D (limestone) were deposited and as the Aulacogen was settling later in the Paleozoic.

The depositional environment for the Arbuckle Group was a carbonate platform system with predominately tidal facies. The tectonic regime in Oklahoma and carbonate platform system help explain the heterogeneity of the Arbuckle across Oklahoma. The deposition fluctuated between intertidal-subtidal zones and supratidal-intertidal zones (Fritz et al., 2012; Ragland and Donovan, 1991). The intertidal and subtidal zones were identified by laminate bedding structures, stromatolites, scours, peliods, ooids, and carbonate clasts. The supratidal was more defined by the desiccation and evaporites in the uppermost shallow zone (Fritz et al., 2012; Ragland and Donovan, 1991); however, all tidal zones were very similar, and it was hard to differentiate many of the features due to the large percentage of secondary mineralization, dolomitization, and karst features (Figure 6).

The Idema core was compared to the Amoco Shads No. 4 (Shads) core in Rogers, County to understand a more regional view of the Arbuckle lithology. The Shads' well was in the north-eastern Cherokee Platform. The core was well preserved with all formations of the Arbuckle, Timbered Hills, and about 460 feet (about 140 meters) of the basement described. Core descriptions suggested the Shads well was deposited in a shallower environment than the Idema well, allowing for more karst processes to occur (Derby et al., 1991). Derby et al. (1991) reported conodont studies that provided more accurate age dating and correlation between the Ozark region and south-central Oklahoma. The Powell and Cotter formations were not laterally continuous over a study region and usually mark the unconformity between the Arbuckle and the overlying Simpson sands (Derby et al., 1991; Ethington et al., 2012). These two formations are composed primarily of dolomite and can be correlated to the West Spring Creek formation in central Oklahoma (Derby et al., 1991; Ethington et al., 2012). The lithology of the Shads core was primarily dolomite with interbedded sandstone and a smaller percentage of shale. Brecciated chert, vugs filled with dolomite, algae, and other fossils were also present (Derby et al., 1991). More limestone and shale was found in the Idema core while the Shads core was predominately dolomite at the top of the Arbuckle with more vugs infilled with dolomite. Both cores had evidence of secondary minerals which included iron bearing minerals (e.g. pyrite), glauconite, calcite and dolomite.

Formation tops were validated using geophysical log software (Petra) for initial log responses found on the caliper (CAL), gammaray density (GRD), gammaray neutron

(GRN), spontaneous potential (SP), and resistivity (RS) logs. Further detailed interpretation was completed through the analysis of each individual log by hand and compared depths from geophysical log software, well log summary reports, and scout tickets. The stratigraphic thickness of the Arbuckle ranged from an average of 300–1500 feet (91–457 meters) regionally. The exact depth and thickness for the Arbuckle, Timbered Hills, and Precambrian Basement were difficult to constrain with limited information from logs on the three groups, as also stated by Carrell (2014) from his study in northern Oklahoma. Geophysical well log summary reports indicated the total depth (TD) or total deviated depth (TVD) into the basement rock; however, many of the logs stopped logging/reporting at the top of the Arbuckle. Where reporting was completed, lines were extrapolated between wells to give an estimated top of formation until more information becomes available.

The top of the West Spring Creek (Cotter and Powell) was marked by a transgressive formation boundary between overlying sand unit or conglomerate. The Arbuckle was distinguished from the overlying sediments with a gamma ray log that shifts strongly to the right with a correlating shift to the left of the resistivity curve, as this was indicated as a shift from clean sands to a dirty sand/more carbonate rich lithology. The West Spring Creek is a carbonate-rich sand with interbedded shale and mudstone. Very few of the shale beds were distinguished in the logs, but some of the larger shales have a strong gamma ray response to the right with a correlating shift in the resistivity curve.

The West Spring Creek and Fort Sill were the easiest units to identify in the well logs. The Oklahoma City oil field is located in the center of the study area, providing numerous well logs in Cleveland, Logan, and Oklahoma Counties; however, the logs were obtained with much older technology and not all of them penetrate the total depth of the Arbuckle to basement rock. The biggest challenge working in central Oklahoma was finding well logs with information into or near the basement. More recent wells were drilled in Payne and Logan County to produce at shallower zones, and the need for a log in the Arbuckle was not deemed necessary. More logs were recently found in northern Oklahoma where there was an increase in drilling and increase in saltwater disposal wells.

Identifying the Kindblade (Jefferson City) formation required the analysis of multiple wells. The Kindblade tends to thicken and thin but had an average thickness of 30–50 feet (9–15 meters) in the study area. On most logs, it was easy to identify regression of the West Spring Creek sediments. In some wells, a sandy limestone unit was well defined. Markers between the Cool Creek (Roubioux) and the McKenzie Hill (Gasconade) followed a similar pattern. The tops for their formations were marked along sharp transgressive and regressive surfaces. Following the log curves for the Cool Creek, the SP and GR indicated the Cool Creek was more dolomitic with few shale or mudstone beds. Additional analysis of the RS curve provided evidence the McKenzie Hill had more shale and mudstone in the limestone composition. The McKenzie Hill limestone was dolomitized or partially dolomitized throughout the study area. The Fort Sill was not easily found in many of the logs, due to the depth constraints on the geophysical logs. The Fort Sill was typically 30 feet (9 meters) thick in logs and was characterized by a kick in the SP curve to the right with a corresponding RS curve to the right or a GR kick to the left with a corresponding RS response to the left.

4.2 Small-scale Permeability

Bradley (2013), described the Arbuckle in Kansas and the idea of studying the permeability of different formations for a cap rock or zones within the Arbuckle which might be impermeable. While this was not the scope of the current project in central and northern Oklahoma, this information would be beneficial in understanding the movement of water within the Arbuckle and underlying basement.

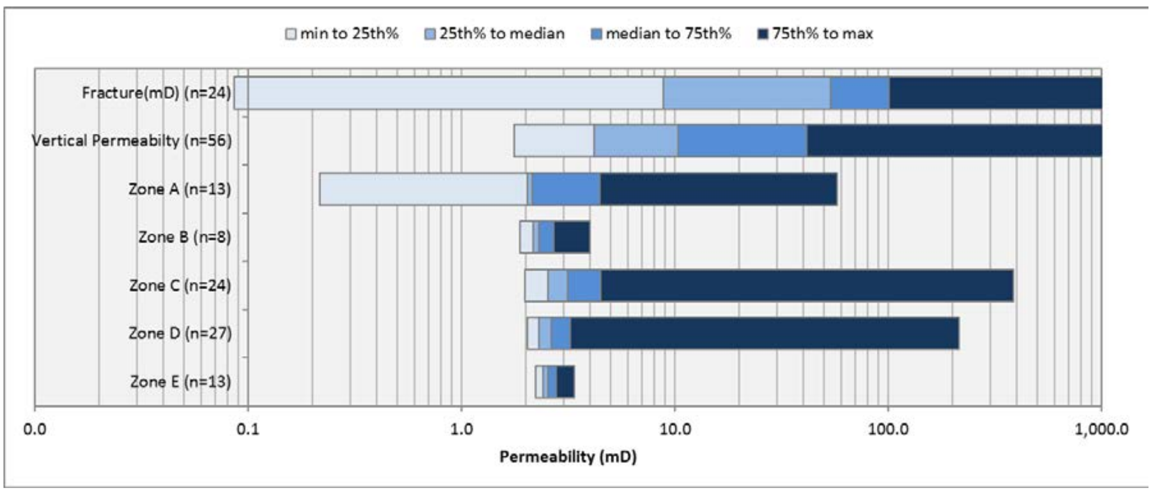

Figure 7 Small-scale permeability from Union Texas Idema

The apparent horizontal permeability has an overall median permeability of 2.6 millidarcies (mD) (Figure 7). The top zone A had the greatest variability with a minimum of 0.2 mD, maximum of 57.4 mD, and median of 2.2 mD with a slightly lower overall permeability. This zone was relatively impermeable compared to other zones. Zone B had the smallest range in values. The minimum was 1.8 mD, the maximum was 4.0 mD, and the median was 2.3 mD. Zone C (n= 24) and D (n=27) was sampled more heavily due to an increase in stratigraphic thickness and heterogeneity. Zone C had a minimum of 2.0

mD, maximum of 387.2 mD, and a median of 3.2 mD. Zone D had a minimum of 2.0 mD, maximum of 214.8 mD, and median of 2.6 mD. Samples were measured in dolomite, algal boundstones, along shale beds, and crystalline limestone, accounting for the highly variable permeability ranges. The other zones had more consistent lithologies over a thicker stratigraphic distance. The lowest zone E (13 measurements) has the smallest range in permeability values, with a minimum value of 2.2 mD, maximum of 3.3 mD, and median value of 2.6 mD. The values calculated indicated an impermeable zone in the apparent horizontal direction. The lithology of this zone was limestone and dolomite with algal boundstones.

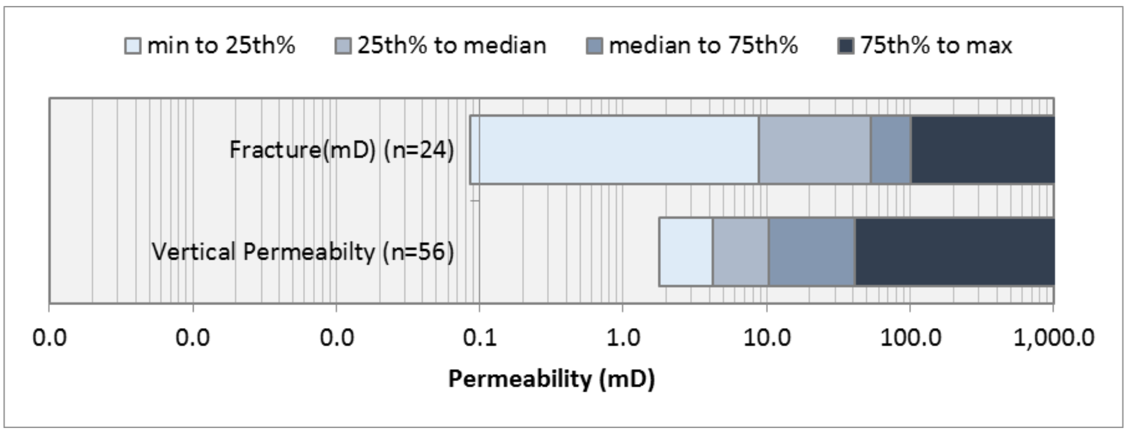

Figure 8 Fractured and Vertical Permeability

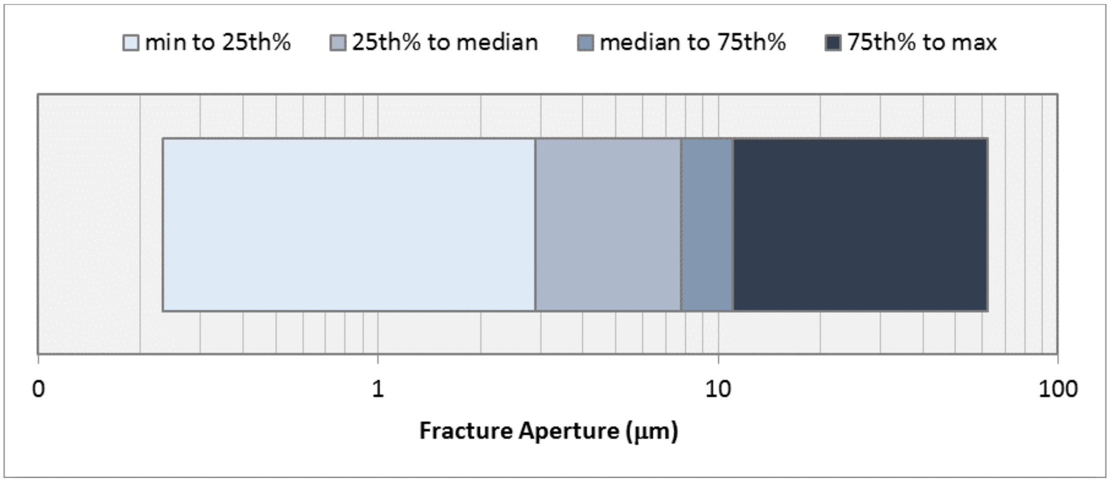

Figure 9 Fracture Aperture

Measurements from the face of the core and on the top and bottom of pieces of the core, which were fractured along the broken plane, were used to obtain fracture aperture values. The data was hard to obtain due to the rough surface of the broken planes. More measurements were taken along the face of the core where vertical fractures and offset of bedding surfaces was visible. The fracture aperture in the Idema had a minimum of 0.000 mD, maximum of 0.0062 mD, and median of 0.008 mD (Figure 8 and Figure 9). This was indicative of the small opening and infilled fractures which were filled with calcite. Fracture apertures that fell in the 75% to max range were beginning to open or were never mineralized. In Figure 10 and Figure 11, the permeability measurement results were divided into the lithologies found in the Idema core. Comparing the permeability results of the lithologies to the zone A-E permeabilities, the lithologic permeability shows more detail on why the zones and depths are more permeable. The lithologic permeability measurements help to explain the overall range of permeabilities when gaps in core are missing. In the vertical lithologic permeabilities, values of permeabilities are higher in brecciated dolomite/chert, dolomite, and dolomitized limestone, while in the apparent horizontal matrix measurements permeability is higher in dolomite and shale. Through the process of dolomitization, dolomite crystals alter the original fabric of the matrix and may be the cause for increasing the interconnectivity between crystals.

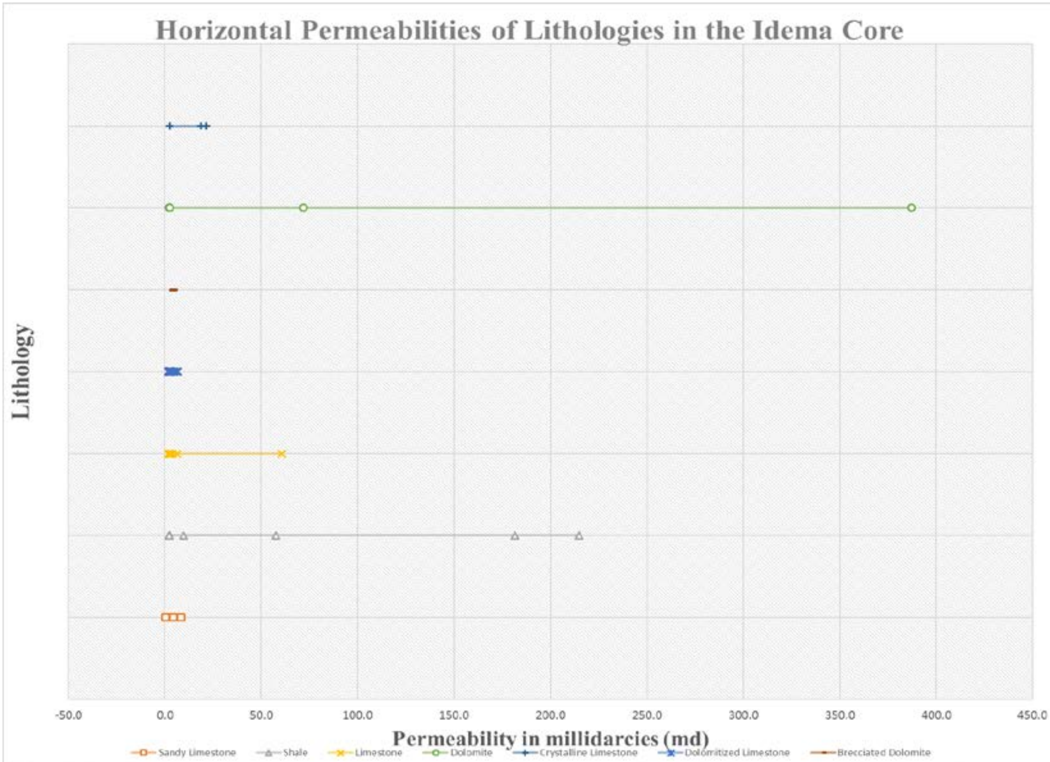

Figure 10 Permeability of based on lithology in the apparent horizontal direction of the Idema core

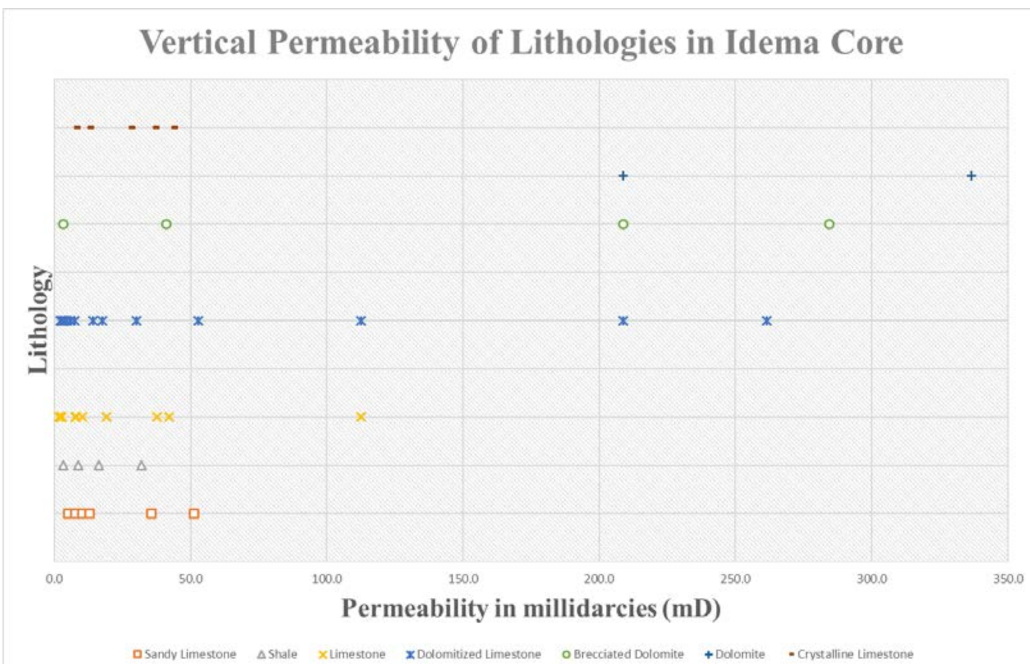

Figure 11 Permeability measurements based on lithology in the Idema core in the vertical direction

4.3 Fracture Characterization

A total of 125 fractures were measured in the Idema core that were in the vertical and vertical–sub-vertical direction. Limitations discovered when counting the number of fractures and length included: 1) the starting and termination of the vertical fracture had to be present to measure the length of a vertical fracture; 2) sub-vertical and horizontal fracture lengths could not be measured because they may extend further into the formation, and the core showed a relatively small areal extent; and 3) identifying which fractures were drilling induced versus formed during natural processes. Most of the vertical fractures had small splay fractures, measuring 0.1 feet (0.03 meters), off them. On average, the vertical fractures measured 0.8 feet (0.3 meters) long and the longest fracture was 5.1 feet (1.5 meters).

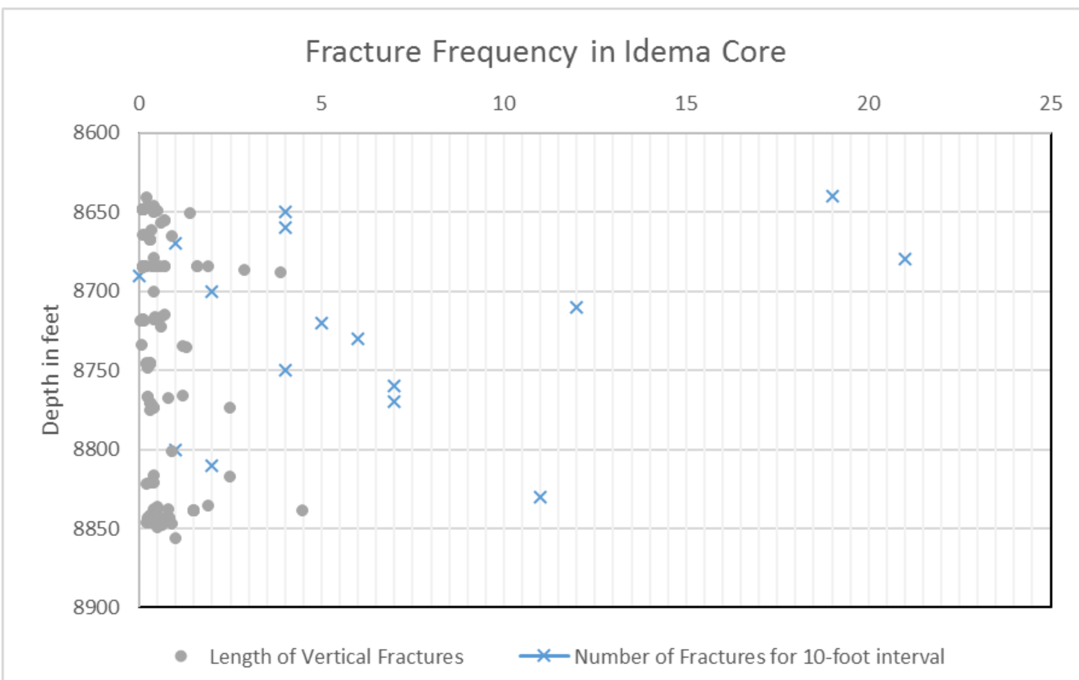

Figure 12 Fracture density in feet in Idema core

Nearly all observed fractures were filled with calcite. A large percentage of the fractures were concentrated in the central portion of the core (Figure 12), indicating a potential conduit for fluid migration and increased permeability. There was not a strong apparent relationship between the length of fractures and depth (Figure 12). It does not appear that any part of the Arbuckle was likely to be completely impermeable based on the vertical fractures observed throughout the core.

Orientation measurements of the fractures in the Idema core were to be measured, however, due to limited information only a relative orientation could be measured. The Idema core was not oriented; therefore, lines marking the direction of the core were used. The black and red lines indicate when the redline is on the right side the core is up-direction. Many of the fractures did not cross the red- line used for measuring the angle and could not formally be measured using this method. Many of the fractures were close to 0 degrees (close to vertical) and parallel with these lines.

4.4 Laboratory Results from Amoco Shads No. 4

Preliminary results from seven plug samples from the Amoco Shads No. 4 well are listed in Table (3) below. Samples taken from plugs were useful to validate results calculated using measurements from inactive saltwater disposal wells and small-scale permeability. One limitation of the plugs could be that permeability increased in the rock matrix when the rock was cut. However, the values calculated at different pressures in the preliminary results provided a range that was useful is creating models based on validated porosity and permeability values.

Table 3 Results of Porosity and permeability from seven plug samples from the Shads.No. 4.

Porosity	Cotter/Powell	Jefferson City	Roubidoux	Gasconade	Gasconade/Gunter Sandstone	Reagan	Precambrian Basement
Conf. Pressure	Sample 1	Sample 15	Sample 18	Sample 22	Sample 25B	Sample 26	Sample 29
800	12.49%	10.82%	8.28%	8.46%	0.35%	17.00%	0.36%
1500	12.51%	10.68%	8.21%	8.35%	0.27%	16.74%	0.34%
3000	12.41%	10.47%	8.24%	8.27%	0.28%	16.57%	0.26%
4000	12.42%	10.41%	8.26%	8.22%	0.23%	16.51%	0.20%
5000	12.44%	10.36%	8.14%	8.16%	0.17%	16.45%	0.19%
Permeability (mD)							
Conf. Pressure	Sample 1	Sample 15	Sample 18	Sample 22	Sample25B	Sample 26	Sample 29
800	1.902	1.334	0.045	0.119	0.002	0.929	0
1500	1.904	1.276	0.037	0.107	0.001	0.867	0
3000	1.899	1.198	0.028	0.094	0	0.803	0
4000	1.894	1.17	0.025	0.09	0	0.78	0
5000	1.895	1.151	0.023	0.087	0	0.762	0

4.5 Drill Stem Measurements

Drill stem test (DST) measurements located inwere in five counties of the study area. Each county had one or more tests with available data. From Cleveland County and the Idema I core, one DST was identified from well summary information provided by IHS (IHS, 2010). Drill stem tests from Cleveland and Oklahoma Counties had the largest sample sizes and best spatial distribution with 26 DST from 15 separate wells in Cleveland County and 20 DST from 8 different wells in Oklahoma County. Payne County had tests from two different wells and Lincoln County had three tests from two wells. Logan County had eight DST from seven wells. Overall, the spatial and vertical distribution of tests and wells provided more information characterizing individual intervals of the Arbuckle. The thickness and depth of the DST interval and spatial distribution across the study are two important measurements for the reliability in comparison of the drill stem test measurements to the small-scale permeability measured at specific depths.

Calculations to determine permeability from the DST followed the model used by Carrell (2014) in his master's thesis work, as he calculated the permeability of the Arbuckle in Kay County, Oklahoma. The calculations he used are applicable to the same study in central Oklahoma to form a hydrogeologic model of the Arbuckle where limited information was available. Out of the drill stem tests available in central- Oklahoma, 24 of the 59 total were able to be used in permeability data calculated based on the amount of information provided on the well summary data sheet (IHS, 2010).

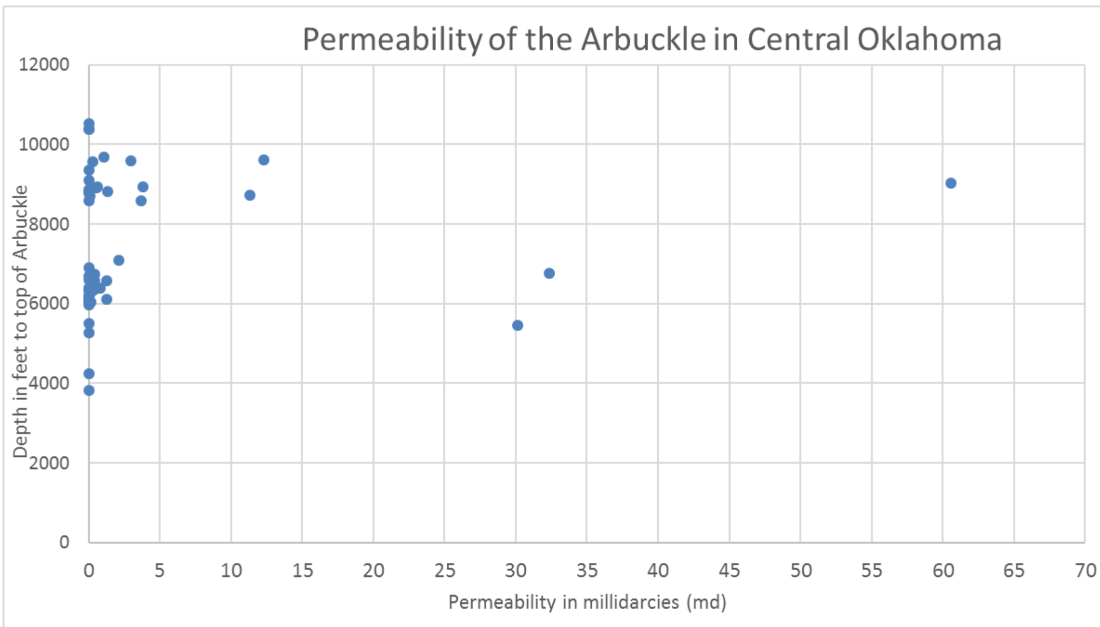

Figure 13 Permeability calculated from drill stem tests in five counties from the central Oklahoma Cherokee Platform Region

Values of permeability were calculated between 0.005 101.2 mD for Cleveland, Lincoln, Logan, Oklahoma, and Payne counties (Figure 13). These counties were used as part of the 'type log' study of the lithology and permeability of south central region of the Cherokee Platform where increased seismic activity in this region has raised concerns, and Carrell (2014) provided DST results in his master's thesis which focused on northern

Oklahoma and selected other regions throughout the State. By comparing the results from Carrell (2014) and results in the current study, it is evident that the permeability range is highly variable across regional scale. Carrell (2014) reported higher values of permeability in northern Oklahoma. The large range in permeability can be attributed to: 1) differences in depth of measurement, 2) differences in selected intervals which were tested, 3) lithologic differences including karst features and 4) differences in porosity type. Values of zero were calculated because the information needed to calculate permeability was not recorded.

4.6 Solid Earth Tides

Evaluating the solid earth tides required filtering the data to evaluate the earth tides from the fluid elevation changes. By using the fast Fourier transform filter (Figure 14), the solid earth tides were accentuated. Two cycles were detectable per day (Figure 14) using the parameters 1.5 and 1.0 cutoff frequency and bandpass in cycles per day. From the water level elevation data, the fluid levels are steadily dropping over time. The date of installation was February 2, 2017, and the last day of data analyzed was March 14, 2017. The spectrum below was for Noble 13 that was completed in the Arbuckle.

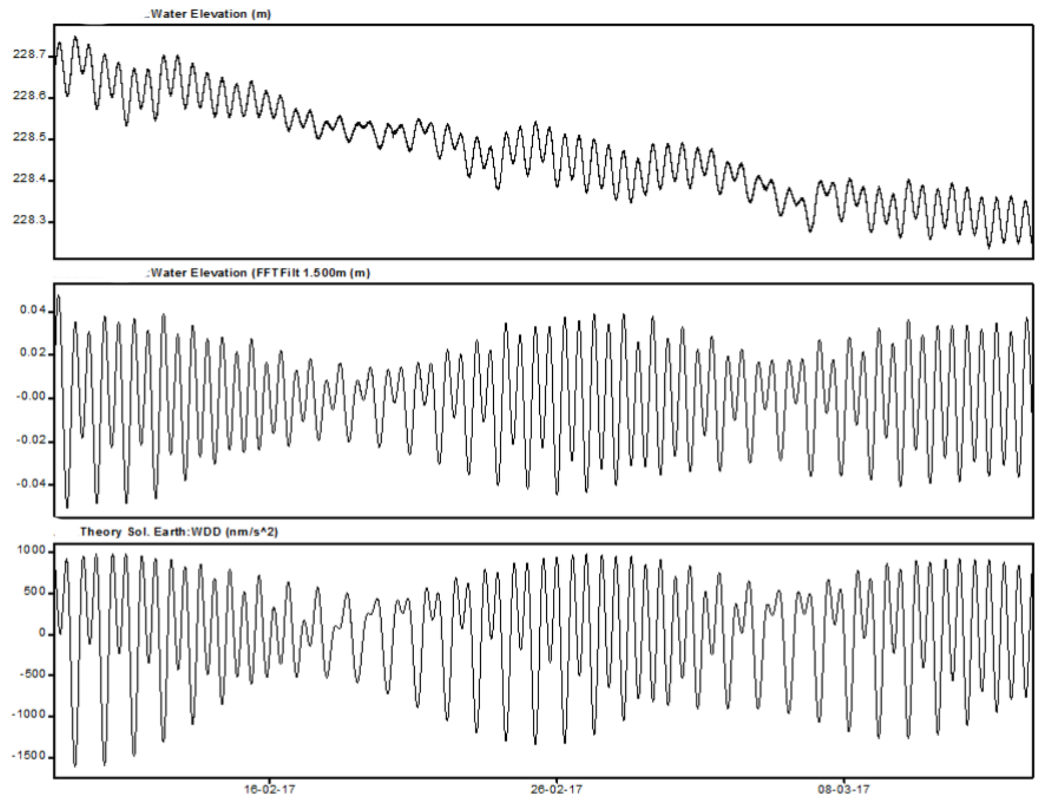

Figure 14 Raw data filtered with fast Fourier transform filter using Tsoft and displaying the theoretical solid earth tide at the latitude of Noble 13 (Van Camp and Vauterin, 2005)

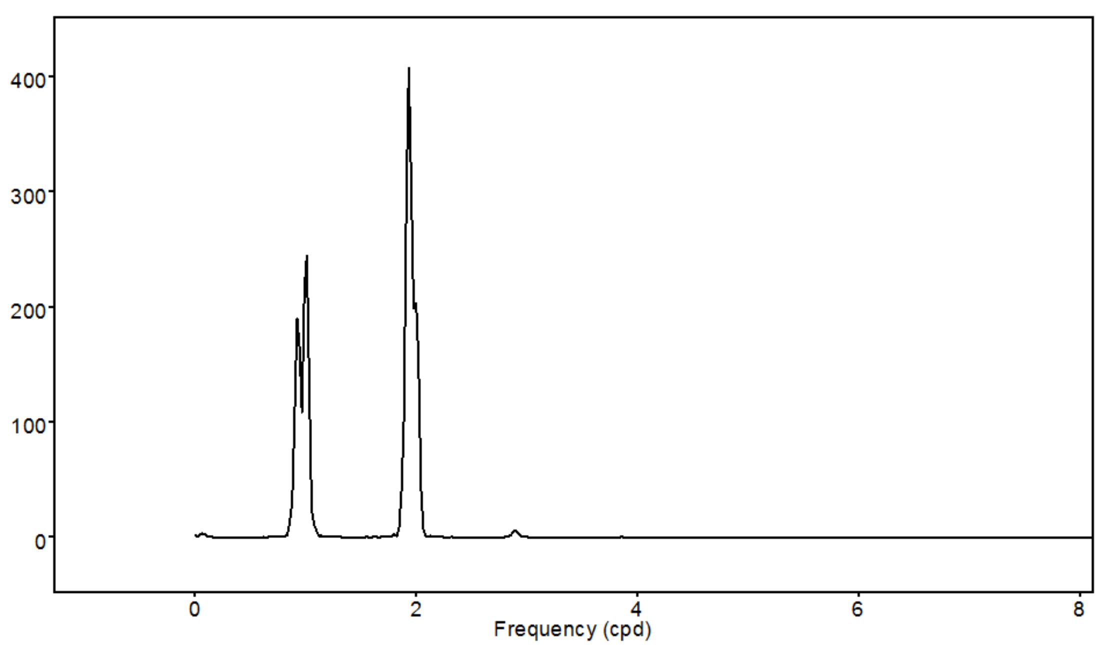

Figure 15 Noble 13 Fast Fourier transform spectrum using Tsoft (Van Camp and Vauterin, 2005)

The spectrum in Figure (15) shows the tidal components after the fluid elevation was filtered. The data matches the tidal pattern for two cycles per day with the O_1 tidal component at one cycle per day and the M_2 at 2 cycles per day. Noble 13 filtered data responds similar to examples of theoretical solid Earth tide components, where the O_1 (principle lunar) component has 0.9295 frequency (cpd) in a period of 1.0758 days, while the M_2 (principle lunar) component has 1.9324 frequency in a period of 0.5175 days (Cutillo and Bredehoeft, 2011). From this spectrum, the height of the M_2 and S_2 peaks were used to calculate the ratio between S_2 and M_2 for calculating barometric efficiency (Acworth et al., 2015).

The tidal components computed in Tsoft software are presented in Table 4.

Table 4 Results from Tsoft for tidal components in Noble 13

Noble 13	Minimum Frequency	Maximum Frequency	Amplitude (m)	Phase Shift (degrees)
O_1	0.921941	0.940016	0.00003	106.0527
M_2	1.924679	1.942753	0.00005	-174.312
S_2	1.994524	2.002738	0.00004	179.7359

From the results using Tsoft, porosity, permeability, storativity, and transmissivity were calculated and are shown in Table 5 for Noble 13. The values of specific storage and transmissivity are identical for Noble 13 and 14 because the specific storage was dependent on the latitude function which varied by a small degree because the wells are in close proximity. The dimensionless transmissivity values were the same because the casing of the well and specific storage for the wells were identical. To calculate the transmissivity, graphs plotting the storativity as a function of the amplitude and dimensionless transmissivity were provided by Merritt (2004). The values began to vary when calculating permeability, porosity, hydraulic conductivity, and storativity which are dependent on the amplitude of the tidal components and the thickness of the open interval. The thickness of the open interval for Noble 13 was 393.5 meters thick and 310 meters for Noble 14. The barometric efficiency was calculated as zero using the method described in this paper for Noble 13. Therefore, the porosity was not calculated for Noble 13. The calculation was zero in this well because the amplitude of the M_2 and S_2 tidal components were both 0.0002 mm; however, the barometric efficiency was close to zero with a high porosity value.

Table 5 Results from Noble 13 solid Earth tides

Noble 13	Specific Storage(m^{-1})	Transmissivity (m^2/d)	Storativity	Barometric Efficiency	Porosity	Permeability (mD)
O_1	-1.31386E-09	~100–360	5.17006E-07	0.38	22.44%	285.5–1027.81
M_2	6.54947E-10	~100–360	2.57722E-07	0.38	11.18%	285.5–1027.81

The results for barometric efficiency found in wells Noble 13 and Noble 14 were indicative of a confined aquifer (Table 6). The results of Noble 13 and Noble 14 were a barometric efficiency of 0.38 and 0.63, respectively. Values typically range between 0 and 1, with values closer to 1 indicating a confined aquifer. The tidal components used to solve for the hydraulic parameters for Noble 14 are shown in Table 5.

Table 6 Results from Tsoft for tidal components in Noble 14

Noble 14	Minimum Frequency	Maximum Frequency	Amplitude (m)	Phase Shift (degrees)
O_1	0.921941	0.940016	0.00006	89.5602
M_2	1.924679	1.942753	0.00003	177.5164
S_2	1.994524	2.002738	0.00004	126.9871

The values in Table 7 were based on the calculation of barometric efficiency, permeability, porosity, specific storage, storativity, and transmissivity for Noble 14 after the well was plugged back 208 feet (63.4 meters). The well was originally drilled into the basement and plugged back into the Arbuckle.

Table 7 Result from solid Earth tides from Noble 14

Noble 14	Specific Storage(m^{-1})	Transmissivity (m^2/d)	Storativity	Barometric Efficiency	Porosity	Permeability (mD)
O_1	-1.31386E-09	~100–360	5.17006E-07	0.63	36.91%	362.5–1304.74
M_2	6.54947E-10	~100–360	2.57722E-07	0.63	18.24%	362.5–1304.74

4.7 Slug Test

The Hvorslev slug test method was applied to the injection data by finding the highest water level rise and plotting the time until it reached static levels (Figure 16). The time at t_{37} was applied to the equation to find the hydraulic conductivity and permeability.

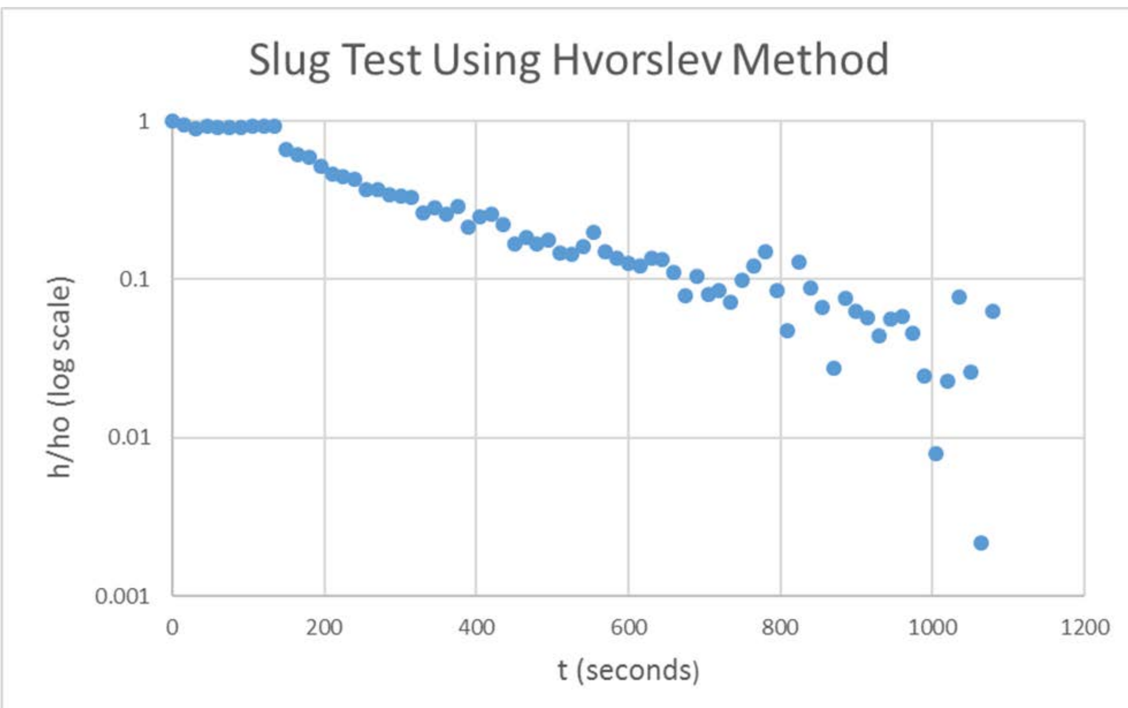

Figure 16 Permeability calculated from injection using Hvorslev slug test method.

The t_{37} in seconds was 255 with the max height of water level rise of 936.5 feet (285.4 meters) and the initial static level was 710.5 feet (216.6 meters). The hydraulic conductivity was 0.062 ft/d (0.019 m/d) and the permeability was 0.12 ft/d (0.37 m/d).

Chapter 5 Conclusions

The methods I-V were measured on different scales with the results listed based on the smallest-scale of permeability measured up to largest areal extent. The top of the Arbuckle was identified in the Cherokee Platform, but a 'type log' was not developed due to the number of logs that that penetrate the entire open interval of the Arbuckle to the Precambrian Basement. Characterization of individual formations within the Arbuckle Group from core was not identified in the Idema core. Zones A–E were marked by the transgressive and regressive sequences in the Idema well log used in the core characterization and small-scale permeability. Permeability results were obtained using different methods that affected different volumes of material. Ranges in permeability were identified for the different methodologies and can be used to create hydrogeologic and geomechanical models.

The small-scale permeability results found Zones C and D had the highest median permeability which is attributed to the heterogeneity in lithology and increased stratigraphic thickness, so more measurements were taken throughout these zones. Zone A had the lowest median permeability. The permeability ranged from 0.2 – 387.2 mD (matrix) in 165 total measurements. The range is 0.09 – 2399.3 mD in the fractured measurements. The drill stem test measurements were from a specific interval and not representative of the entire Arbuckle. The permeability ranged from 0.005–101.2 mD. From the largest interval of the Arbuckle, permeability was measured from the observed solid earth tides in Noble County were 285.5–1027.8 mD and 362.5–1304.7 mD from Noble 13 and Noble 14. Permeability from injection data using the Hvorslev slug test method from Pawnee 11 was calculated as 0.12 ft/d.

From the permeability measurements calculated and descriptions from core characterization, the information in this thesis was developed for scientists, researchers, industry, and policy makers to better understand the Arbuckle and its hydrogeologic relationship with the underlying basement rock where recent seismic events have originated. From the study of the Cherokee Platform, the range in permeability values could be used to create better hydrogeologic and geomechanical models to improve drilling practices. More studies should be conducted to improve the formation level characterization and provide better petrophysical characterization of the Arbuckle. The hope would be to identify specific intervals where fluids could be injected safely and they can be constrained by an impermeable layer or layers. This type of information is necessary to determine if disposal in the Arbuckle is feasible within certain formations and certain volumes of injected wastewater. From this analysis, there appears to be highly brecciated zones and fractured zones. There are areas with few fractures, but more studies would have to be completed to constrain exact thickness, depth, and lateral continuity of fractured zones across the Cherokee Platform.

Chapter 6 Discussion

From the small-scale permeability measurements, there were not any impermeable zones identified in the horizontal direction. Zones A and B had the lowest overall median permeabilities. The highest median permeabilities were in zones C and D with the most heterogeneous lithology in these two zones. The range for permeabilities was variable and ranged from 0.2 mD in zone A up to 387.2 mD in zone C. Vertical fractures exist in zones A-E, with many of the fractures offsetting bedding planes. The fractures created are likely to represent conduits for fluid movement to underlying Precambrian Basement. The small-scale permeability represents the lowest end member of permeability values due to the limitations of the hand held permeameter. Some surfaces were not suitable for measurement with this technique. Comparing the permeability measurements calculated in each lithology, the permeability in the vertical orientation of the Arbuckle from Idema core was higher when the core composition was predominately brecciated dolomite, dolomite, or dolomitized limestone and shale. From measurements in the apparent horizontal direction, dolomite and shale resulted in the highest permeability values. Intercrystalline porosity was observed in crystalline limestones; however, permeability values in these formations was generally low.

Drill stem test measurements were only applicable for specific intervals of measurement but lack detail for finer scale determinations and are also not representative of the entire Arbuckle. Small-scale permeability measurements captured permeability at a specific point on a rock surface, whereas observed solid earth tides and injection methods using a slug test represent the approximate depth weighted average permeability for the entire thickness of the Arbuckle at that point. From small-scale to real-time monitoring, conclusions can be drawn that the permeabilities of the Arbuckle on average are around 0-10 millidarcies on the lower end member and can range to values over one darcy. This regional study is important for understanding the hydraulic parameters of the Arbuckle where little to no information has been generally available.

Calculations of solid earth tides estimated the specific storage, storativity, porosity, permeability, and transmissivity in Noble 13 and 14 monitoring wells. The values resulted in similar results between the two wells, indicating the wells were injected into a confined reservoir, the Arbuckle. The barometric efficiency from Noble 13 is 0.38 and Noble 14 is 0.63. These barometric efficiency values are reasonable for a confined aquifer, which typically range between 0 and 1, but are typically closer to 1 for confined aquifers. Factors that could be affecting the fluid levels include nearby injectors, wells currently being drilled, or tectonic shifts. The wells, Noble 13 and 14, were assumed to be from in a confined aquifer in this analysis based on the information available. From plots in Tsoft and values calculated, there is not a sharp decline in fluid elevation; rather, there is slow steady decrease in Noble 13, and in Noble 14 there was a slight increase in pressure followed by a steady decrease. Injection volumes have reduced across the state of Oklahoma, concurrent with the pressure and fluid elevation decreases in Noble 13 and 14. The pressure changes in the wells are visible by water level fluctuations. It appears the water levels are declining to a normal static level before injection volumes increased in 2009, and water is migrating to other subsurface formations (i.e. the Timbered Hills and Precambrian Basement). The Arbuckle was assumed to be a confined aquifer, but the measurements for the thickness were measured using the open interval reported by industry. The values reported here only represent one interval which may only include one formation within the Arbuckle. The open intervals in Noble 13 and 14 are 913 feet (278 meters) and 993 feet (303 meters) below the ground surface. This shallow depth is one explanation for why the wells have mixed unconfined and confined aquifer results. The formation and lithology of the open interval is another possible explanation.

Further investigation will continue to constrain the formations that are included in the Arbuckle. The continued efforts to better characterize the Arbuckle with formation level detail would help quantify relatively simple characteristics such as the stratigraphic thickness, where the measurements for the hydraulic parameters are from, and more accurate drilling practices. The wide range of heterogeneity and known karst features could also be better understood.

The Arbuckle in the study area was deposited along the continental shelf in central Oklahoma. Along the shelf in Oklahoma, near Oklahoma County, the composition of the Arbuckle changes from limestone to dolomite (Johnson, 1991). This area is referred to as the hinge line, and this hinge line is a possible explanation for the difference between the Idema core in Cleveland County being composed of predominately limestone, which has been dolomitized, and the Shads core in Rogers County being dolomite with sandstone and shales (Derby et al., 1991). The tectonic history of the area might also explain the relatively thin stratigraphic thickness of the Arbuckle in central-Oklahoma. The Arbuckle was reported as a tidally influenced environmental system in south-central Oklahoma and south-eastern Oklahoma (Fritz et al., 2012). During the deposition of individual formations, there could have been a lag in depositions from the transgressive-regressive sequence, inhibiting deposition in central-Oklahoma. The location of the core was extracted from a well along the west side of

Cleveland County near the Nemaha fault zone where truncation of formations within the Arbuckle may have occurred due to uplift and/or erosion. The Arbuckle is found to be deposited in a shallower region in northern Oklahoma. Denison (1981) indicated that the Arbuckle was deposited on the basement in northern Oklahoma and other studies suggest the Arbuckle was never deposited on high basement reliefs (Derby et al., 1991). The Arbuckle, which is part of the Great Carbonate Bank, deposited in the Sauk III (Morgan, 2012), can be correlated across the United States but tends to thicken and thin and even pinch out in some areas. The composition of the carbonate group has widespread heterogeneity with limestone and dolomite being predominate and sandstone, shales, and anhydrites interbedded (Derby et al., 1991; Ethington et al., 2012; Johnson, 1991; Lynch and Al- Shaieb, 1991; Morgan and Murray, 2015; Morgan, 2012; Williams, 2017).

Chapter 7 Future Work

Characterization of the Arbuckle in formation level detail, petrophysical analysis of rock properties from plugged core, and calculations from pressure monitoring wells will continue as a part of a project in Oklahoma to understand the relationship between the properties of the Arbuckle and induced seismicity in the underlying basement. Analysis of the Amoco Shads. No. 4 plug samples is currently in progress in the Integrated Core Characterization Lab. The plugs are cut and polished before testing. Testing will start in in mid-April 2017.

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