Spring 2024

Subsurface Mapping of Intra-Arbuckle Shale in North-West Kansas Using Well Log Data

Cole M. Denny
Fort Hays State University, coledenny88@gmail.com

SUBSURFACE MAPPING OF INTRA-ARBUCKLE SHALE

IN NORTH-WEST KANSAS USING

WELL LOG DATA

A Thesis Presented to the Graduate Faculty

of Fort Hays State University in

Partial Fulfillment of the Requirements for

the Degree of Master of Science

by

Cole Denny

B.S. Geosciences, Fort Hays State University

Date 4/17/2024

Approved ______________________
Major Professor

Approved ______________________
Dean of the Graduate School

This Thesis for

The Master of Science Degree

By

Cole M. Denny

has been approved

Dr. Jonathan Sumrall, Committee Chair

Dr. Henry Agbogun, Committee Member

Dr. Todd Moore, Committee Member

Dr. Todd Moore, Chair, Dept. of Geosciences

ABSTRACT

The aim of this research was to enhance knowledge of Intra-Arbuckle Shale (IAS) distribution and structure through new maps, cross sections, and well log correlations. Understanding the shale(s) ultimately advances the discernment of complex Arbuckle reservoirs that are critical to the Kansas petroleum industry. IAS has been intercepted by oil wells throughout Kansas, but this study focuses on their presence in portions of Ellis, Rooks, Graham, and Trego counties. To study the distribution and structure of IAS, data from micro-resistivity and gamma ray well logs were collected from more than three hundred Arbuckle oil and gas wells. On each well log, properties such as sub-sea level elevation and depth were taken for both the Arbuckle top contact and shale interceptions. Properties specific to shale included: gamma ray and resistivity values, number of shales present (number of barriers), and reservoir (zone) thicknesses. With these data, maps were created using an inverse distance weighted (IDW) spatial analyst technique through ArcGIS Pro 2.7.0. These maps included a basic Arbuckle top contact structure/elevation map, IAS structure/elevation map, potential number of IAS barriers map, and two zone thickness maps. From the same data, several cross sections and well log correlations were produced. The results from these data, maps, and figures suggest that IAS acts as an impermeable barrier to fluid flow, creating the potential for untapped reservoirs of oil and gas to accumulate beneath them. They also indicate that Intra-Arbuckle Shale in this region has undergone structural deformation and has been subjected to erosion and karstification, resulting in a complex alteration of reservoirs (zones). With help from this study, two things are hoped for: 1) an increased understanding of IAS distribution and structure will benefit the oil industry in future Arbuckle explorations and 2), future researchers will use the information produced to conduct in-depth studies on the Arbuckle formation’s depositional and diagenetic history.

ACKNOWLEDGEMENTS

I would like to express my appreciation towards Dr. Jonathan Sumrall, Dr. Todd Moore, and Dr. Henry Agbogun. I want to thank them for guiding me through the Master of Science in Geosciences program at Fort Hays State University and encouraging me to strive for success.

I would also like to give a special thanks to Austin Klaus with John O. Farmer, Inc. for providing me with professional advice and insight into the local petroleum industry and being open to having discussion regarding Intra-Arbuckle Shale.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The Arbuckle formation is arguably the most important oil producing formation in the state of Kansas (Carr et al., 1986; Franseen, 1999; Franseen et al., 2004; Rocke, 2004; Barati et al., 2006). It has accounted for 35-40% of oil in Kansas production history and is still producing. Peak production of oil in the Kansas Arbuckle took place during the 1950's (Franseen et al., 2004), but has been slowly decreasing since. Most Arbuckle oil is produced from the top 50 ft. of the formation (Franseen et al., 2004; Wright, 2013) at structural highpoints. Because of this, most well logs only record measurements of the top 50 ft of the Arbuckle, which has resulted in a lack of understanding the important formation. Throughout Kansas there are several regions where impermeable shale(s), named Intra-Arbuckle Shale (IAS) (Franseen et al., 2003), are found within the top 50 ft. of the Arbuckle. Studies of Intra-Arbuckle Shale have been few and far between and are rarely mentioned throughout Arbuckle literature (Mullins & Ireland, 1967, Franseen et al., 2003). This should spark some curiosity, knowing that in the past these Arbuckle shales have allowed for non-depleted zones of oil to accumulate beneath original well completion depths (Mullins & Ireland, 1967) because of shale's ability to prevent fluid flow (Mullins & Ireland, 1967; Haldorsen & Lake, 1984; Michael, 2014; Snedden, 2014; Klaus, personal communication, 2023).

The goals of this study were to collect enough IAS data for the production of maps and cross sections, use these data to increase understanding of IAS distribution and structure, and open the door to future research into the Arbuckle formation's depositional and diagenetic history. With the completion of these goals and the contribution of hypotheses brought forth, new understanding of IAS and the role they play in Arbuckle compartmentalization will ideally benefit oil producers in their exploration of highly diverse and complex Arbuckle reservoirs.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 Background of Study Area

2.1.1 Central Kansas Uplift (CKU)

More than 50% of Arbuckle oil production takes place along the Central Kansas Uplift (Franseen et al., 2003), which is the largest structurally high subsurface feature of Kansas (Kansas Geological Survey, 2006). The Central Kansas Uplift developed after the Mississippian period and before the Mesozoic era. It has been covered by the deposition of later sediments of which the Arbuckle formation is included, and therefore is invisible from the surface.

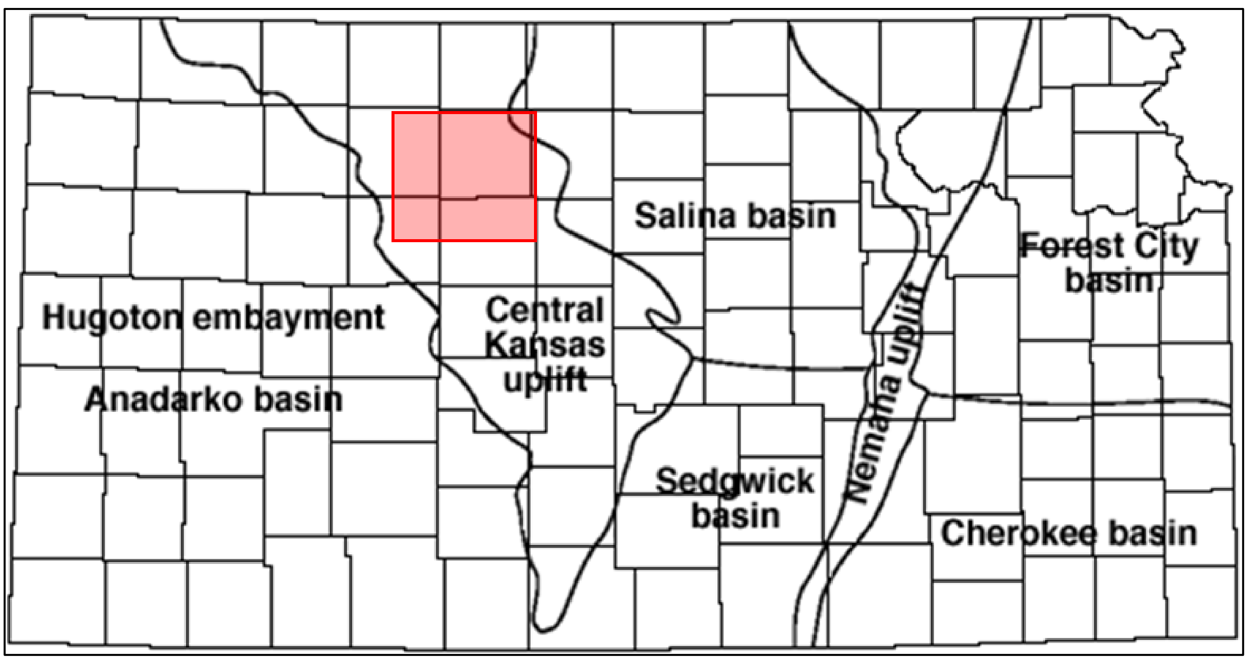

***Figure 1**: Kansas map of uplifts and basins. Red square shows where study region is relative to Central Kansas Uplift (Modified from Baars et al., 1989).*

2.1.2 County Production

The four counties that are within the study area include Ellis, Rooks, Graham, and Trego. Ellis, Rooks, and Graham counties have three of the highest oil production rates in Kansas

(Kansas Geological Survey, 2023). All counties in the study area are located above or near the CKU, with Ellis and Rooks predominantly covering the structure more than Graham and Trego. Because of the structurally high nature of the CKU, the oil-bearing formations directly above it have been major targets for oil production in Kansas. Most of Kansas's oil has been produced from the formations above the CKU, and much of that oil has been produced by the Arbuckle formation (Carr et al., 1986; Franseen, 1999; Rocke, 2004; Franseen et al., 2004; Barati et al., 2006).

2.1.3 Arbuckle Formation

The Kansas Arbuckle formation, predominantly dolomite within the study area, is Cambrian-Ordovician in age and is distributed through a vast majority of Kansas. It was deposited during subtidal to peritidal conditions during North America's past and has extensive unconformities at both contacts (Franseen et al., 2004). Arbuckle reservoirs can be highly complex and are still somewhat misunderstood. This is due to the formation's intense stratification and the lack of homogeneity throughout Kansas (Mullins & Ireland, 1967). Stratification and heterogeneity of the formation enables the possibility for the zoning or compartmentalization of reservoirs, which means that a single well may have the potential for producing from two separate reservoirs. There are other factors at play within this formation, though one holds some significance.

2.1.4 Intra-Arbuckle Shale (IAS)

Shales known as Intra-Arbuckle Shale are present somewhat periodically throughout Kansas and get their name because of their nature. They are within the Arbuckle, which indicates that they were deposited at the same time as the Arbuckle during low energy periods (Franseen et al., 2004). The distribution of shale can be very important to take into consideration when studying hydrocarbon reservoir potentials (Haldorsen & Lake, 1984). Especially in a formation like the Arbuckle that is water driven and dominated by a vertical migration of fluids. Not all shale within the Arbuckle is considered Intra-Arbuckle Shale, there are also many fracture fill shales (Franseen et al., 2004). Shales within the Arbuckle have the potential to create barriers to fluid migration, allowing them to act as hydrocarbon traps within the Arbuckle (Mullins & Ireland, 1967). Distribution of IAS has been highly misunderstood and debatable in the past. Some believe that IAS occurs in small lenses that are unpredictably scattered throughout the state, while others believe they occur as horizons that cover certain areas of Kansas (C. Longpine, personal communication, 2023; A. Klaus, personal communication, 2023).

2.2 Literature Review

The Arbuckle formation was discovered in the early 1900's by a well that was drilled in Eastern Kansas (Franseen et al., 2004), and has been extremely important to Kansas oil production (Carr et al., 1986; Franseen, 1999; Franseen et al., 2004; Rocke, 2004; Barati et al., 2006). The first attempts at mapping the Arbuckle came from data collected through wildcatting (exploration for oil in an unexplored field) around the year 1930 (McClellan, 1930, as cited in Franseen, 2004). Though these maps were not highly accurate, insight into the formation's structure and economic potential were gained, and a race to understand more began.

During the late 1940's, more accurate maps, along with cross sections were created using studies on insoluble residue from wells drilled around KS (Keroher & Kirby, 1948, as cited in Franseen et al., 2004). Their cross-sections stretched across Kansas from East to West and provided details on Arbuckle characteristics like thicknesses and composition. This was highly accurate for its time and lack of modern technology. As well logging and seismic studies became more prevalent for exploration towards the 1950's and 1960's, the Arbuckle reached its peak production levels (Winchell, 1959; Carr et al., 1986; Franseen, 1999; Franseen et al., 2004). This was during a time when mapping and cross-sections were accurate and reinforced the importance of good subsurface maps.

A challenge with mapping via well logs, was that most of the wells only penetrated several feet into the Arbuckle formation (Mullins & Ireland, 1967; Henry & Hester, 1995; Franseen et al., 2003; Franseen et al., 2004) that can reach thicknesses of more than 1000 ft. Because of shallow Arbuckle penetration, knowledge of the Arbuckle has been subpar. This lack of knowledge has presented many struggles for modern producers living in times of post-peak, decreasing Arbuckle production (U.S. Energy Information Administration, 2022).

The struggle to increase hydrocarbon production has led to an increase in Arbuckle well depths, but there is still great need for new studies using recent data and generating modern maps (Franseen et al., 2004). One method to achieve these needs is through the study of well log data using technology like ArcGIS Pro to create predictive maps/models. ArcGIS may lead to future increases in KS oil production, as it is being reliably used today for modeling and predicting subsurface geology in 2D and 3D (Barrell, 2000; Setijadji, 2003; Ondreka et al., 2007; Rahmatizadeh & Naseri, 2009; Krassakis et al., 2022). With capabilities like Kriging and IDW (Inverse Distance Weighted) interpolation techniques, ArcGIS Pro is proving itself highly beneficial for advancing the understanding of subsurface geology (Setijadji, 2003; Devleeschouer & Pouriel, 2006; Kienzle et al., 2006; Rahmatizadeh & Naseri, 2009; Xie et al., 2017; Krassakis et al., 2022).

Another hope for modern Kansas oil producers is the presence of shale(s) within the Arbuckle formation in specific regions, that create the potential for untouched oil reserves developing beneath them. Shales have been known in Kansas and around the world to act as traps and seals within petroleum systems (Mullins & Ireland, 1967; Haldorsen & Lake, 1984; Michael, 2014; Snedden, 2014; A. Klaus, personal communication, 2023), and Intra-Arbuckle Shale (Franseen et al., 2003; Franseen et al., 2004) is present in several locations throughout KS. One study in Ellsworth Co., KS, shows that shales within the Arbuckle had undiscovered and economically significant amounts of oil below them, because the vertically migrating oil had accumultate underneath beneath the thin impermeable barriers (Mullins & Ireland, 1967). No other studies of Intra-Arbuckle Shale were conducted afterward, which has left a door open for new research and potential undiscovered petroleum reserves throughout these locations in KS.

CHAPTER III

DATA AND METHODS

3.1 Investigating Intra-Arbuckle Shale Using Well Logs

3.1.1 A Description of Well Logs

Well logging is a method of data collection that measures rock characteristics present within a borehole and plots the measurements electronically to create a visual representation of the subsurface lithology. Well logs are created by lowering special tools down into an existing borehole before well completion. After the tools have been lowered to the bottom of the borehole, they are slowly raised back up while measurements of the surrounding rocks are sent to a computer at the surface. The computer then plots data from the borehole so geologists and oil producers can study the well's production potentials and determine whether completion of the well is worth the cost.

3.1.2 Well Log Data

There are many types of well logging tools, and therefore, many types of data that can be collected. Data may include fluid resistivity, gamma radiation, porosity, permeability, neutron density, sonic frequencies, and much more. For this study, online public well log data were obtained from the Kansas Geological Survey's (KGS) Interactive Oil and Gas Map at kgs.ku.edu.

While many wells on this map had useful log data, not every well on the map had corresponding well logs, drill stem tests, and/or well completion reports. Some wells had corresponding data, but not in the forms needed for the study. Other wells had all the correct data available, but these data were aged and illegible. Lastly, not all regions within the study area had Arbuckle wells, rendering them useless for data collection. A heat map showing the location density of wells that were used in researching the Intra-Arbuckle Shale is shown below (Figure 1).

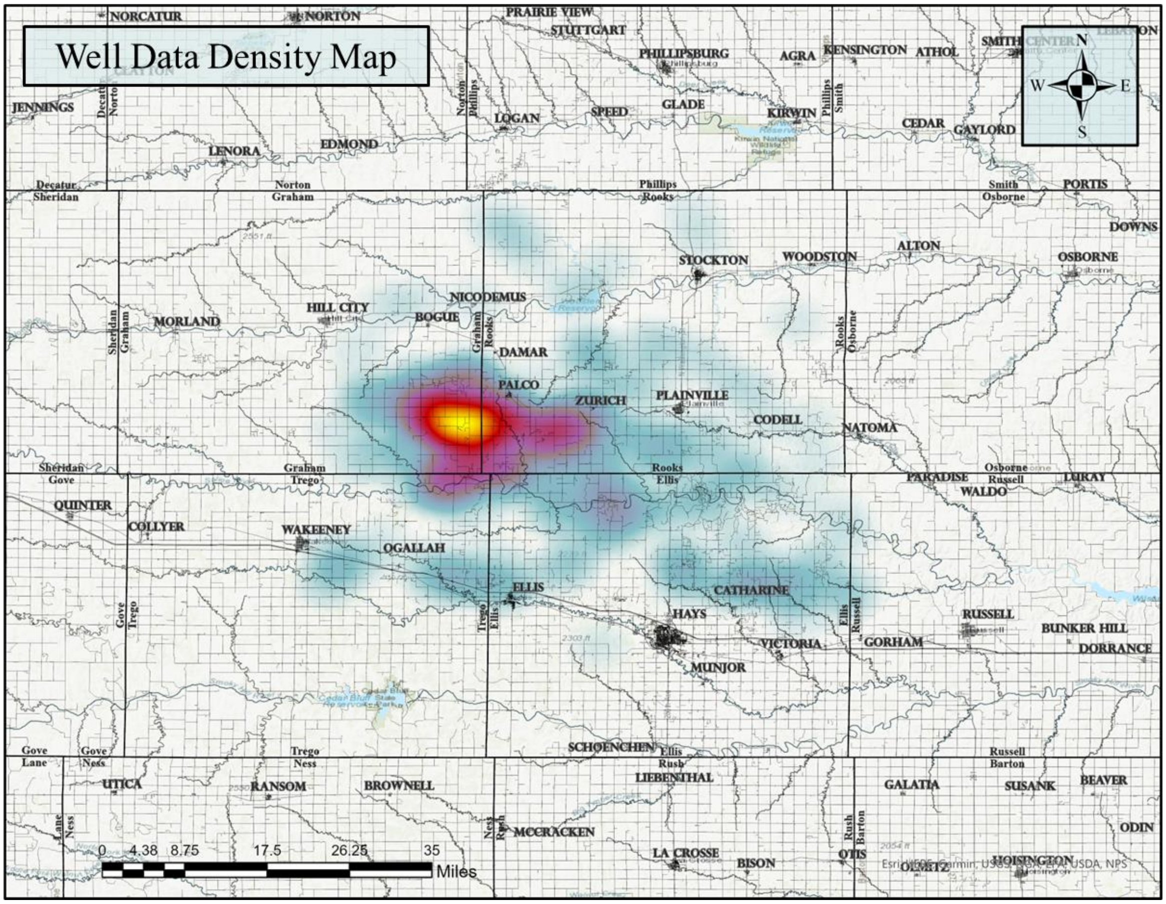

Figure 2: Map showing density of well log data collected. Purple and yellow areas represent high density. Blue represents low density. No color represents areas where no data were collected.

To locate Intra-Arbuckle Shale, data that is most useful and reliable to study are gamma radiation and fluid resistivity values. These data are collected from the use of micro-resistivity (fluid resistivity/permeability) and gamma ray (gamma radiation) well logs. These logs are useful for locating shale for two specific reasons. The first is that shale is much less permeable than limestone, sandstone, dolostone, or any other rock within the study area. The second is that shales carry high concentrations of radioactive particles that other rocks (especially carbonates) within the study area do not contain.

3.1.3 Micro-resistivity Well Logs

Micro-resistivity logs have several uses (determining fluid types/amounts, measuring porosity), but are helpful for indicating subsurface shales because they gauge the fluid resistivity of a rock that correlates to permeability. Since shales have very low permeability, a zone of impermeability on the micro log may indicate the presence of shale. Permeable zones can be seen on the micro log where the dotted line (micro normal 2'') has a higher resistivity value than the solid line (micro inverse 1x1*)*. Shale can be located where there is no difference between the micro normal and micro inverse values, or where the micro normal is less than the micro inverse (Asquith & Krygowski, 2004). The permeable zones below (Figure 2) are represented by the shaded regions. While potential shales are represented by intersections between the solid and dotted lines (red arrows).

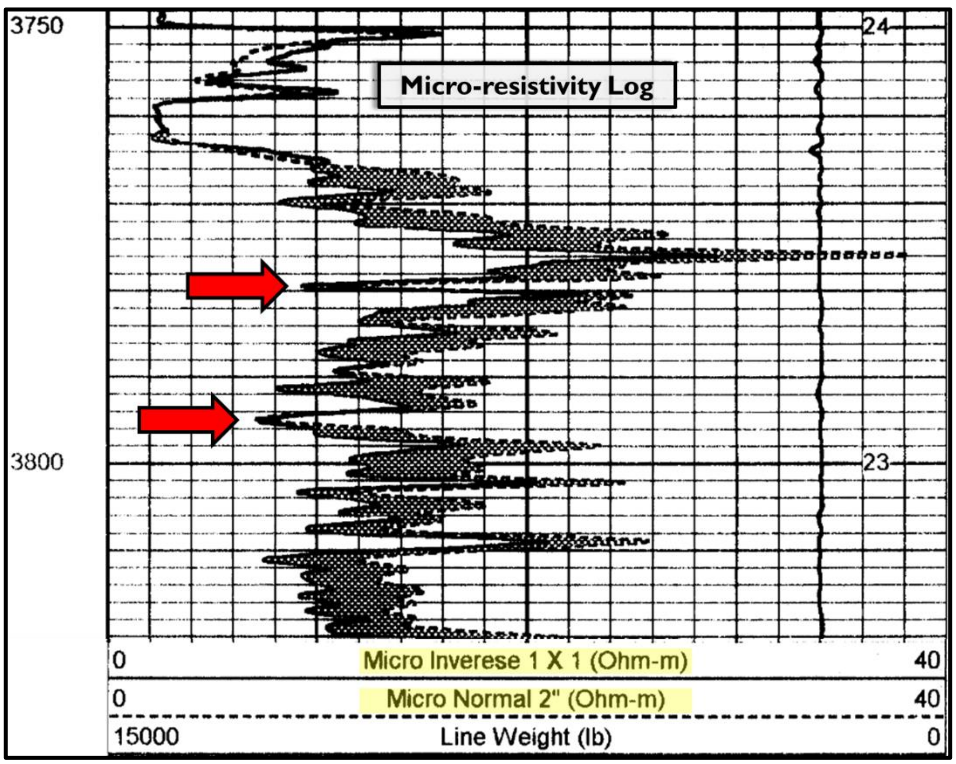

Figure 3*: Example of micro-resistivity well log. Red arrows represent impermeability potentially caused by shale.*

3.1.4 Gamma Ray Well Logs

To correctly identify a shale, more than one well log should be used to authenticate the shale's presence. Gamma ray well logs are another type of log that can successfully indicate the presence of a suspected shale. Gamma ray logs are specifically used to measure radioactivity within a formation to determine lithology. They do this by measuring gamma ray emission and amounts of thorium, uranium, and potassium within specific formations (Asquith & Krygowski, 2004). Shales naturally contain these radioactive particles in the form of clay minerals, so they will have much higher measurements than carbonates or sandstones. Within the study area, Intra-Arbuckle Shale gamma ray values (GAPI) range from 40-105 GAPI (with some being reported as low as 34 GAPI by wellsite geologists) and average 53.58 GAPI. Carbonates and sandstones of the region in study range from 15-30 GAPI, with cherts sometimes ranging in the high 30's. The difference between shales and carbonates on a gamma ray well log is shown below (Figure 3).

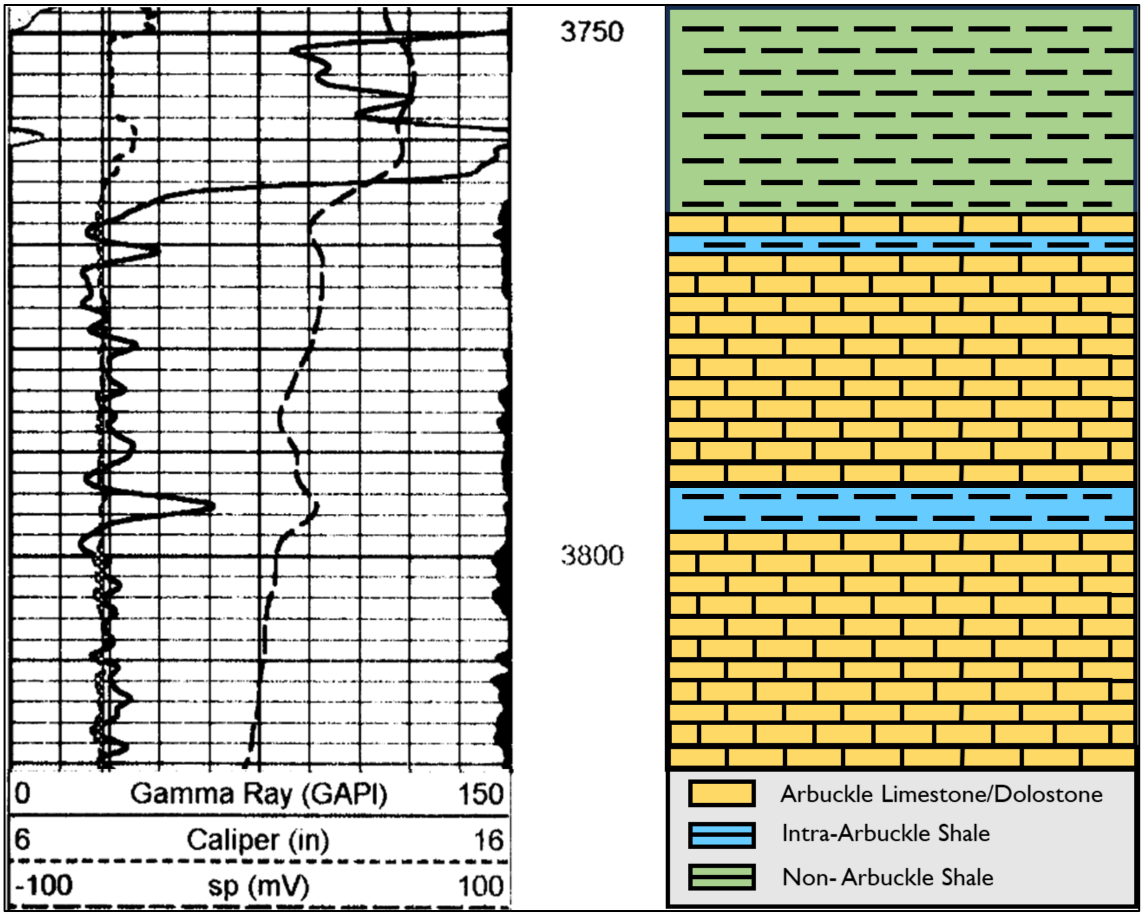

Figure 4*: Example of gamma ray well log and lithology interpretations. Gamma ray spike at 3795' resembles shale.*

3.1.5 Identifying Intra-Arbuckle Shale

Within the study area, most micro-resistivity logs are taken side by side with a gamma ray log. This allows for a quick and justifiable interpretation of permeable zones and/or lithology at the same time. Using these two well logs alongside each other helps to confirm the presence of Intra-Arbuckle Shale within the Arbuckle. A micro-resistivity well log of the Kansas Arbuckle located in Southwestern Rooks County is shown below (Figure 4). There are 4 boxes between the two logs that point out key features to take into consideration for this study. Box A represents the top contact of the Arbuckle, and B represents Intra-Arbuckle Shale. Boxes 1 and 2 show two zones of carbonate reservoirs that are separated by IAS.

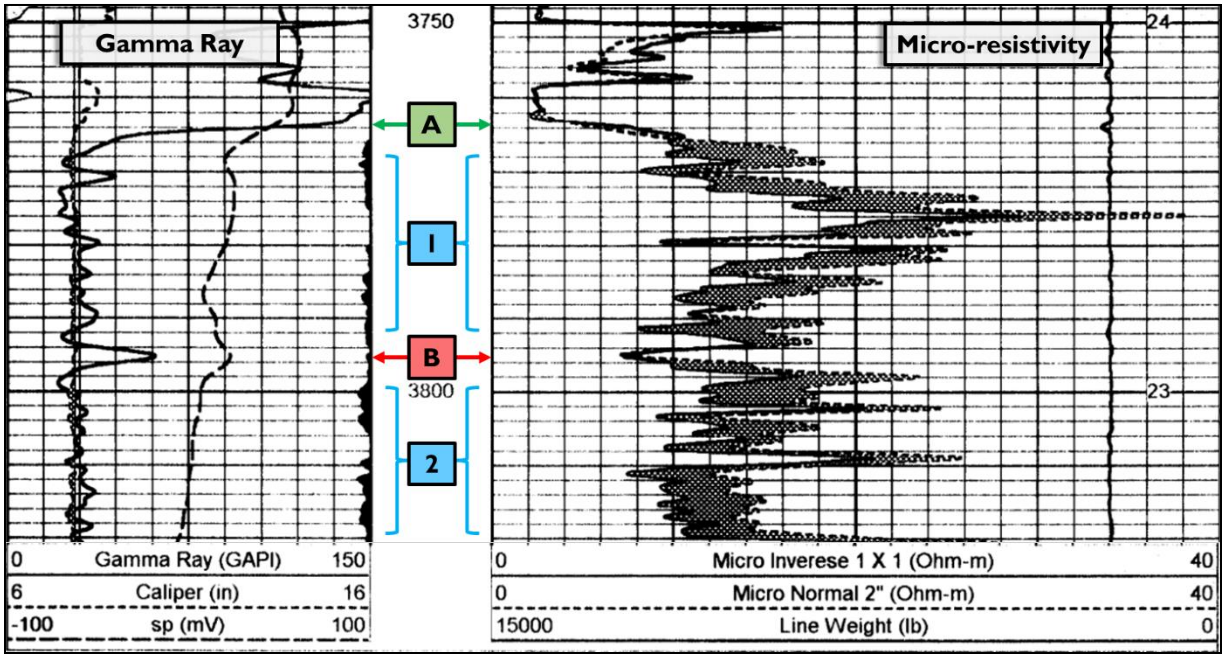

***Figure 5**: Example of micro-resistivity well log paired with gamma ray well log. A represents the Arbuckle top contact, 1 and 2 represent potential reservoirs (zones), B represents IAS.*

In portions of the study area, there were no shales to be identified on well logs. These logs that lacked IAS were important to collect data from, because they too provided insight into the subsurface distribution of the shale. If there was not a kick over of the gamma log values greater than forty beneath the Arbuckle top contact, the log was considered shale free. There was an exception to this rule in some cases though. If the well site geologist took note of shale in the log report, the shale was deemed important, and the corresponding data were collected. Figure 5 represents a well log that is shale free below the Arbuckle top contact (Box A) and has one continuous zone (Box 1) despite some tight spots on the micro log.

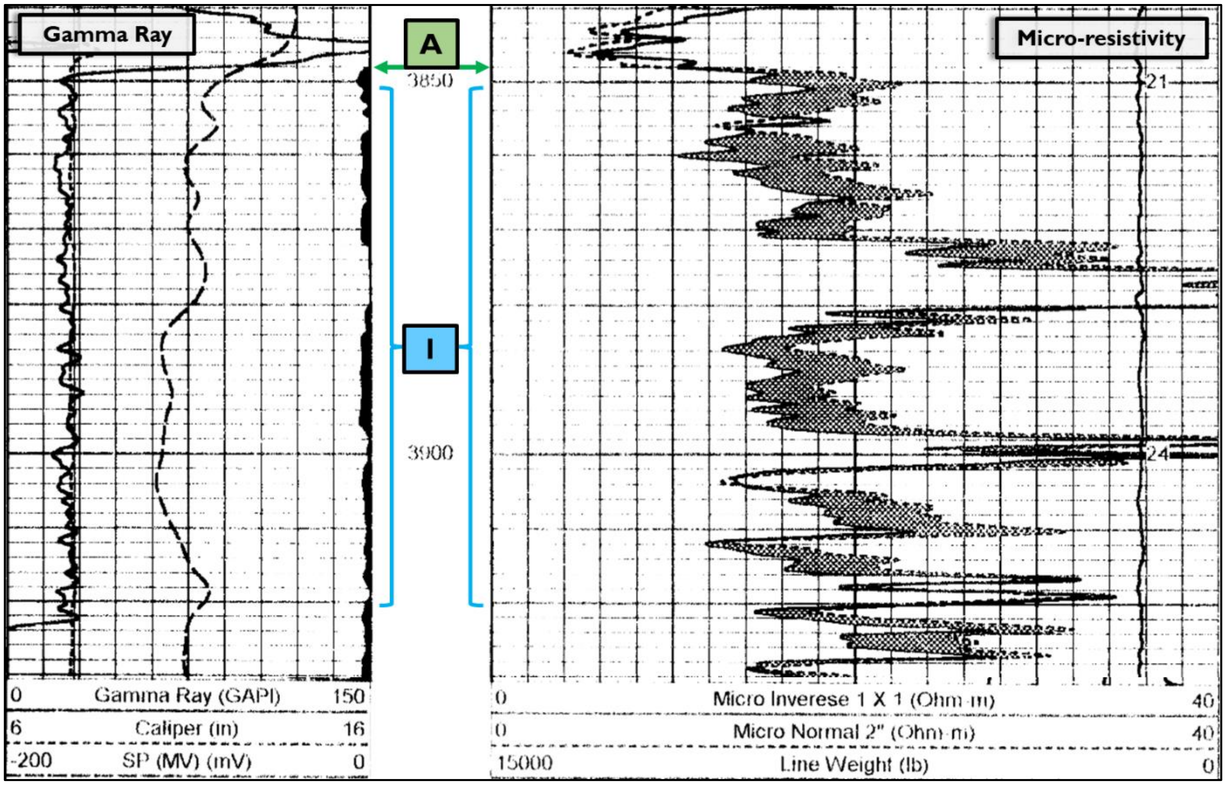

Figure 6*: Example of well log with no IAS. Shale could be absent from the area, or deeper than well log depth.*

3.2 Extracting Well Log Data

3.2.1 Wells Used for Data

For a well log to be used in this study, it had to meet a couple requirements. These included sufficient well log depth (>10 ft below Arbuckle top contact), well log data legibility, and penetration of the Arbuckle formation. All well logs that met these requirements, whether they intercepted Intra-Arbuckle Shale or not, were gathered and used in the study (Figure 6).

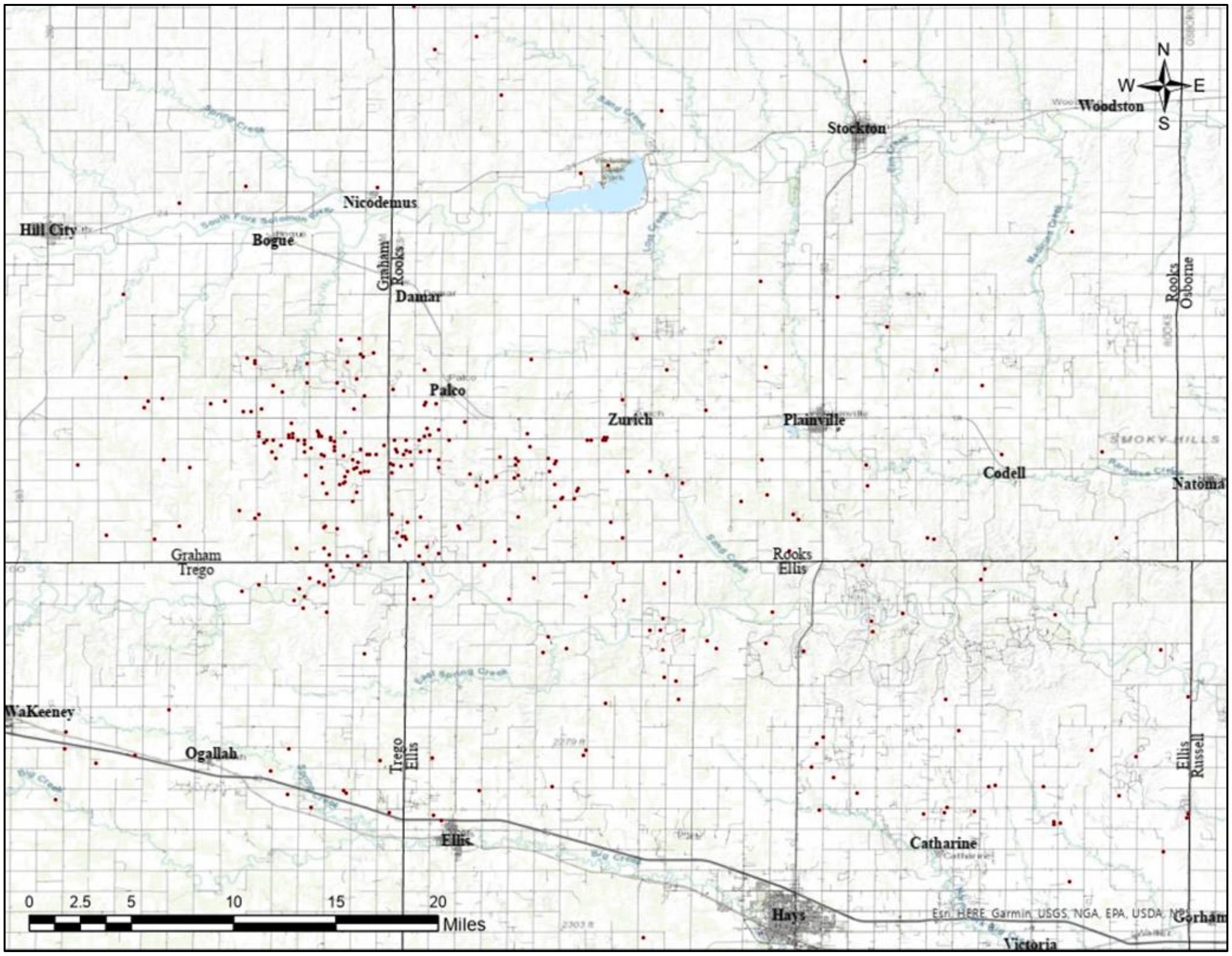

Figure 7*: Arbuckle wells that were used for data collection. Wells represented by red data points.*

3.2.2 Microsoft Excel

Depending on whether Intra-Arbuckle Shale was located on a well log or not, certain qualitative and quantitative data were transferred to a Microsoft Excel Spreadsheet. If IAS was present, these data included the shale's peak gamma (GAPI) value, Micro-Normal value, and depth. The Arbuckle top contact depth was collected also, along with the KB (drilling rig height) of the well. Reservoir thicknesses were measured last (shale thicknesses were determined by this measurement as well), though thicknesses did not play a key role in shale correlation from well-to-well. Each well had the following data collected:

- Well API number.

- Latitude/Longitude.
- KB (drilling rig height).
- Arbuckle top contact depth.
- Intra-Arbuckle Shale depth.
    - Multiple Shales on a log denoted by number following IAS. Ex. IAS (1), IAS (2).
    - The depth of the shale was taken from the peak of the gamma ray spike on the gamma ray log, which usually fell in the middle of the shale occurrence.
- Gamma ray (GAPI) values for each shale present on log.
- Micro-normal values for each shale present on log.
- Number of potential zones.
- Zone top(s) and bottom(s).
    - Also used for shale thicknesses (difference between bottom and top of different zones).

Qualitative and quantitative data from drill stem tests, well completion reports, and geologist logs were also studied if available, and added to the spreadsheet by adding a detailed note to the corresponding log. Not all well logs had these three corresponding documents though, but when available, they had significant value in well-to-well correlation of shales. Data from these documents included:

- Top/Bottom perforation depths.
- Perforation records.
- DST intervals.
- DST recovery descriptions/volumes.
- Geologist descriptions (color, texture, inclusions).

3.2.3 Well API Number

Well logs were identified by their API numbers to locate and to keep track of wells that had been investigated. The KGS Interactive Oil and Gas Map contains a search function where wells can be searched by their corresponding API numbers. This made for easy navigation through their map and sped up the process of revisiting specific well logs.

3.2.4 Latitude and Longitude

Latitudes and longitudes from the North American Datum of 1927 (NAD 27) were used for this study. This was not for any specific reasoning, but because these latitude and longitude values were listed on an oil wells information tab. Latitude and longitude were specifically collected for mapping purposes through ArcGIS Pro. These values allow the software to accurately plot points for oil and gas wells.

3.2.5 KB (Drilling Rig Height)

Other data that were necessary for the study, specifically for mapping, included the sub-sea levels of the Arbuckle top contacts and each Intra-Arbuckle Shale occurrence. To find the sub-sea level of these important features, the depth of the feature (depth from surface) was subtracted from the KB (drilling rig height representative of sea level). Because the depth of an Arbuckle feature was always larger than the KB, the results were negative and represented a sub-sea level value. Sub-sea levels of the Arbuckle top contact ranged from -2039 ft to -1400 ft, with depths ranging from 4380 ft to 3267 ft. IAS sub-sea levels ranged from -1779 ft to -1415 ft, with depths ranging from 4220 ft to 3345 ft.

3.2.6 Drill Stem Tests (DST)

In this study, drill stem tests were not necessarily useful in identifying shale, but they were helpful in confirming an Intra-Arbuckle Shale’s role in reservoir compartmentalization. The key sections of Arbuckle DST reports to take into consideration included the testing intervals and recovery descriptions. There are several DST reports within the study area that have testing intervals directly above and below Intra-Arbuckle Shale. This not only implies that some oil producers in the region of study suspect that the shale creates compartmentalization throughout the Arbuckle, but also that there are economical reserves of hydrocarbons below IAS.

The recovery descriptions contain information about what type of fluids (oil, gas, water) were produced and their volumes. Many of these descriptions added to the justification of Arbuckle reservoir compartmentalization due to the presence of IAS simply due to the change in fluid type above and below the suspected shale. In most cases, these descriptions would either show gas above and oil below the shale, or oil above and gas below. For example, if there was shale at a depth of 3800 ft., and two DST reports. One DST report might show a testing interval of 3790-3799 with a recovery of 16 bbl of free oil. While the other may have a testing interval of 3802-3810 with a recovery of 6 bbl of 10% gas, 15% oil, 75% water. In this example, there is a clear separation in reservoirs above and below the shale.

3.2.7 Well Completion Reports (WCR)

Like the drill stem tests, well completion reports did not play a role in the identification of Intra-Arbuckle Shale but helped in justifying reservoir compartmentalization suspicions. More times than not, a well log would not have corresponding drill stem tests but would have a WCR. Because the well completion reports contained the perforation records of a well, they could be used in place of a DST to determine if the shale was believed to have compartmentalization capabilities. If there is IAS located at a depth of 3800 ft on a log, and the WCR shows that there were perforations from 3790-3799 and another from 3802-3810, this implies that the oil company believed the shale was acting as a barrier between two zones.

There were several well logs that had gamma ray spikes representative of shale (40+ GAPI) within five feet of the Arbuckle top contact. Correctly determining whether to label these kickovers as IAS or shale from the formation above was sometimes solely decided upon by the WCR. If the WCR recorded perforations directly above and below the potential shale, it was considered important to the study and labeled as Intra-Arbuckle Shale.

3.2.8 Geologist Reports

Many wells within the study area had corresponding reports on the KGS Interactive Oil and Gas Map that were written up by the geologist of that well near the time of completion. A geologist report, unlike DST and WCR, sometimes played a role in the identification of shale. A few times during the study, there were gamma spikes on a well log less than 40 GAPI (but greater than 34) that were considered IAS because the geologist took note of shale and described it. These reports were also highly beneficial for correlating shale from well to well if the geologist took note of the shale by describing its characteristics. These characteristics included colors, textures, inclusions like pyrite, and sometimes quantities of shale.

3.3 Geographical Methods

3.3.1 ArcGIS Pro

After well log data were collected using an excel spreadsheet, these data were transferred over to a geographical information system software. The software used to analyze and visualize well log data was ArcGIS Pro 2.7.0. This software was chosen because of its dynamic 2D and 3D mapping capabilities, user-friendly interface, and because it was the major software available at Fort Hays State University.

Data from the spreadsheet was uploaded into ArcGIS Pro through a folder connection and displayed as XY data on the default map. To build maps and models of the Arbuckle and

Intra-Arbuckle Shale with this data, an Inverse Distance Weighted (IDW) technique was utilized. For other maps and analyzing Arbuckle and IAS data statistics, a technique called kriging was selected. Both techniques are useful for predicting unknown values between points, making them the perfect tools for this study.

3.3.2 Inverse Distance Weighted (IDW) Spatial Analyst

Referring to figures 1 and 6 (heat map of wells, and well locations), it is obvious that the well data collected was not equally distributed throughout the region of study. Because of this, there were specific regions that could not be mapped directly from Arbuckle well log data. Because IDW can interpolate unknown values between two points, it was the tool of choice when approaching this challenge.

Using IDW was a simple process that contained the following steps below:

- ArcGIS Pro 2.7.0 was started, and a new map template was created.
- Once the template was opened, the spreadsheet containing the well log data was uploaded to the contents pane from a folder connection.
- The spreadsheet was then displayed as xy data.
    - For the IDW tool to run correctly, data were converted to long integer form. This was accomplished by adding a new field in these data’s attribute table and using the calculate function to obtain the desired values.
- From the Analyst tab’s geoprocessing toolbox, the IDW (spatial analyst) tool was opened.
- For the input point features drop down box, the xy data option was selected.
- Depending on which data were desired for mapping, either the Arbuckle top sub-sea level or IAS sub-sea level data were selected for the z value field.

    - The output raster was named based on what data were used and connected to an appropriate folder to keep the workspace organized.

- The remaining parameters were used at their default values: output cell size (2.65394560000004E-03), power (2), search radius (variable), number of points (12), maximum distance and input barrier polyline features were left blank.
    - After the IDW map of the Arbuckle top was produced, the primary symbology was changed to classify by geometric interval with 32 classes.
- For the Intra-Arbuckle Shale sub-sea level data, all the parameters were the same as the Arbuckle top, except that the z value selected was one of the IAS sub-sea level datasets.
- To add a better predictive capability to the IDW tool another process was carried out. adding 1000 random points to help fill in the areas of missing data.
- The create random points tool was used to do this. For this tool, there was no constraining feature selected, but the constraining extent was the same as the xy point data. After adding 1000 points at a minimum distance of 1 mile from each other, all other parameters were left at their default selections.
    - After the random points were generated, the extract values to points function was used to give the new points a value based on their location within the existing IDW raster. To run this tool correctly, the interpolate values at point locations box were checked.
    - Finally, the merge tool was utilized to combine the random points with the existing data points. For this step, the two sets of points were selected for the input datasets and the output field, and sources were selected appropriately.

- Once this process was carried out, 1000 random points were successfully generated and given values. The same IDW process was carried out with the same parameters, except for using the new point data for the input point features. Figure X below shows the random points that were used to create two of the IDW maps.

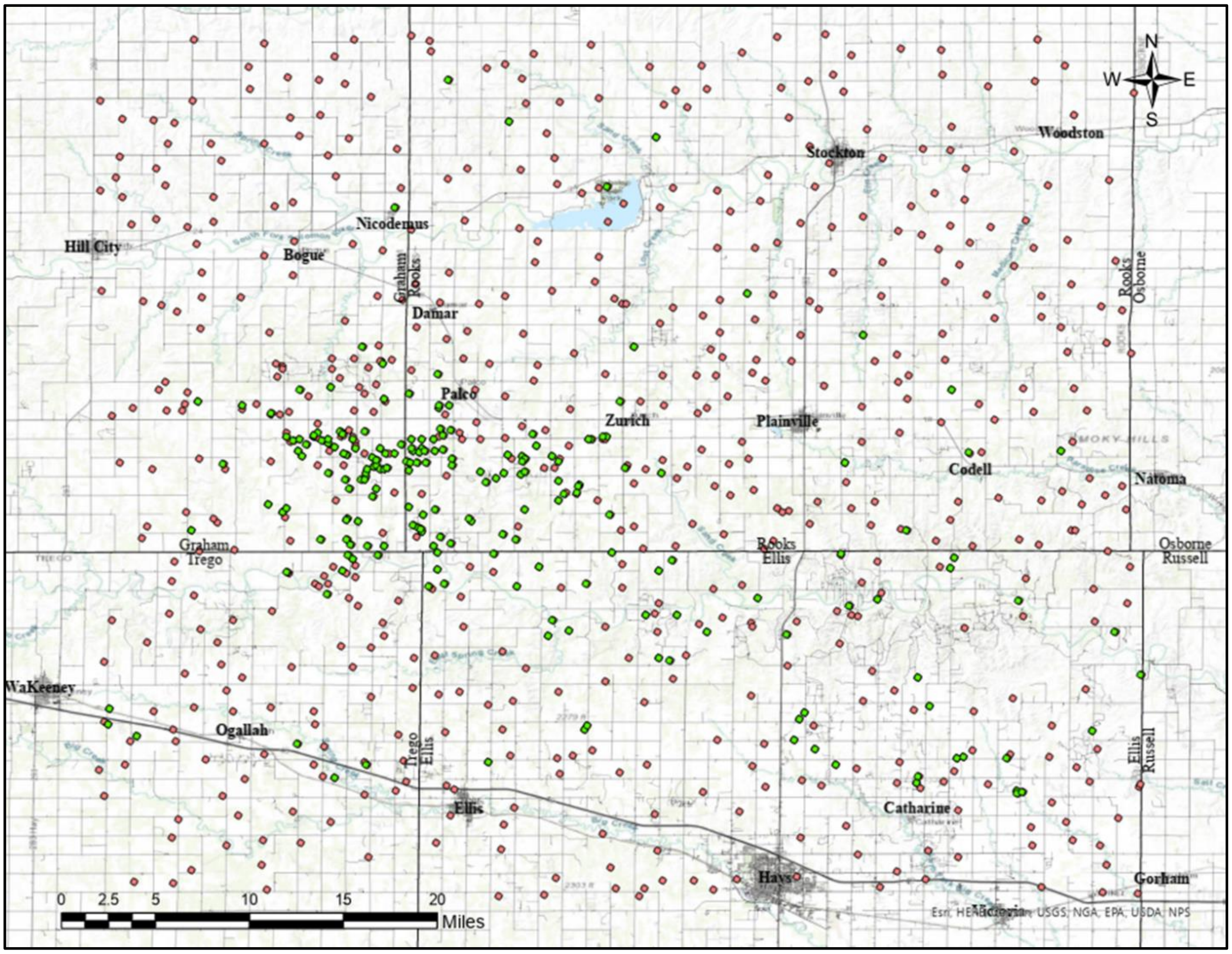

***Figure 8**: Map with random points. Green points are original data points collected from well logs. Red points were randomly generated.*

CHAPTER IV

SHALE CORRELATION

4.1 Lateral Distribution of Shale

Defining the lateral distribution of Intra-Arbuckle Shale has the potentiality of dramatically increasing the knowledge, lifespan, and treatment of Arbuckle reservoirs. Measuring the lateral distribution of shale simply means determining its extension across a certain area/region. There is ample evidence of reservoir compartmentalization due to Intra-Arbuckle Shale, specifically in SE Graham, NE Trego, Northern Ellis, and Southern Rooks Counties. Reservoir compartmentalization (or separation of reservoirs by a barrier) in this case would be the presence of two distinct hydrocarbon pay zones that are vertically stacked. Considering the evidence, it is obvious that understanding the distribution of IAS could lead to the locating of untapped hydrocarbon reserves below normal well completion depths. Deepening of wells below Intra-Arbuckle Shale in the past have led to an increase/restoration of well production rates/lifespans (Mullins & Ireland, 1967), so there is potential to do the same today. Accurately measuring the distribution of the Intra-Arbuckle Shale at depths of 4,200 ft within the subsurface depends on the ability to correlate data between wells.

4.2 Correlative Vs. Non-Correlative Shale

Because there are multiple Intra-Arbuckle Shales present within the study area, successfully determining the lateral distribution of the shale was very difficult. The possibility of mapping out the distribution of IAS depends on whether a shale is correlative or non-correlative between wells. This type of correlation describes two shales that have corresponding stratigraphy and lithology (Neuendorf et al., 1980) rather than a statistical relationship. According to Haldorsen and Lake (1984), a shale that can be correlated from one well to another is a

"Deterministic Shale", while a shale that cannot be correlated is considered a "Stochastic Shale". The study area contains a mixture of both types of shale, and whether this be from the presence of random shale lenses or the lack of data between wells can be discussed.

Within the study area, there are several distinct Intra-Arbuckle Shales. The deterministic shales that can be correlated from well to well in the study area are green, turquoise, and multicolored shales. The stochastic shales in the study area that are non-correlative include brown, red, white, grey, yellow, and purple shales. These shales are not recorded very often and may be classified as fracture fill or lenses.

4.3 Correlating Shale Characteristics

One method to correlate Intra-Arbuckle Shale was comparing IAS characteristics including gamma ray (GAPI) values, elevation (sub-sea level), and geologist report descriptions (color/texture). For example, Figure 8 represents how data and characteristics were used in this process.

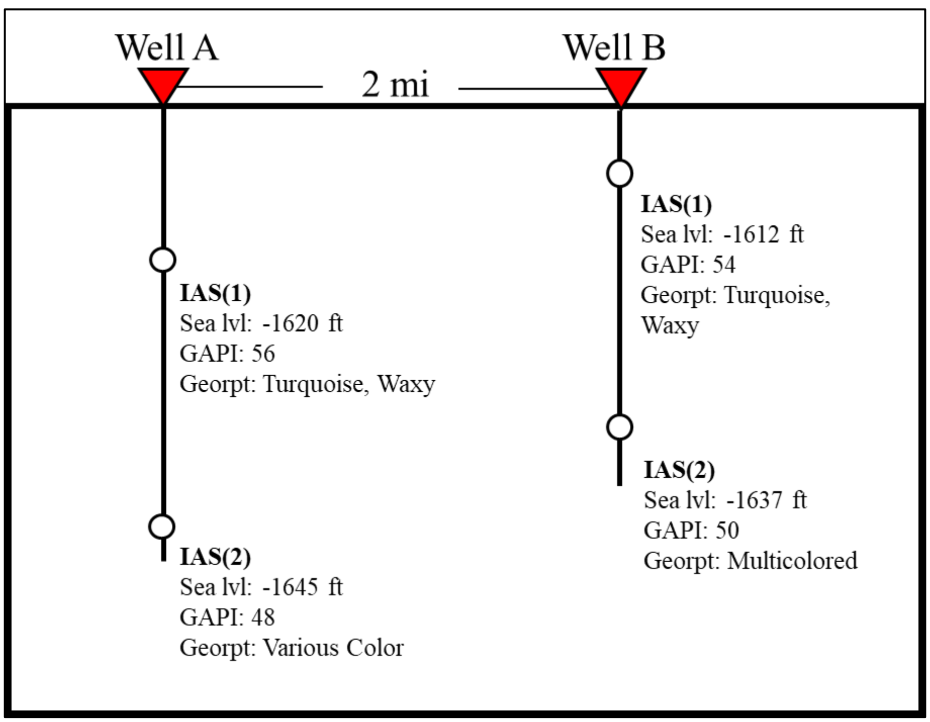

Figure 9*: Example of cross section showing IAS interceptions along with sea level, gamma ray value, and geologist descriptions.*

Looking at Wells A and B on a spreadsheet would show similarities between GAPI values and shale characteristics, and a small correlation may be achieved. Once they are put onto a cross section though, it is seen that IAS (1) on both A and B are very similar. The GAPI values are nearly the same, both are described by the well site geologist as being turquoise and waxy. IAS (2) on both wells also appears to show some correlation. They also have similar GAPI values, and they are both described by the well site geologist as having many colors. The sub-sea levels between the shales are not the same, but from the cross section we can see a sequence that is being followed. Both wells have two shales that are exactly 25 ft apart in depth, and the upper shale in both instances is turquoise while the lower shale is multicolored.

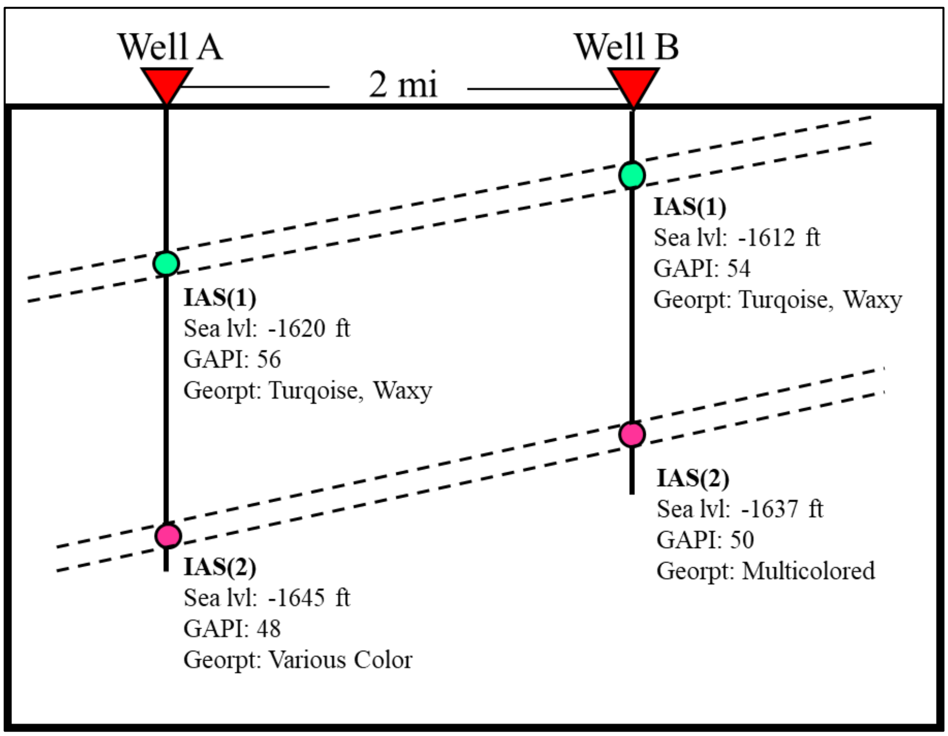

Figure 10*: Example of cross section showing IAS interceptions with shale colored in along with sea level, gamma ray value, and geologist descriptions.*

An example of correlating shale using a dotted line that is representative of Intra-Arbuckle Shale is shown above (Figure 9). An accurate correlation means that the depth of a certain shale can be estimated between two or more shales, which allows the subsurface lateral distribution of the rock to be visualized.

4.4 Well Log Correlation

A second method of correlating Intra-Arbuckle Shale is by the comparison and correlation of well logs. In this study, certain well logs were used to study and compare IAS gamma ray signatures from well to well. This process is different from using geologic cross sections in that gamma ray and sea level values are useful, but not necessary for shale correlation. Instead of simply using gamma ray values, this process also uses the gamma ray signature of a shale.

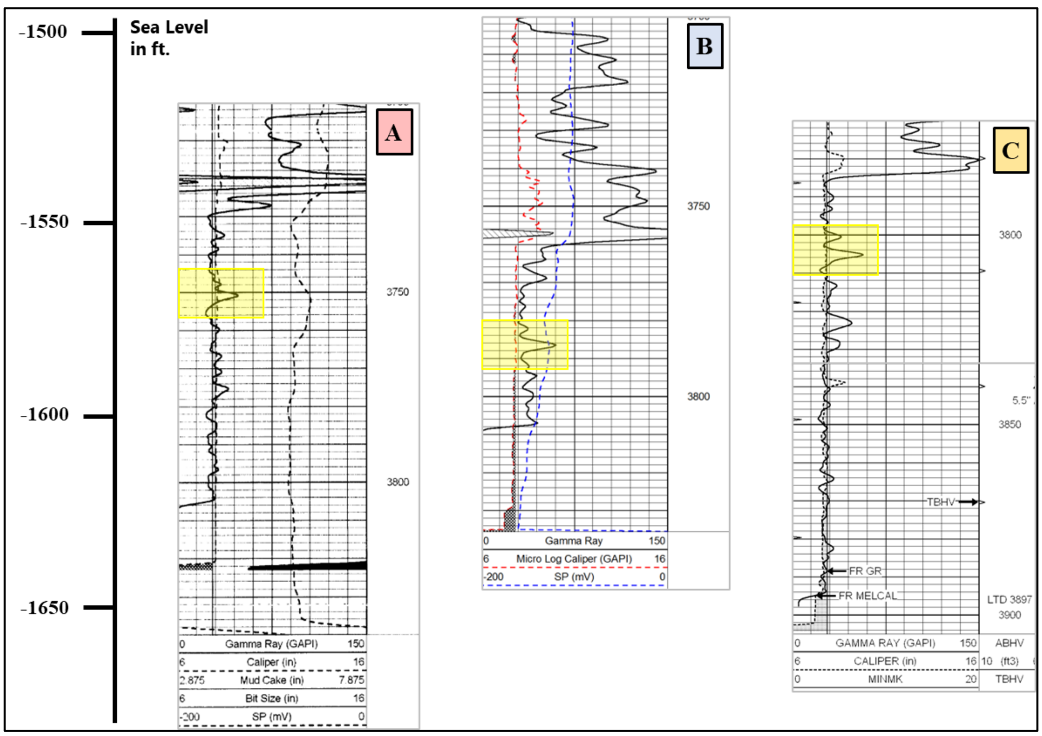

Figure 11*: Example of well log correlation (pre-correlation). A, B, and C represent three separate gamma ray well logs spread out across the region of study.*

Above is an example of well logs that can be correlated to each other (Figure 10). All three logs were taken from the study area and have an Arbuckle top contact, and IAS interception present. The black lines that run down the logs are representative of gamma ray values at individual locations and leave distinct signatures, shapes, or patterns for IAS. As seen above, the yellow boxes highlight some of these shale signatures. Though there are differences in both the gamma ray and sea level values for each shale, it is obvious that the same shale is appearing on each log.

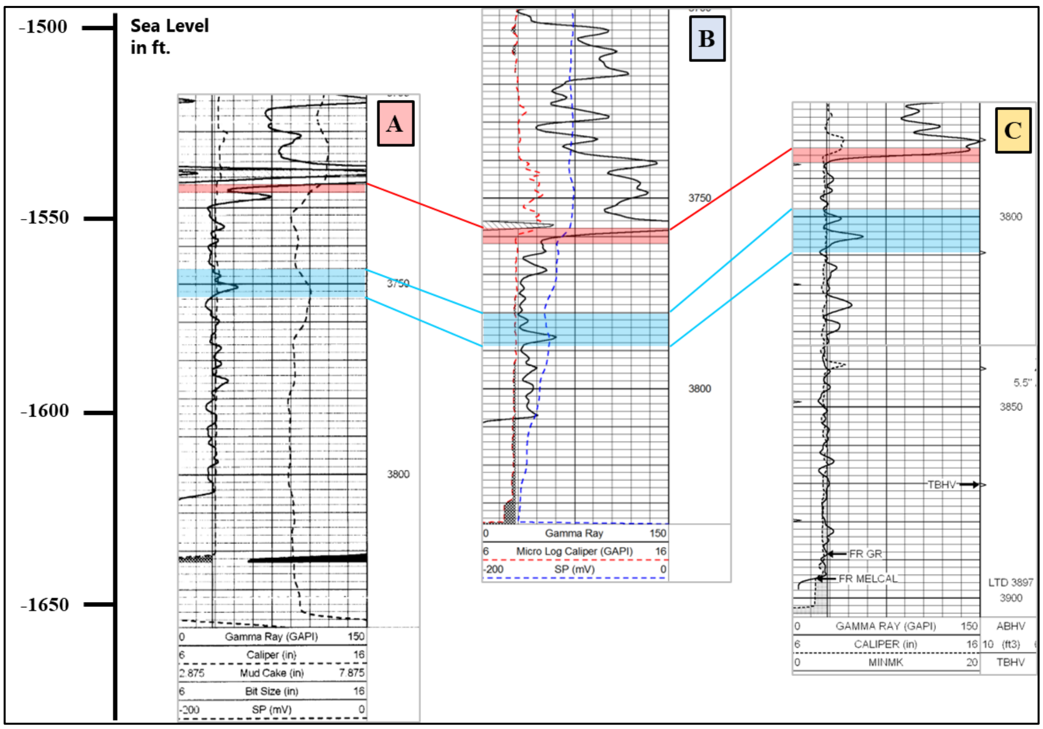

Figure 12: Example of well log correlation (post-correlation). A, B, and C represent three different gamma ray well logs found within the region of study.

If IAS is identified on several well logs, and their gamma signatures are similar from one log to the next, this IAS can be classified as deterministic, and a correlation can be made (Figure 11). The blue highlights represent correlated IAS, and the red highlights represent the Arbuckle top contact (Figure 11).

CHAPTER V

RESULTS AND DISCUSSION

5.1 The Need for Well Log Studies

It has been documented that Intra-Arbuckle Shale is present throughout Kansas in several regions, including the four-county area of Ellis, Rooks, Graham, and Trego Counties (Mullins & Ireland, 1967; Franseen et al., 2003; Franseen et al., 2004). Though the presence of IAS is recognized in this area, the lateral distribution has remained highly speculated and solely reliant on drilling oil and gas wells (Franseen et al., 2004; C. Longpine, personal communication, 2023; A. Klaus, personal communication, 2023). The influence that IAS has on complex Arbuckle reservoirs has also remained somewhat mysterious with at least one study showing IAS compartmentalization tendencies in Kansas (Mullins & Ireland, 1967). To better comprehend abstruse Arbuckle reservoirs, Franseen and Byrnes (2004) mention the need for regional and local modern well log studies and maps of specific Arbuckle strata.

This study produced regional maps, cross sections, and well log correlations with the use of modern well log data. To improve understanding of IAS distribution and their influence on Arbuckle reservoirs. With this enhanced IAS knowledge, valuable insights into the Arbuckle formation’s depositional and diagenetic history can be obtained.

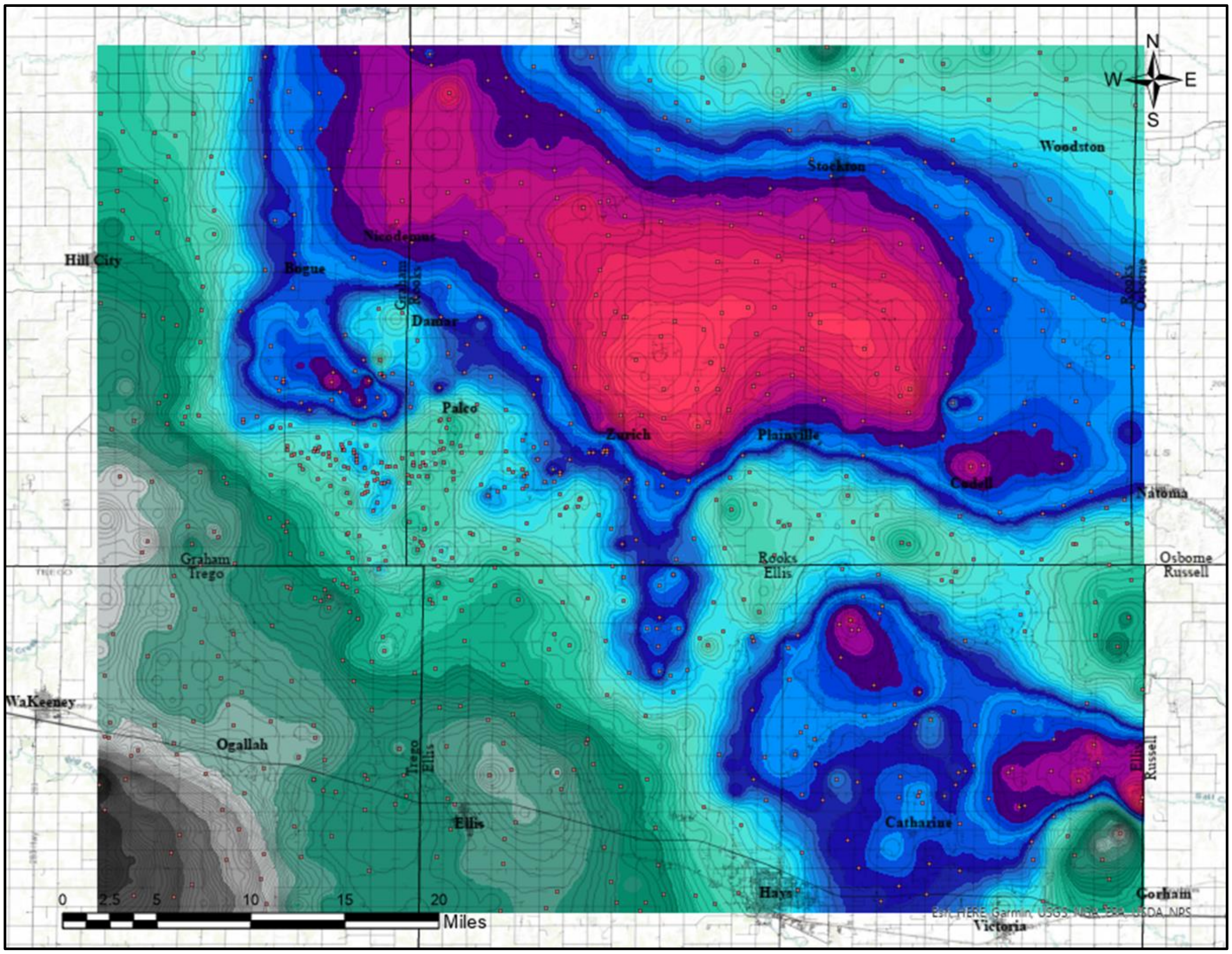

Figure 13: Arbuckle top contact structure/elevation map. Red/purple = highest elevation (-1,400 - -1,496 ft); blue = high elevation (-1,497 - -1,555 ft); greens = mid-range elevation (-1,556 - -1,721 ft); greys = low elevation (-1,722 - -1,949 ft); black = lowest elevation (-2,039 - -1,950 ft).

The sea level data of the Arbuckle top contact was displayed using an IDW map (Figure 12). This map represents the subsurface structure of the Arbuckle formation in Ellis, Rooks, Graham, and Trego counties. Within the region of study, these sea level values range from -2,039 ft in central Rooks County to -1,400 ft in Northwestern Trego County. The depths of the Arbuckle top contact range from 4,380 to 3,267 feet below the surface.

This map reveals similar structures found on the few regional scale Arbuckle maps available (Nissen et al., 2005), but with much more detail, notably the V-shaped structure located in Central Rooks County. The spike in elevation from Trego County to Central Rooks represents the presence of the Central KS Uplift that trends Northwest to Southeast (Kansas Geological Survey, 2006). New findings of this study document island-like structures in Northern Ellis and Eastern Graham Counties, and the channel that trends East to West on the Ellis-Rooks County line (Figure 12).

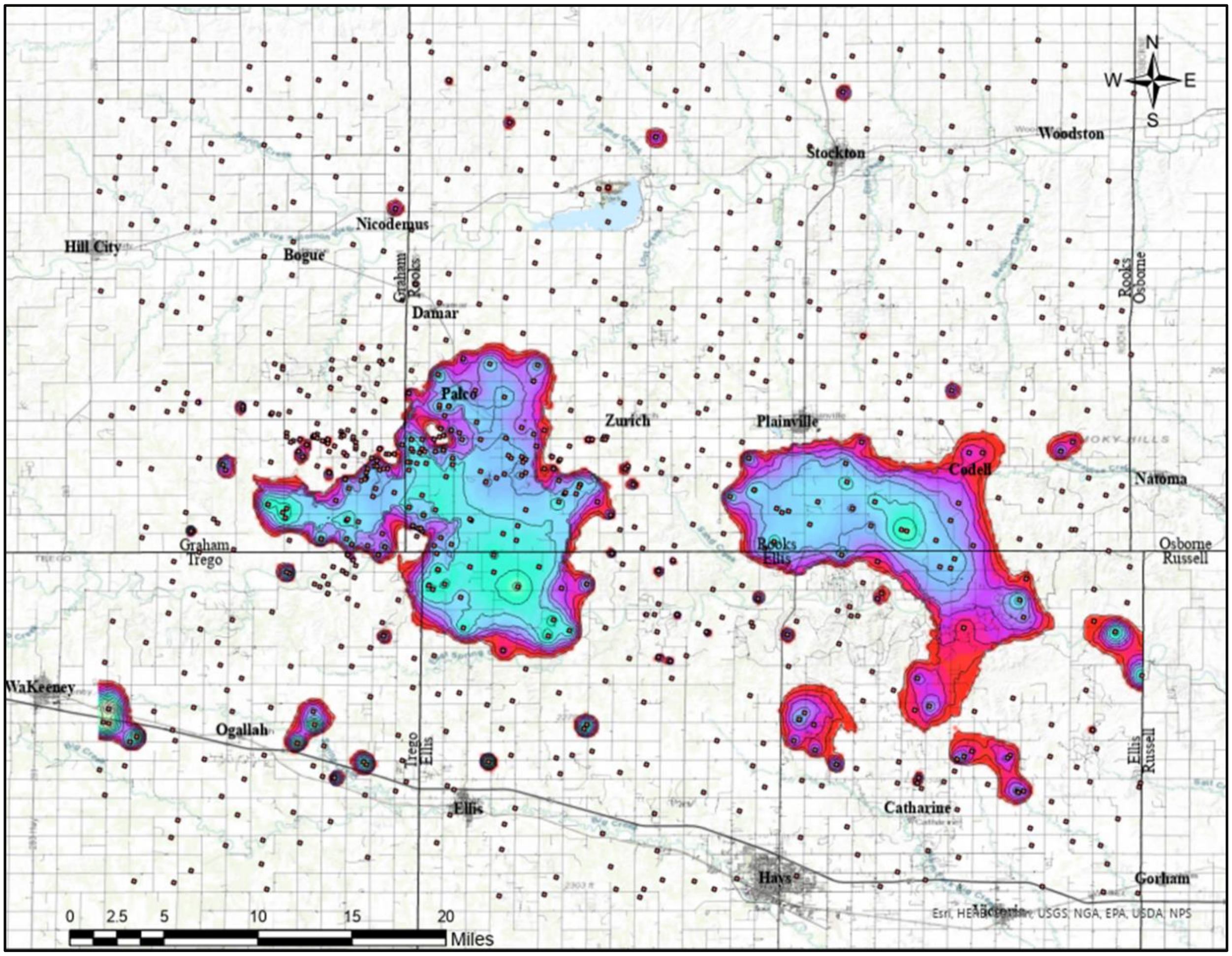

Figure 14*: Intra-Arbuckle Shale distribution/elevation map. Blues = low elevation (-1,650 - -1,555 ft); Purple = mid-range elevation (-1,554 - -1,475 ft); Red = high elevation (-1,474 - -1,415 ft); no color = no shale present or shale is deeper than well log depth.*

Sub-sea level data for Intra-Arbuckle Shale in the region of study was also displayed using an IDW map (Figure 13). Intra-Arbuckle Shales were mostly found in the Northern portions of Ellis and Trego, and Southern Graham and Rooks counties. Because IAS-2 and/or 3 did not exist without IAS-1 being present above, only IAS-1 was represented on the map.

5.2 Interpolating Depth/Elevation

Within the mapping region, shale depths ranged from -1,779 feet to -1,415 feet below sea level. When viewing the color scale for depth or elevation, it is very important to consider the interpolative quality of ArcGIS Pro's IDW technique. Though some shale was recorded at high elevations, the red areas of the map do not assert that there must be shale present, but rather there may be shale located at a higher elevation as distance increases from a shale intercepting data point.

5.3 Intra-Arbuckle Shale Location and Structure

Before the completion of this map, there were no available maps or figures aiming to show the location and/or structure of IAS. There is now an understanding of the general location (lateral distribution) and structure of IAS in the study region (Figure 13). With this data, better interpretations of Arbuckle reservoir compartmentalization and their stratigraphic influences may be discussed.

An interesting observation can be made about the location of IAS (Figure 13). This is the increased interceptions of shale at the mid-range elevations (light green areas) of the Arbuckle top contact. There are IAS interceptions at the higher and lower elevations, but these interceptions seem to act more as stochastic shale lenses rather than deterministic shale horizons. These stochastic shales most likely represent fracture fill shale rather than Intra-Arbuckle Shale that would have been deposited with the Arbuckle.

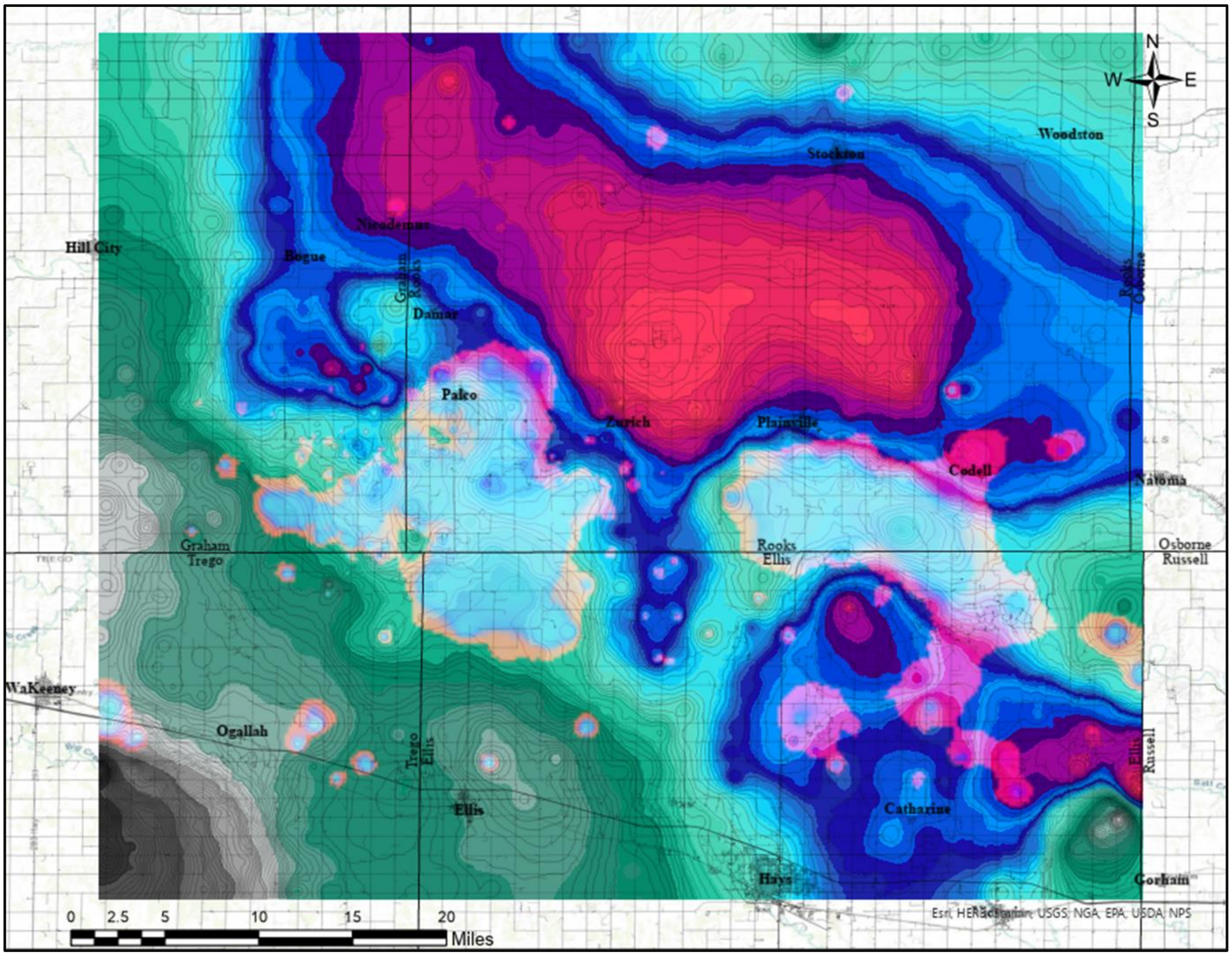

Figure 15: *Overlay map of Intra-Arbuckle Shale and Arbuckle top contact. Arbuckle and IAS Elevations are the same as Figures 12 and 13. Well log data points are also the same as Figures 12 and 13 but are not shown for visual clarity.*

By examining the overlay map of Intra-Arbuckle Shale distribution and the structure of the Arbuckle top contact above (Figure 14), another observation emerges: there seems to be a degree of congruity between the shale and the Arbuckle structure. This alignment is especially true within the channel-like structure on the Ellis-Rooks County line, where IAS seems to wrap around the structural high points of the Arbuckle (Figure 14). Two potential explanations for this interesting circumstance will be addressed at the closure of this section.

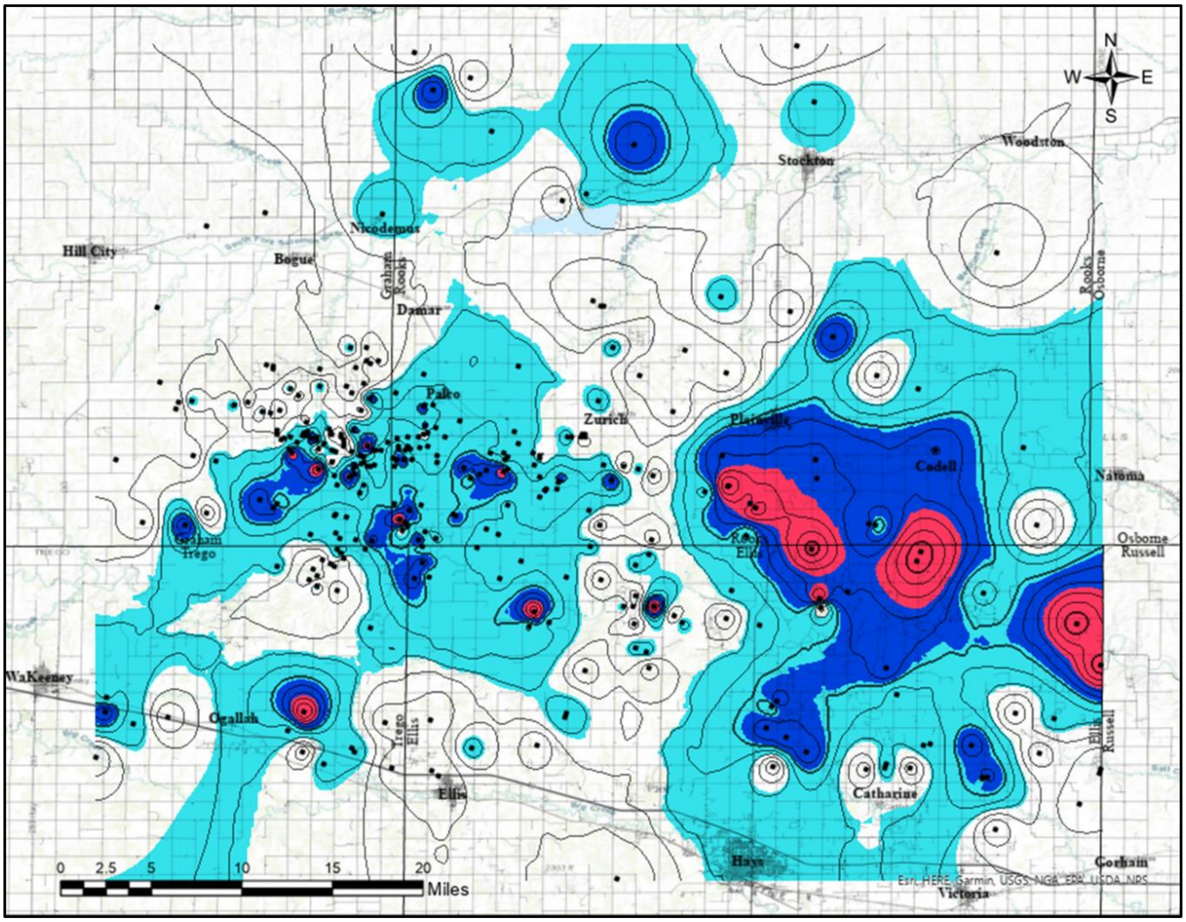

Figure 16*: Potential IAS barrier map. Pink = 3 or more potential shale barriers, Dark Blue = 2 or more potential shale barriers, light blue = at least 1 potential shale barrier, no color = no shale present or deeper than well log depth.*

To gain a better perspective on IAS distribution, another map was produced that predicts the number of potential IAS barriers based on location and shale interceptions by well logs. This map appears different from Figure 13 because it used the number of IAS barriers intercepted (0, 1, 2, or 3) rather than the elevations of IAS. The difference between elevation values was much more variable than the number of barriers.

Though the barrier map is different from Figure 13, the predictions made could show where IAS has a high likelihood of existing. A lack of IAS may simply reflect well logs that did not penetrate deep enough for shale interception, rather than the absence of shale (Figure 43).

Considering the number of barriers is important because of the potential for IAS to compartmentalize Arbuckle hydrocarbon reserves (Mullins & Ireland, 1967). If there are up to three possible IAS barriers present in some of these locations, there could potentially be four separate zones of oil and/or gas.

A brief survey of this map shows that most wells (if shale was intercepted) only recorded one shale. The Ellis-Rooks County line was one area that had multiple well logs that intercepted at least 3 shales beneath the Arbuckle top contact. Logs with at least 3 IAS interceptions could either represent locations with fracture fill shale, places where shale has not been eroded, or regions where well logs were drilled deep enough to reach more IAS.

5.4 IDW Zone Thickness Maps

5.4.1 Defining Zones

Intra-Arbuckle Shale separates Arbuckle reservoir rocks like dolomite and limestone into multiple potential pay zones. In the case of reservoir separation by IAS, zones are listed as A, B, C or D from the top down starting with zone A. Mullins and Ireland (1967) realized that compartmentalization of Arbuckle zones was created by repeated sequences of dolomite/limestone and shale. If this is the case in other portions of KS (Ellsworth County), it may be true in the study region as well. Therefore, it was important to map the zones that had enough supporting data (zones A and B).

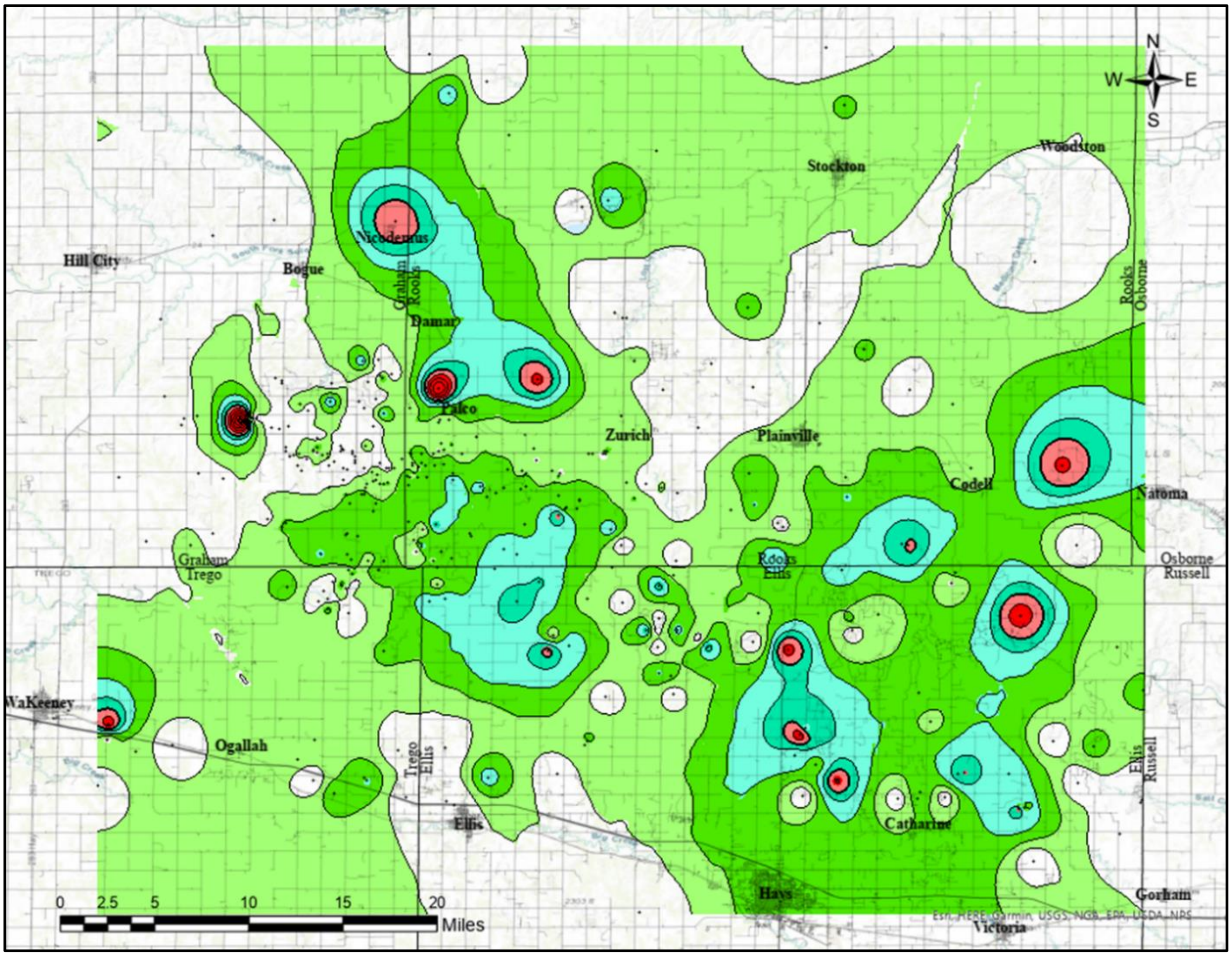

Figure 17: *Zone A thickness map. Light green = 5-19 ft, dark green = 20-29 ft, light blue = 30-39 ft, dark blue = 40-49 ft, red = zone thickness 50 ft or more, no color = no shale or shale deeper than well log depth.*

With the possibility of more than one zone existing, a map of zone A (zone between the Arbuckle top and IAS-1) was created (Figure 16). As before, the map appears somewhat different than the other IAS figures above because of the values used. Values used for this map were zone thickness values (10 ft, 15 ft, 20 ft, etc.) rather than changes in elevation.

A greater understanding of IAS distribution and structure can be gained from a few observations about the variability of zone A thickness (Figure 16). The first being that most of the map shows a zone A thickness of 5-19 feet. Because there were multiple IAS interceptions at 5-10 ft, the IDW technique will naturally predict these low values around areas of greater thickness. There is predictive potential in the light green areas, but there are also large portions of these areas where IAS was not intercepted.

It is crucial to note the distribution of red, blue, and non-colored areas on the map. These specific areas display dramatic changes in zone thicknesses. Several of these apparent changes in zone thicknesses are also located where the Arbuckle top contact has either decreased or increased in elevation. To explain the dramatic changes in zone A thicknesses, it is first necessary to make observations of zone B thicknesses as well.

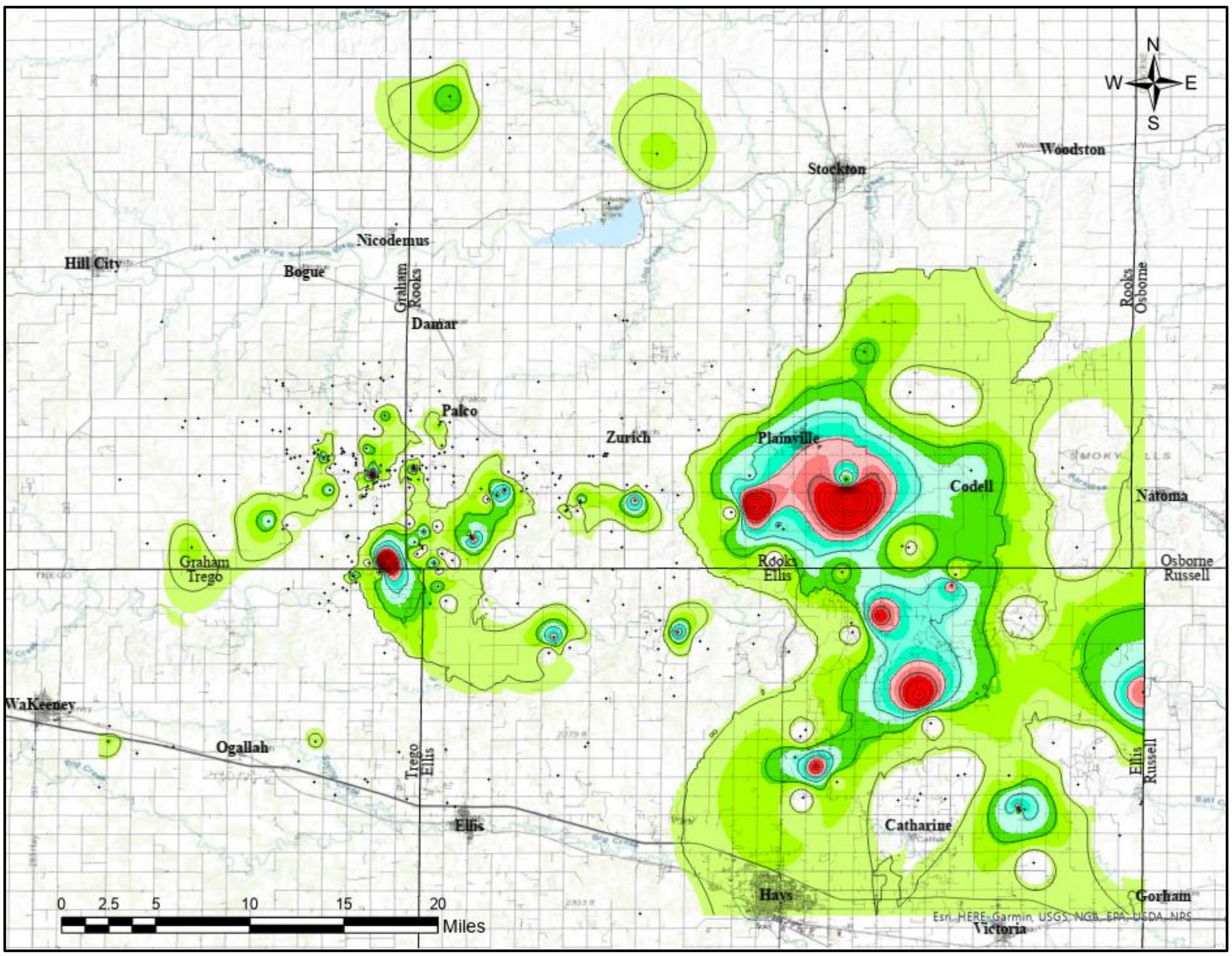

Figure 18*: Zone B thickness map. Greens = 5-19 ft thick, Blues = 20-35 ft, light red = 35-49 ft, dark red = zone B thickness potentially greater than 50 ft, no color = no shale or shale deeper than well log depth.*

Zone B thickness is shown above (Figure 17). The map was generated using the same IDW technique as before (Figure 16). Zone B represents potential reservoir thicknesses between the topmost shale (IAS-1) and the second shale (IAS-2) if present. Areas with no color represent where a second shale was not intercepted due to insufficient well log depth, or where a second shale was absent.

Similar to Figure 16, paying attention to the blue, red, and uncolored regions of the map yields observations of dramatic changes in zone B thicknesses that could offer insights into the structure and distribution of IAS. Several areas where zone B thicknesses dramatically change appear where predicted zone A thicknesses range from 5 ft to 29 ft. The possibility of zone A having a thickness of 5 ft, suggests that IAS-1 may be as little as 5 ft beneath the Arbuckle top contact.

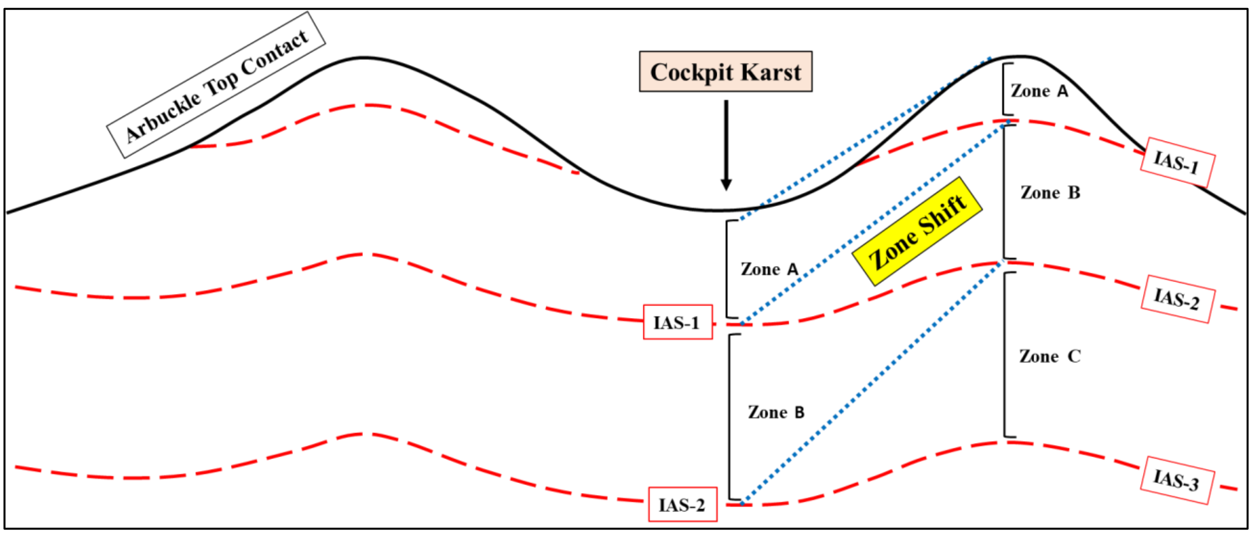

Figure 19*: Demonstration of zone shift caused by cockpit karst (paleo-karst). Zones and IAS labels change based on karstification of Arbuckle. Solid Black line represents Arbuckle top contact; red dashed lines symbolize IAS; blue dotted lines show zone shift.*

As IAS-1 trends closer to the Arbuckle top contact, the possibility of erosion or being affected by paleo-karst increases greatly. If IAS-1 is eroded or affected by paleo-karst, the second to top shale (IAS-2) on one log would be perceived as IAS-1 on another well log, causing a perceived zone shift to occur on the zone thickness maps (Figures 16 and 17). Zone shifting conveys that zone B would appear as zone A, and zone C would appear as zone B on the map. Cockpit karst features have also previously been recognized in several Arbuckle studies (Carr et al., 1995; Franseen et al., 2004; Nissen et al., 2005). With this knowledge, it is reasonable to explain some of these sudden/dramatic changes in reservoir thicknesses with zone shifting caused by paleo-karst.

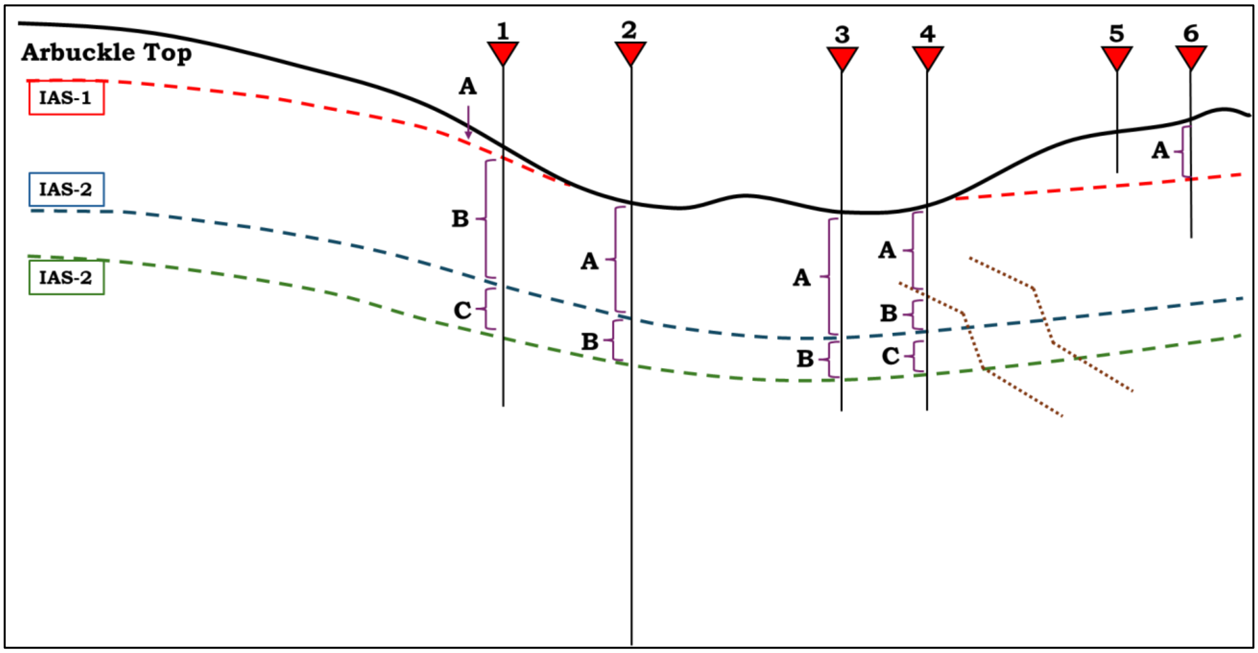

Figure 20: *Zone shifting (paleo-karst, fracture fill shale, and insufficient well log depth). 1, 2, 3, 4 represent 4 separate Arbuckle wells. A, B, and C represent Arbuckle zones. Brown dotted lines represent fracture fill shale withing the Arbuckle.*

Other than paleo-karst, two more possible explanations for zone shifting are shown above (Figure 19). Wells 1 and 2 depict a scenario where paleo-karst has caused a perceived zone shift. Wells 3 and 4 give an example of where fracture fill shale that was labeled as IAS on a well log could give the perception of a zone shift occurring. Lastly, wells 5 and 6 possibly explain the areas of no color on the zone thickness maps (Figures 16 and 17), where an Arbuckle well may have had insufficient depth to intercept IAS.

5.5 Arbuckle Cross Sections

Cross sections of the Arbuckle were drawn using data that were utilized for the IDW maps. Cross sections bring a different perspective on the relationship between the irregular Arbuckle surface and the distribution of Intra-Arbuckle Shale. Below are several figures of the cross sections produced from the study. Cross sections were drawn from lines connecting two well log data points. The points chosen for the cross section were either intersecting the line or within one mile of the cross-section line (when sufficient data were lacking).

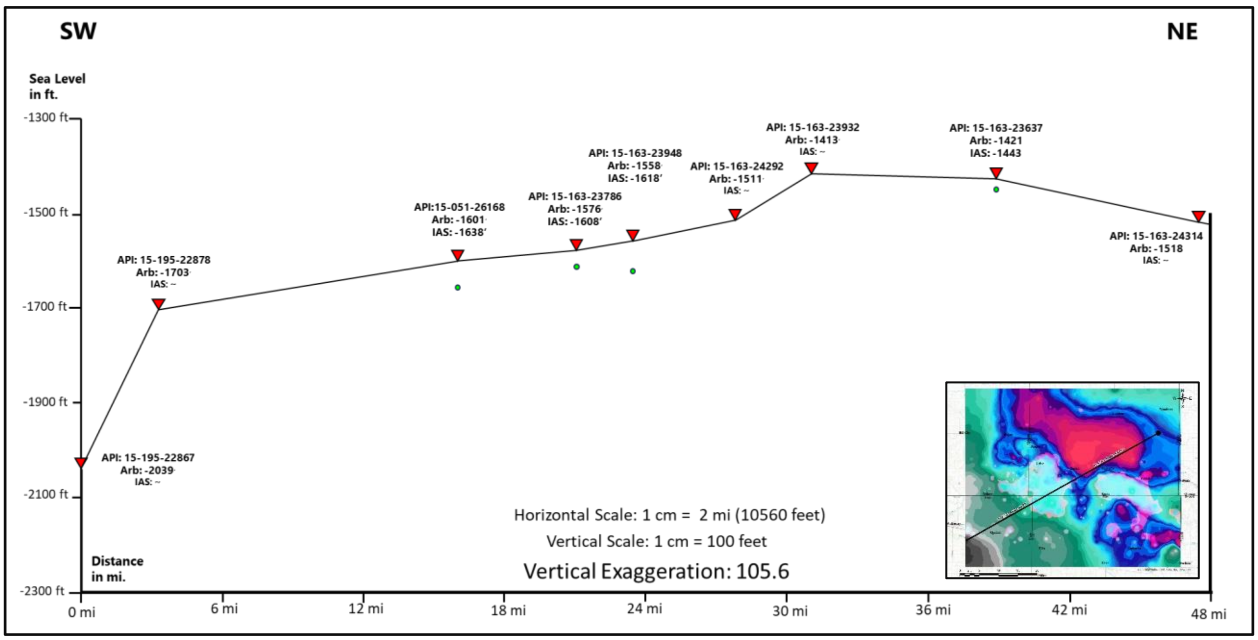

Figure 21*: SW to NE Arbuckle cross section. SW point taken from Trego County; NE point located in Rooks County. Red triangles represent well log locations, while their corresponding API number, Arbuckle sea level, and Intra-Arbuckle Shale sea level/gamma ray units are displayed above them. The black line connecting the triangles symbolizes the Arbuckle top contact, and the green circles beneath represent where IAS was intercepted.*

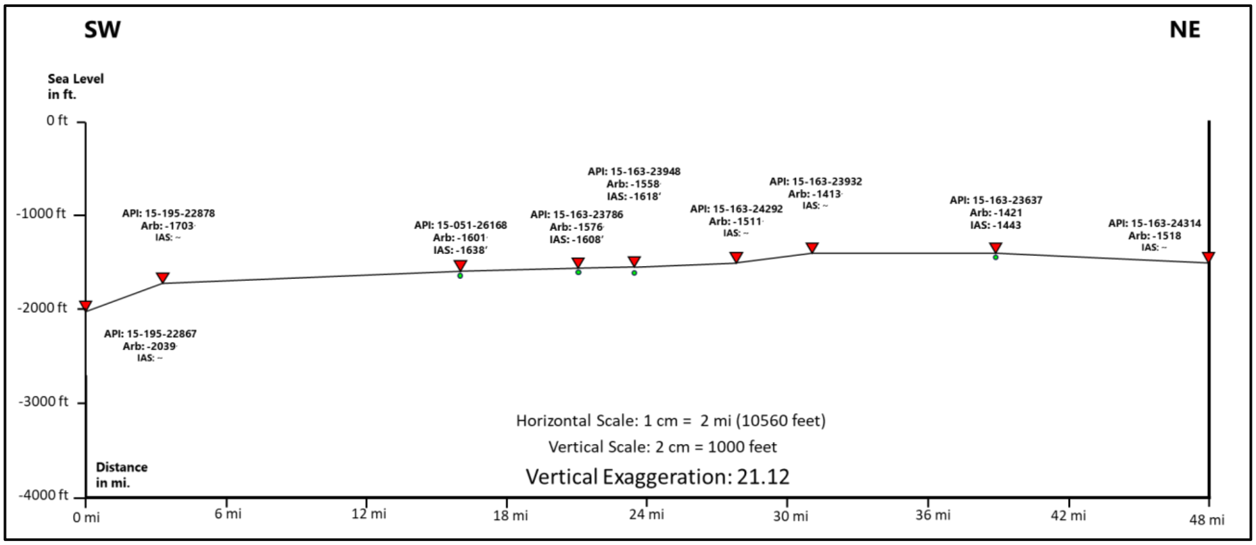

***Figure 22**: SW to NE Arbuckle cross section with different vertical exaggeration, but same point data as Figure 20.*

The deepest Arbuckle top contact value in the study region was found at Well 15-195-22867, with a sea level of -2,039 ft (Figures 20 and 21). The shallowest Arbuckle top contact value of the figure was located at Well 15-163-24314, with a sea level of -1,518 ft. Intra-Arbuckle Shale is present on the cross section, but only appears between miles 16 and 24. Because of this, a well log correlation for this cross section was not produced.

Figure 21 was drawn with the same data as Figure 20, but with a vertical exaggeration of 21.12 rather than 105.6. This change in vertical exaggeration was made by changing the vertical scale to 2 cm = 1,000 ft while keeping the horizontal scale at 1 cm = 2 mi and was done to display a more realistic view of the Arbuckle top contact.

There are Arbuckle cross sections available that contain portions of the study area (Keroher & Kirby, 1948, as cited in Franseen, 1999) that display large regions of the formation and individual Arbuckle sequences. They also display similar Arbuckle structures in central Rooks County compared to Figure 12 above.

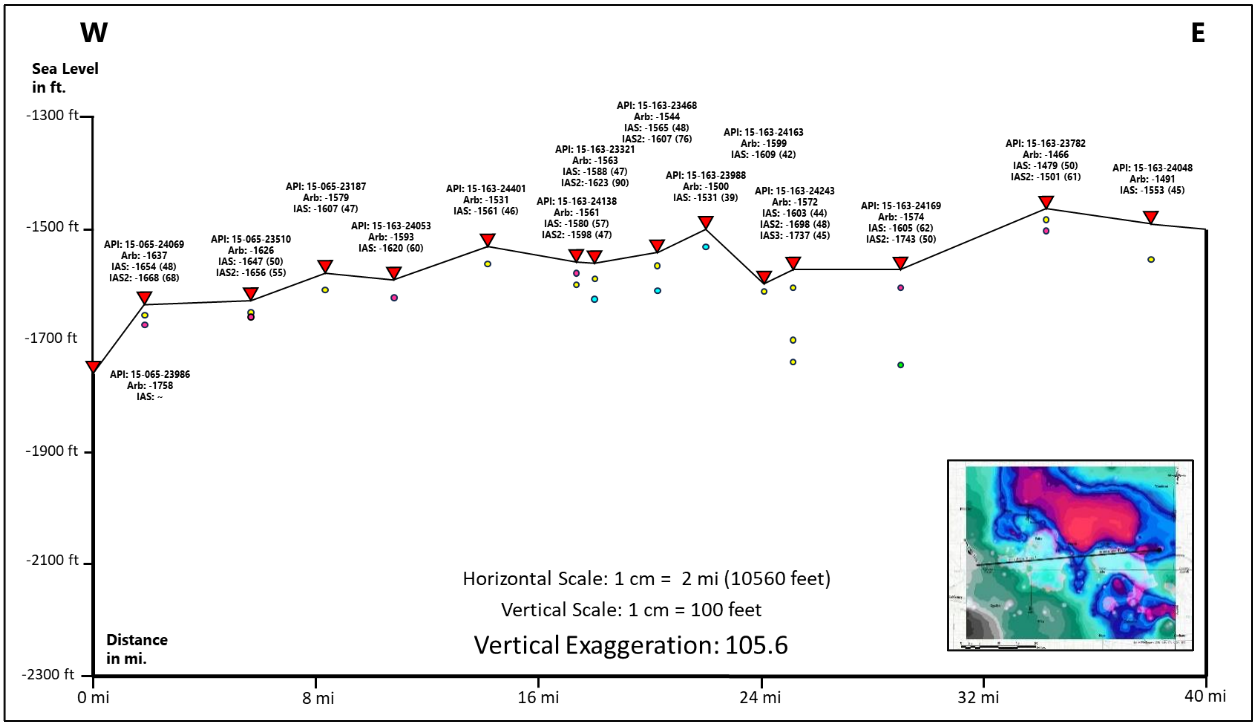

Figure 23*: West to East Arbuckle cross section with Intra-Arbuckle Shale. Red triangles represent well log locations, while their corresponding API number, Arbuckle top sea level, and Intra-Arbuckle Shale sea level/gamma ray units are displayed above them. The black line connecting the triangles symbolizes the Arbuckle top contact, and the circles beneath represent where IAS was intercepted.*

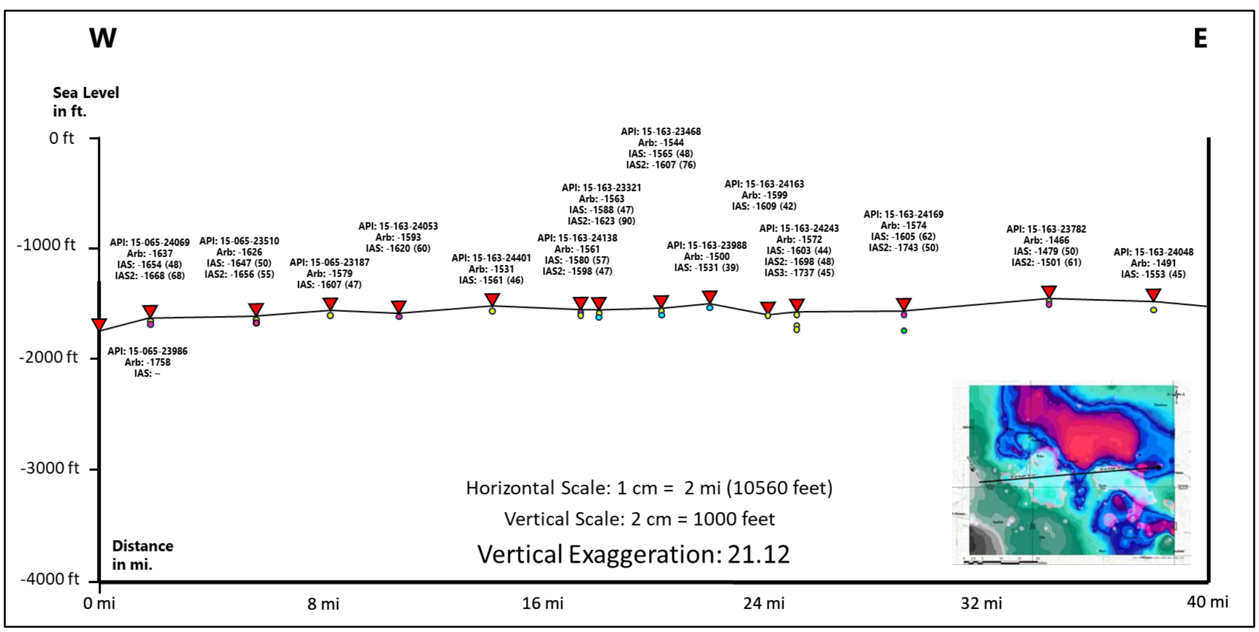

Figure 24*: West to East Arbuckle cross section with IAS (different vertical exaggeration). The same data points from Figure 22 were used.*

The next cross section of the Arbuckle created spanned from the West to the East portion of the study area. The West most point was in Southern Graham County and the East most point was in Southern Rooks County. This line was specifically chosen to contact as many IAS-intercepting data points as possible from a West to East orientation.

Figure 23 is the same cross section as Figure 22, but with a more realistic vertical exaggeration of 21.12. This difference in vertical exaggeration was achieved by changing the vertical scale to 2 cm = 1000 ft.

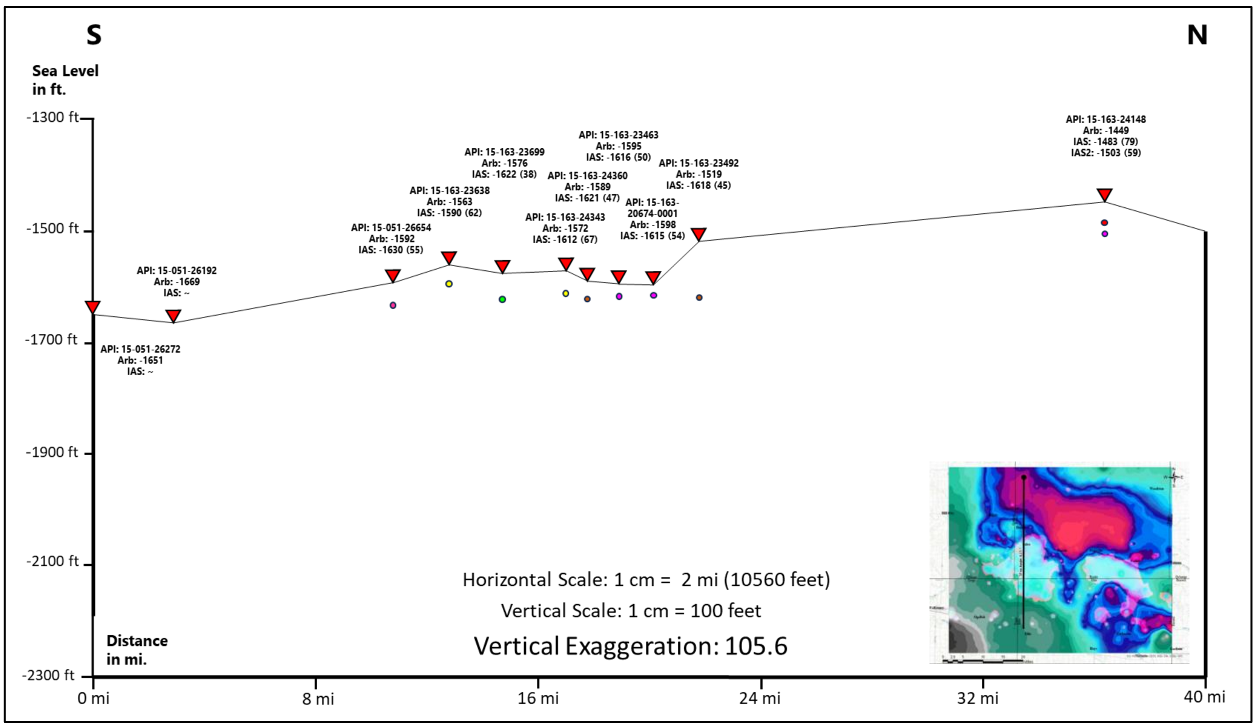

***Figure 23**: South to North Arbuckle cross section with Intra-Arbuckle Shale. Red triangles represent well log locations, while their corresponding API number, Arbuckle sea level, and Intra-Arbuckle Shale sea level/gamma ray units are displayed above them. The black line connecting the triangles symbolizes the Arbuckle top contact, and the colored circles beneath represent where IAS was intercepted. Dotted lines connecting shale points represent correlation.*

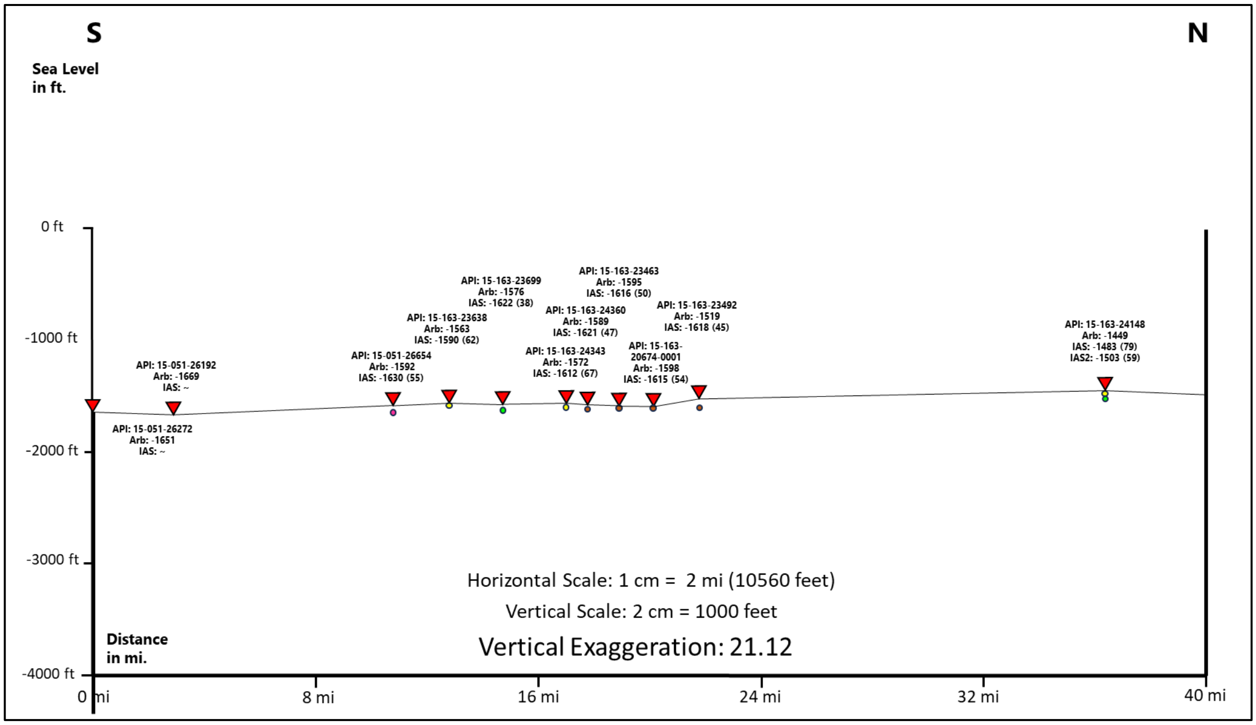

Figure 24*: South to North Arbuckle cross section with IAS (different vertical exag.). The same data points from Figure 24 were used.*

This cross section (Figure 24) displays Arbuckle characteristics from the South side to the North side of the study region. The cross-section line was drawn to intercept as many IAS intercepting well logs as possible from a S-N orientation. Well 15-051-26192 has the deepest Arbuckle top value of -1651 ft. Well 15-163-24148 has the highest elevation with a sea level of -1449 ft.

Figure 25 is the same as the previous South to North cross section (Figure 24), but with a vertical exaggeration of 21.12 rather than 105.6. This change was made by converting the vertical scale from 1 cm = 100 ft to 2 cm = 1000 ft for a more realistic display of the Arbuckle top contact.

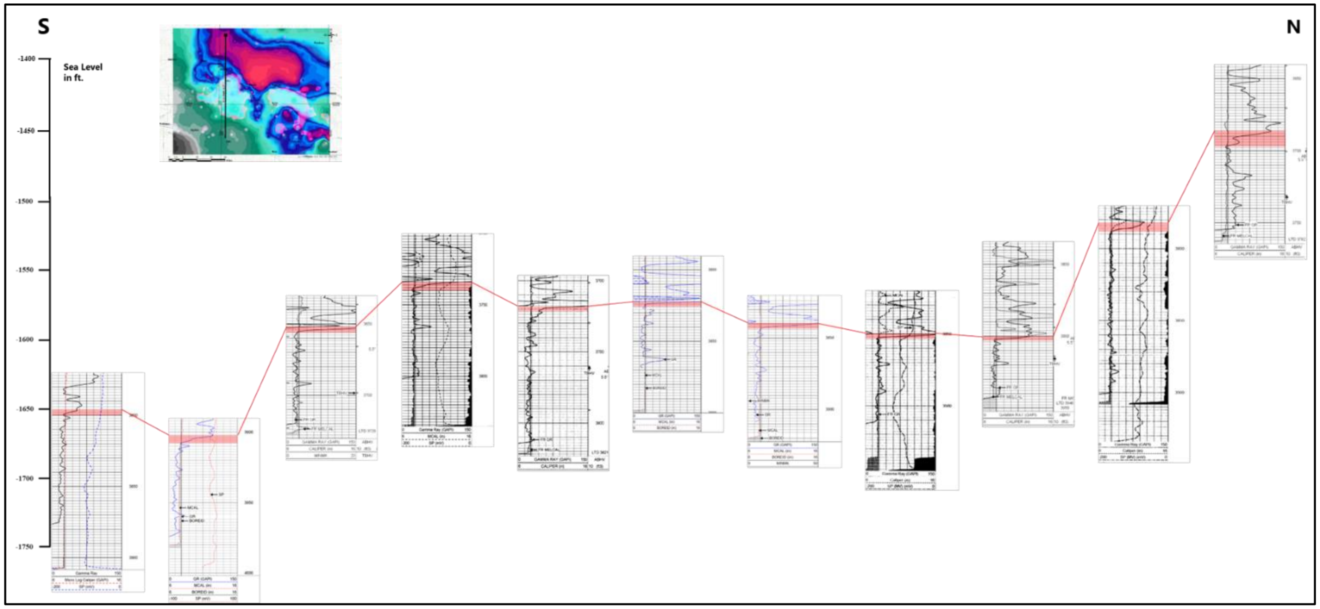

__Figure 28__: South to North well log correlation. Red highlights symbolize Arbuckle top contact as listed on geologist report.

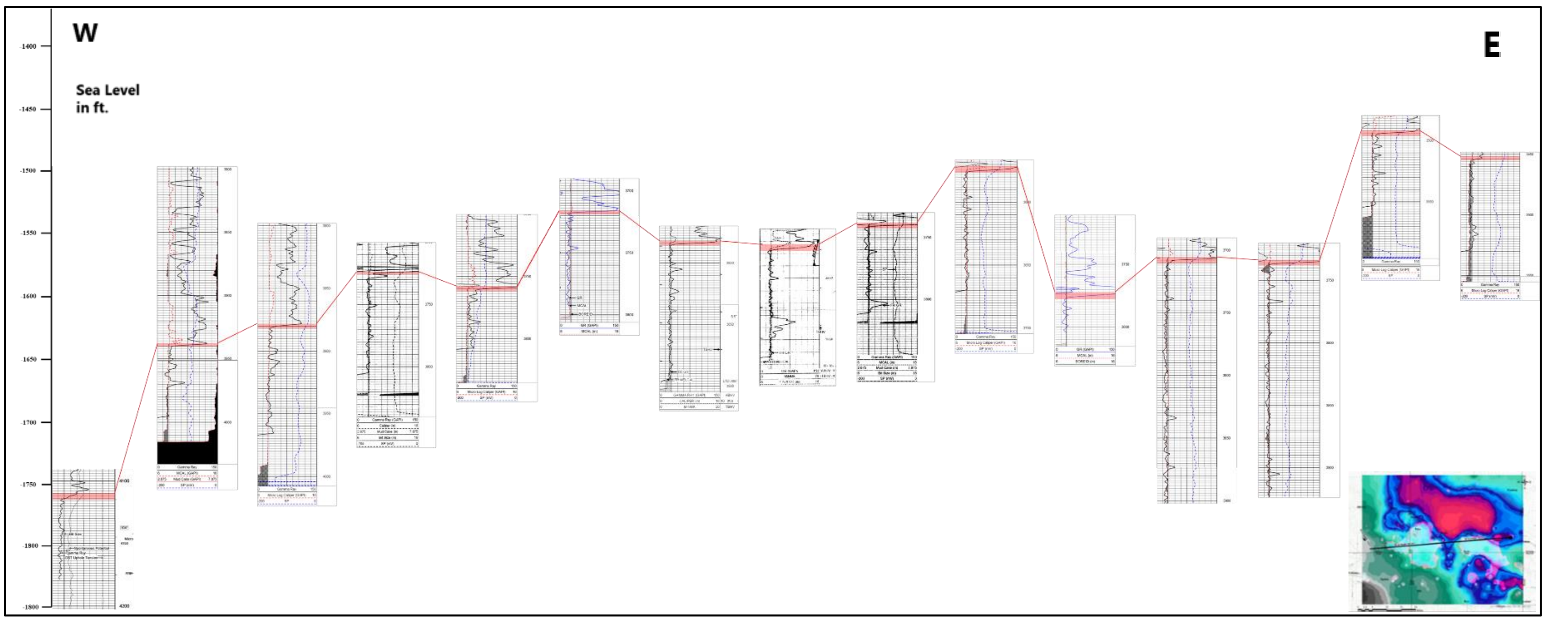

__Figure 27__: West to East well log correlation. Red highlights symbolize Arbuckle top contact as listed on geologist report.

Two sets of log correlations (Figures 26 and 27) were produced from the same West to East and North to South cross section lines used earlier in the study (Figures 22 and 24). Correlations were made from gamma ray well logs found on the KGS Interactive Oil and Gas Map. The red line moving from well to well symbolizes the Arbuckle top at the depth it was listed by the wellsite geologist. To show accurate relationships between logs, elevations based on sea level were used. Equal spacing was used instead of the true distances to fit the well logs into the figures.

Cross sections from Arbuckle well log correlations have been created in the past (Franseen et al., 2004), but few from the region of study are available. Most cross sections of this type, though very detailed, consist of very few well logs.

Log correlations produced in this study were produced using up to 15 well logs but were not as detailed compared to other log correlations. The goal was to aid in the understanding of shale distribution and structure by targeting IAS alone, rather than correlating other features and/or sequences of the Arbuckle formation.

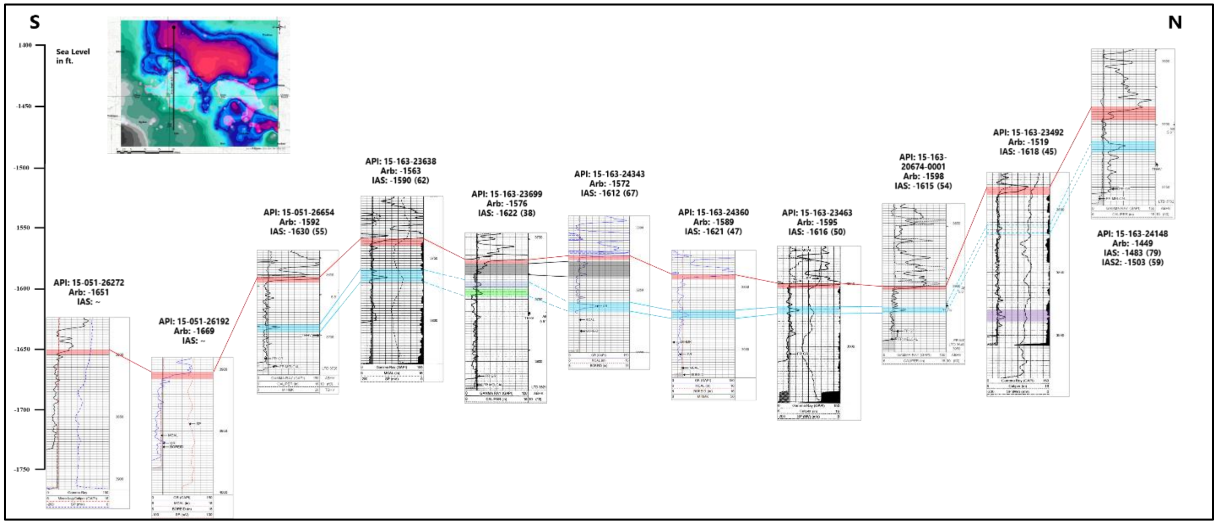

Figure 30: *South to North well log correlation with highlights. Red highlights symbolize Arbuckle top contact. Blue, purple, green, grey highlights represent potential IAS correlation.*

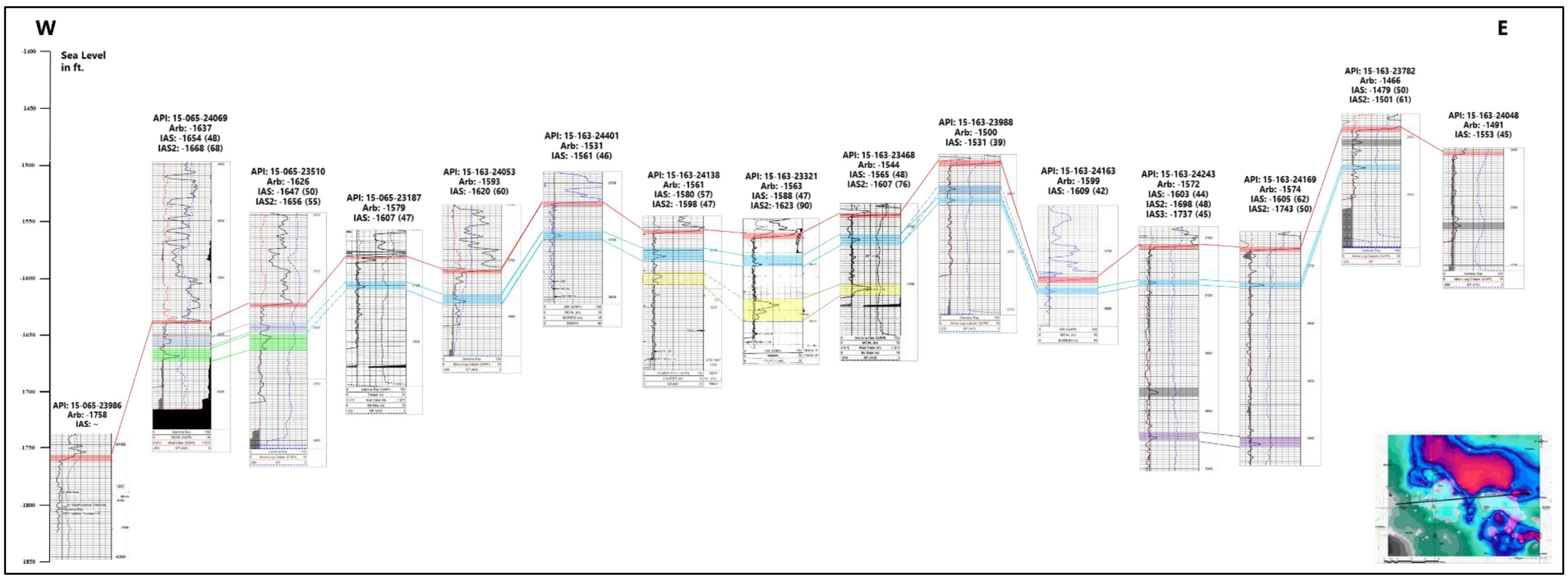

Figure 29: *West to East well log correlation with highlights. Red highlights symbolize Arbuckle top contact. Blue, yellow, purple, green, grey highlights represent potential IAS correlation.*

Several potential stratigraphic and lithologic correlations between Intra-Arbuckle Shale were displayed (Figure 28 and 29). The highlighted areas connected by lines were not created to indicate that IAS on one log must be the same IAS on another, but simply suggesting that they could be the same. While some of the IAS gamma ray signatures appear to be the exact same, there is still enough variety between them to make exact correlations difficult.

5.6 Geologist Report Shale Descriptions

Some well logs had corresponding geologist reports that would occasionally contain color and texture descriptions of IAS. Franseen and Byrnes (2004) mention that IAS is present as wavy horizontal beds, but do not give any description of shale color or texture, besides stating the green color of fracture fill shale. Below, is a collection of IAS intercepting logs that had shale descriptions from a corresponding geologist report. Some of the shales present on these logs are possibly fracture fill, but many of them have distributions too large to be considered fracture fill shales.

None of the highlighted logs below (Figures 30-35) were positioned based on elevation or specific distances. The features on one log (Arbuckle top contact or IAS depth) may appear higher or lower than another, but this perception does not accurately reflect true depths or elevations. The goal for creating groups of common IAS characteristics was not to correlate them based on elevation, distance, or gamma ray signature, but to reveal the different IAS colors and textures discovered in the study.

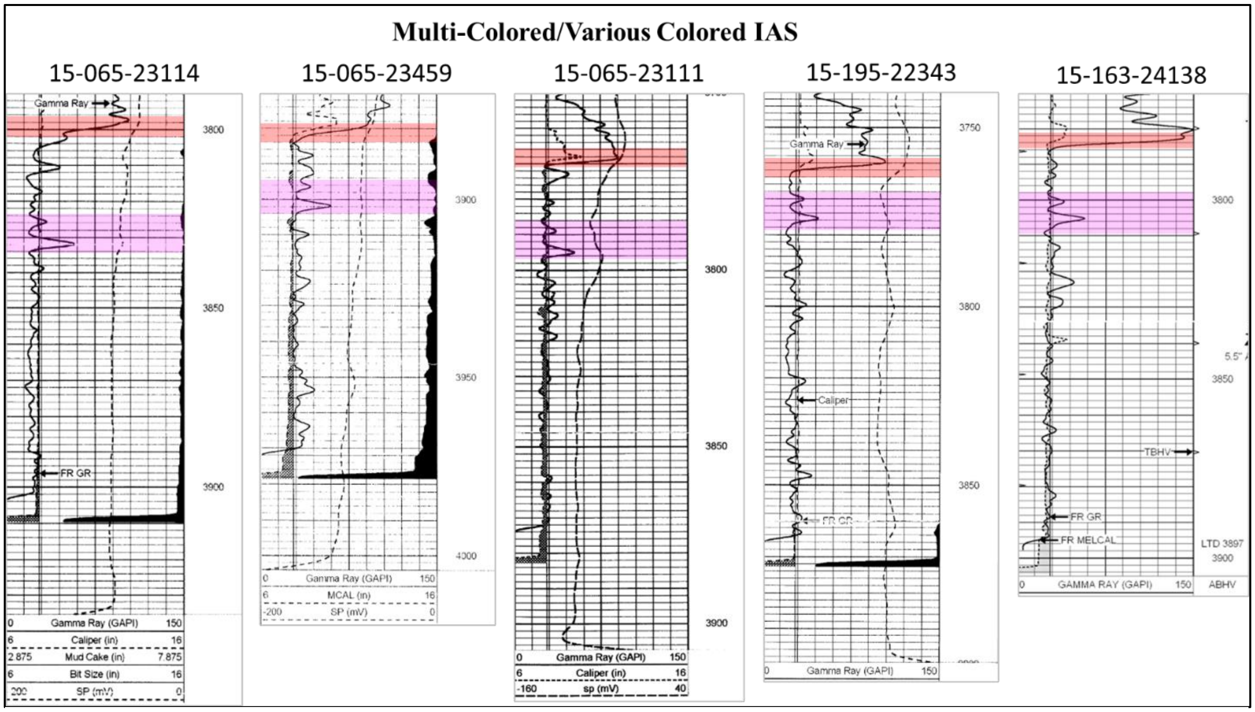

***Figure 31**: Gamma ray well logs showing multi-colored or various colored IAS (pink highlights), and Arbuckle top contact (red highlights). Descriptions based on corresponding geologist report.*

Multi-colored Intra-Arbuckle Shale was one of the most common shales mentioned by wellsite geologists within the study region. Most multi-colored IAS was in the corner of SE Graham, NE Trego, NW Ellis, and SW Rooks County. When a DST report was also available for one of these well logs, it was very common to find gassy oil beneath the shale and no gas above, though there were a few exceptions. Overall, there was very little variation in the gamma ray signatures of multi-colored IAS.

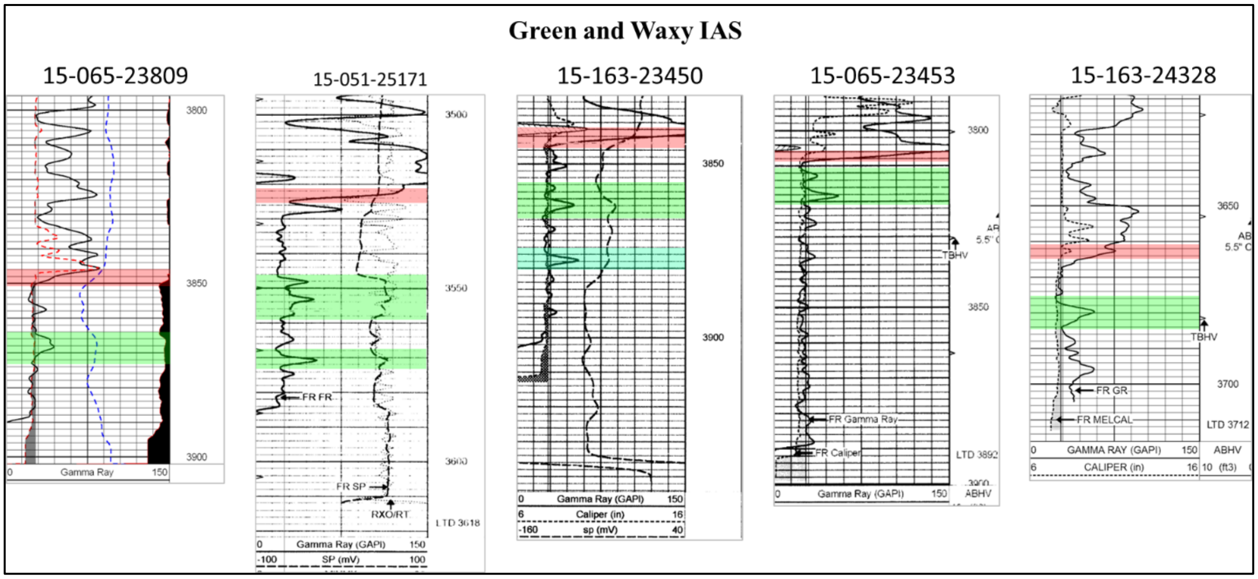

***Figure 32**: Gamma ray well logs showing waxy green IAS (green highlights), and Arbuckle top contact (red highlights). Blue highlight on 15-163-23450 represents turquoise IAS. Descriptions based on corresponding geologist report.*

Waxy Green IAS was the second most prolific shale mentioned by wellsite geologists in the study region. IAS of this kind was usually found anywhere that shale was intercepted by a well log. One observation to be made is noticing that some of the waxy green IAS gamma ray signatures are almost identical to multi-colored shale. For instance, the waxy green shale 15-065-23453 and multi-colored shale 15-163-24138 are very similar. If these two shales are the same, this indicates that at least one of them has been exposed to some factor that has resulted in a color change. Whether this be from the presence of gas underneath multi-colored IAS, or some other factor is unknown at this point.

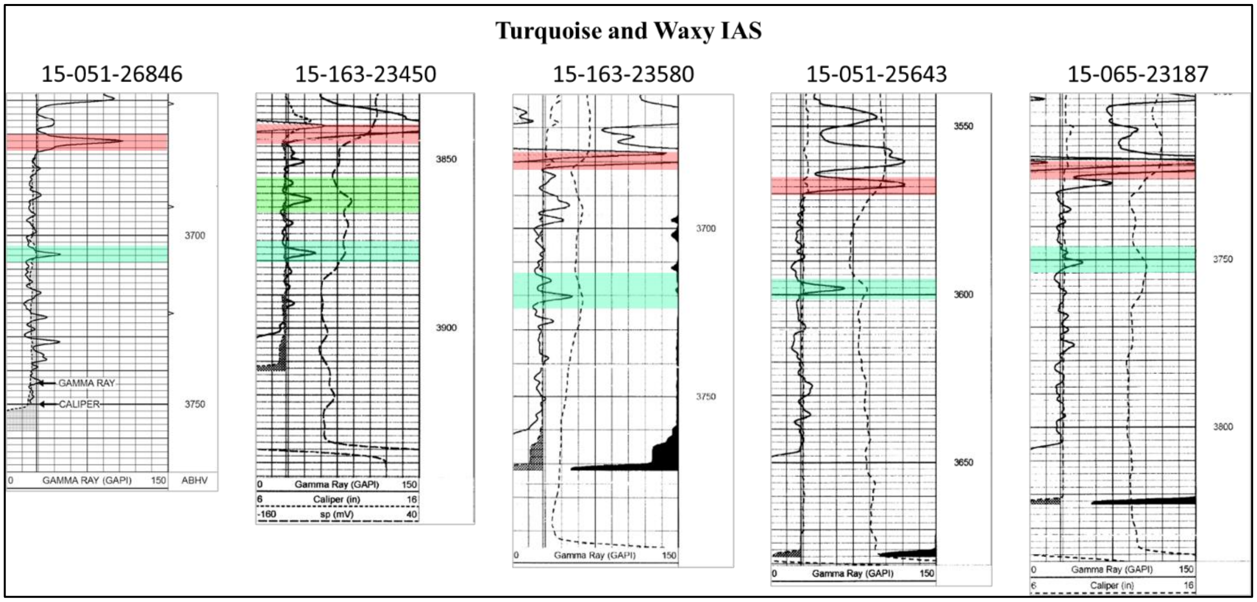

Figure 33*: Gamma ray well logs showing waxy turquoise IAS (blue highlights), and Arbuckle top contact (red highlights). Green highlight on 15-163-23450 represents green IAS. Descriptions based on corresponding geologist report.*

Waxy Turquoise IAS was by far the most described shale by wellsite geologists in the study region. This kind of IAS was found almost everywhere shale was intercepted. Unlike multi-colored IAS, this kind had much more variable gamma ray signatures. There were also some waxy turquoise shales that had similar gamma ray signatures to the green and multi-colored shales, suggesting a post-depositional color change by one or more of the shales. Some other common descriptions of this shale included: Wavy, platy, blocky, firm, and mint green or teal in color.

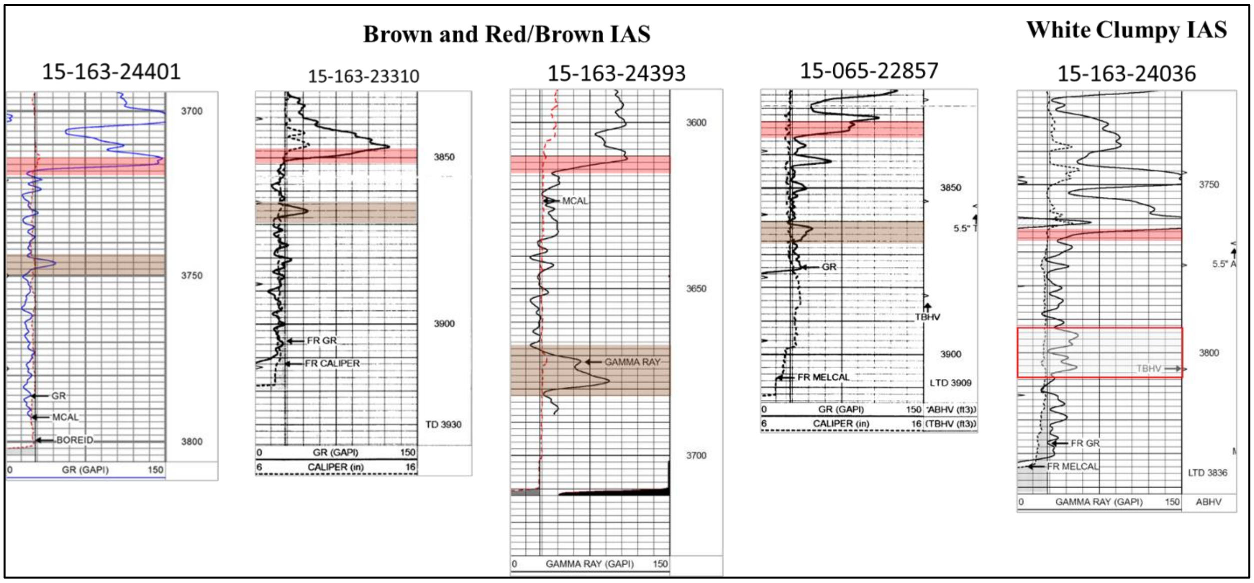

Figure 34*: Gamma ray well logs showing brown, red/brown, and clumpy IAS. Brown and red/brown shale- brown highlights, clumpy white shale- white highlight with red outline, and Arbuckle top contact- red highlights. Descriptions based on corresponding geologist report.*

A less common shale that was described by wellsite geologists in the region of study were brown and/or reddish-brown Intra-Arbuckle Shale. The locations for this kind of IAS were more sporadic throughout the study area. The randomness of this shale could be a result of geologists not taking note of it, or because it could be a type of fracture fill shale that occurs less often. Another characteristic occasionally given to this shale was that it was sub waxy and/or maroon in color.

A type of potential IAS that was very rarely described by wellsite geologists was clumpy white shale. This shale was intercepted in SW Rooks County and described only once in the whole study region. This shale was considered possible IAS though, because there are several other logs that have gamma ray signatures very similar to this one. One more characteristic of this shale was that it was sticky.

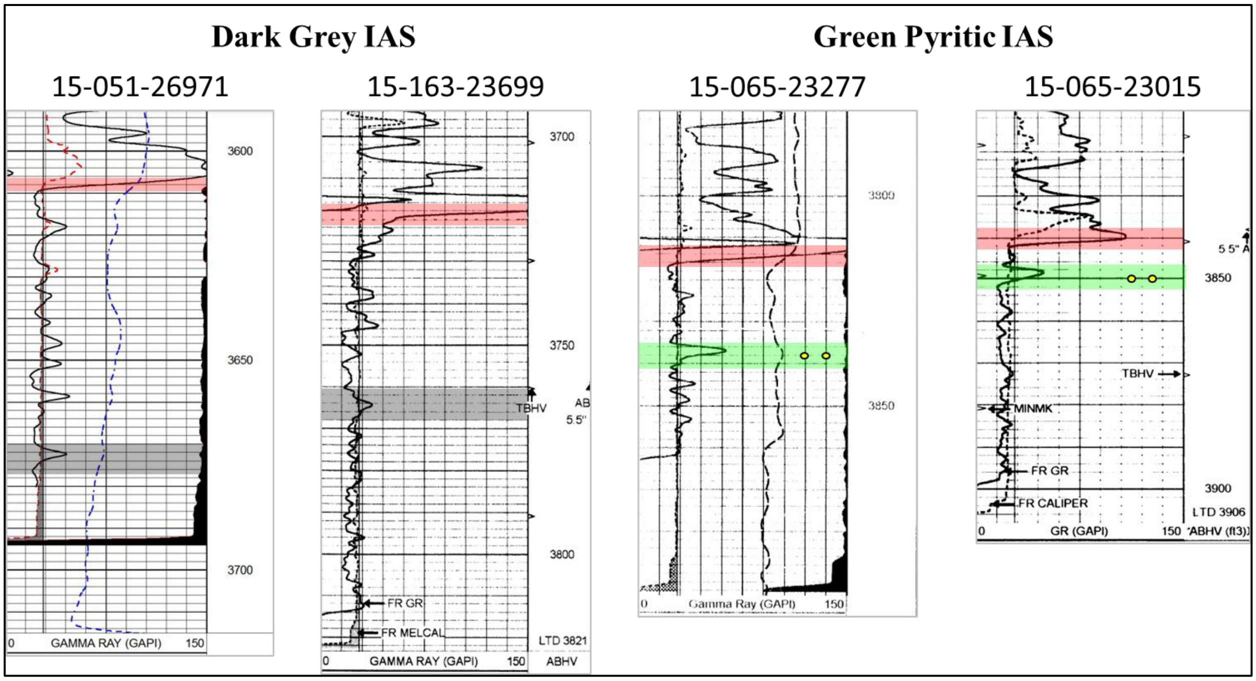

Figure 35*: Gamma ray well logs showing dark grey and green pyritic IAS. Dark Grey shale- grey highlights, green pyritic shale- green highlights with yellow dots, and Arbuckle top contact- red highlights. Descriptions based on corresponding geologist report.*

Another potential IAS that was less commonly described by geologists in the study region was grey/dark grey shale. The lack of grey shale recorded could be the result of geologists not describing it, well logs not being deep enough to intercept it, or because it is fracture fill rather than IAS.

Green pyritic IAS is most likely related to either the waxy green shale or waxy turquoise shale. Both logs were in the SE corner of Graham County. There was also a geologist report in the study region that described a pyritic turquoise shale that was below the gamma log completion depth, so an image could not be provided. This well log was in North Central Ellis County.

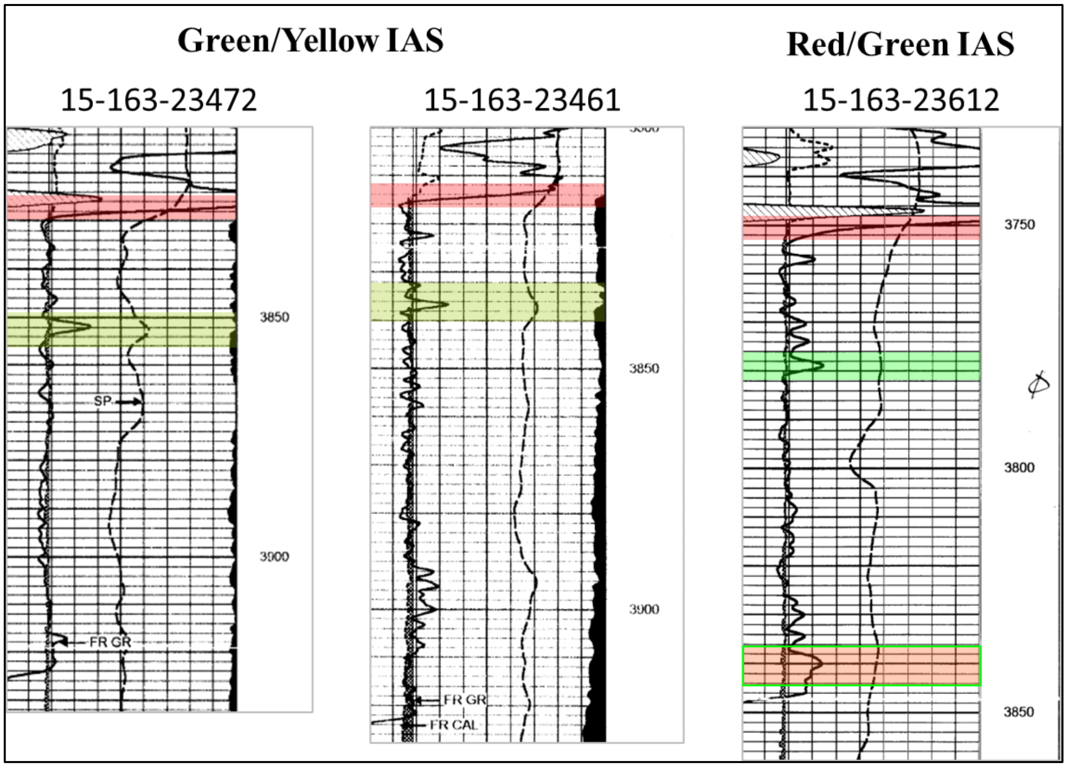

Figure 36*: Gamma ray well logs showing green/yellow and red/green IAS. Green/yellow shale- greenish yellow highlights, red/green shale- red highlight with green outline, and Arbuckle top contact- red highlights. Green highlight on 15-163-23612 represents green shale. Descriptions based on corresponding geologist report.*

The last two potential Intra-Arbuckle Shales that were described by wellsite geologists were greenish yellow shale and reddish green shale. Because of the gamma ray signature, it is most likely that the greenish yellow shale is part of the waxy green IAS group or the waxy turquoise IAS group. The reddish green shale may be IAS, but since it was only described by a geologist once, it may be better classified as fracture fill.

5.7 Reservoir Compartmentalization

From studying DST reports from more than 200 wells that intercepted IAS, the previous research of Mullins and Ireland (1967), and the nature of shale to act as barriers to fluid flow (Haldorsen & Lake; 1984; Franseen et al., 2004; Michael, 2014; Snedden, 2014). It is evident that IAS within the study region is compartmentalizing the Arbuckle into many hydrocarbon accumulating zones.

If a well intercepted IAS, the DST report (if available) would be downloaded and studied. Evidence of Arbuckle zone compartmentalization came from the test intervals and recovery sections of these DST reports. Many times, when shale was present on a log, the corresponding drill stem test would show a testing interval directly above the shale and directly beneath the shale, and the recovery sections from these two testing intervals were often very different. Testing intervals directly above and below IAS indicate that some oil producers and geologists in the area have an existing knowledge of the zone separating capabilities of the shale. The different recovery results above and beneath IAS provide evidence for potential zones of oil and gas below them that could be untapped because of shallow Arbuckle well depths (Henry & Hester, 1995; Franseen et al., 2004). They also show evidence of reservoir compartmentalization if recovery descriptions are different above and below IAS.

The presence of a shale barrier does not guarantee that an economically beneficial reserve of oil and gas is beneath it though. Mullins and Ireland (1967) found that there were several criteria that the barriers had to meet to successfully trap hydrocarbons beneath them. One criterion was the need for a structural high point where vertically migrating fluids would be trapped. Unfortunately, the mapping technique used in this study did not contain enough data to model these types of structural features.

Below are several DST's, well completion reports, and Micro-resistivity logs (Figures 36-40) collected from the study region that demonstrate Arbuckle reservoir compartmentalization by IAS. The examples provided represent a few good examples from the study area, and more could have been used.

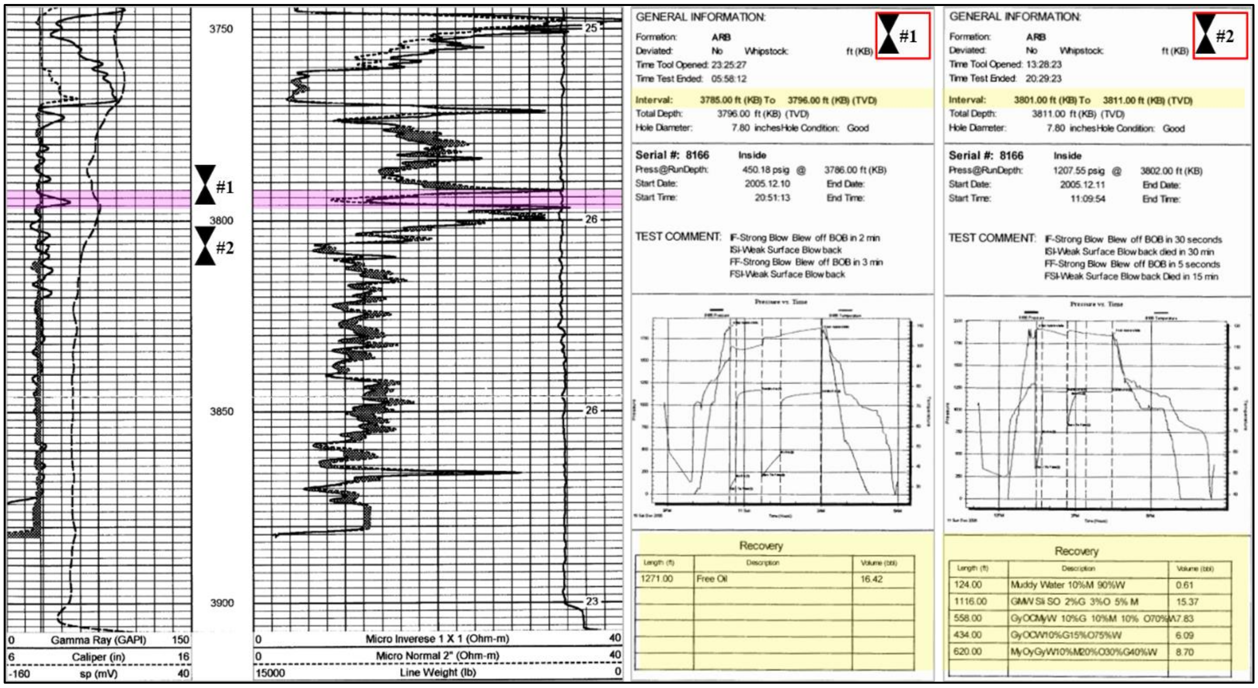

__Figure 37__: DST and Micro log from Well 15-065-23111. Geologist report described IAS as various colored. Bowties show DST intervals. Yellow highlights show testing intervals and recovery descriptions.

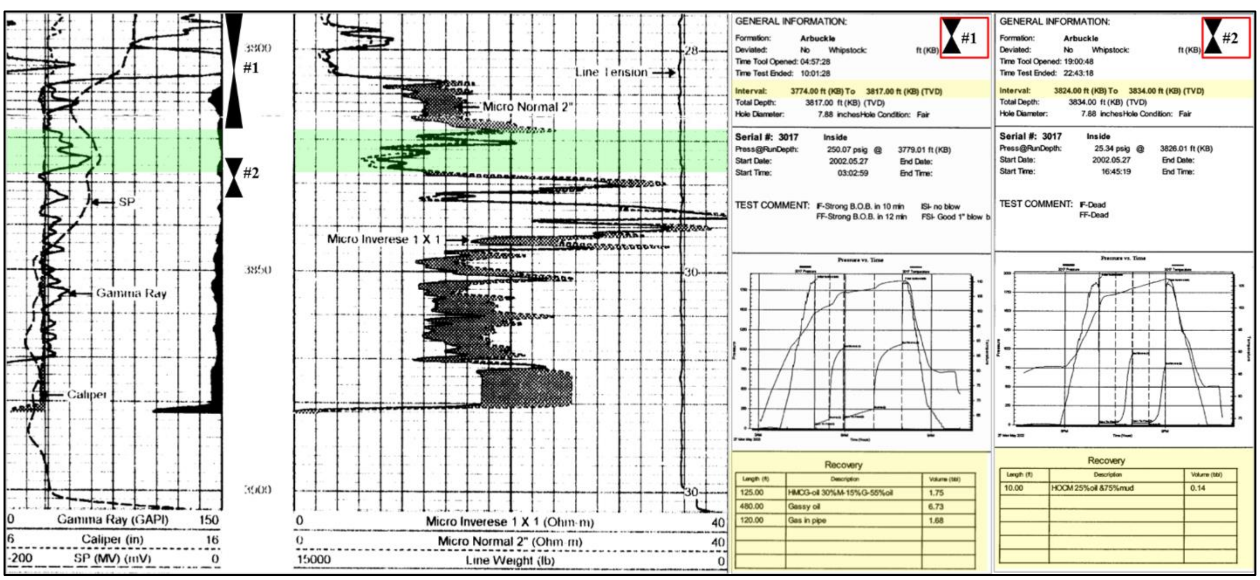

__Figure 38__: DST and Micro log from Well 15-065-22837. Geologist report described IAS as green and waxy. Bowties show DST intervals. Yellow highlights show testing intervals and recovery descriptions.

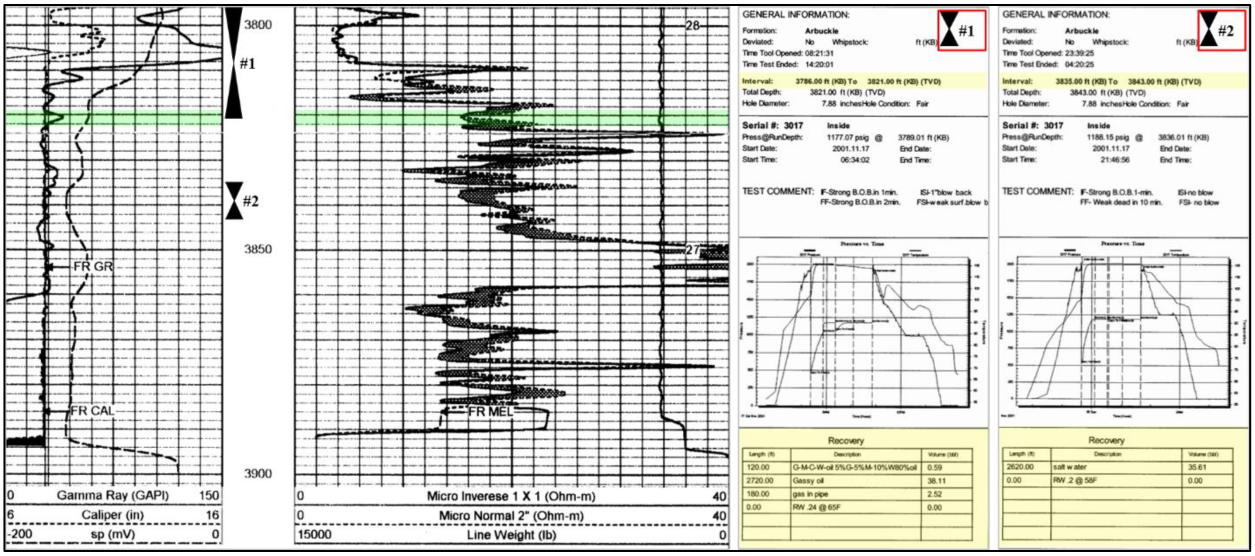

***Figure 39**: DST and Micro log from Well 15-163-23327. Geologist report described IAS as green and waxy. Bowties show DST intervals. Yellow highlights show testing intervals and recovery descriptions.*

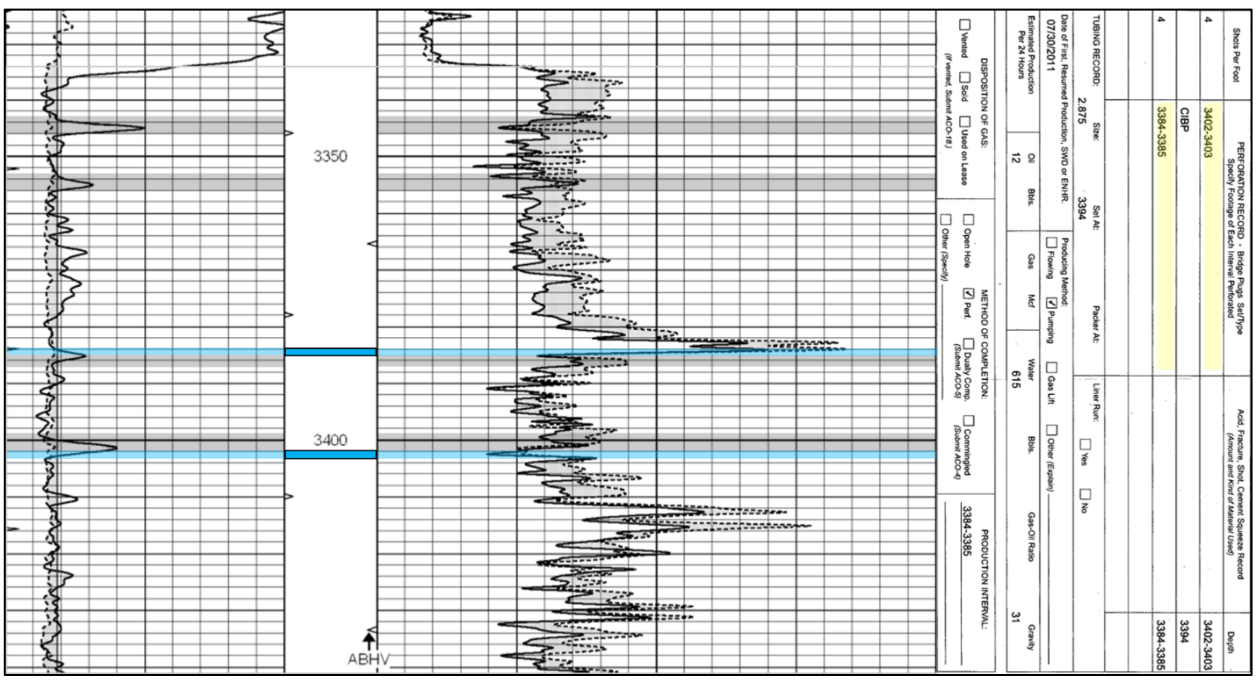

***Figure 40**: WCR and Micro log from Well 15-051-26156. Geologist report had shales drawn in, but not described. Grey highlights show where IAS is, and blue highlights represent perforations made according to well completion report. Yellow highlights show perforation record.*

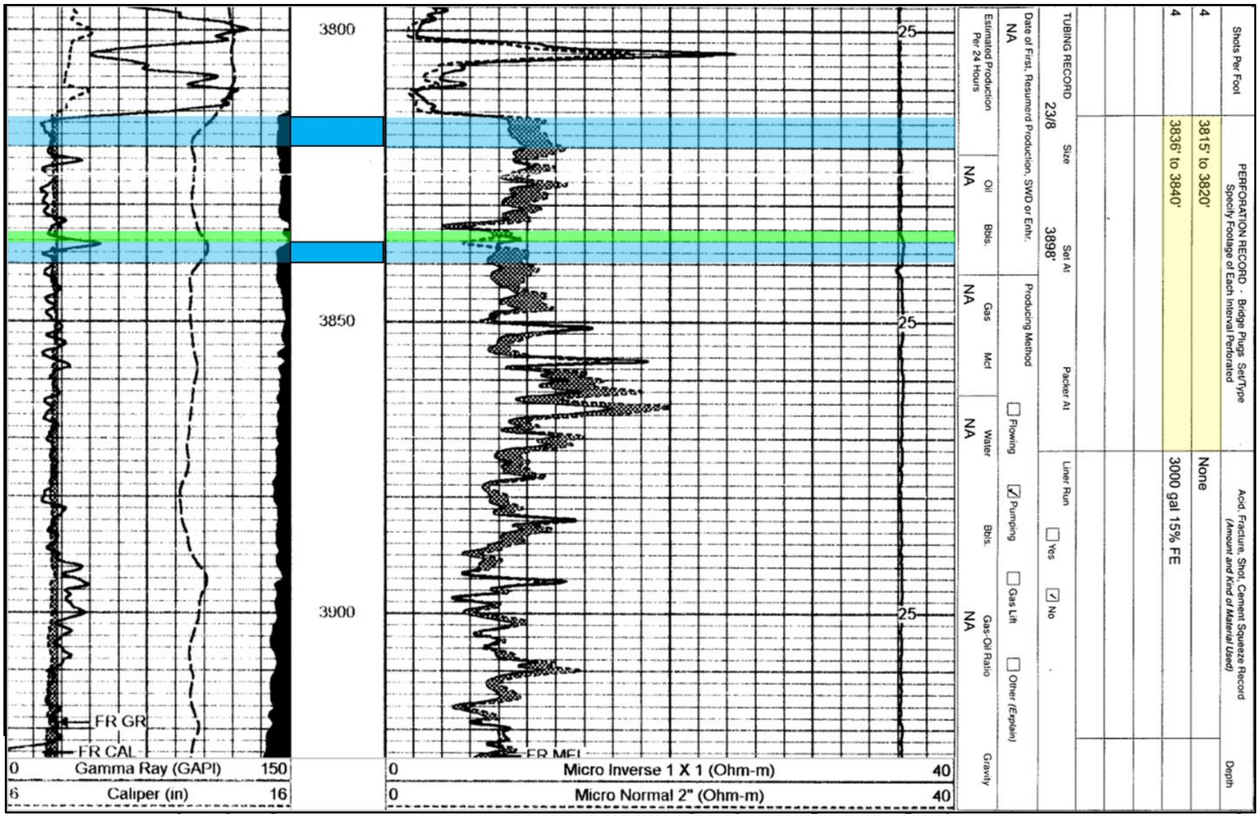

Figure 41*: WCR and Micro log from Well 15-163-23461. Geologist report described IAS as turquoise and yellow. Blue highlights represent perforations made according to well completion report. Yellow highlights show perforation record.*

5.8 IAS Hypotheses

While the distribution of Intra-Arbuckle Shale can be better understood from the figures and maps above, the structural nature of shale within the Arbuckle still needs some explanation. From the zone thickness maps (Figures 16 and 17), IAS in some portions of the study region are possibly affected by karstification and/or subaerial Arbuckle erosion. IAS presented on the well log correlations (Figures 28 and 29) also exhibit some structural deformation, possibly indicative of folding and/or faulting. Lastly, from grouping together all types of IAS that were described by wellsite geologists, common gamma ray signatures were discovered between shales. With this knowledge, a hypothesis can be made.

Intra-Arbuckle Shale (within the study region) was deposited during Arbuckle deposition (Franseen et al., 2004), and exists as separate, identifiable horizons that have been folded, faulted, and eroded by karstic processes in various regions. IAS compartmentalizes Arbuckle reservoirs by acting as effective barriers to fluid flow, potentially storing economically substantial quantities of hydrocarbons beneath them (Mullins & Ireland, 1967).

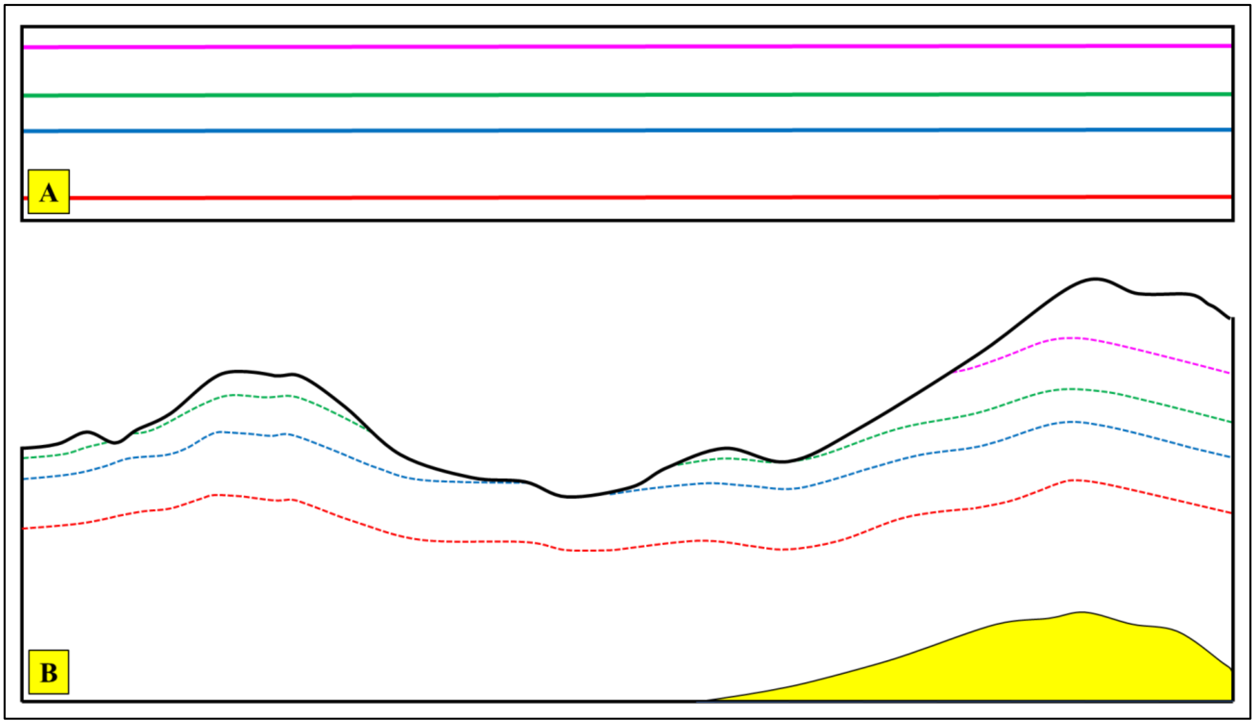

Figure 42*: Demonstration of IAS distribution and structure throughout the Arbuckle in Rooks, Ellis, Graham, and Trego Counties. This figure does not represent an actual cross section of the Arbuckle. The colored lines (pink, green, blue, and red) represent IAS, the black curvy line represents the Arbuckle top contact.*

Figure 41 above is a demonstration of the IAS hypothesis developed from this study. The top representation (Box A) in the figure displays the Arbuckle formation as it was most likely deposited. Box B represents the Arbuckle formation's structure as depicted from the maps above (Figure 12). The Central KS Uplift is symbolized by the yellow shape in the bottom right corner of the figure.

The structural deformation and erosion/karstification that the Arbuckle was exposed to most likely affected IAS as well. This would have caused previously existing horizons of IAS to appear as smaller shale lenses whose distribution and structure are less predictable.

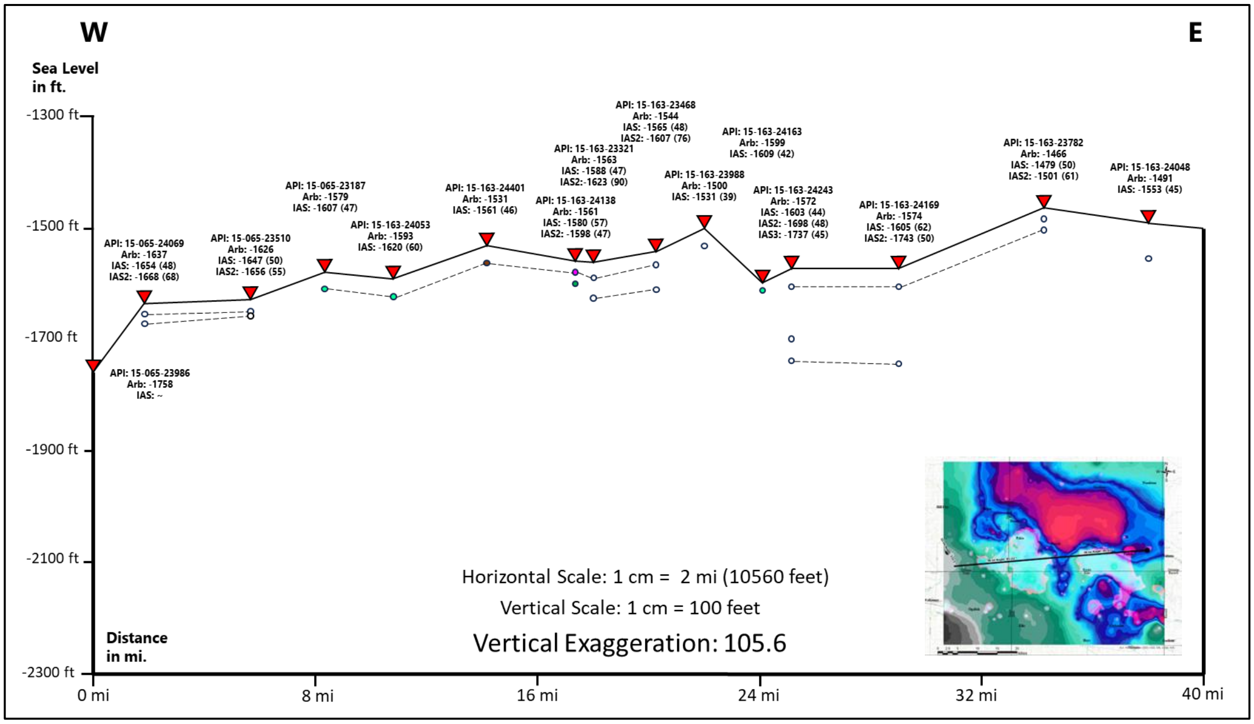

Figure 43*: West to East Arbuckle cross section with Intra-Arbuckle Shale correlations. Red triangles represent well log locations, while their corresponding API number, Arbuckle top sea level, and Intra-Arbuckle Shale sea level/gamma ray units are displayed above them. The black line connecting the triangles symbolizes the Arbuckle top contact, and the circles beneath represent where IAS was intercepted. Dotted lines connecting shale points represent correlation.*

An updated version of the cross section previously displayed in Figure 22, is shown above. On the updated version, IAS was correlated using gamma ray signatures and geologist reports if available. Shales that displayed similar well log characteristics were connected by dotted lines, and shales that could not be confidently matched were left alone.

One potential issue with this hypothesis is the lack of shale intercepted at the higher and lower Arbuckle elevations from Figure 13. Simply looking at the IAS distribution/elevation map

(Figure 13) would suggest that lenses would better define the shale rather than a distinctive horizon. The lack of shale intercepted does not necessarily indicate a lack of shale though.

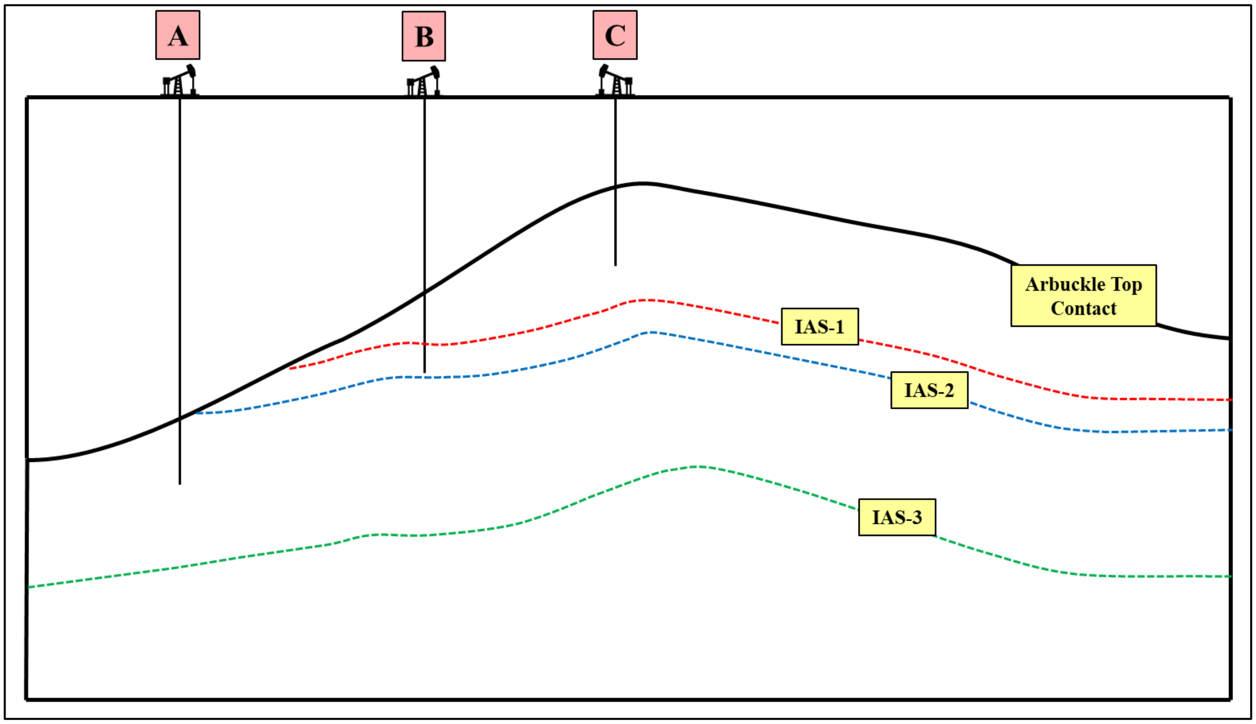

Figure 44*: Demonstration of IAS intercepting well logs. Dotted lines represent IAS, black line symbolizes the Arbuckle top contact, and A, B, and C represent drilled oil wells.*

A better suggestion for a lack of IAS intercepting well logs in specific areas is displayed above (Figure 43). A and C are examples of wells that would not intercept IAS based on where they penetrated the Arbuckle top contact. This figure also displays the tendency for Arbuckle wells to have shallow penetrating depths less than 50 ft. (Henry & Hester, 1995; Franseen et al., 2004). Even though IAS is mostly intercepted on the Ellis-Rooks, and Trego-Graham County lines (Figure 13), there is a great possibility that it exists across the whole region of study.

CHAPTER VI

SUMMARY AND CONCLUSION

Arbuckle data from Ellis, Rooks, Graham, and Trego Counties were collected through micro-resistivity and gamma ray well logs. From these data, subsurface maps of the Kansas Arbuckle formation have been created to locate and reveal the distribution of Intra-Arbuckle Shale. Though the evidence produced has brought forth understanding of IAS distribution, IAS structure remains less definitive.

Several hypotheses generated from the subsurface mapping of Intra-Arbuckle Shale using ArcGIS Pro should be taken away from the study:

- IAS exists as multiple distinguishable horizons that have been structurally deformed (faulted/folded) with the Arbuckle to some degree. This structural deformation is likely related to the Central Kansas Uplift. IAS horizons have also potentially been subjected to chemical alteration evidenced by color changes.
- IAS horizons are distributed throughout the whole study region of Ellis, Rooks, Graham, and Trego Counites, and only appear as absent because a large majority of Arbuckle well logs are too shallow (Henry & Hester, 1995; Franseen et al., 2004).
- Arbuckle zones are affected by erosion and karstification (Figure 19), resulting in zone shifts that alter reservoir characteristics (number of zones/zone thicknesses) and hydrocarbon potentials.
- A relationship exists between reservoir characteristics (number of zones/zone thicknesses) and the presence of the IAS barriers. Barrier qualities of the Intra-Arbuckle Shale gathered from this study correspond to similar Arbuckle studies throughout Kansas

(Mullins & Ireland, 1967; Franseen et al., 2003), and may hold true in other locations outside of KS.

- IAS Compartmentalizes Arbuckle reservoirs and creates the potential for untapped reservoirs below original well completion depths. Economic potentials for lower compartments vary and depend heavily on the local structure of IAS barriers as mentioned by Mullins and Ireland (1967). This potential is very important for Kansas oil production especially when Arbuckle production is slowly but steadily decreasing (Franseen et al., 2004).

6.1 Future Studies

The maps and data from this study also open the door for oil producers and researchers to carry out more in-depth examinations of Arbuckle geology. Studies that would be highly beneficial to the correlation of IAS across Ellis, Graham, Rooks, and Trego Counties include:

- IAS intercepting core studies
- Petrographic analysis of IAS
- More well log and DST research

Well site geologists could also aid future well log and core studies by taking more detailed notes regarding IAS on geologist reports. As future studies advance our understanding of Intra-Arbuckle Shale, comprehension of complex Arbuckle reservoirs will also expand.

REFERENCES

Asquith, George., and Daniel Krygowski. *Basic well log analysis*. Vol. 16. Tulsa: American Association of Petroleum Geologists, 2004.

Barati, R., D. W. Green, and J. T. Liang. "Simulation of gelled polymer treatments in the Arbuckle formation, Kansas." *In SPE Improved Oil Recovery Conference*, pp. SPE-100067. SPE (2006).

Barrell, Kirk A. "GIS: The exploration and exploitation tool." *Geographic information systems in petroleum exploration and development* 4 (2000): 237-248.

Baars, D. L., W. Lynn Watney, Don W. Steeples, and Erling A. Brostuen. *Petroleum: A Primer for Kansas.* Kansas Geological Survey, 1989.

Carr, Jerry E., Harold E. McGovern, Tony Gogel, and J. H. Doveton. "Geohydrology of and potential for fluid disposal in the Arbuckle aquifer in Kansas." No. 86-491. *US Geological Survey* (1986).

Carr, Timothy R., John Hopkins, Neil L. Anderson, and Dennis E. Hedke. "Case History of Hampton Field (Arbuckle Group), Rush County, Kansas." *Bulletin (Kansas Geological Survey)* 237 (1995): 145-152.

Devleeschouwer, Xavier, and Franck Pouriel. "Brussels Urban Geology (BUG): a 2D and 3D model of the underground by means of GIS." *In Proceedings of the 10th IAEG Congress*, Nottingham, United Kingdom, submitted. 2006.

Franseen, Evan K., Alan P. Byrnes, Jason R. Cansler, D. Mark Steinhauff, and Timothy R. Carr. "The geology of Kansas—Arbuckle Group." *Current Research in Earth Sciences* (2004): 1-43.

Franseen, Evan K. "A review of Arbuckle Group strata in Kansas from a sedimentologic perspective." *Open-File Report* 49 (1999).

Franseen, Evan K., Alan P. Byrnes, Jason R. Cansler, D. Mark Steinhauff, Timothy R. Carr, and Martin K. Dubois. "Geologic controls on variable character of Arbuckle reservoirs in Kansas: An emerging picture." *Kansas Geological Survey Open-file Report* 59 (2003).

Haldorsen, Helge H., and Larry W. Lake. "A new approach to shale management in field-scale models." *Society of Petroleum Engineers Journal* 24, no. 04 (1984): 447-457.

Henry, Mitchell E., and Timothy C. Hester., "Arbuckle Oil and Gas Play". *Kansas Geological Survey, Digital Petroleum Atlas* (1995).

Keroher, Raymond P., and Jewell Kirby. "Upper Cambrian and Lower Ordovician Rocks." *Kansas Geological Survey* (1948).

KGS Oil and Gas Interactive Map (2024): https://maps.kgs.ku.edu/oilgas/index.html

Kienzle, Alexander, Dieter Hannich, Wolfgang Wirth, Dominik Ehret, Joachim Rohn, Viorica Ciugudean, and Kurt Czurda. "A GIS-based study of earthquake hazard as a tool for the microzonation of Bucharest." *Engineering Geology* 87, no. 1-2 (2006): 13-32.

Krassakis, Pavlos, Konstantina Pyrgaki, Vasiliki Gemeni, Christos Roumpos, Georgios Louloudis, and Nikolaos Koukouzas. "GIS-based subsurface analysis and 3D geological modeling as a tool for combined conventional mining and in-situ coal conversion: the case of kardia lignite mine, Western Greece." *Mining* 2, no. 2 (2022): 297-314.

McClellan, Hugh W. "Subsurface distribution of pre-Mississippian rocks of Kansas and Oklahoma." *AAPG Bulletin* 14, no. 12 (1930): 1535-1556.

Michael, Karsten. "More than a seal-the impact of shales on the flow and evolution of formation water." (2014).

Mullins, Claud A., and W. C. Ireland. "Additional Arbuckle Reserves Developed Below Original

Completion Depth in Stratified Reservoir." *In SPE Annual Technical Conference and Exhibition*, pp. SPE-1963. SPE (1967).

Neuendorf, Klaus KE., James P. Mehl, Jr., and Julia A. Jackson. *Glossary of Geology*. Springer Science & Business Media (2005): 145.

Nissen, Susan, Saibal Bhattacharya, W. Lynn Watney, and John Doveton. "Improving geologic and engineering models of midcontinent fracture and karst-modified reservoirs using new 3-D seismic attributes." *University Of Kansas Center for Research Incorporated* (2009): 10, 17.

Ondreka, Joris, Maike Inga Rüsgen, Ingrid Stober, and Kurt Czurda. "GIS-supported mapping of shallow geothermal potential of representative areas in south-western Germany—possibilities and limitations." *Renewable Energy* 32, no. 13 (2007): 2186-2200.

Rahmatizadeh, Sh., and Z. Naseri. "Design and Implement 3D Subsurface Geological Model for Petroleum Exploration in GIS". *ResearchGate* (2009).

Rocke, Benjamin Joseph. "Paleokarst morphologies and reservoir implications of the Arbuckle Group on the Central Kansas Uplift, Russell and Barton counties, Kansas." PhD diss., University of Kansas (2006).

Setijadji, Lucas D., "GIS for Subsurface Modeling". *ESRI* (2003): 20.

Snedden, John W. "Estimating effective shale area distributions from subsurface data." *Marine and Petroleum Geology* 49 (2014): 35-44.

U.S. Energy Information Administration (2023): https://www.eia.gov/state/print.php?sid=KS

Winchell, Richard L., "Law Southeast Pool--A Successful Seismic Discovery in Graham County, Kansas." *Kansas Geological Survey* (1959).

Wright, Bennett. "MONTGOMERY COUNTY OPPORTUNITY". *Bennet Geological Services*

(2013): 11.

Xie, Jiayu, Gongwen Wang, Yazhou Sha, Jiajun Liu, Botao Wen, Ming Nie, and Shuai Zhang. "GIS prospectivity mapping and 3D modeling validation for potential uranium deposit targets in Shangnan district, China." *Journal of African Earth Sciences* 128 (2017): 161-175.

Fort Hays State University
FHSU Scholars Repository
Non-Exclusive License Author Agreement

I hereby grant Fort Hays State University an irrevocable, non-exclusive, perpetual license to include my thesis ("the Thesis") in *FHSU Scholars Repository*, FHSU's institutional repository ("the Repository").

I hold the copyright to this document and agree to permit this document to be posted in the Repository, and made available to the public in any format in perpetuity.

I warrant that the posting of the Thesis does not infringe any copyright, nor violate any proprietary rights, nor contains any libelous matter, nor invade the privacy of any person or third party, nor otherwise violate FHSU Scholars Repository policies.

I agree that Fort Hays State University may translate the Thesis to any medium or format for the purpose of preservation and access. In addition, I agree that Fort Hays State University may keep more than one copy of the Thesis for purposes of security, back-up, and preservation.

I agree that authorized readers of the Thesis have the right to use the Thesis for non-commercial, academic purposes, as defined by the "fair use" doctrine of U.S. copyright law, so long as all attributions and copyright statements are retained.

To the fullest extent permitted by law, both during and after the term of this Agreement, I agree to indemnify, defend, and hold harmless Fort Hays State University and its directors, officers, faculty, employees, affiliates, and agents, past or present, against all losses, claims, demands, actions, causes of action, suits, liabilities, damages, expenses, fees and costs (including but not limited to reasonable attorney's fees) arising out of or relating to any actual or alleged misrepresentation or breach of any warranty contained in this Agreement, or any infringement of the Thesis on any third party's patent, trademark, copyright or trade secret.

I understand that once deposited in the Repository, the Thesis may not be removed.

Thesis: Subsurface Mapping of Intra-Arbuckle Shale in North-West Kansas Using Well Log Data

Author: Cole M. Denny

Signature: [signature]

Date: 4/19/2024