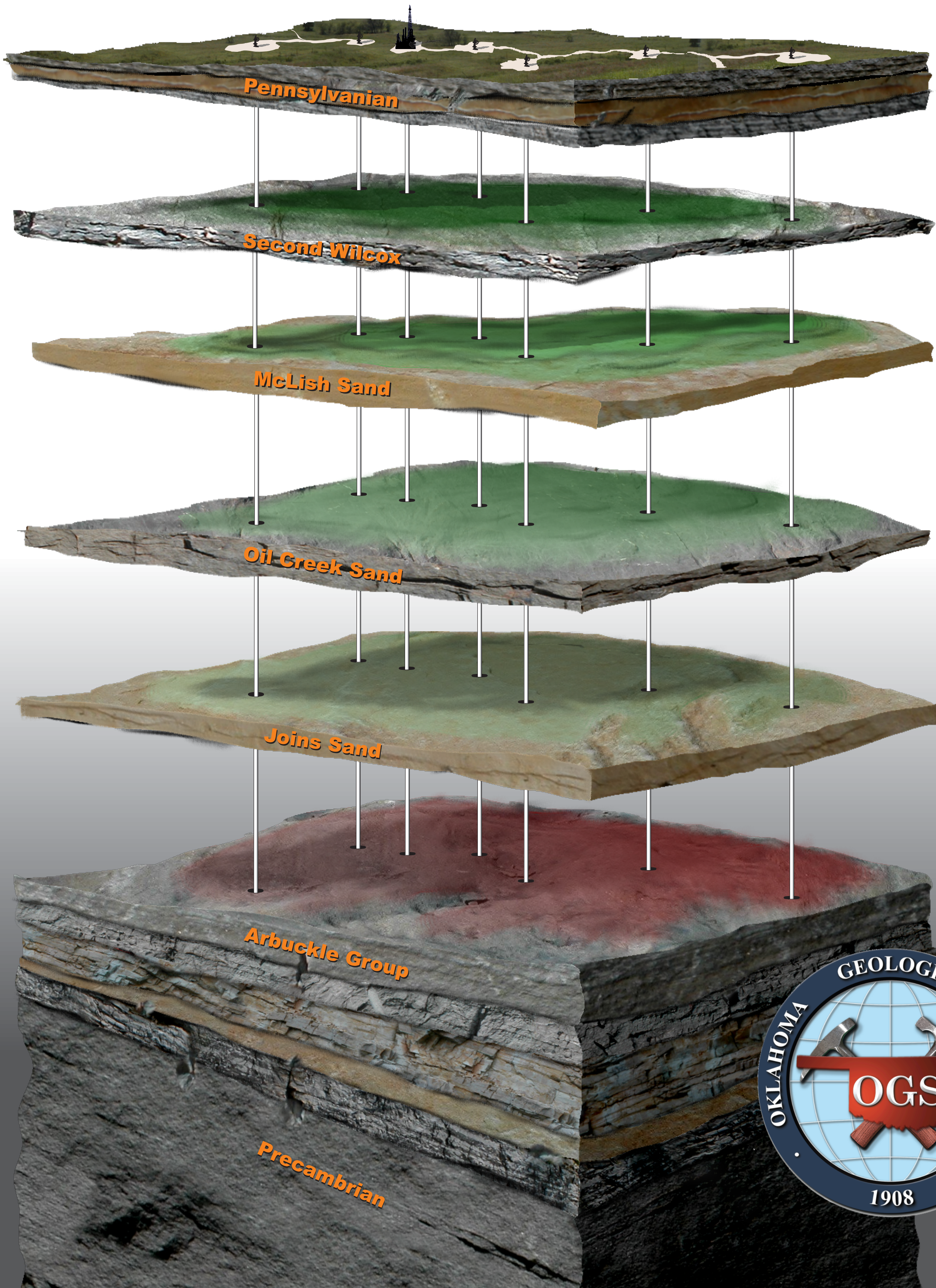
Open-File Report 21-2018

Well-Log Characterization of the Arbuckle Group in Central and Northern Oklahoma:

Interpretation of the Impact of its Depositional and Post-Depostional History on Injection Induced Seismicity

by
Kurt Rottmann



Oklahoma Geological Survey Open-File Report Disclaimer

Request For Review

The Oklahoma Geological Survey is interested in receiving comment and response to the concepts presented in this Open File Report. They may have important bearing on actions to minimize seismic activity related to injection of produced formation water into the Arbuckle Group. It remains unclear whether the complex history proposed here for creating the underpressuring of the Arbuckle is capable of producing that underpressuring, and whether the gas saturations interpreted to occur exist. The thoughts of the relevant technical community would be helpful in preparing an updated version of the report.

Send feedback to ogs@ou.edu or by calling 405-325-3031.

Also, please note that full-size pdfs of all figures shown in this report are available to open and download. Simply click on the figure, and the full-size pdf will open in your default web browser.

Best,

Jeremy Boak

Jeremy Boak
OGS Director

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Executive Summary

The Cambrian and Ordovician Arbuckle Group and the Cambrian Timbered Hills Group (herein referred to as the Arbuckle) are the deepest sedimentary rock units overlying the basement rock of Oklahoma. Significant oil and/or gas reserves have been produced from structural closures in the Arbuckle, but operators have also known that the Arbuckle has exceptional quality as a zone for saltwater disposal. Particularly from the 1980s on, disposal of very large quantities of produced saltwater was important for the economic success of the Hunton de-watering and the Mississippian Limestone horizontal plays of central and north central Oklahoma respectively.

From the 1930's to the late 1980's, injection of saline formation water into the Arbuckle had few apparent seismic consequences. Since the 2000s, operators have injected increasing amounts of saltwater into the Arbuckle, and seismic activity increased in areas of injection beginning in 2009. The primary purpose of this study was regional scale characterization of the Arbuckle Group's hydrogeologic system from geophysical well logs. Features of the history of the Arbuckle and overlying sedimentary rocks identified during this study appeared to offer an interpretation of the underpressuring of the Arbuckle with implications for the relationship of injection and seismicity.

Definition of the Problem and Study Area: The study area for this report was chosen to include areas that experienced the bulk of the seismic events since 2008 in two areas. The first is associated with the Hunton de-watering play in central Oklahoma, defined as T11N-24N and R4W-5E. The second involves the Mississippian Limestone horizontal plays of northcentral Oklahoma, defined as T20N-29N and R3W-18W. To better define the history and behavior of the Arbuckle, the area was enlarged to T5N-29N and R7E-26W, and previous work on the Arbuckle in northeastern Oklahoma was incorporated to support the concepts discussed. Available publications were reviewed in this study. Through the generosity of the Gatewood family, a copy of the unpublished Lloyd Gatewood Arbuckle study was obtained and parts were also incorporated in this report.

Definition of Log Character of the Top of the Arbuckle and Formation Boundaries: One goal for this study was to provide an accurate and consistent Arbuckle top database and guidelines for correlating internal markers within the Arbuckle Group from open hole geophysical well logs (hereafter referred to as well logs). 580 wells with a consistent, readily interpretable well log suite were reviewed to define characteristics of the Arbuckle, and these and other logs were incorporated into 30 regional cross sections. These cross sections are provided as a separate database as part of this report. Stratigraphers have broken down the Arbuckle into formations based on biostratigraphic and other petrologic data. This report sought to define stratigraphy based on well logs. Although consistent markers for the top and base of the Arbuckle were identified, the formations comprising the Arbuckle are not readily defined on well logs.

Basement Geomorphology and Arbuckle Onlap onto the Basement Surface: Oklahoma, and much of the Mid-Continent underwent extensive erosion of the Precambrian prior to deposition of the Arbuckle, resulting in pinnacles, mounds, hills, and monadnocks, with relief approaching 2000 feet. These features were preserved by Arbuckle deposition in transgressive Cambrian and Early Ordovician seas. Of 526 basement wells reported in central, north central and northeastern Oklahoma, less than three dozen have penetrated the basement more than 200 feet, but well logs from these suggest the basement is similar to Precambrian metamorphic and igneous rocks observed in outcrop in the Wichita Mountain uplift. Thus, features identified in outcrop, particularly fractured and altered igneous dikes, may exist and serve as conduits for injected water to stimulate critically stressed faults or fracture planes at depth.

Post-Arbuckle Deposition and Erosion and Effects on Formation Pressure: The Arbuckle and younger sedimentary rocks were deposited as an onlap sequence progressively burying and preserving the Precambrian geomorphic features. Thus, the overlying sediment was thinner over the basement highs. Compaction of the Arbuckle shale layers and to some extent the carbonate rocks themselves occurred during or shortly after deposition. Periods of erosion removed part of the Arbuckle prior to deposition of the Ordovician Simpson Group.

This study identified six log-defined sedimentary facies composed of both clastic and carbonate sedimentary rocks deposited on top of the Arbuckle during Simpson time. Two of the six consist of moderately to highly permeable rock, whereas four consist of impermeable rocks. The properties of these six facies may have controlled reservoir pressures in the Arbuckle during subsequent emergence and reburial. The following outline highlights those events and their effects on the formation pressure of the Arbuckle.

1. Burial and first phase compaction of the Arbuckle Group. Deposition of overlying Ordovician-Devonian Simpson Group, Viola Group, Sylvan Shale, and Hunton Group. Formation pressures most likely were at their greatest at this point. First phase of saltwater and hydrocarbon migration and pressure/depth equalization.
2. Uplift and erosion of all or part of the Ordovician-Devonian during late Devonian (pre-Woodford Shale deposition). Pressure depletion through fluid loss where Arbuckle was exposed or overlain by permeable cap rock facies. The permeable facies overlying Arbuckle rocks provided a pathway for migration and pressure reduction, but not complete expulsion of the evolved gas phase. Little or no fluid and pressure depletion under impermeable cap rock.
3. Re-burial and deposition of Devonian Woodford Shale, Mississippian, and early Pennsylvanian strata. A second phase of hydrocarbon generation and migration probably occurred within the Arbuckle from Woodford and Mississippian source beds.
4. Uplift and erosion of early Pennsylvanian and Chesterian (lower Mississippian) strata, providing a second opportunity for Arbuckle reservoir depletion through surface exposure or release into permeable cap rock facies. Gas saturations in the Arbuckle were probably at their highest, and higher where the cap rock was permeable.
5. Deep re-burial, dolomitization, and secondary compaction of the Arbuckle with deposition of middle to late Pennsylvanian and Permian strata.

This series of events affected pore volume, gas saturations, and formation pressures.

Arbuckle Dolomitization: Dolomitization of the Arbuckle had a direct bearing on pore volume and the formation pressure. In Osage County, it was recognized that shallow Pennsylvanian structural closures were superimposed on Simpson and Arbuckle closures that were in turn superimposed on Precambrian geomorphic features. The shallow closures were much greater than the 2% that compaction models predicted.

Rock volume decrease through dolomitization could have led to secondary compaction of the enhanced pore volume further than initial burial compaction. This compaction would be greatest where the Arbuckle is the thickest and least where the Arbuckle is thinnest. The secondary compaction of the Arbuckle would account for observed structural closures for the shallow and deep structural horizons. Secondary compaction would also alter the gas pore volume fraction present before and during dolomitization, reducing the degree to which secondary porosity due to dolomitization could account for regional underpressure in the Arbuckle.

Underpressured State of the Arbuckle and Saltwater Injection: The regional underpressured characteristic of the Arbuckle can be observed from shut-in bottom hole pressures of Drill Stem Tests (DSTs) in the Arbuckle, Second Wilcox, Hunton and Misener Sandstone. In general, the hydrostatic gradient for the Arbuckle is lower than that for the Second Wilcox and the Hunton/ Misener. Also, the hydrostatic gradient for the Arbuckle is lower in locations where the Simpson cap rock facies is permeable. The hydrostatic gradient is higher for those areas where the cap rock facies is impermeable. The amount of depletion and fluid loss within the Arbuckle during its depositional history may account for differences in hydrostatic pressures. This progressively decreasing degree of underpressure upward in the section, if fully confirmed, will be important to demonstration that injection into the Arbuckle is the primary driver of seismicity in Oklahoma.

The area of impermeable Arbuckle cap rock facies and the location of recent seismic activity appear to coincide. The seismic activity interpreted as being caused by saltwater injection is minimal or absent in areas of injection where the sedimentary unit on top of the Arbuckle (the Arbuckle cap rock) is permeable, or the Simpson Group is absent due to erosion. In areas where the Arbuckle cap rock is impermeable, seismic activity is generally strong. The gas-saturated pore volume formed and modified over the Arbuckle's depositional, structural, and diagenetic history may be a central control on the amount of saltwater that can be injected before seismic events are triggered. The Arbuckle with the larger gas saturated pore volume may be able to receive more injected saltwater than that with less gas saturated pore volume in areas of relatively equal thicknesses.

The Arbuckle permeable and impermeable facies maps may offer the Oklahoma Geological Survey (OGS) and the Oklahoma Corporation Commission (OCC) an opportunity to better manage Arbuckle disposal wells by giving a guide to areas where seismic events might occur given pre-determined disposal water volumes. The present standard procedure concerning the Arbuckle is to assume that injection of saltwater would yield similar results in all areas. This report offers an alternative approach to dealing with seismicity resulting from Arbuckle disposal in certain areas.

Several of the major concepts described within this report were only realized well into the term of the project. These concepts include the relationship of cap rock facies and seismic activity, the concept of higher Arbuckle gas saturations due to uplift and depressurization, and the DST pressure gradient interpretations of the Arbuckle, Second Wilcox and Misener/Hunton. Even though the evaluation for these concepts is incomplete, the interpretations warrant inclusion here and represent the basis for future study.

Recommendations: This study makes five recommendations regarding continuation of this effort:

1. Complete a full evaluation of the complex mechanism for creation of gas saturation in the Arbuckle rocks overlain by porous and permeable rock types to determine whether sufficient differences in gas saturation could be created by this mechanism. Further evaluation of the indication of progressive decrease in the degree of underpressure up section will be very important to understand the relationship between injection and seismicity.
2. Complete the Arbuckle cap rock facies map, including evaluation of the cap rock facies of the Arbuckle in the vicinity of seismically active areas as well in areas adjacent to them. This study should also include examination of available data to determine whether gas saturation can be identified in areas beneath these two facies types.
3. Review available core and petrographic data on Arbuckle rocks for evidence of compaction of secondary porosity created by dolomitization.
4. Conduct a study of the temporal relationship of water injection and initiation of seismicity in the vicinity of Arbuckle disposal wells in areas of the two main facies types described here. The study would attempt to define the relative amounts of water that could be expected to be injected in the Arbuckle where cap rock consists of either impermeable or permeable strata before seismic activity could be anticipated to occur.
5. Conduct additional study of basement characteristics in cores, and outcrops to understand fracture pathways and determine whether diagenetically altered intrusive rocks could serve as preferential pathways for injection pressure to reach the depths of current earthquakes.

1 - Definition of the Problem and of the Study Area

Earthquakes in Oklahoma are not a new phenomenon. They have been occurring since technology has had the ability to record them, and long before. Figure 1 illustrates the locations for those seismic events recorded from 1882 through 2008, as catalogued by the Oklahoma Geological Survey (OGS) (Oklahoma Geological Survey, 2018). The magnitudes of those events have been fairly low, generally M3.0 or less. Most of the earthquakes are natural, but since the industrialization of Oklahoma, some of the earthquakes may have been induced by human activities (Hough and Page, 2015). Oklahoma experienced an average of 1.6 earthquakes of Magnitude 3 or greater (M3.0+) from the 1980s through 2008 (Boak, 2017).

Since 2009, the frequency has increased dramatically as illustrated in Figure 2 (Oklahoma Geological Survey, 2017), and larger magnitude earthquakes have been more common. Since that year, seismicity has increased to 903 M3.0+ earthquakes in 2015 (all earthquake frequencies are from Oklahoma Geological Survey, 2018). Earthquake frequency declined in 2016 to 623 M3.0+ earthquakes; however, Oklahoma experienced its largest earthquake, a M5.8 event in September, near Pawnee. Combined with the M5.1 event in northwest Oklahoma in February, and the M5.0 event near Cushing in November, more seismic energy was released in 2016 than in any year in the state's history. Earthquake frequency continued to decline in 2017, with only 304 M3.0+ earthquakes. More than 95% of these earthquakes occur over only ~17% of the area of Oklahoma (Figure 2).

Earthquakes can be induced by changes in lithostatic pressures, such as from the filling of reservoirs and artificial lakes (Johnson, 2017). They can also be caused by fluid withdrawal from lakes or by subsurface extraction of oil and gas, with subsequent compaction (Manrique, 2000). A third primary mechanism for induced earthquakes is reduction of effective normal stress on optimally aligned faults due to pore pressure rise caused by extensive injection of fluid [National Research Council, 2013].

There is a strong correlation between the location of the recent seismic events and the location of saltwater disposal wells injecting into the Arbuckle in the Mississippian Limestone play and the Hunton de-watering play of north central and central Oklahoma respectively (Murray 2015). This pattern is generally attributed to increased injection of saline formation water co-produced along with oil and gas into the underpressured and relatively permeable Arbuckle Group, which lies directly on top of Precambrian crystalline basement (for example, Walsh and Zoback, 2015). Pressure communication from the Arbuckle to faults in the basement through fractures and other faults, is interpreted to have reduced effective normal stress on the faults. This stress reduction allows faults aligned favorably with respect to the stress field in Oklahoma (S_{HMax} = N 85° E – Alt and Zoback, 2017) to move.

The OGS has led the investigation into these events, in response to the request (and funding) of the Governor of Oklahoma for studies of the source, occurrence, and consequence for this increased seismic activity. The blue and red outlined areas of Figure 3 represent the core area for those studies. The study area for this report was chosen to include those areas that constitute the bulk of the seismic events since 2008. These seismic events are in two primary areas. The first area is associated with the Hunton de-watering play in central Oklahoma and was informally defined as T4W-5E and R11N-24N. The second area involves the Mississippian Limestone horizontal plays of north central Oklahoma and was defined as T3W-18W and R20N-29N. The author's previous work on the Arbuckle in northeastern Oklahoma was also incorporated into this report as support for many of the concepts discussed herein.

The red dashed line of Figure 3 represents the outline of the significant seismic events that have occurred since 2009, and this area will be used in figures throughout this report. Figure 3 also illus

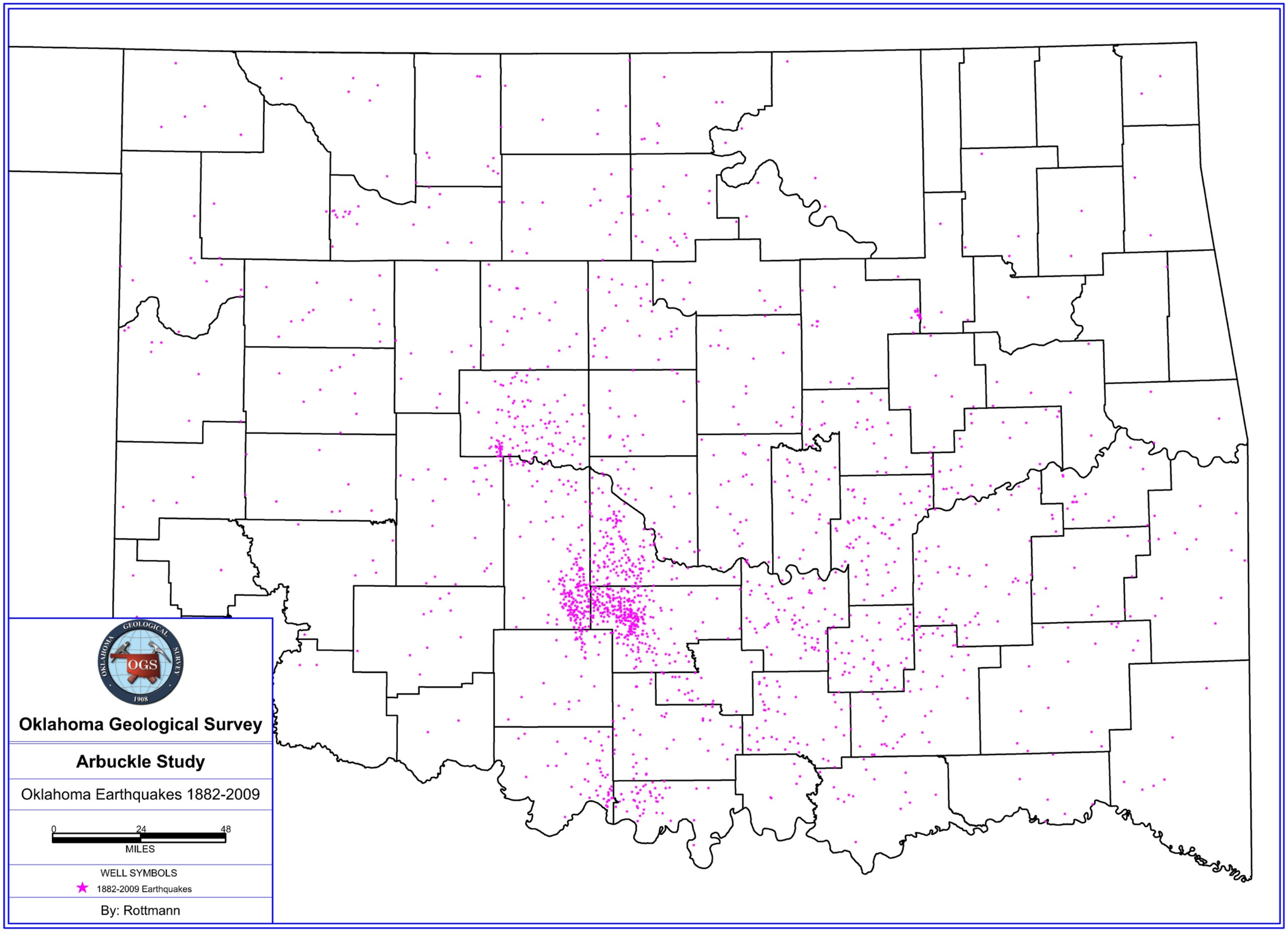

Figure 1: Oklahoma earthquakes 1882 through 2008.

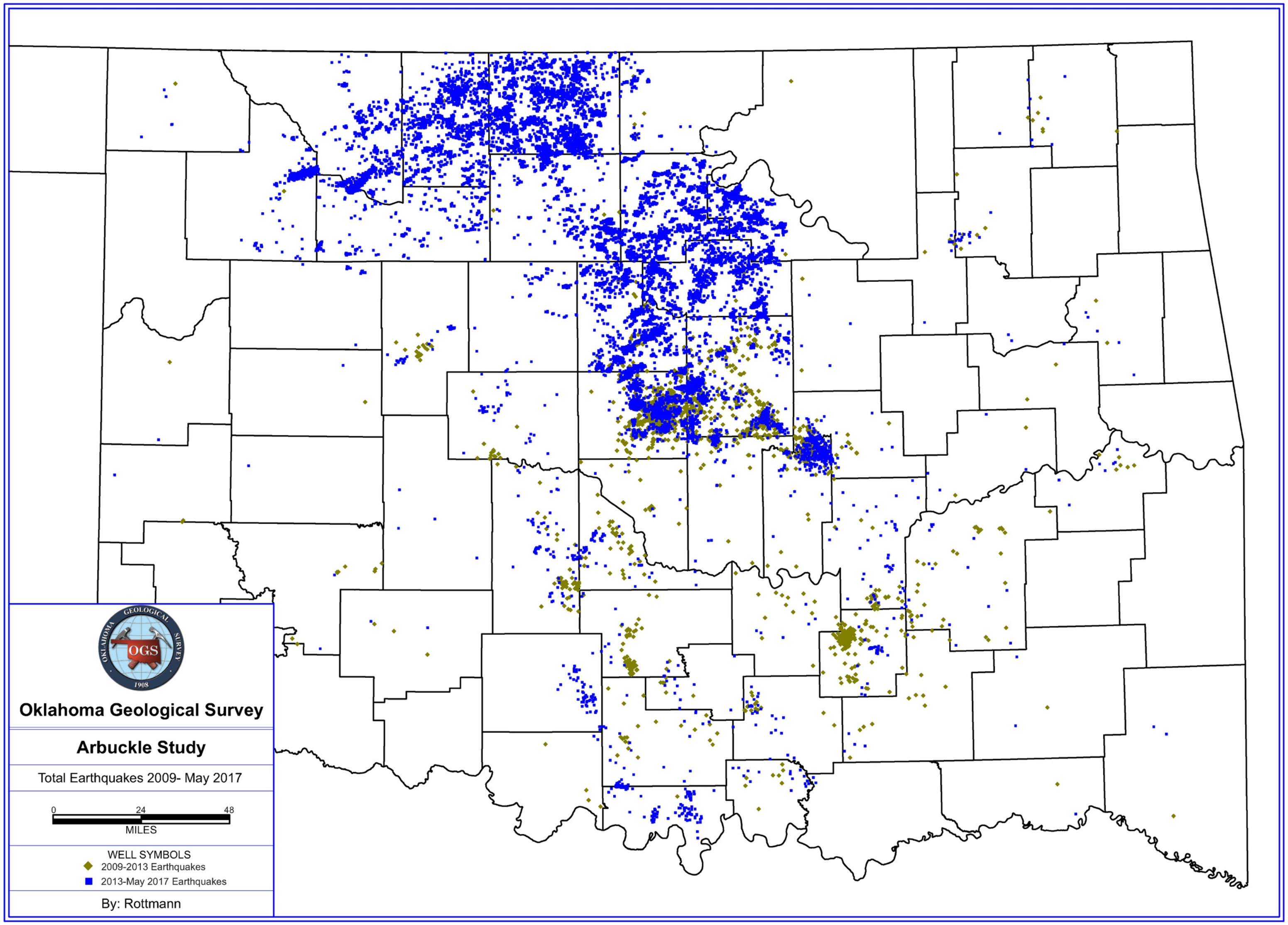

Figure 2: Total earthquakes 2009 to May 2017. Green symbols – 2009-2013; blue symbols – 2014-May 2017

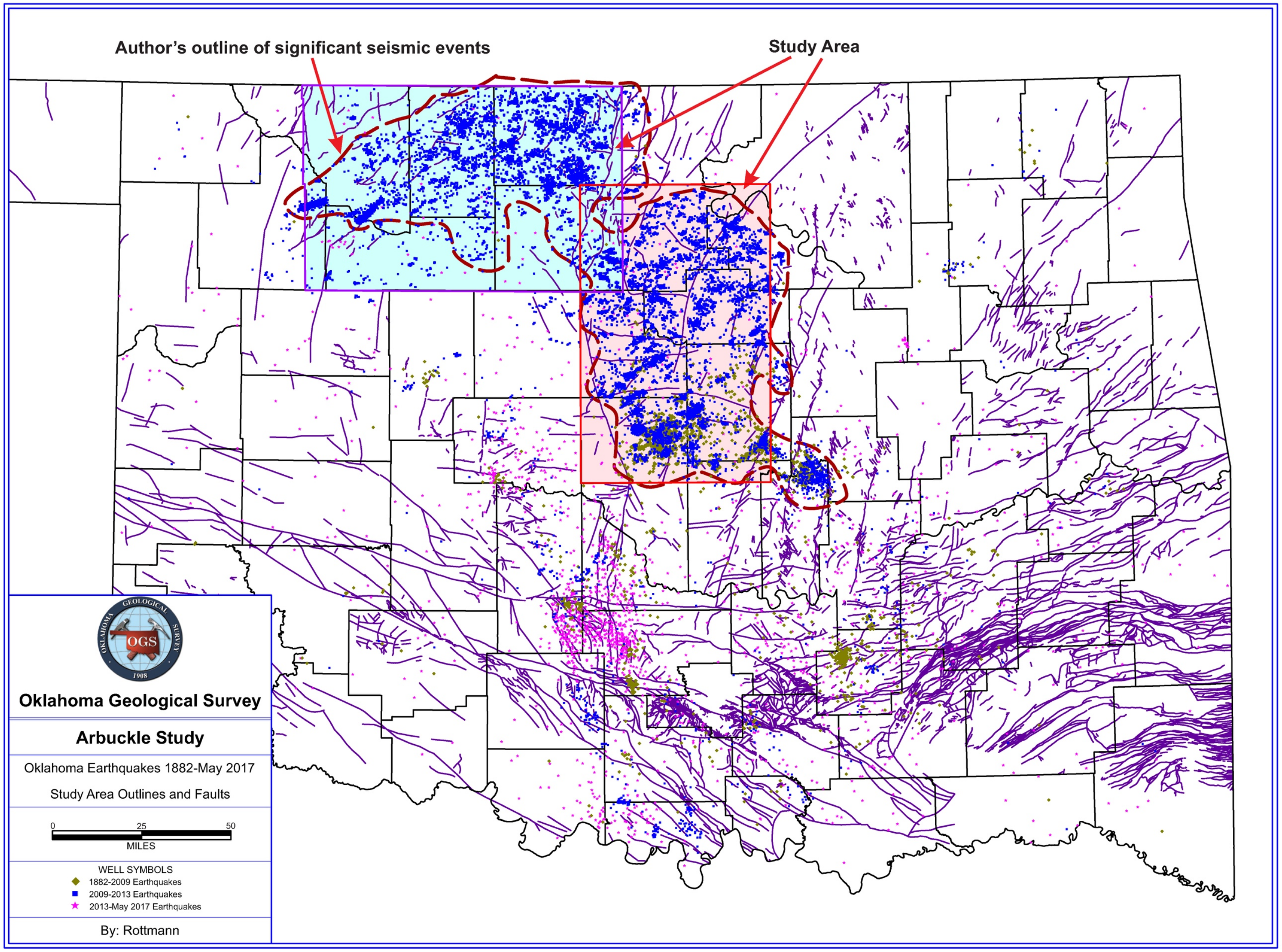

Figure 3: All Oklahoma earthquakes, Oklahoma Geological Survey fault database, outline of the significant seismic events, and the primary study areas for this report.

trates faults that have been reported or observed from various sources and compiled into the OGS's fault database (Marsh and Holland, 2016).

Area Investigated in this Study

Figure 4 illustrates the location of wells penetrating the Arbuckle in Oklahoma. The map shows all types of wells including dry holes, producers, injectors, *etc*. There are approximately 16,250 Arbuckle penetrations, with the greatest concentrations of wells occurring in Osage County, southern Oklahoma, the Nemaha Fault Zone, and on the up-thrown side of the Wichita uplift. The circled wells on this map are those wells used in regional correlation cross sections in Lloyd Gatewood's private study of the Arbuckle. Gatewood studied cores and samples of the Arbuckle extensively. The correlations and results of those studies are shown on these cross sections. In 2016, the family of Lloyd Gatewood generously donated his work to the OGS as a Legacy Collection. This study was used as a resource for parts of this study.

Figure 5 illustrates those wells that have penetrated the Precambrian basement in Oklahoma. The source for these penetrations is the OGS's basement database compiled by Campbell and Weber (2006) and other sources. There are approximately 1,390 wells that penetrated the basement, with most of those being in Osage County in the north, and on the up-thrown side of the Wichita Mountains uplift in the southern part of the state.

As previously described, the colored boxes represent the initial area of coverage for this report. However, to understand adequately the stratigraphy of the Arbuckle, it is important to understand those same characteristics adjacent to the study area. Therefore, the red dashed line of Figure 6 represents the expanded study area for this report. Approximately 2,942 wells with well logs were correlated for this study. These wells were incorporated into 30 regional cross-sections. The thin red lines represent those regional cross sections that were used for the correlations. The cross sections were then used to make four primary regional correlations:

1. Basement top,
2. Arbuckle top and intra- and inter-formation boundaries,
3. Paleozoic formation top, and
4. Arbuckle cap rock facies interpretations.

Literature for the stratigraphy and biostratigraphy within the study area proved to be limited. However, information from a few of the better papers were used in this report and those articles are listed in the reference section. The cross-section lines shown on figure 7 are those from the Gatewood study.

Figure 8 is a stratigraphic column of the Cambrian and Ordovician sedimentary units for Oklahoma, modified from a column published by Fay (1989). Gatewood tied his sample descriptions into the well logs when he picked his formation boundaries. The notes and samples from this work may be lost, but the OGS has much of the information in its Lloyd Gatewood Legacy collection.

Prior to the application of modern well logging tools, detailed sample descriptions including insoluble residue studies were commonly an integral part of formation evaluation. Insoluble residues have been used to differentiate units of the Arbuckle Group for the Ozark Region of Missouri [McCracken, 1964]. As will be discussed in following sections, stratigraphic subdivision of the Arbuckle Group is difficult and studies such as this are important in determining formation boundaries within the Arbuckle Group.

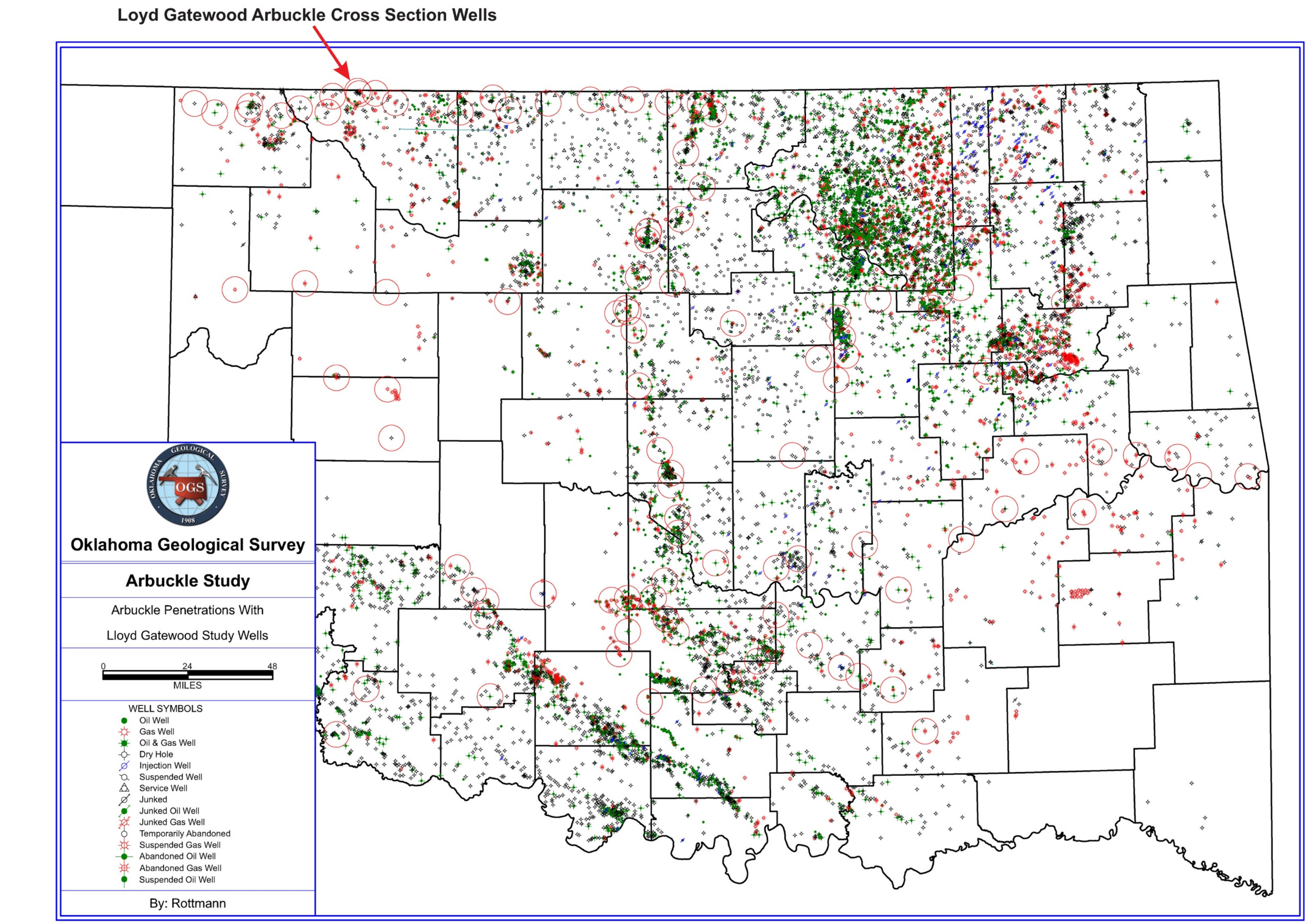

Figure 4: Location of Arbuckle penetrations of Oklahoma.

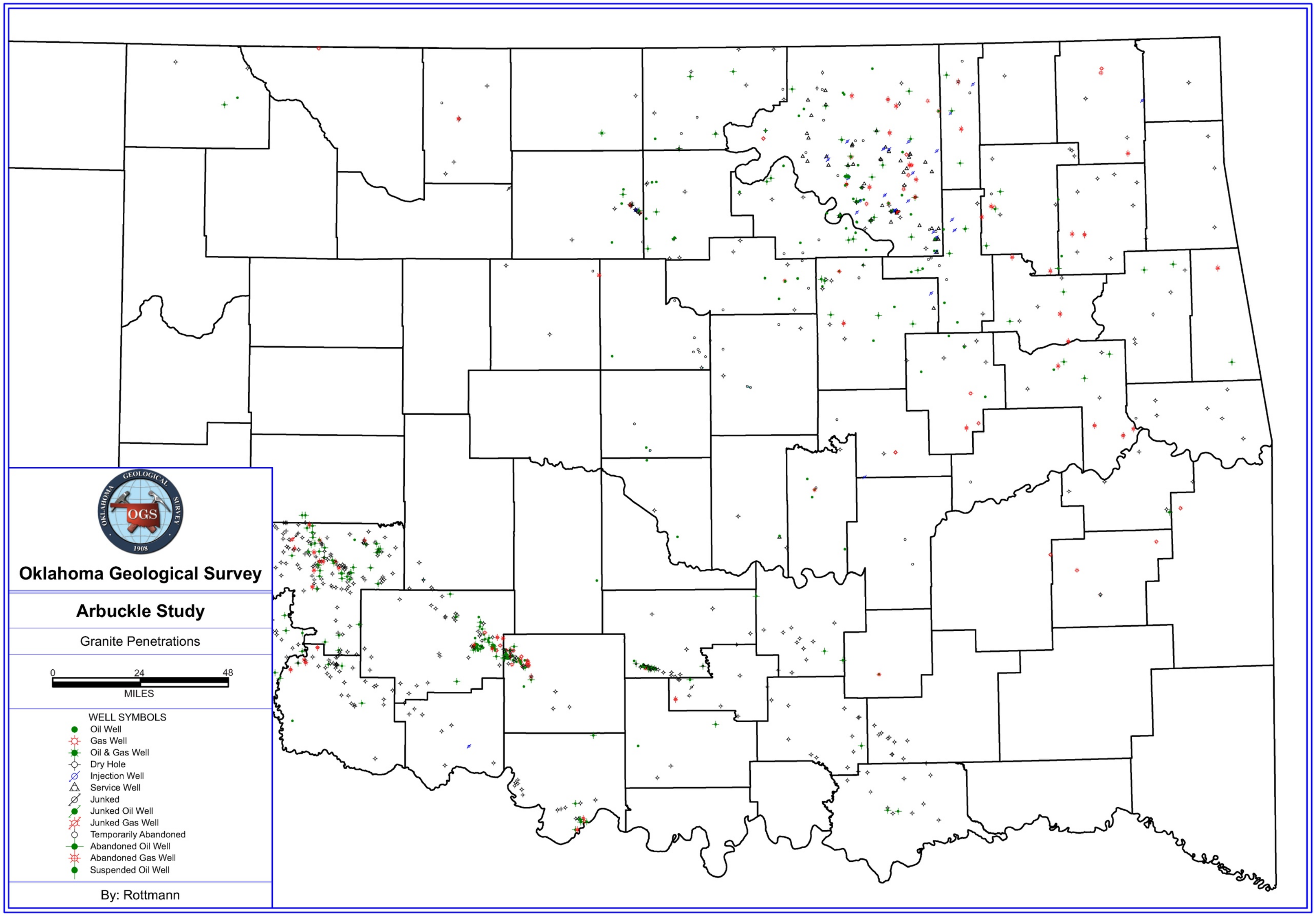

Figure 5 Location of Precambrian penetrations in Oklahoma wells.

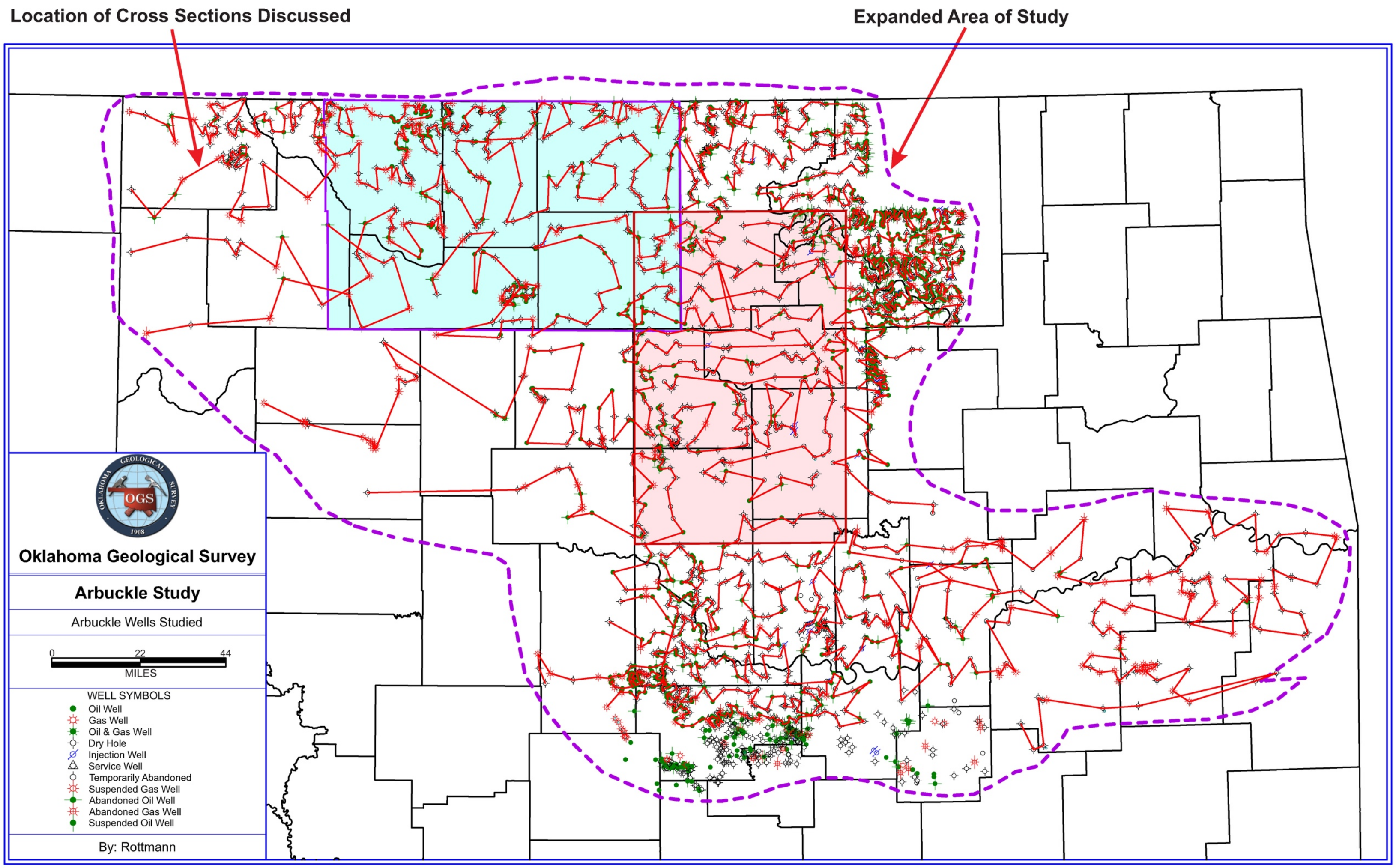

Figure 6: Location of the cross sections and corresponding study wells for this report.

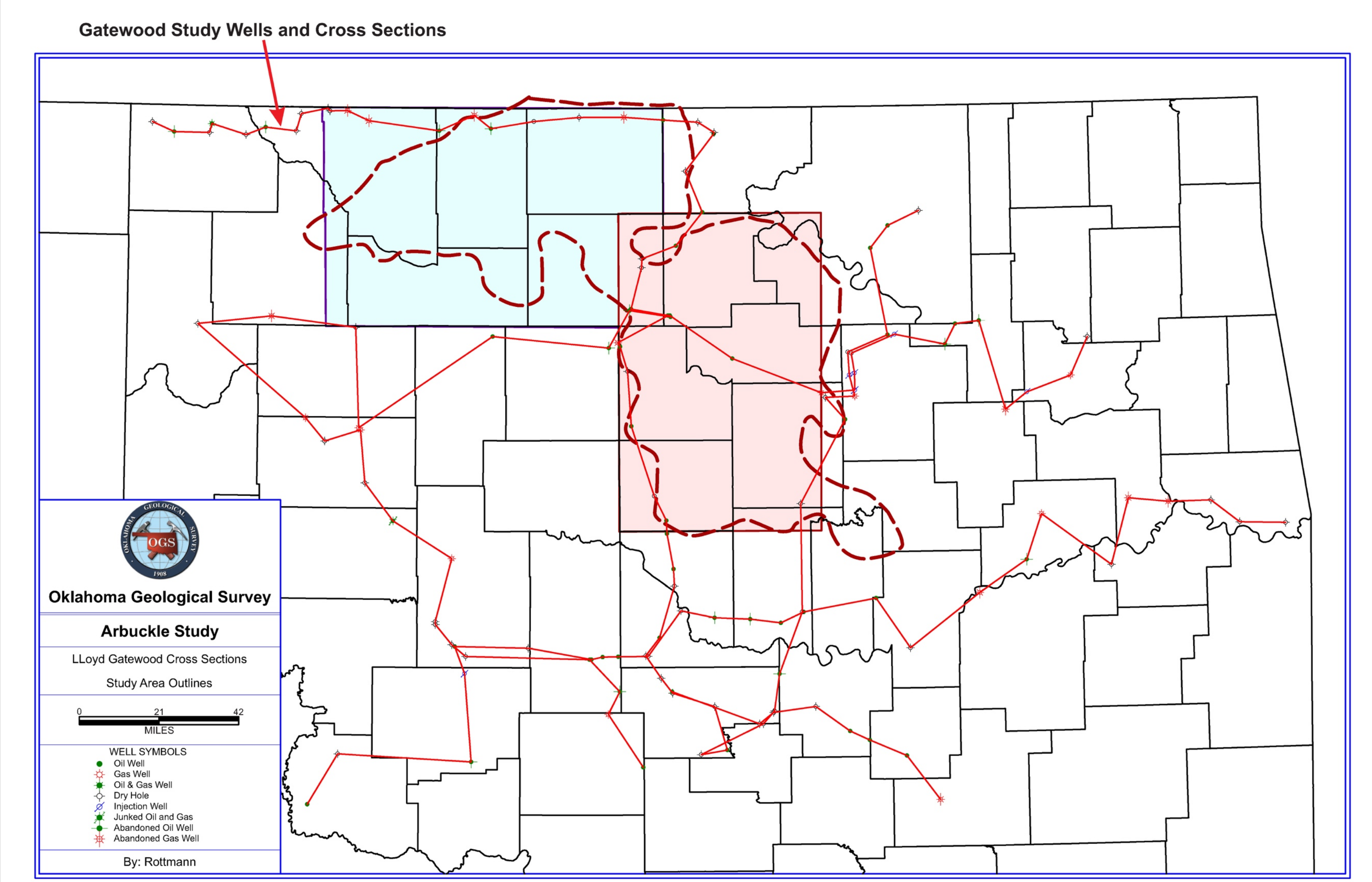

Figure 7: Location of the Gatewood Arbuckle cross sections.

System	Group and Formation	
Pennsylvanian	Skiatook Group	Checkerboard Limestone
	Marmaton Group	Oswego Formation
	Cherokee Group	Pink Limestone/Red Fork Sandstone
Mississippian	Osage Limestone	Mississippian Limestone
Upper Devonian		Woodford Shale
Lower Devonian	Hunton Group	Bois d'Arc Limestone
		Haragan Formation
Silurian		Henryhouse Formation
		Clarita Limestone
		Cochrane Limestone
Ordovician		Keel Limestone
		Sylvan Shale
	Viola Group	Fernvale Formation
		Viola Springs Formation
	Simpson Group	Bromide Formation (Wilcox)
		Tulip Creek Formation
		McLish Formation
		Oil Creek Formation
		Joins Formation
	Arbuckle Group	West Spring Creek Formation
		Kindblade Formation
		Cool Creek/Roubidoux Formation
		McKenzie Hill Formation
		Butterfly Dolomite
Cambrian		Signal Mountain Formation
		Royer Dolomite
		Fort Sill Dolomite
	Timbered Hill Group	Honey Creek Limestone
		Reagan Sandstone
	Colbert Rhyolite	
Precambrian Basement		

Figure 8: Stratigraphic column for sedimentary units in the study area. Major unconformities highlighted in bold lines. After Fay (1989)

2 – Definition of Log Character of the Top of the Arbuckle and Formation Boundaries

One goal for this study was to consistently pick the top of the Arbuckle from a common set of geophysical log characteristics in the study area. Lloyd Gatewood spent years studying Arbuckle samples to determine specific formation contacts and included them on his regional cross sections. Unfortunately, as difficult as it is to correlate formation boundaries within the Arbuckle Group, Gatewood tops do not commonly agree with geologic tops reported on scout tickets. One goal of this study was to clarify formation tops within the Arbuckle, but it quickly became apparent that correlation from logs alone, without the benefit of samples, cores, residue studies, and biostratigraphic data would be nearly impossible, and would require a separate study devoted exclusively to this topic.

This study was, however, able to define accurately a true top for the Arbuckle. using density and density/ neutron well logs that also have a Photoelectric Effect (PE) curve. 581 wells had this combination of log curves that were used to pick the Arbuckle top for this study. Almost all the density/neutron logs used were run using a limestone matrix (density = 2.71 g/cc) to calculate porosity. This results in abundant negative porosities calculated in the Arbuckle section, as the porosities should be calculated on a dolomitic (2.85-2.87 g/cc) matrix. The sedimentary unit above the Arbuckle is composed of sandstone, shale, and limestone/dolomite. The Arbuckle in the study area is almost exclusively dolomite with dolomitic shale. Shale and dolomite have a PE value of 3.0. Sandstone, within the lower Simpson Group, has a PE value of about 2.0.

Figure 9 is an example of a density/neutron and PE well log used to pick the Arbuckle top. The PE curve displays consistent values of ~3.0 below a depth of 6,836 feet. Above this depth, the density porosity curve is regularly, but not uniformly, less than 2.70. Even the higher gamma ray zones within the Arbuckle that may represent thin shale layers, have very low porosity values as compared to those in the Simpson Group (above 6,836). This is probably due to the fact that these shale laminae are dolomitic. The criteria of low porosity values, a PE of 3.0, a relatively low gamma ray value, and generally higher resistivity values were used to determine the Arbuckle top for this study.

Figure 10 is a cross section in northcentral Oklahoma whose datum is the top of the Arbuckle as defined in this study. The thin black line is the top of the Arbuckle from scout tickets. The pick for the Arbuckle may be above or below that picked by the criteria described above and is very common for the Arbuckle top from scout tickets. Due to the variability of the Arbuckle tops from the scout tickets, it is not recommended that they be used without confirmation of their consistency.

Figure 11 is a structure map on the top of the Arbuckle in the study area using the tops from this study. The faults on this structure map are selected as faults that greatly affect Arbuckle structure. They were chosen from the OGS's fault database and those mapped by the author. Many of the OGS faults were not shown due to the small amount of throw and the large contour interval.

Figure 12 illustrates an example of an Arbuckle section whose density porosity was run on a limestone matrix. Section A is an obvious porous zone that has a density porosity of 10% calculated from a limestone matrix, and 18% porosity calculated from a dolomite matrix. Section B has a density porosity of -1 % porosity with a limestone matrix, and 7% porosity calculated from a dolomite matrix. It is obvious how the log matrix dramatically affects the porosity values on these curves. What is significant is that the marginal porosities of 6-8% for a carbonate reservoir have a negative porosity when run on a limestone matrix and may be totally overlooked as potential porous zones.

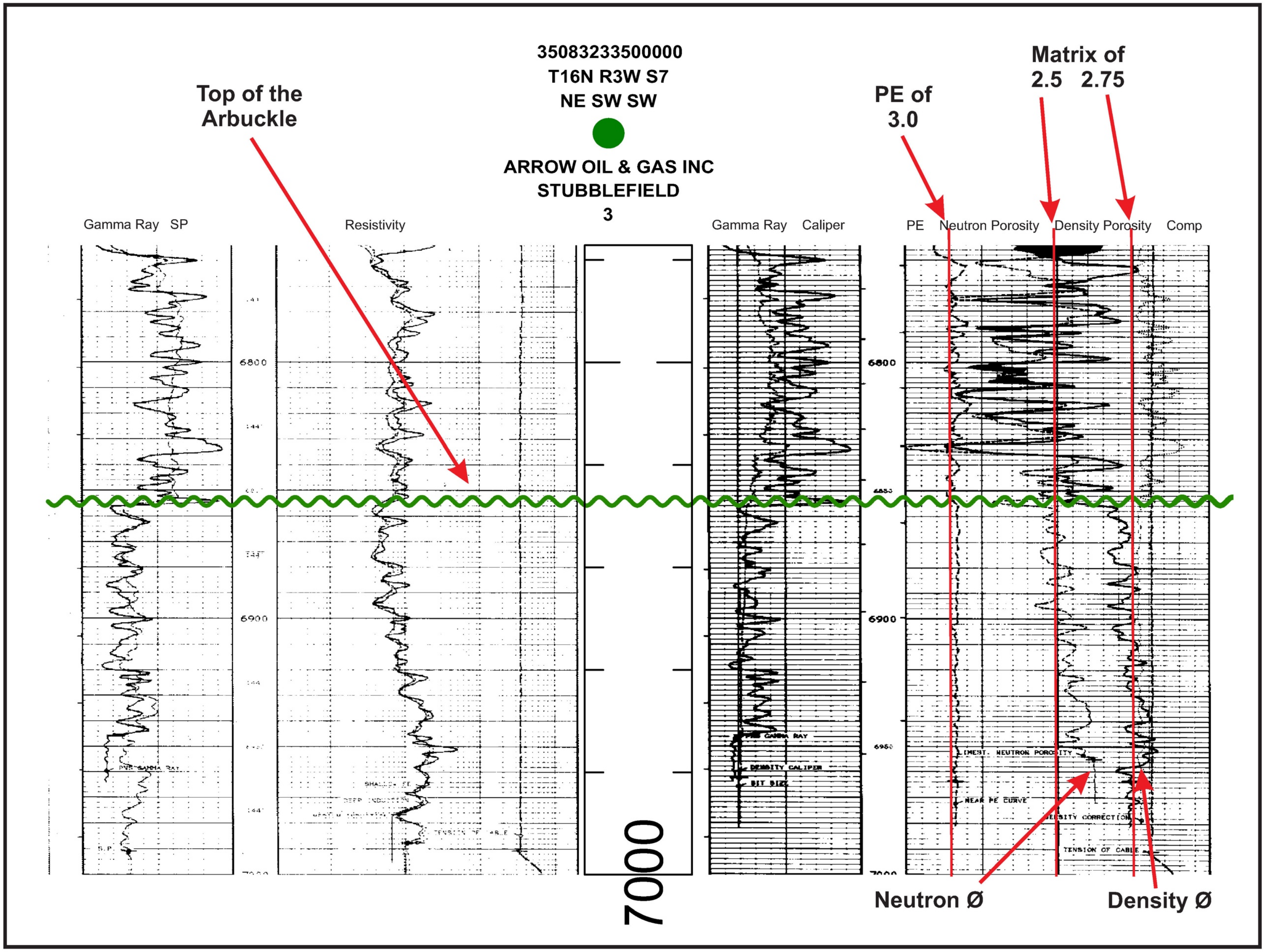

Figure 9: Example of density log with PE curve.

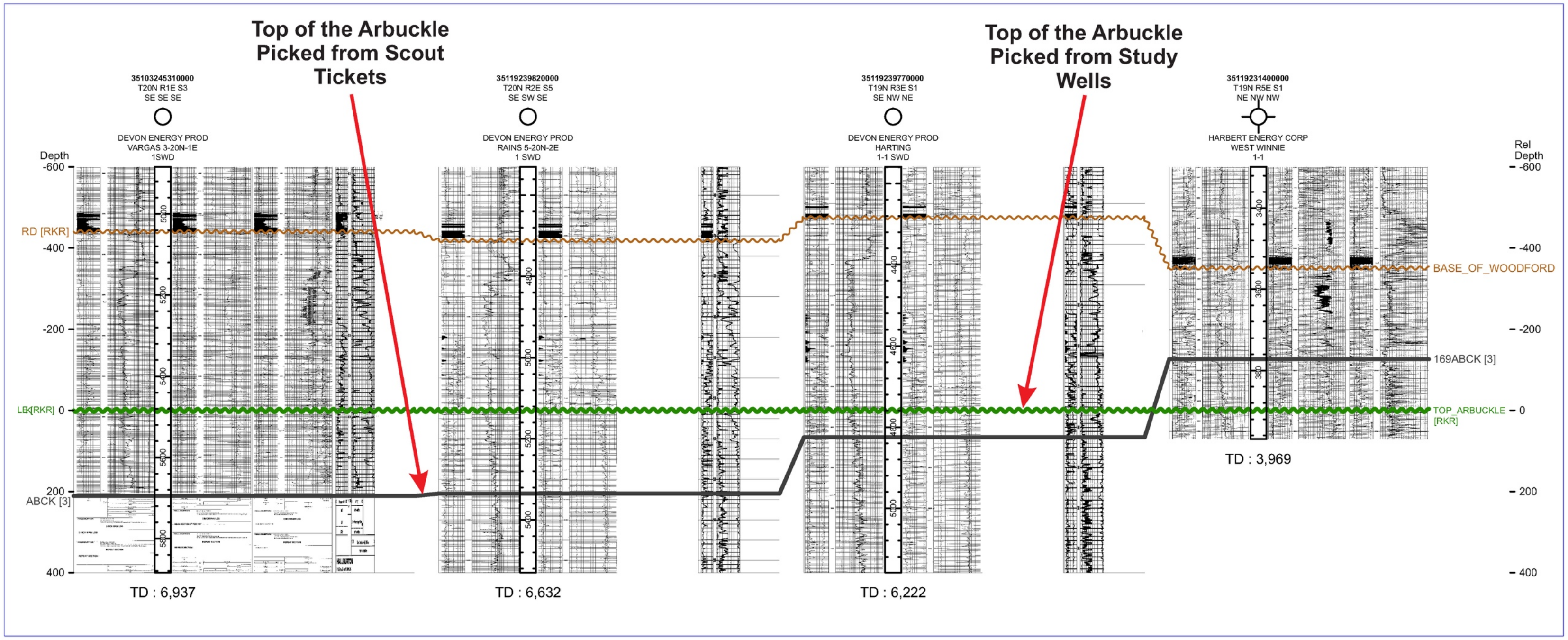

Figure 10: Example of disagreement in picking of the top of the Arbuckle Group.

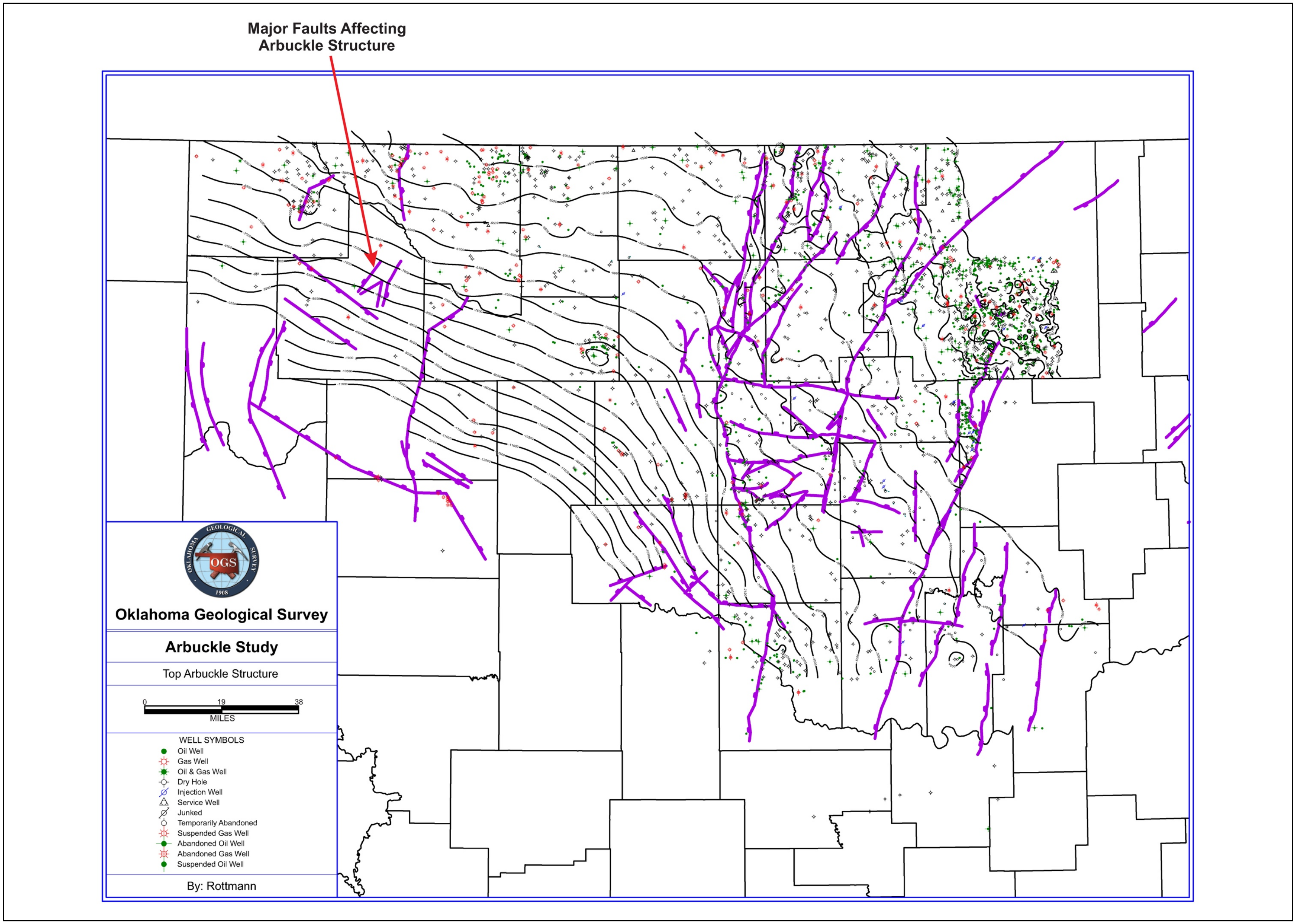

Figure 11: Structure contour map on the top of the Arbuckle. Enlarged on Plate 1.

2 - Definition of Log Character of the Top of the Arbuckle and Formation Boundaries

Plate 2 represents a well whose formation tops within the Arbuckle Group may actually be close to the actual formation boundaries and thus may be considered a type well for the study area. As mentioned earlier, without sample, core, and/or biostratigraphic data, formation tops within the Arbuckle Group may not be accurately picked except possibly for the West Spring Creek/Kindblade contact. This contact generally has a characteristic drop in the Spontaneous Potential (SP) value from the West Spring Creek Formation to the Kindblade Formation. There appears to be a dolomite/shale package at the base of the West Spring Creek that is regionally present. The presence of the dolomite shale within this package is what causes the SP response to be higher. The Kindblade is a cleaner rock type which results in the SP decreasing in value downward throughout its interval. An excellent example of this regional dolomite/shale package at the base of the West Spring Creek can be seen on Figure 12.

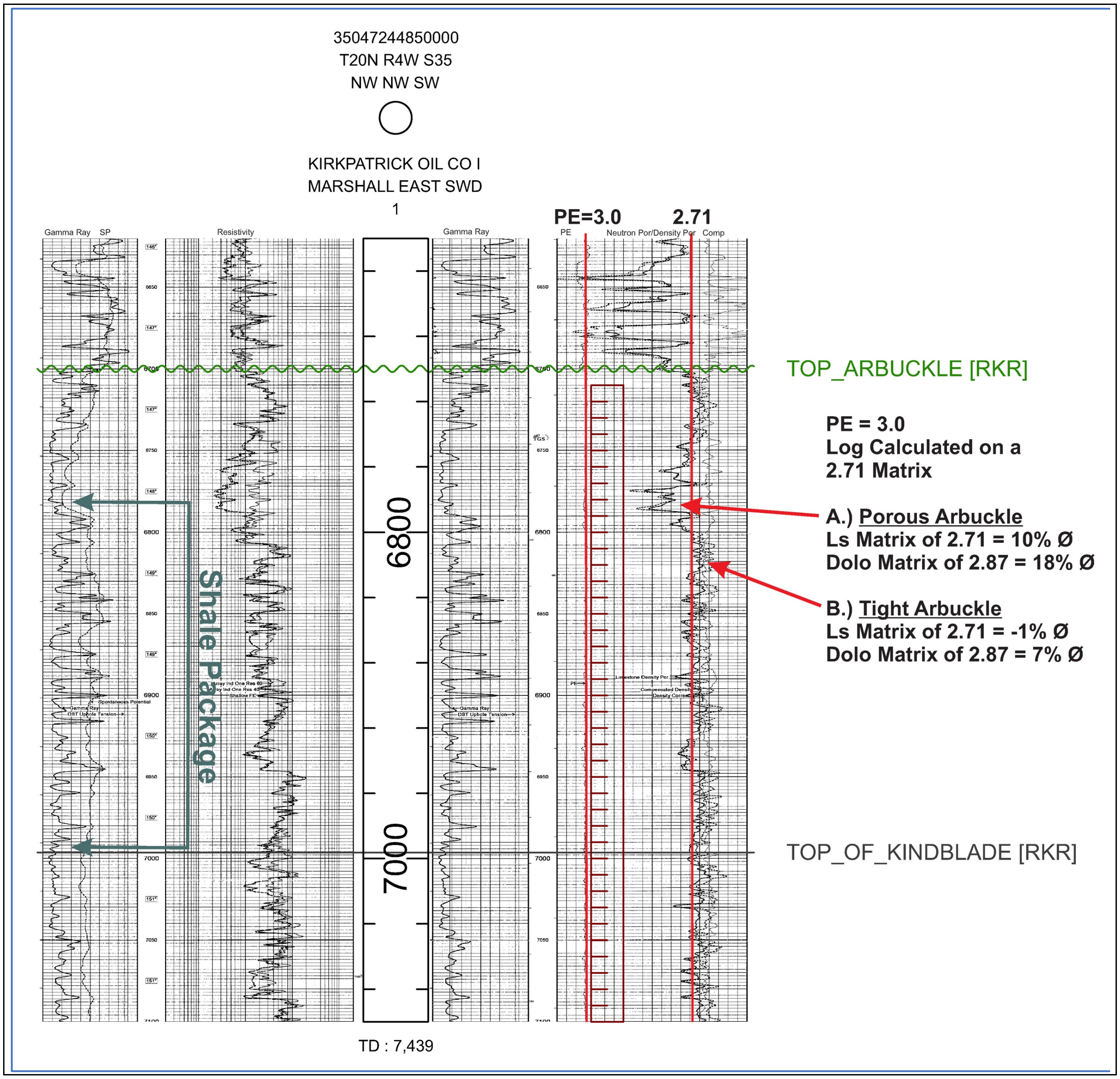

Figure 12: Example of porosity calculation differences using various density matrix values. Red boxed interval within log represents area of shows.

2 - Definition of Log Character of the Top of the Arbuckle and Formation Boundaries

Correlating the top of the Arbuckle can be difficult when this package is at or near the Arbuckle/Simpson contact. However, the dolomitic Arbuckle shale density is generally greater than 2.75 and the Simpson shale density is generally less than 2.75 (see Figure 12).

Figure 13 is an enlarged section of the proposed type log (see Plate 2) centered around the West Spring Creek/Kindblade contact. This figure illustrates the drop in SP observed for almost all of the West Spring Creek well log penetrations for this study area.

Figure 14 consists of three regional log cross sections within the study area. These three sections show the top of the Arbuckle, the contact between the West Spring Creek and the Kindblade Formations, and the top of the granite, as picked for this study. Plate 3 provides an enlarged version of this cross section.

Figure 15 is an isopach of the Arbuckle with the locations of the north-south regional cross sections of Figure 14. All of the wells in these cross sections have the dolomite/shale package at the base of the West Spring Creek illustrated in Figure 13. The top of the Arbuckle and basement granite picks are reasonably certain. The pick for the West Spring Creek/Kindblade Formation contact could be modified by further study as discussed. The continuity of the dolomite/ shale package in all of the wells in the expanded study area with gamma ray logs is of importance, because it is the only internal formation boundary that can be observed on the well logs. The location map for cross sections A-A´, B-B´, and CC´ also includes the location for a potential hinge line (dashed green line) interpreted based on rapid soutwestward thickening of the Arbuckle. The line probably represents the shift from a platform environment to a shelf environment, and examination of the cross sections suggests, in particular, a thickening in the West Spring Creek Formation.

The total Arbuckle isopach can be made from the limited data available, as shown in Figure 15, which highlights areas where the Arbuckle may be anomalously thin. The Arbuckle is thinnest over high points in the Precambrian erosional topography that were preserved when the Arbuckle was deposited, burying the topographic highs (See Basement Geomorphology section). The area circled in red is known as the Tulsa Mountains.

Figure 16 is a structure map on the top of the Precambrian basement. The closures mapped represent those areas where Precambrian erosional features exist. They were interpreted based on the thickness of the Arbuckle Group. In those areas were the Arbuckle Group's thickness is normal regionally, the closures represent structural uplift.

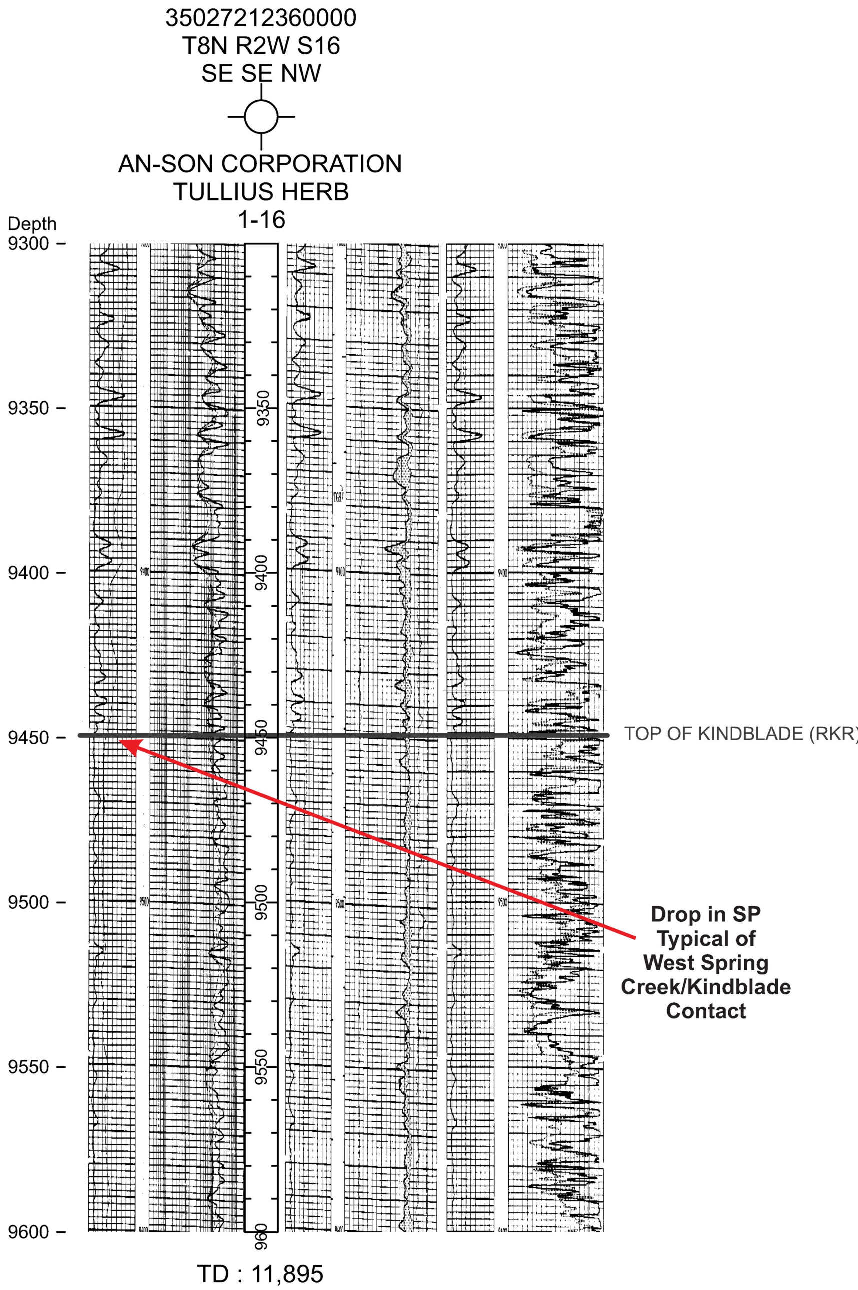

Figure 13: Detailed example of the drop in SP at the West Spring Creek/Kindblade contact.

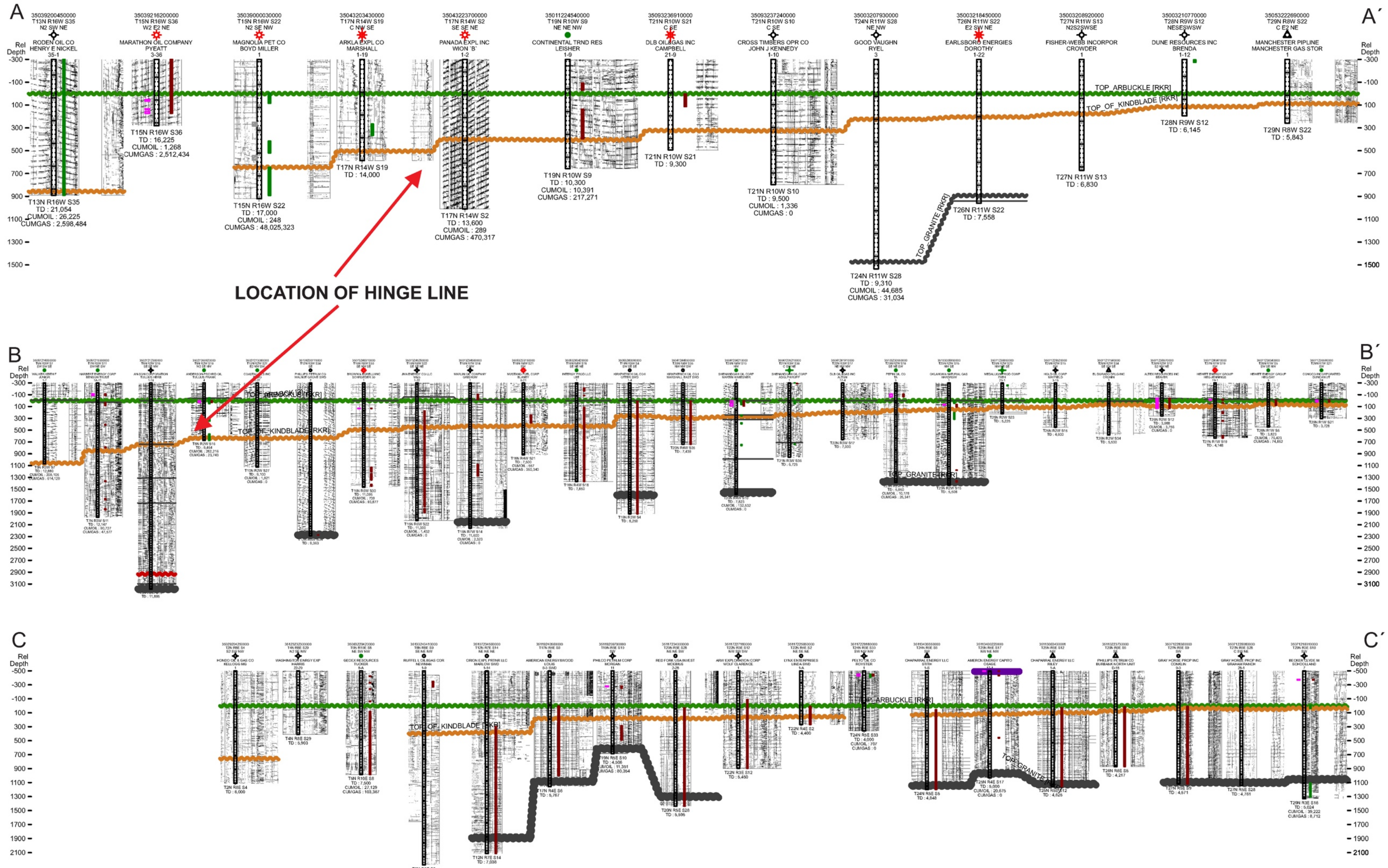

Figure 14: Three regional cross sections illustrating Arbuckle stratigraphy. Enlarged on Plate 3.

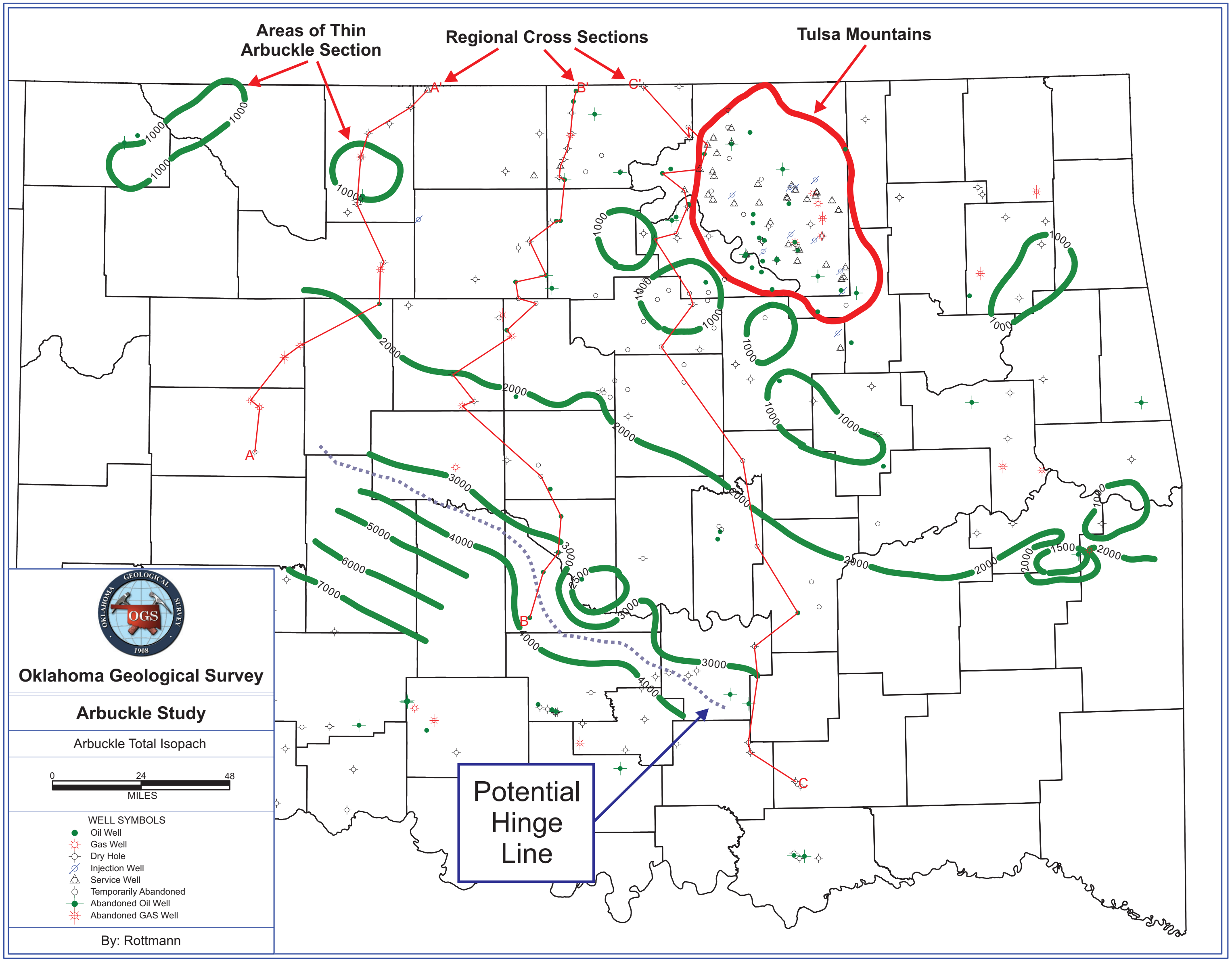

Figure 15: Arbuckle isopach with regional cross sections of Figure 14. Red area is the Tulsa Mountains.

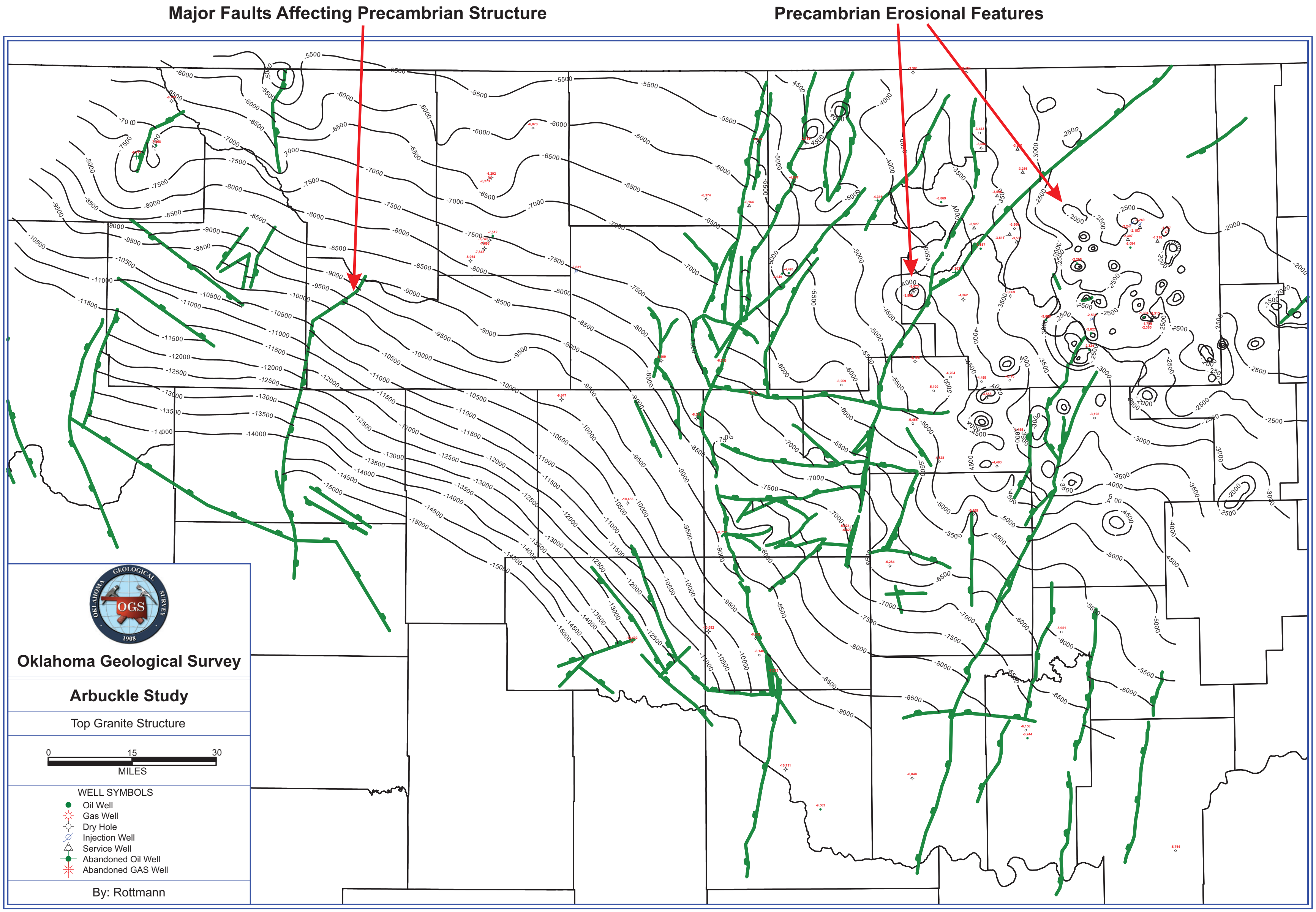

Figure 16: Structure contour map on the Precambrian (granite) surface. Enlarged on Plate 4.

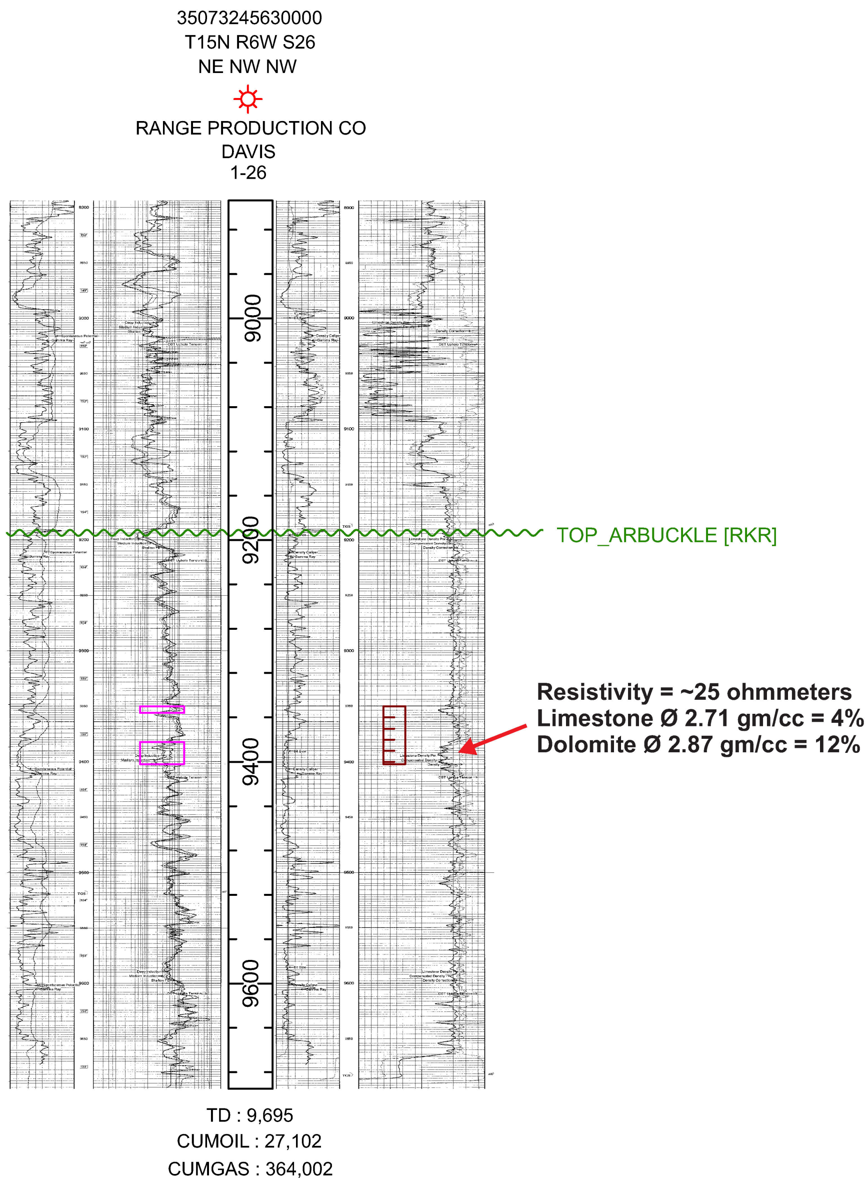

Figure 17: Example of a productive Arbuckle porous zone. Red boxes within log indicate areas of shows.

Figure 17 illustrates a porosity zone located approximately 150 feet below the top of the Arbuckle. The calculated water saturation for the zone is 35%. This pay zone, which was productive in several wells in the field, produced in this well, demonstrates that internal vertical permeability barriers must exist within the Arbuckle. This is counter to the common viewpoint that Arbuckle production only occurs at the top of the formation [Bass 1938]. The presence of productive zones within the deeper parts of the Arbuckle is important as it highlights the fact that barriers (traps) exist within the Group as well as above it.

The porous zone highlighted in Figure 18 is the productive zone discussed in figure 17 and lies approximately 96 feet down dip from location in Figure 17. The water saturation calculated in this well is 100 %.
Water saturation calculations for the Arbuckle Group are not as difficult as those for other pay horizons such as those found in the Mississippian chat, the Hunton Group, or the Simpson Group,

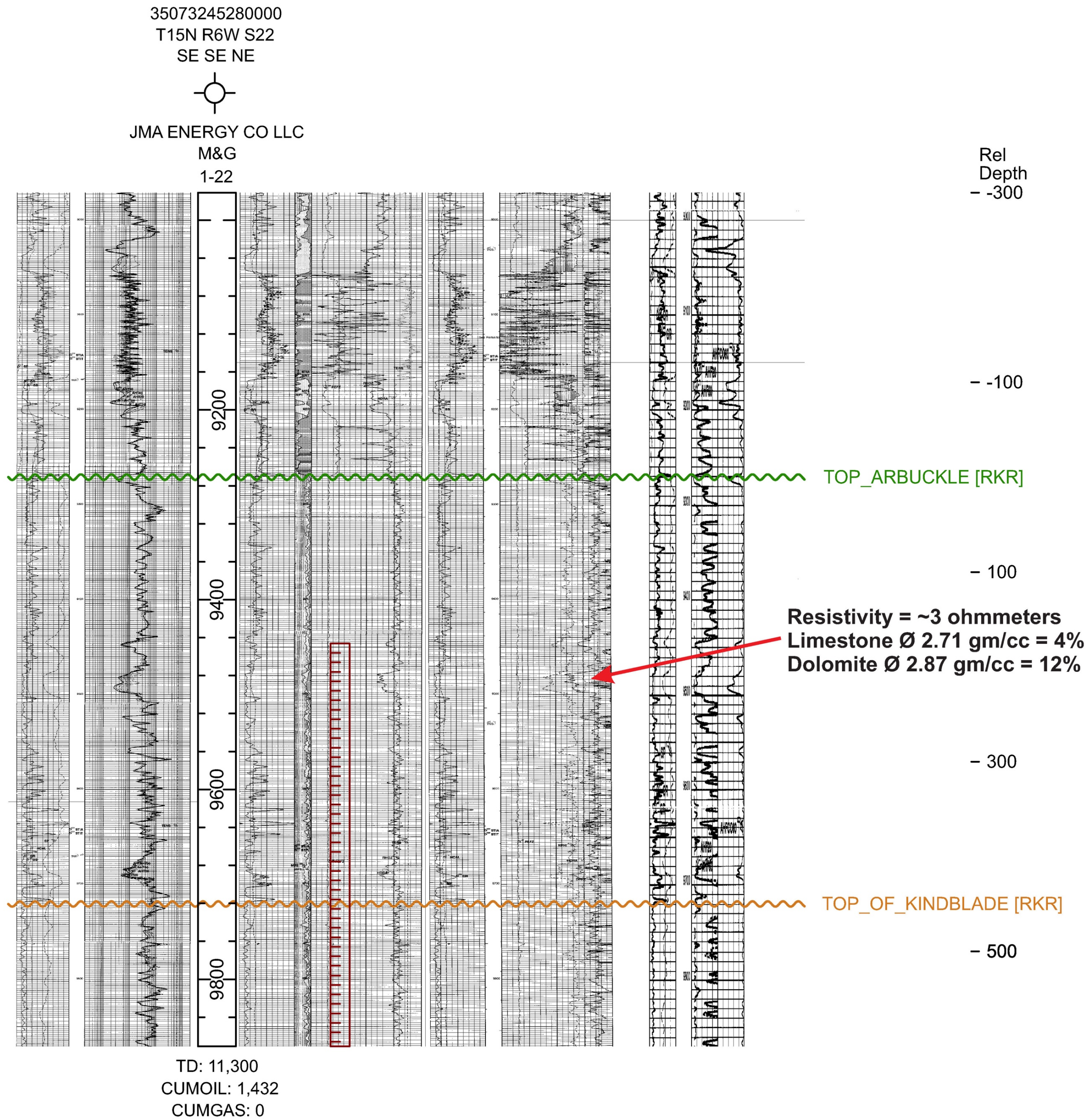

Figure 18: Example of a wet Arbuckle porous zone. Red box within log indicates area of show.

where mineralogy may dramatically affect those calculations.

The highlighted area for the middle well of Figure 19 represents a potential pay zone over 700 feet below the Arbuckle top. The well is a saltwater disposal well whose only log was an electric log with a SP curve. The zone is most likely sandy dolomite or sandstone, and possibly within the Roubidoux Formation (a regional equivalent of the Cool Creek Formation - see Figure 8). The other two wells show the regional correlation for the zone and its potential porous nature. The yellow area on the well on the right represents the basement that was encountered. This well was drilled on the top of a Pre-cambrian erosional geomorphic feature and will be discussed in more detail in the next section.

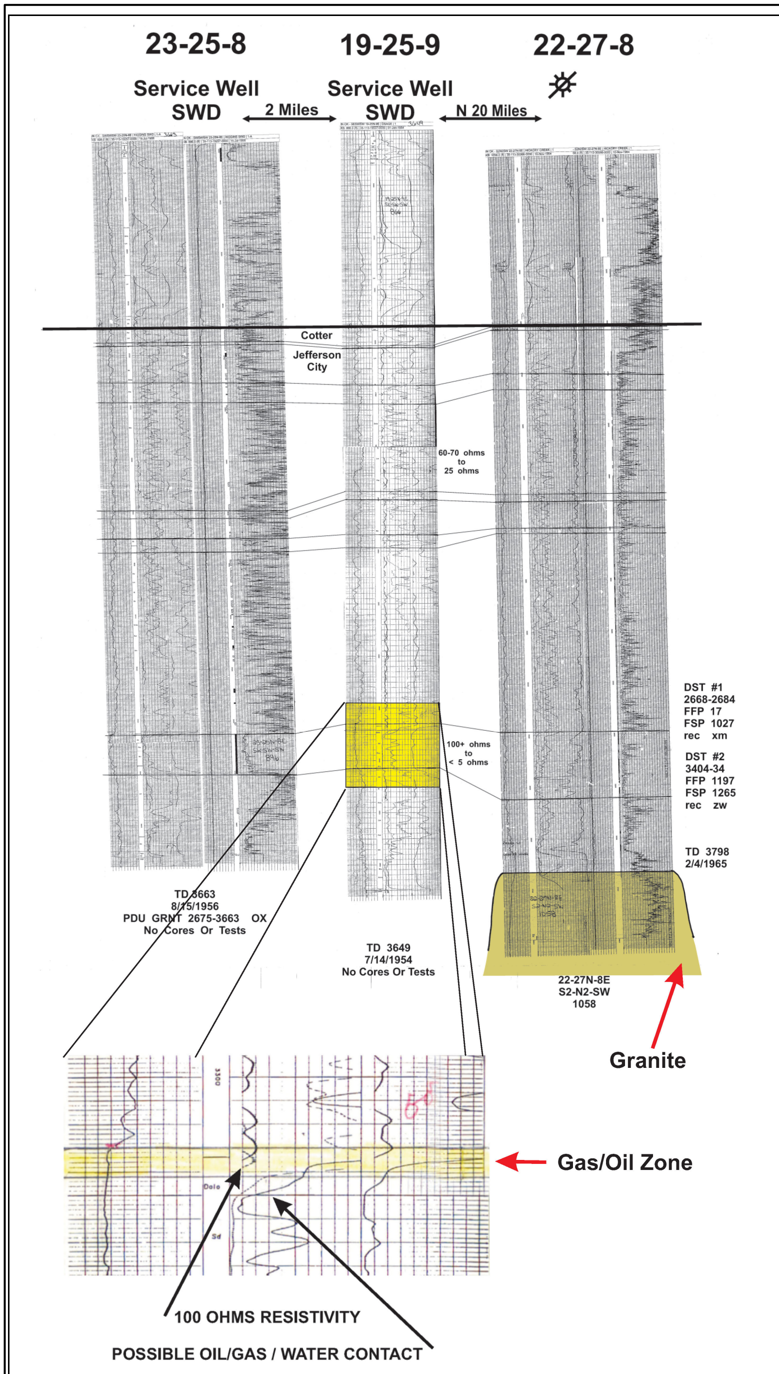

Figure 19: Example of a gas saturated reservoir at the base of the Arbuckle.

The expanded area of Figure 19 illustrates a potential 17-foot gas saturated section within the porosity zone. This demonstrates that gas/oil reservoirs could be located anywhere within the Arbuckle Group as opposed to the assertion that Arbuckle production only occurs at or near the top 50 feet (Bass, 1938). Again, the presence of the gas section in figure 19 suggests that vertical permeability barriers must be present in the Arbuckle although they may not be obvious from the well logs. In fact, rather than the barriers being shale boundaries, it is more likely that the permeability barriers may simply be regional zones of tight dolomite.

Gas saturations within sections of the Arbuckle may be miscalculated if the density porosity log is run on a limestone matrix. Figure 20 represents a section of a neutron porosity/density porosity log for a part of the Arbuckle. The PE curve ranges from about 3.0 to 3.2 throughout the section which suggests the zone is composed predominantly of dolomite for the interval. The density curve shows numerous beds within the dolomite that have density values near or less than 2.71, the zero-porosity value for limestone. In this example, the correct matrix density for the log to be run would be 2.85 to 2.87 g/cc. The section highlighted in red and green is corrected for this effect.

The density porosity is increased by 8%. Adjusting the matrix density from 2.71 to 2.87 reduces the neutron porosity by 3-4% (Schlumberger, personal communication). A six-unit cross over becomes apparent for sections of the Arbuckle when the porosity curves are recalculated using a dolomite matrix density as the base instead of limestone. Zones where gas saturation may be present, as indicated by the crossover of the two porosity curves are highlighted in the figure. The importance of this gas saturation is that not all of the pore volume is water filled, and the implications will be discussed in more detail in the section on Arbuckle Saltwater Injection.

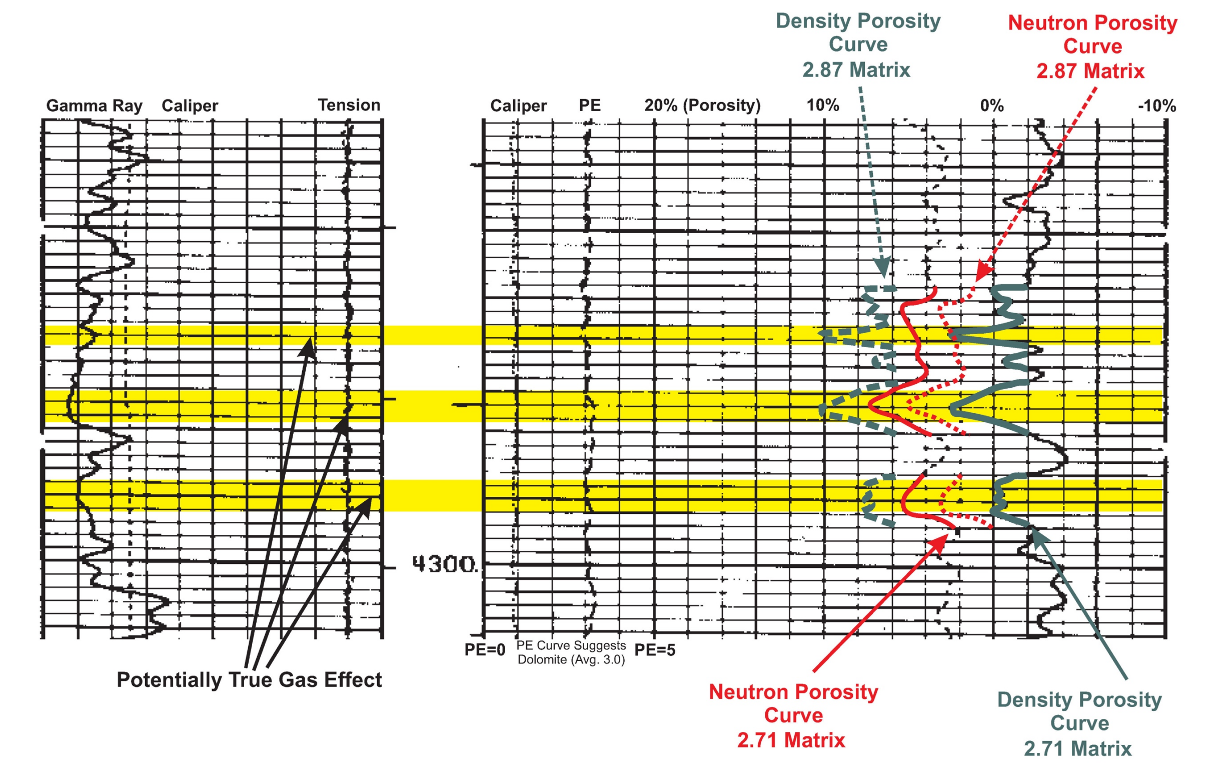

Figure 20 Correction of log porosity for dolomite matrix density. Solid lines show limestone matrix curves; dashed lines show dolomite matrix curves. Neutron/ density porosity crossover, indicating possible gas saturation, indicated in yellow.

3- Basement Geomorphology and Arbuckle Onlap onto the Basement Surface

The goal for this report is to study the hydrogeologic system of the Arbuckle Group. However, to do this adequately, one must also understand some details of the rock units that both underlie and cap the Arbuckle Group. This section discusses the Precambrian basement of the study area, with particular reference to the erosional surface at the base of the Arbuckle. Before the transgression of Cambrian seas, the basement was faulted and deeply eroded, stripping away any Precambrian sedimentary rock, and leaving crystalline basement rock exposed. The erosional event left isolated hills of various sizes, including pinnacles, mounds, and monadnocks. The vertical relief of these features can be up to several thousand feet. Some of the relief can be observed on the basement structure map of Figure 16. This section will not deal with the internal makeup or structure of the crystalline basement but will focus on the pre-Arbuckle erosion surface of the basement and the effect it had on Arbuckle deposition.

Horsey and Donovan (1992) published the series of southwest to northeast cross sections shown in Figure 21, illustrating deposition upon the Precambrian basement from the center of the Anadarko basin in southern Oklahoma to the Tulsa Mountains of Pawnee and Osage Counties. Horsey and Donovan suggest that the same Precambrian geomorphic features found in the Tulsa Mountains area occur in southern Oklahoma. They point out that the deposition of the Arbuckle consists of a series of transgressive sequences progressively burying the basement, which preserved the pre-existing geomorphic features. The older sediments filled in erosional lows and younger sediments onlapped and ultimately buried the Precambrian geomorphic features.

Osage County is a valuable laboratory for studying the basement-Arbuckle relationship and for other concepts that will be discussed in this report as the basement is very shallow and multiple wells have completely penetrated the Arbuckle to the basement. Figure 22 is an isopach map of the Arbuckle in the Tulsa Mountains of Osage County, Oklahoma from Reeder (1973). The yellow areas represent Arbuckle thicknesses less than 500 feet thick and the red colored areas are those places where the Arbuckle is absent. Maximum relief of the granitic erosional features in Figure 22 approaches 2000 feet.

Figure 23 is a structural well log cross section across the Wildhorse Field in Osage County, Oklahoma (field location shown in Figure 22). The vertical relief between the top of the Arbuckle of well #2 and #4 is 1100 feet. The thin Arbuckle in well #2 resulted from the onlapping deposition of the Arbuckle on the Precambrian erosional surface. Markers 1, 2, and 3 illustrate the approximately parallel nature of the Arbuckle correlations. The significant topography of the Precambrian basement erosional surface was noted in the discussion of Figure 15 in the previous section. Walters (1944) published a paper on the granitic hills of central Kansas that demonstrated that the Arbuckle in Kansas was deposited over similar granitic erosional features to those in Osage County, Oklahoma. These features are not as pronounced vertically as they are in Osage County.

Figure 24 is a cross section near the Yellowstone Field of northwest Oklahoma that illustrates a thin section of Arbuckle that occurs in the area. The cross section also illustrates the onlapping nature of the Arbuckle deposits upon the Precambrian erosional surface. Of note is the uniform thickness of both the West Spring Creek and Kindblade Formations, which are present both on the granitic feature and away from it. The likelihood that the formations were deposited by transgressive onlap, and that burial of the basement was complete by the time of these two formations is indicated by the fact that the formations do not thin over the granitic feature.

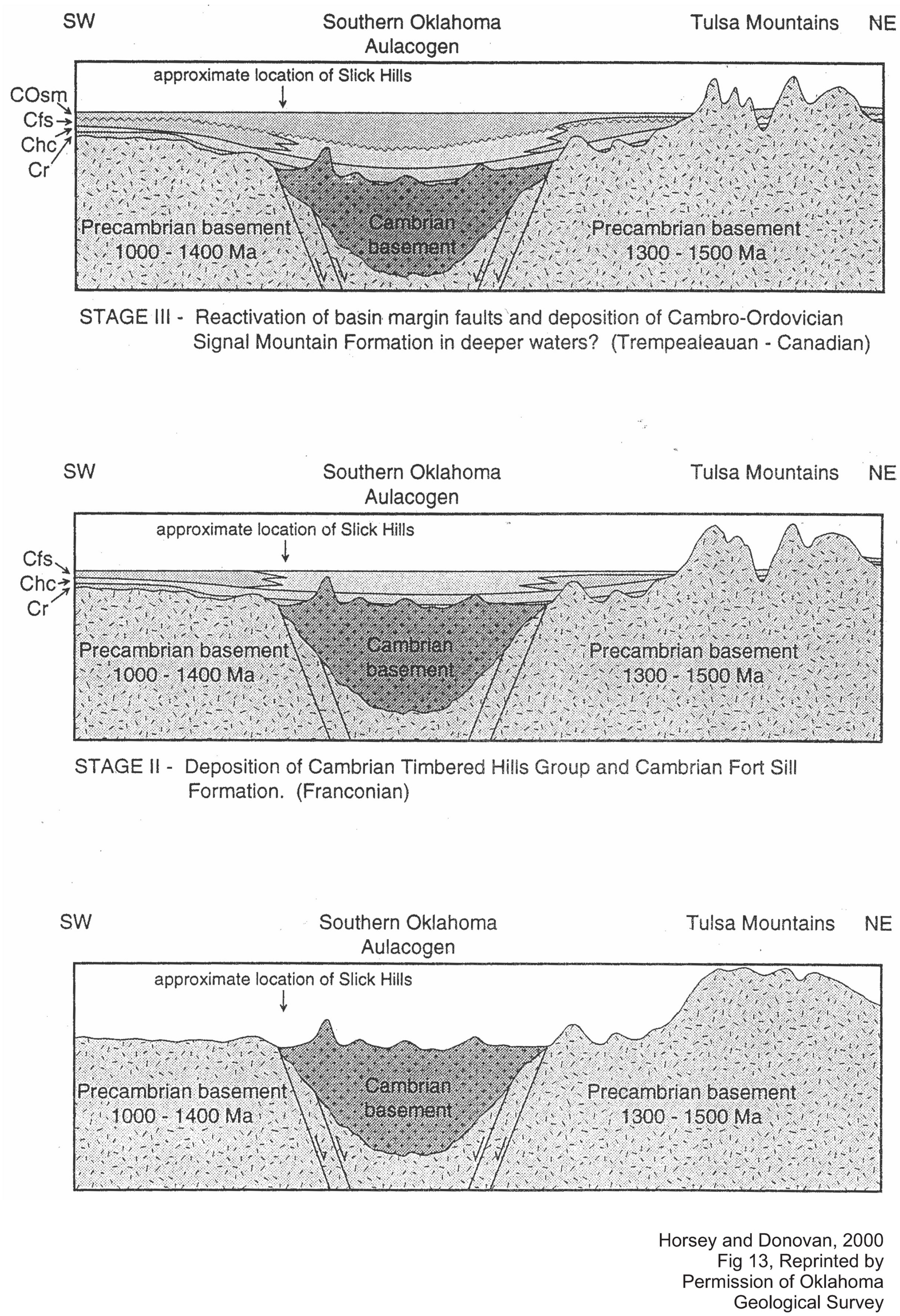

Figure 21: Cross section from Anadarko Basin to Tulsa Mountains illustrating onlap of the Arbuckle Group upon the Precambrian erosional surface. Cr = Cambrian Reagan Sandstone; Chc = Cambrian Honey Creek Limestone; Cfs = Cambrian Fort Sill Dolomite; COsm = Cambrian/Ordovician Signal Mountain Formation.

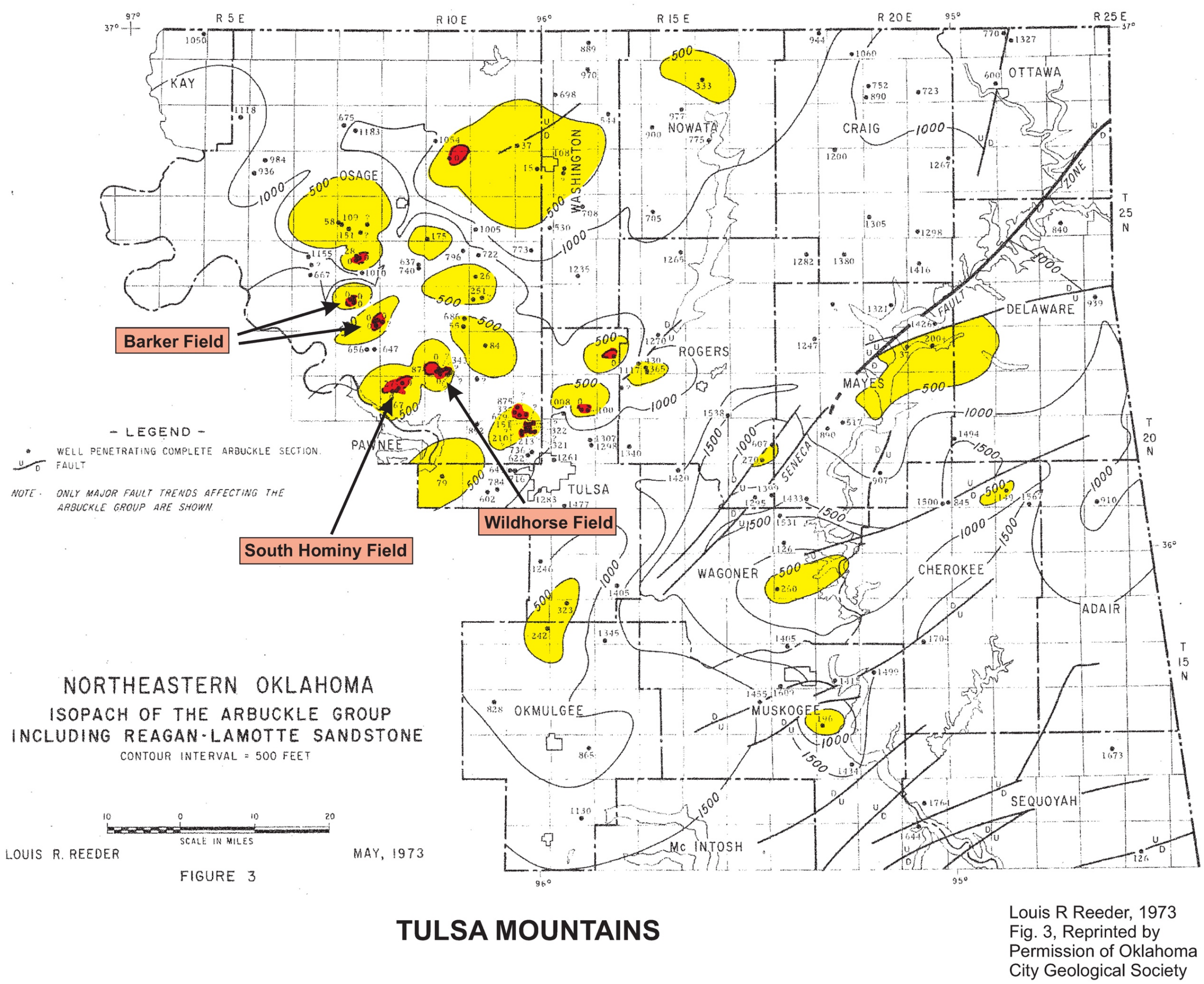

Figure 22: Isopach of the Arbuckle Group in northeastern Oklahoma.

The lack of granitic material in the Arbuckle samples suggests that the granitic features were preserved and not drastically modified during deposition of the Arbuckle. These figures suggest that Arbuckle Group deposition may have occurred until the granitic features were completely buried. Subsequent erosion may have removed the upper part of the Arbuckle until minor granitic exposures occurred in the Tulsa Mountains and elsewhere.

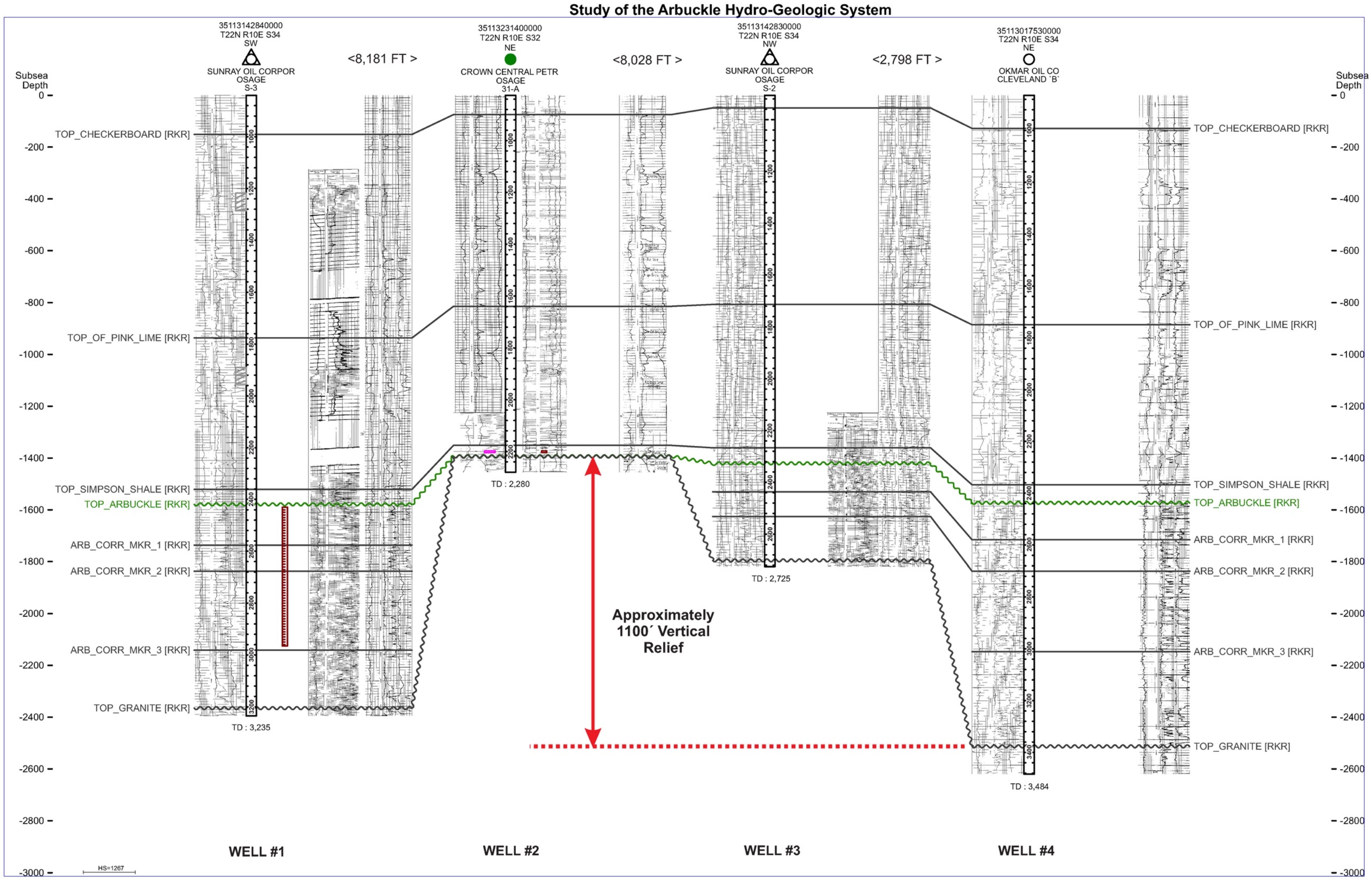

Figure 23: Cross section across the Wildhorse Field area illustrating vertical relief of the Precambrian erosional features.

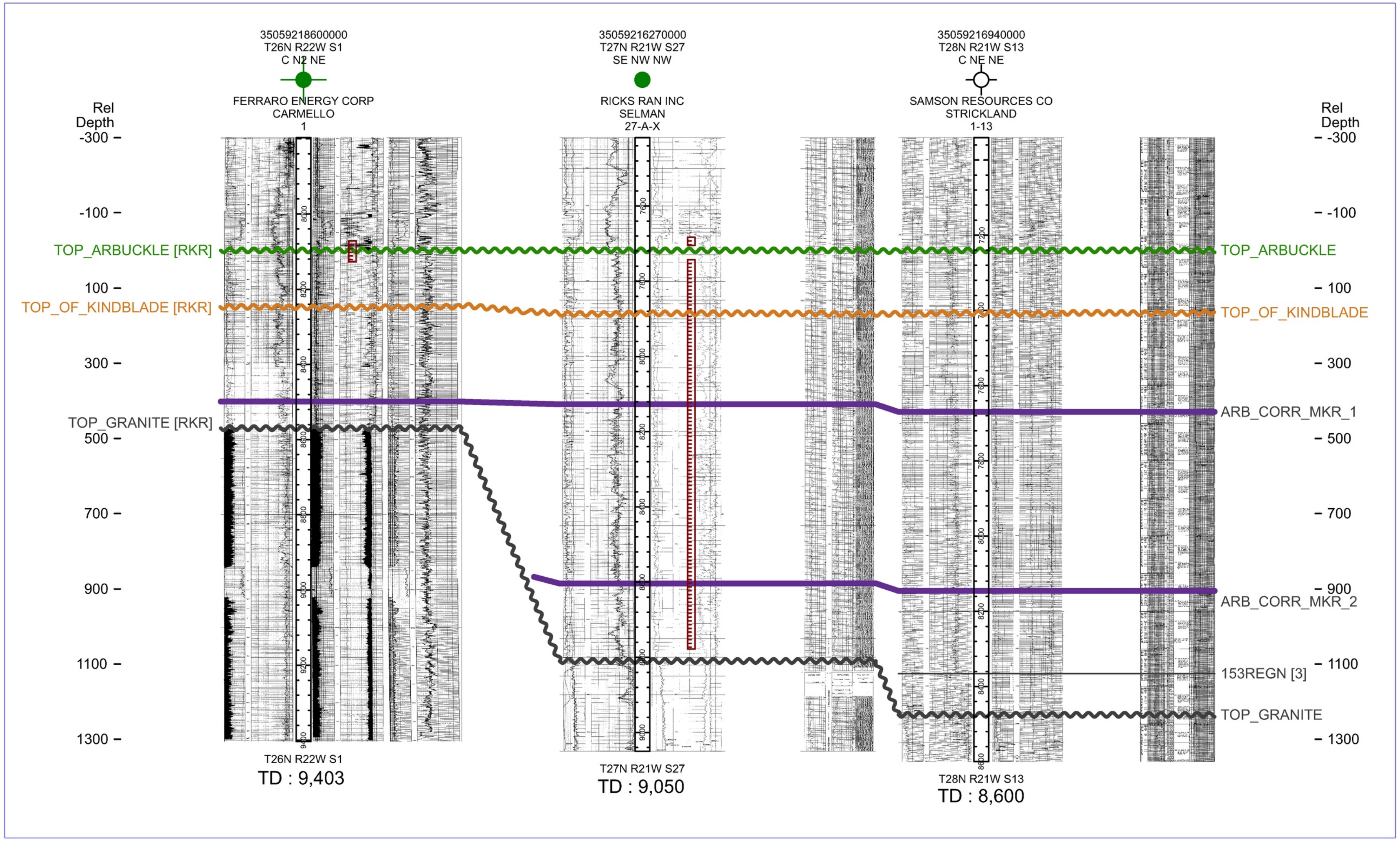

Figure 24: Onlap of Arbuckle sediments over Precambrian high near Yellowstone Field, Oklahoma.

4 – Post-Arbuckle Deposition and Erosion and Effects on Formation Pressure

The Arbuckle group is measurably underpressured over much the area where it has been penetrated. This section will attempt to address the question of how the Arbuckle became underpressured, as this question is important to understanding the relationship between saltwater disposal and seismicity presented in this report.

Figure 25 is a well log plot from the study area that illustrates the informal correlations of the Simpson Group used for this report. Some [List them] of these picks are informal boundaries used to designate certain correlations that have been observed regionally. The McLish sand zone is of particular importance to this study as it is widespread throughout the study area. It is composed of interbedded sand and shale lenses.

Figure 26 is a map that illustrates the subcrop on underlying rock units of the Simpson Group units shown in Figure 25. The Joins Sand was not displayed as its subcrop limit is very near the southern extent of the study area. The subcrop is actually more complicated than expected.

Figure 27 is a schematic graphical cross section that illustrates the geometry of the subcrop/onlap relationship from the Anadarko Basin to the Kansas/Oklahoma border in northeast Oklahoma. The importance of this figure is to show that the geometry of the deposits of the Simpson is more complicated than those typical of an onlapping sequence as might be expected. For example, the McLish is actually the last Simpson Formation displaying an onlap relationship with the Arbuckle. The post-Hunton Group erosional unconformity has removed the section above the McLish, so the nature of any onlap of the higher units is unknown, and we have only the subcrop relationships to the Hunton Group.

This study correlated 510 wells integrated into five regional cross sections, shown in Figure 28. Three primary correlations were generated on these cross sections. These three primary correlations were the top of granite, top of Arbuckle, and the top the first coherent sedimentary unit on top of the Arbuckle, referred to as the cap rock to the Arbuckle. This last correlation is extremely important to the results and conclusions for this report and will be discussed in the following sections. Some additional correlations of formation boundaries and marker beds within the Arbuckle Group were made in wells where a consistent log boundary could be defined.

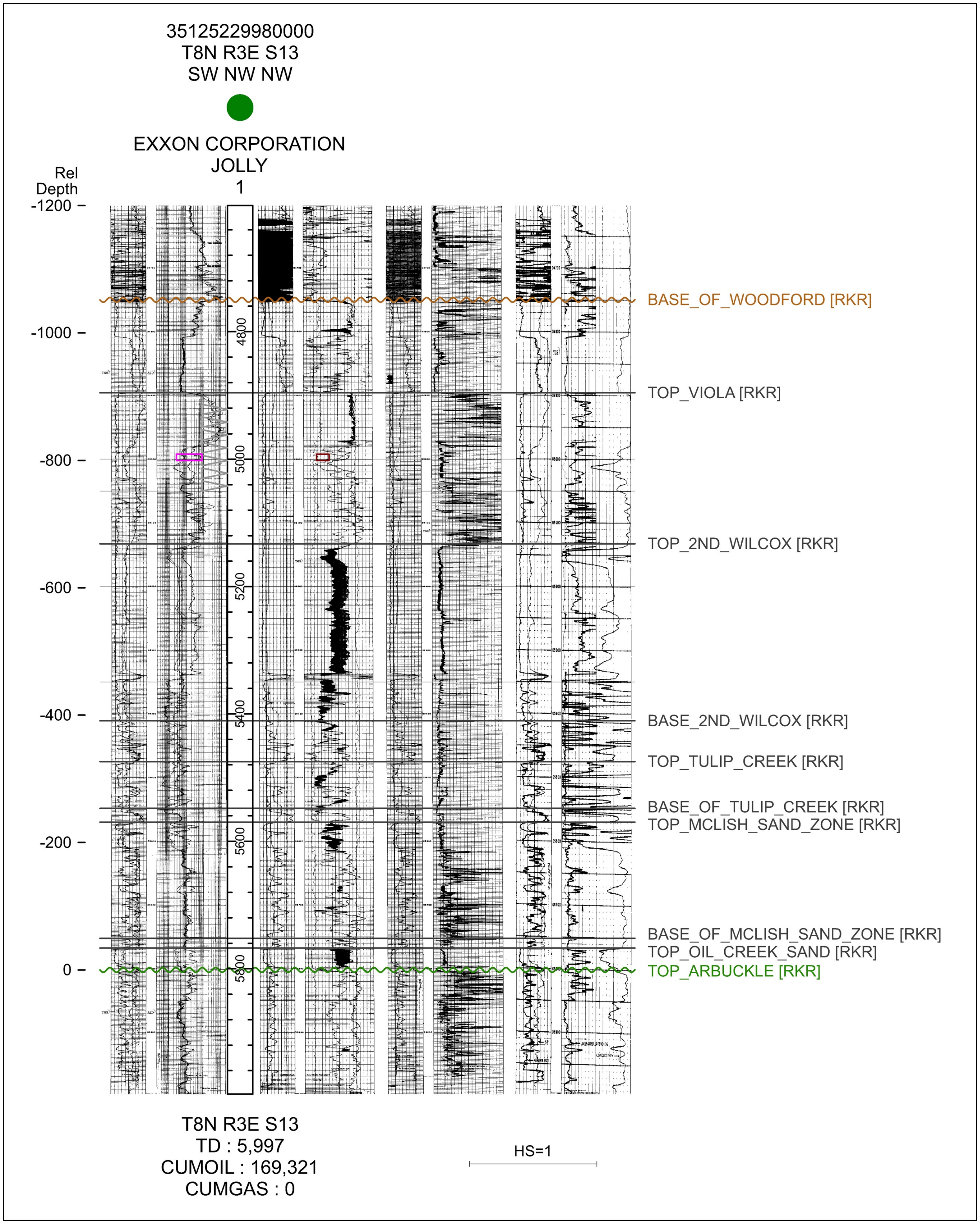

Figure 25: Well logs illustrating Simpson Group subdivisions relevant to this report. Red box within log indicates area of show.

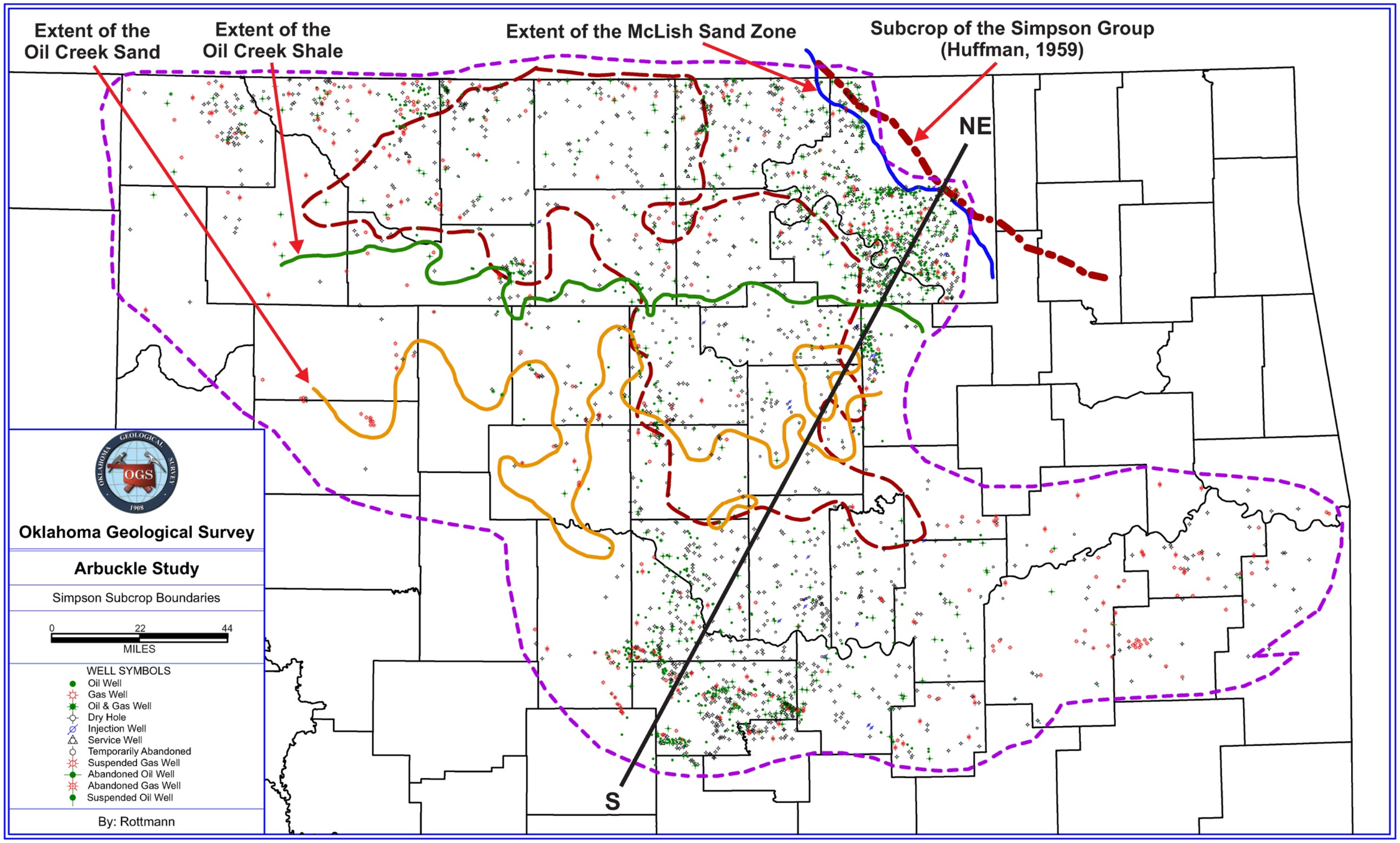

Figure 26: Subcrop limits for various Simpson Group subunits with wells and study area boundaries. Black line represents approximate location of schematic cross section S-NE of Figure 27.

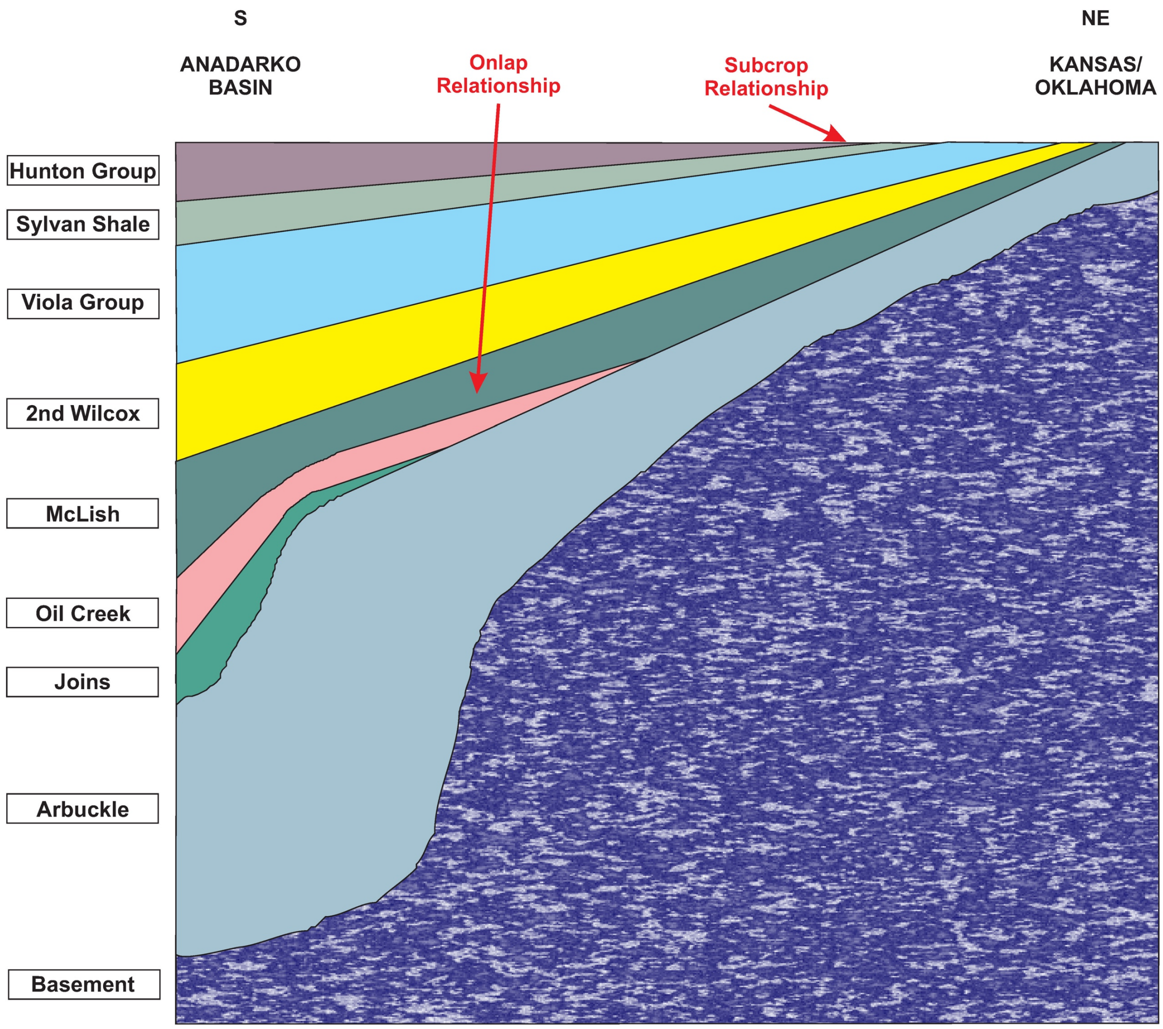

Figure 27: Onlap and subcrop geometries for the Simpson Group from the Anadarko Basin to the Kansas/Oklahoma border.

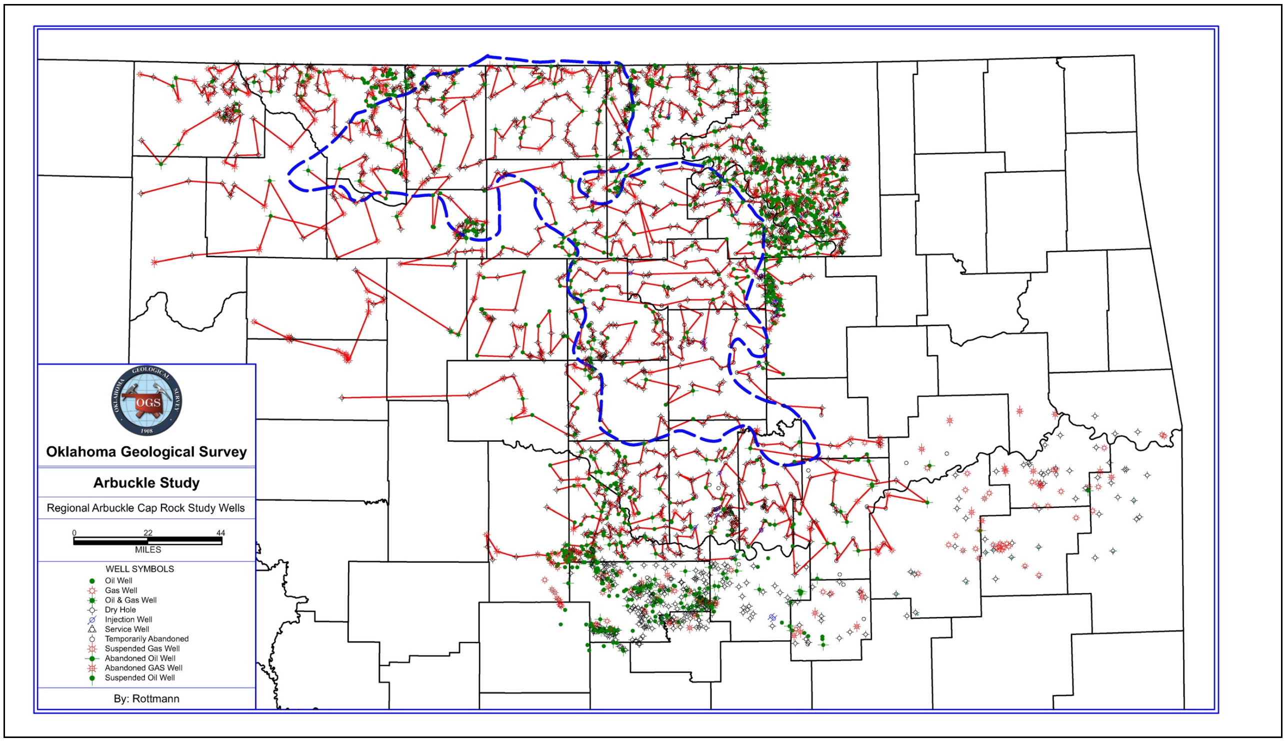

Figure 28: Location of wells used for Arbuckle cap rock facies determination. Dashed blue line represents the author's outline of significant seismic events.

Figure 29 illustrates the well log characteristics of six sedimentary facies observed to overlie the Arbuckle. These facies do not have the rank of formations or members of formations. They constitute the first readily definable and correlatable sedimentary package deposited directly on the Arbuckle. The schematic log signatures of Figure 29 represent the log characteristics that define each facies. The facies vary in overall thickness, as will be discussed in following sections. Annotations for each of the facies types highlight the important log characteristics for each facies. Although there are six types of facies, they can be grouped into two primary categories, those that are porous and potentially permeable and those that are impermeable. These six facies and their log characteristics will be discussed in more detail in the following sections.

Figure 30 is an example of a well whose Arbuckle cap rock facies (cap rock) consists of porous sandstone. The facies is generally characterized by a low SP and gamma ray response, microlog separation from other resistivity curves, mud cake buildup, indicated by a caliper log showing narrowing of the borehole, separation of the resistivity curves indicating invasion of mud filtrate, and greater than 8% on the porosity log. If a porosity log was not available, then the characteristics listed for the electric log would need to be present in order to identify the facies. In some cases, especially in larger continuous areas of porous sandstone, cap rock sections that were slightly less than 8% were also incorporated into this facies group.

The map in Figure 31 shows thickness values for cap rock units in the study area, with the areas where the cap rock consists of porous sandstone highlighted in yellow on figure 31. The numbers in black represent the porous sandstone thicknesses. Almost all of the neutron porosity/density porosity logs in the study area used a limestone matrix to calculate porosities. A density porosity of 10-11% on a log using a limestone matrix to calculate the porosity would equate to 8% sandstone porosity.

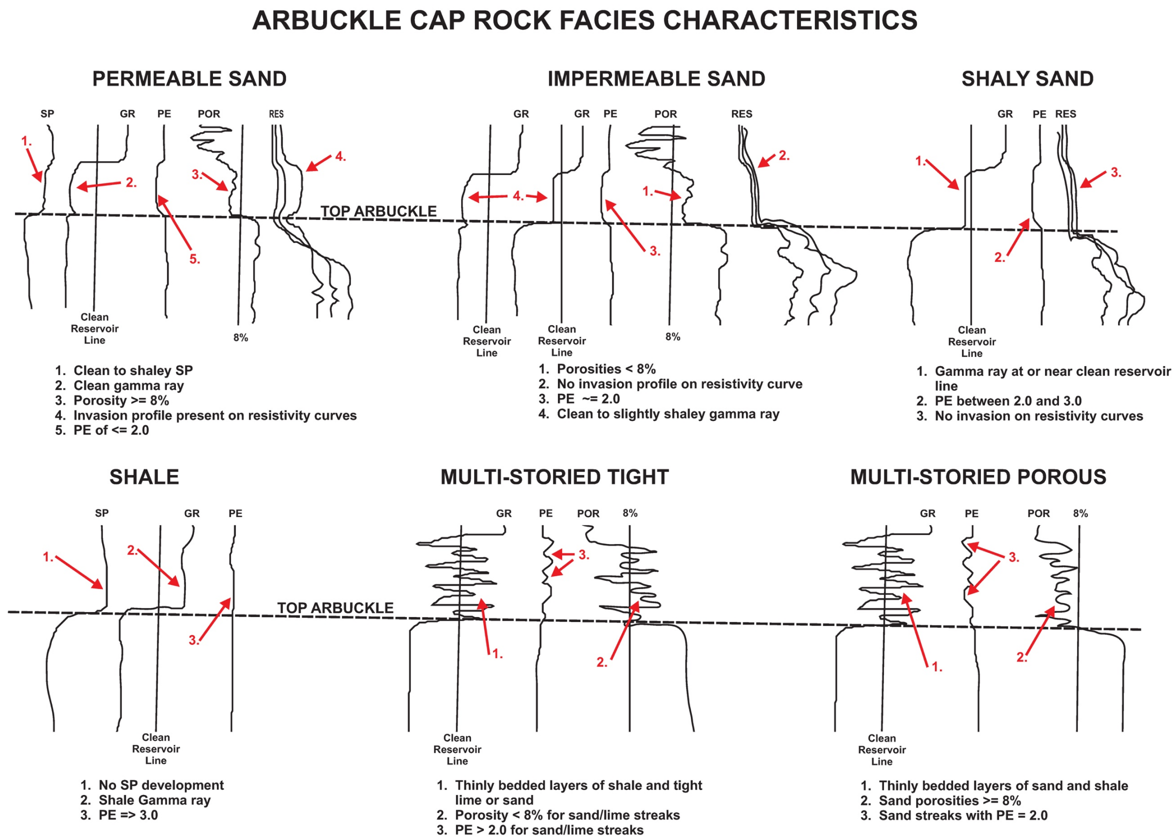

Figure 29: Schematic of electric log characteristics for Arbuckle cap facies types.

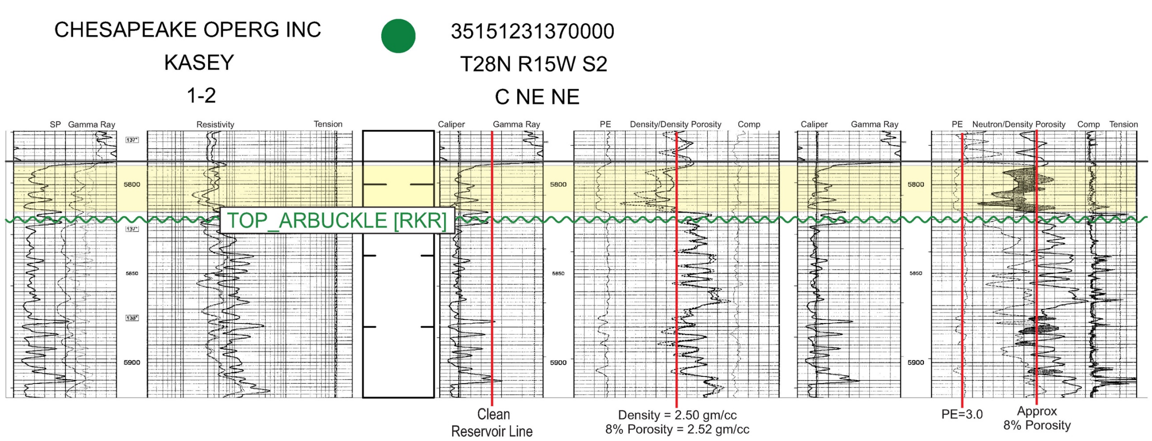

Figure 30: Example of a porous Arbuckle cap rock facies.

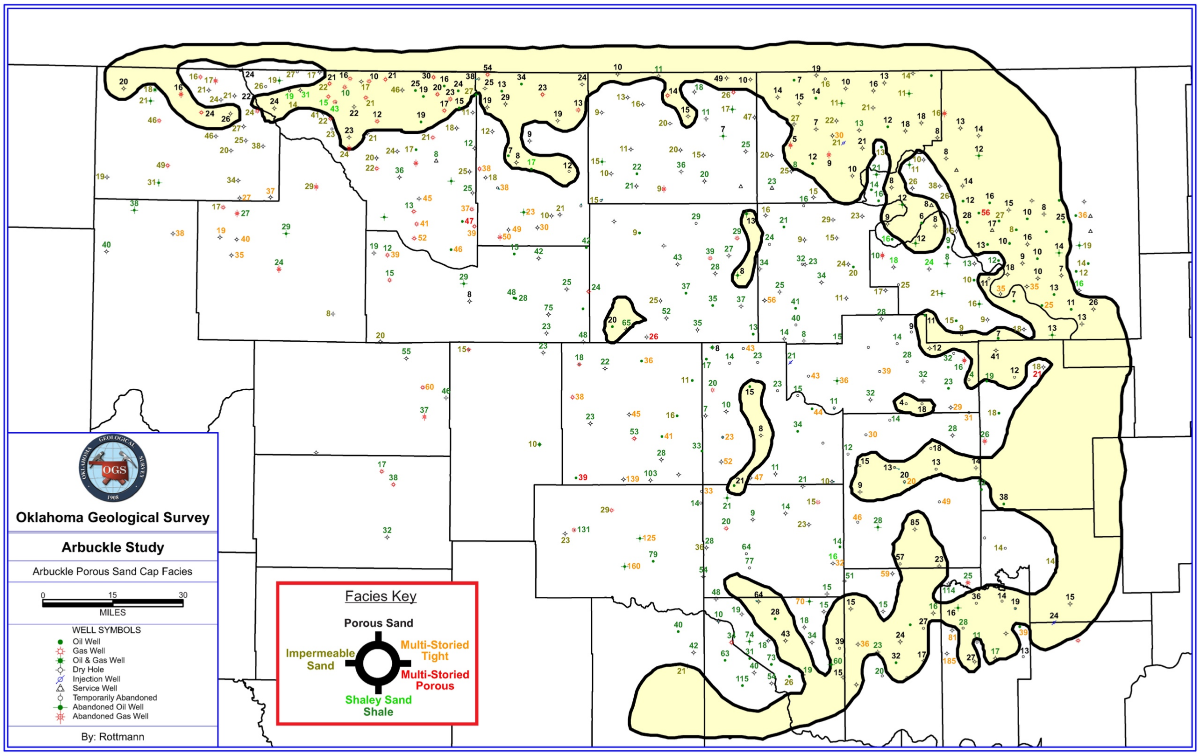

Figure 31: Map of porous Arbuckle cap facies (highlighted in yellow).

Figure 32 shows the logs for a well whose cap rock is a tight sandstone, with porosity less than 8%. These sandstones show variable clay content, which may contribute to their low permeability. These zones almost always have no indication of mudcake and have a tight sandstone profile on the microlog in which the resistivity curves are generally coincident to slightly separated suggesting the impermeability of the sandstone from invasion. The PE log value is commonly greater than 2.0, which results from the clay content of the sandstone. Also, the SP signal is reduced and may not be distinguishable from a shale SP.

The gray colored area of Figure 33 displays the areal distribution of the tight sandstone facies. The area of porous sandstone is also shown (in yellow). The number to the left of the well symbol represents the thickness for the tight sandstone facies.

Figure 34 is an example of a well whose Arbuckle cap rock is composed of shale. The facies can easily be determined by several factors such as no SP development, high gamma ray (to the right of the 50% clean reservoir line (highlighted in red), a PE value of 3.0, and very little separation of the resistivity curves on the electric log.

The green filled area of Figure 35 is that part of the study area where the Arbuckle cap rock facies is composed of shale. The dark green values below the well symbols indicate the thickness of the shale.

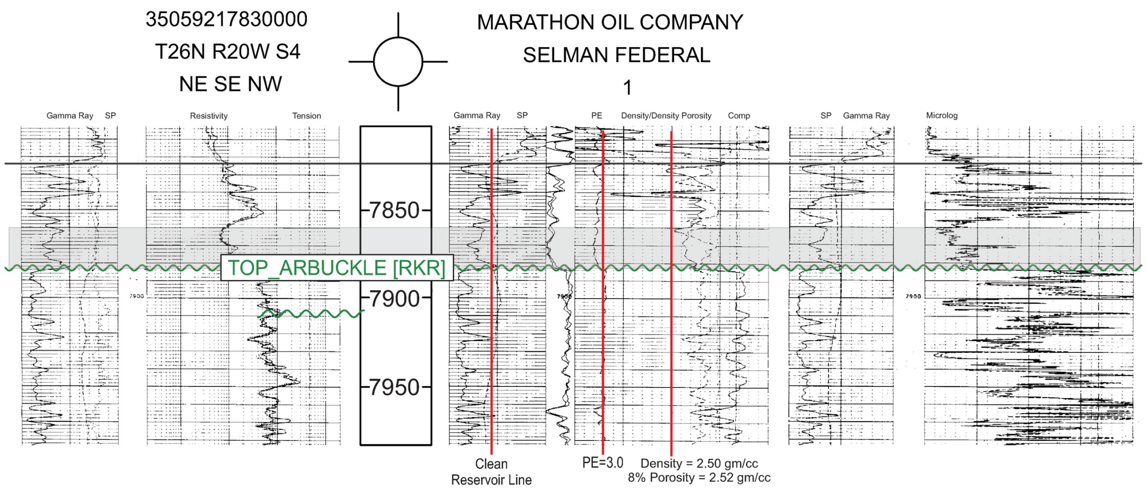

Figure 32: Example of a tight sand Arbuckle cap facies.

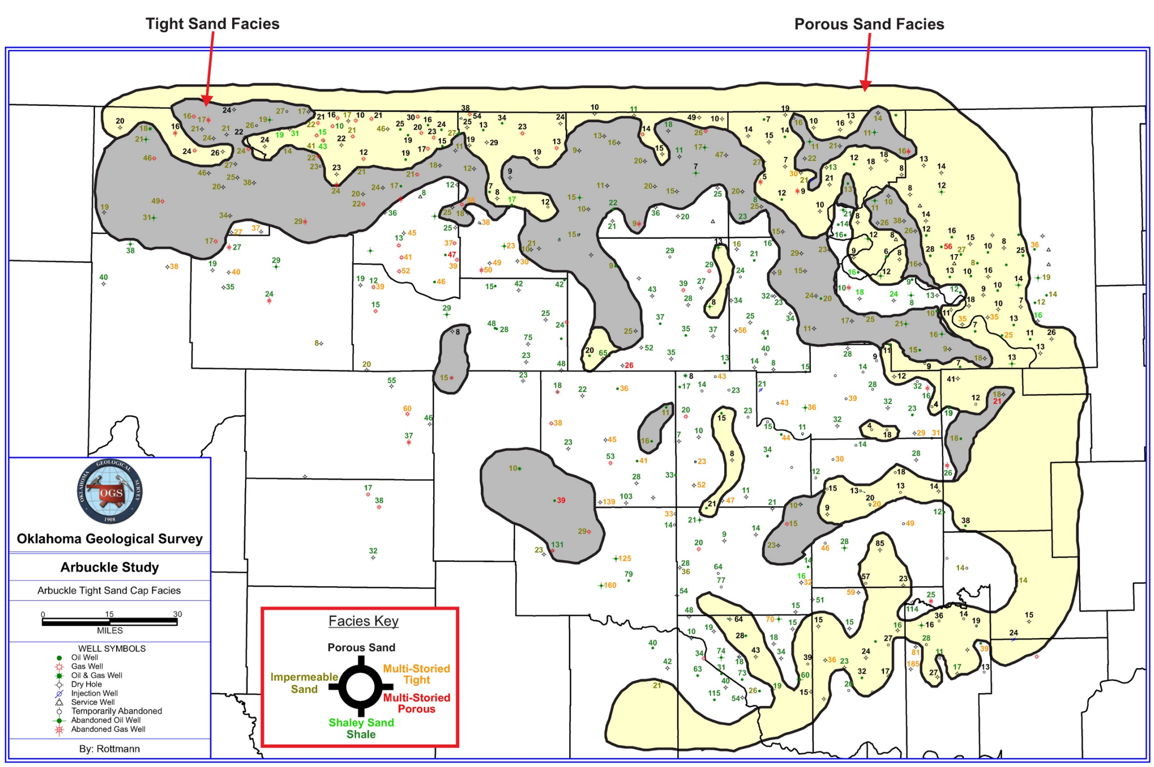

Figure 33: Tight sand (area highlighted in gray) and porous sand (area highlighted in yellow) cap rock facies overlying the Arbuckle.

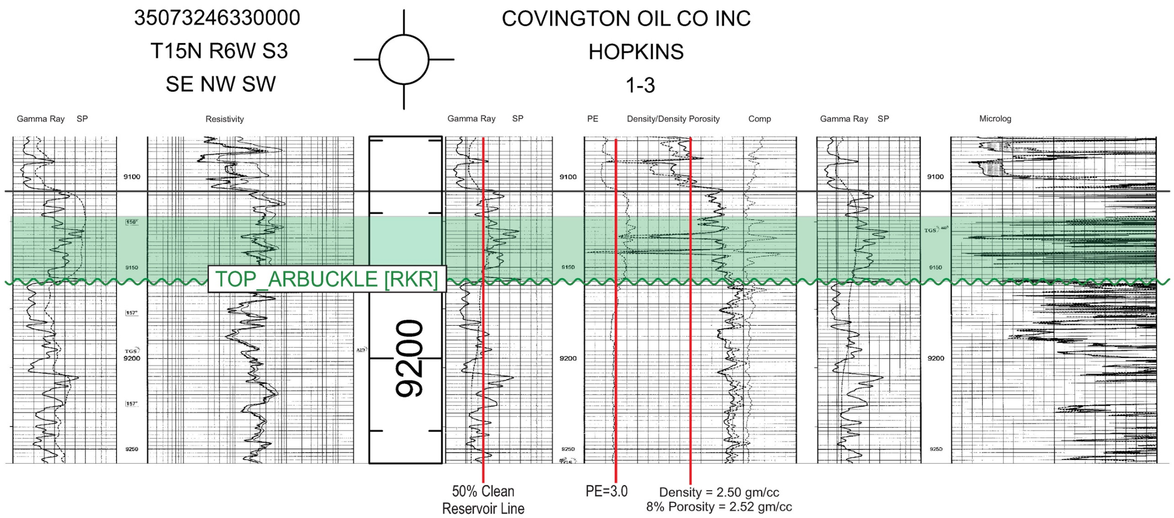

Figure 34: Example of a shale cap facies on top of the Arbuckle.

Figure 36 shows logs for a well whose cap rock facies on the top of the Arbuckle is composed of shaley sandstone. The characteristics of this sandstone are: very low porosity, a PE value ≥2.0 with higher PE indicating greater clay content, and gamma ray values indicating marginal clean reservoir (intermediate) to shale (high). The gamma ray value is generally slightly less than the 50% point

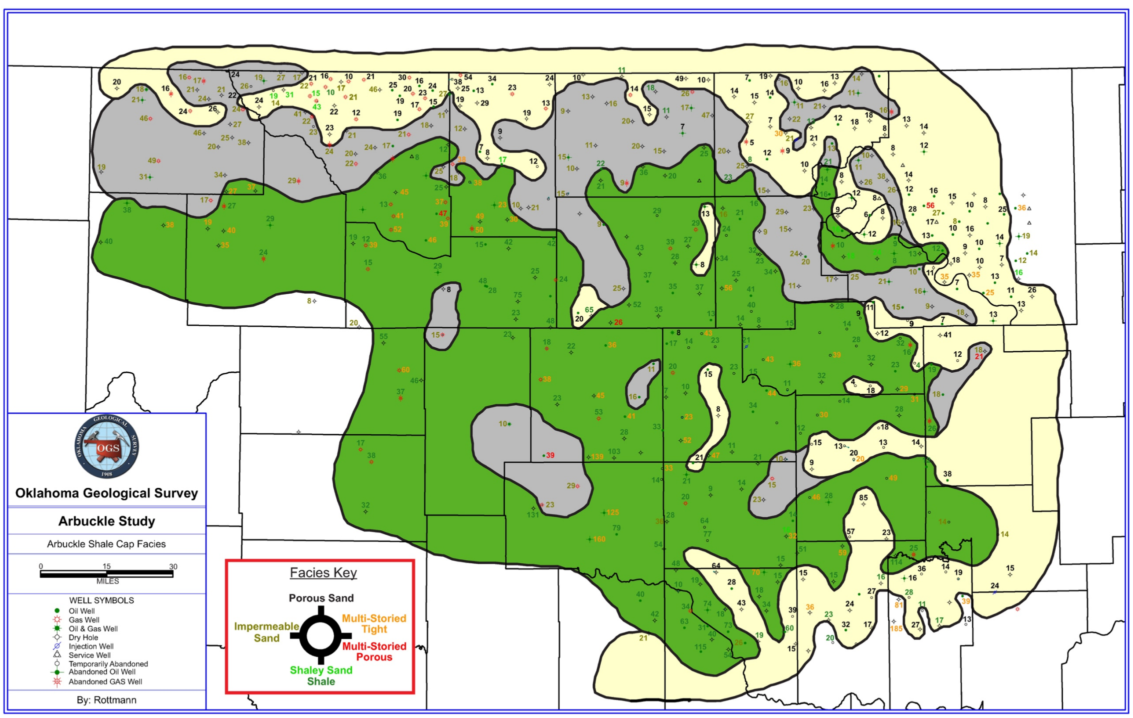

Figure 35: Arbuckle cap rock facies map illustrating shale cap facies (area highlighted in green) with tight sand (area highlighted in gray) and porous sand facies (area highlighted in yellow).

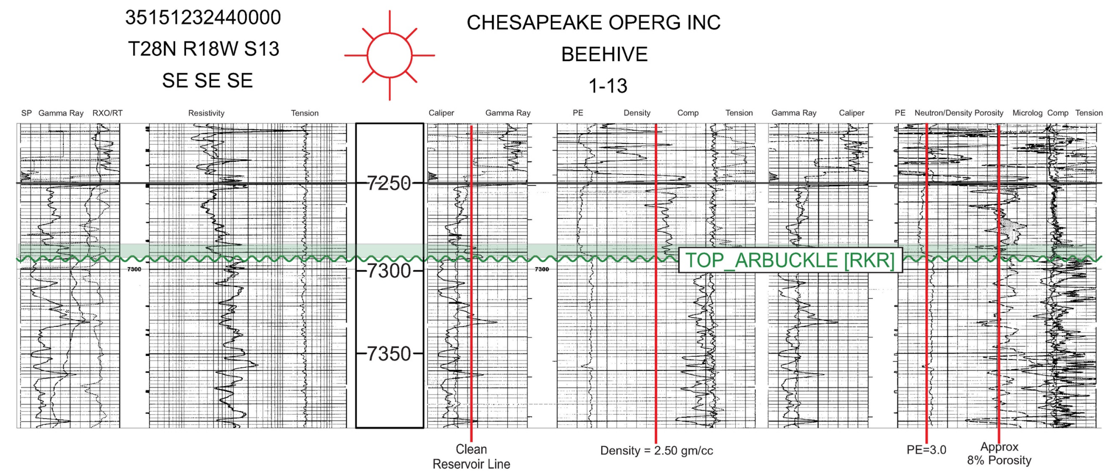

Figure 36: Example of a shaley sand cap facies on top of the Arbuckle.

between a clean gamma ray and the shale line. Because of the PE value, this type of sandstone is included in the tight sandstone facies of Figure 32.

Figure 37 represents a well whose cap rock is a multi-storied limestone/shale sequence. This facies is characterized by a sequence of thinly laminated (<3 feet) or interbedded shale/limestone sequences. The PE curve reads 3.0 for the shale laminae and 4-5 for the limestone beds. The facies is mapped with the shale facies of Figure 32, as it is considered to have low permeability.

4 - Post-Arbuckle Deposition and Erosion and Effects on Formation Pressure

As mentioned previously, this cap rock facies can be easily confused with the interbedded shale/dolomite sequence noted in the lower part of the West Spring Creek Formation. The important difference between this cap rock facies and the zone found in the West Spring Creek is in the value of the density of the shale interbeds. The matrix density of the shale in the Simpson is almost always less than 2.50 g/cc, whereas those of the West Spring Creek are apparently dolomitic and rarely show a density below 2.50.

The last cap rock facies that may overlie the Arbuckle is the multi-storied porous facies, illustrated in Figure 38. This facies is characterized by thinly layered (less than 3 feet for each layer) porous

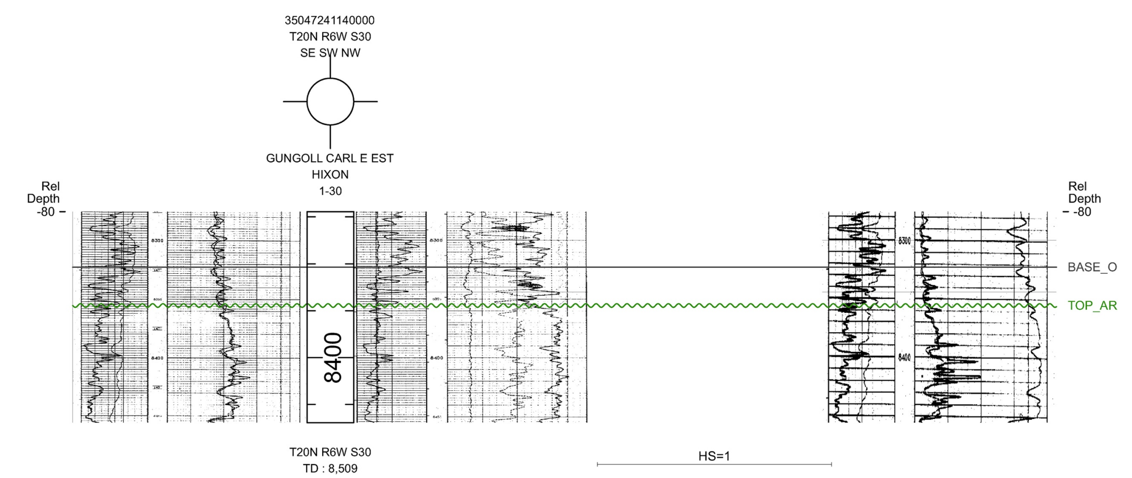

Figure 37: Example of a well with a multi-storied porous facies on top of the Arbuckle.

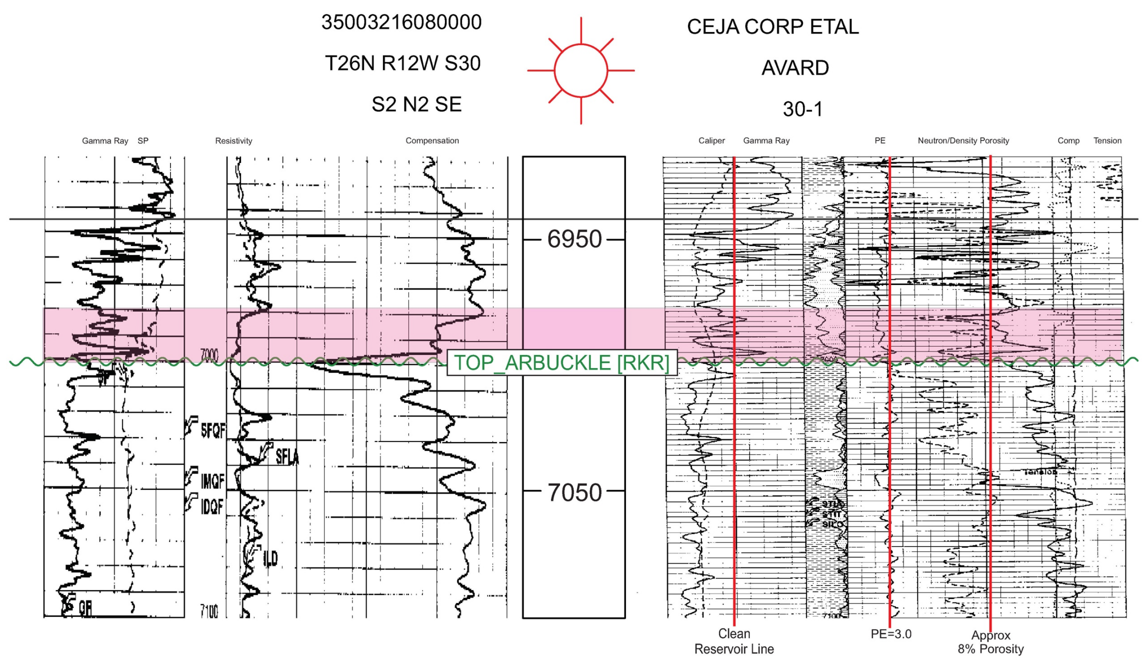

Figure 38: Example of a well with a multi-storied lime/shale Arbuckle cap facies.

sandstone and shale, by a PE of 3.0 for the shale laminae and 2.0 to 3.0 for the porous sandstone layers, with the sandstone porosity values generally greater than 8%.

The facies was only identified 3 times among the 510 wells studied for the cap rock facies. It is included in the tight sandstone facies map of Figure 36, because the thin shale laminae interbedded in the facies are likely to be impermeable.

The cap rock facies is generally greater than 10 feet thick, and may exceed 100 feet in the southwestern part of the study area. As will be seen in subsequent discussion, the thickness of this zone may be an important constraint on the pressure behavior of the Arbuckle. This issue has not been addressed in this report, but probably warrants further consideration.

4 - Post-Arbuckle Deposition and Erosion and Effects on Formation Pressure

This next section discusses the evolution of pressure and gas solution through the history of deposition after Arbuckle time. Figure 39 is a schematic illustration of Arbuckle through Hunton deposition from the Anadarko Basin to the Tulsa Mountains in northeast Oklahoma. Burial of the Arbuckle at this time may have produced the maximum hydrostatic pressure in the Arbuckle Group. Notice in the figure that in some places, the cap rock facies is composed of porous and possibly permeable strata, whereas in the rest of the cross section the cap rock is composed of impermeable strata. The image of the capped soda bottle is used here to illustrate that gas trapped in the Arbuckle is held in solution at this time. This informal image will be used throughout the discussion of the model for pressure changes in the Arbuckle due to changes in overburden.

Figure 40 illustrates the type of Arbuckle hydrocarbon production in parts of Osage County, Oklahoma. The solid red line represents the limit of Simpson deposits. North of the line, the Simpson is absent, and Woodford Shale, which commonly produces gas, overlies the Arbuckle. South of the line the Simpson overlies the Arbuckle and the production is primarily oil. This suggests that impermeable shale of the Simpson prevented oil from escaping from the Arbuckle during the erosional period that removed the Simpson on the north side of the line. The source for the gas production was most likely the Woodford Shale and it probably represents the second generation of hydrocarbons for the area. Bass (1938) noted the differences in Arbuckle production associated

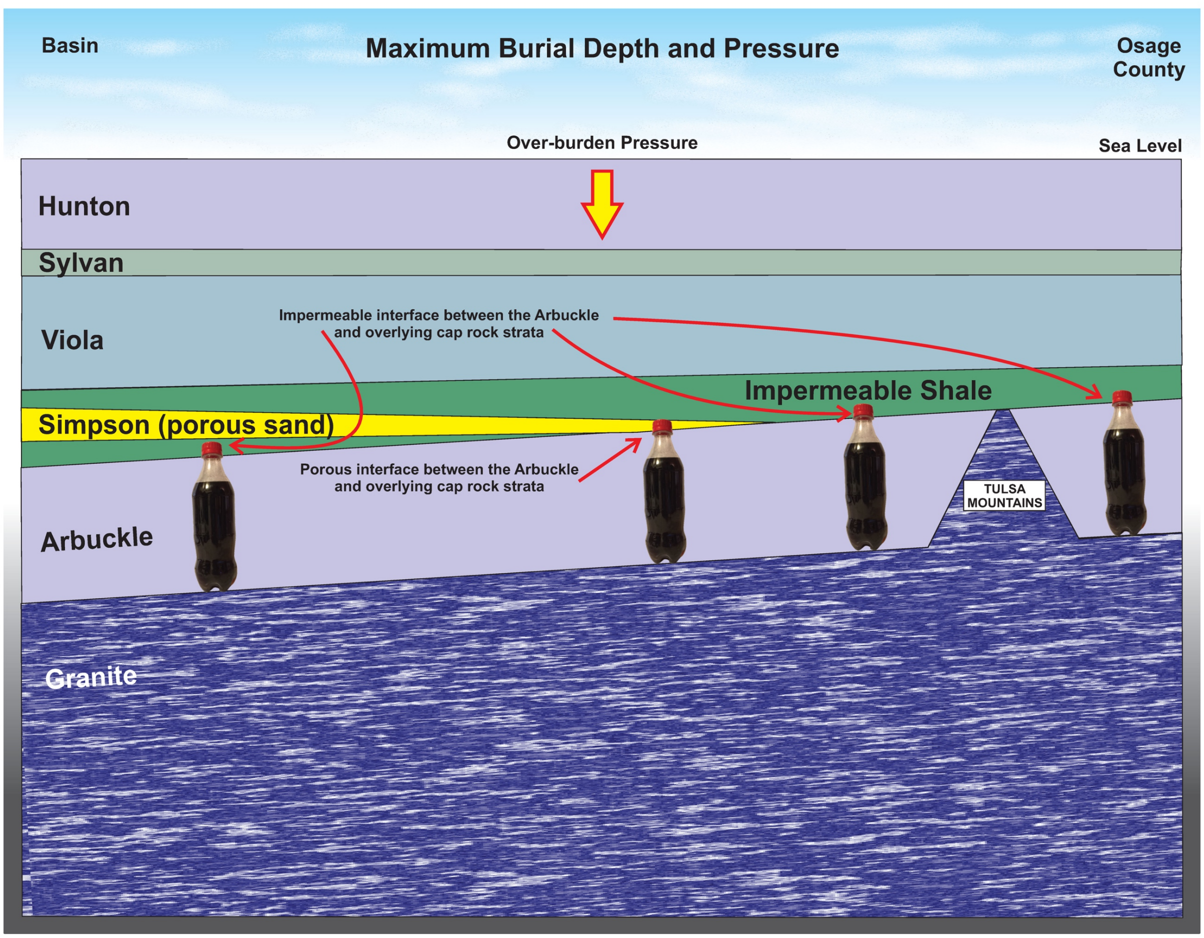

Figure 39: Schematic cross section illustrating deposition of Arbuckle through Hunton sedimentary rocks.

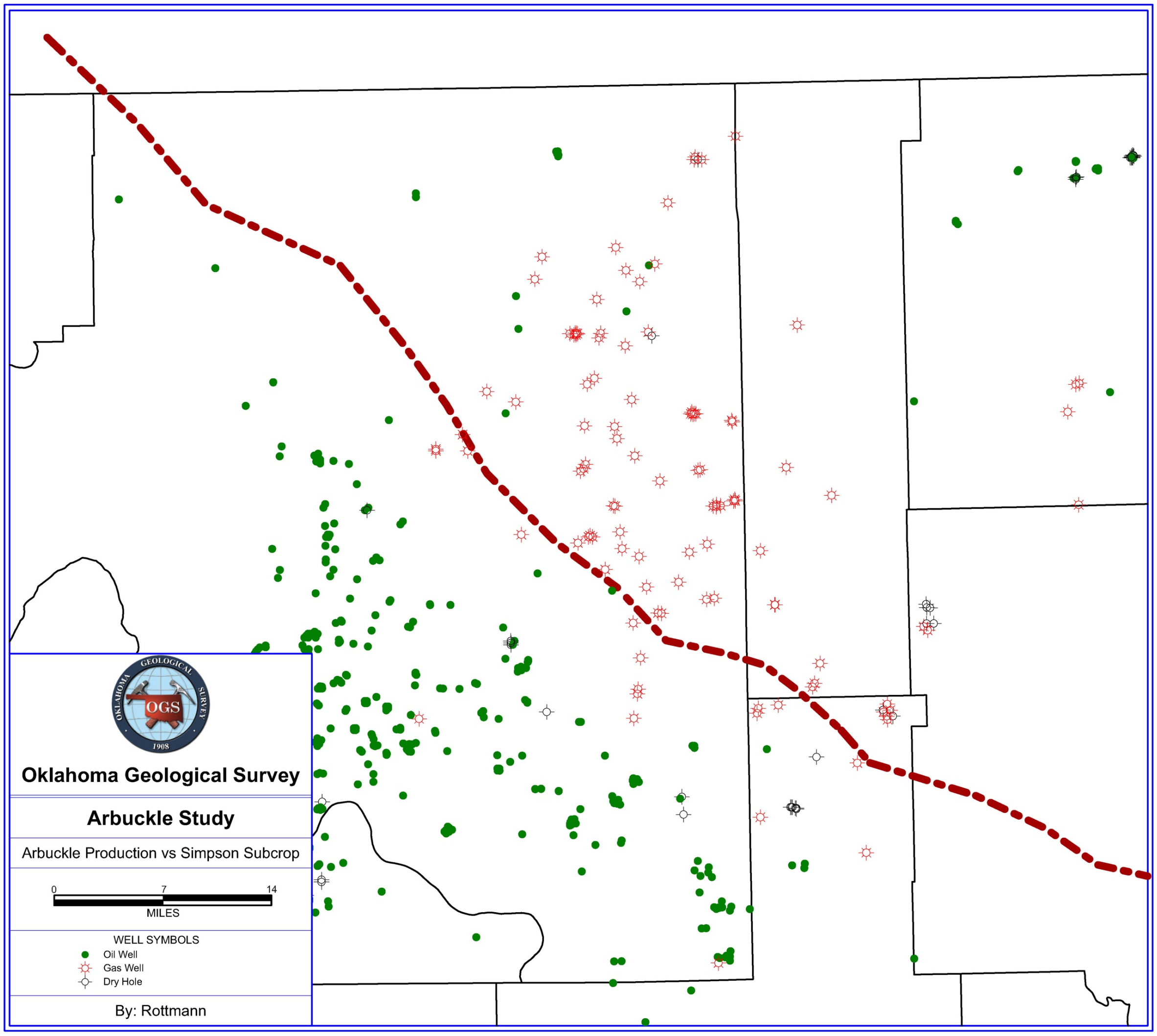

Figure 40: Relationship of Arbuckle production to Simpson subcrop area. Red line indicates the northern most limit of Simpson shale. To the south of the line, Arbuckle production is mostly oil, whereas north of the line the Arbuckle production is mostly gas.

with the erosional edge of the Simpson Group. He attributed the difference in production to different facies producing different products. This relationship would imply gas production below oil production, which is probably not the case in this situation.

Figure 41 is the same schematic as Figure 39, but now represents uplift and erosion of the Cambrian through Early Devonian sediments. Bottom hole pressures within the Arbuckle most likely became overpressured as a consequence of the uplift. The formation pressures quickly declined in those areas where the fluids could escape through a porous and permeable cap rock. The formation pressure also declined, and fluids easily escaped in those areas where the strata on top of the Arbuckle were removed by erosion. The formation pressures are assumed to have remained relatively higher in those areas where the cap rock was impermeable. What is not known is the extent of lateral movement of the fluids near the permeable cap rock or in the areas where the Arbuckle was exposed. Thus, the area of influence of pressure relief is unknown. The model presented in this study for variation in pressure relief depends upon a lateral limit to pressure release during times of uplift through lateral barriers to migration.

Figure 42 represents the next stage in the evolution of the region, involving the reburial of the Arbuckle through Hunton sections with deposition of the Devonian Woodford Shale, and the Mississippian and Pennsylvanian (including Chester, Springer, Morrow, and Atokan sedimentary rocks). With reburial came a second generation of pressurizing the Arbuckle; however due to the fluid loss from the preceding uplift and pressure release, the Arbuckle may have had dramatically different internal gas saturations. In the areas where the cap rock was impermeable, the corresponding gas saturation may be very low, as gas was never exsolved from the fluid phase. In those areas where the cap rock was porous, the gas saturations may be higher, unless reburial was sufficient to redissolve the gas in the fluid phase. The highest gas saturations in the Arbuckle may be expected to be found in those areas where the Arbuckle had been previously exposed.

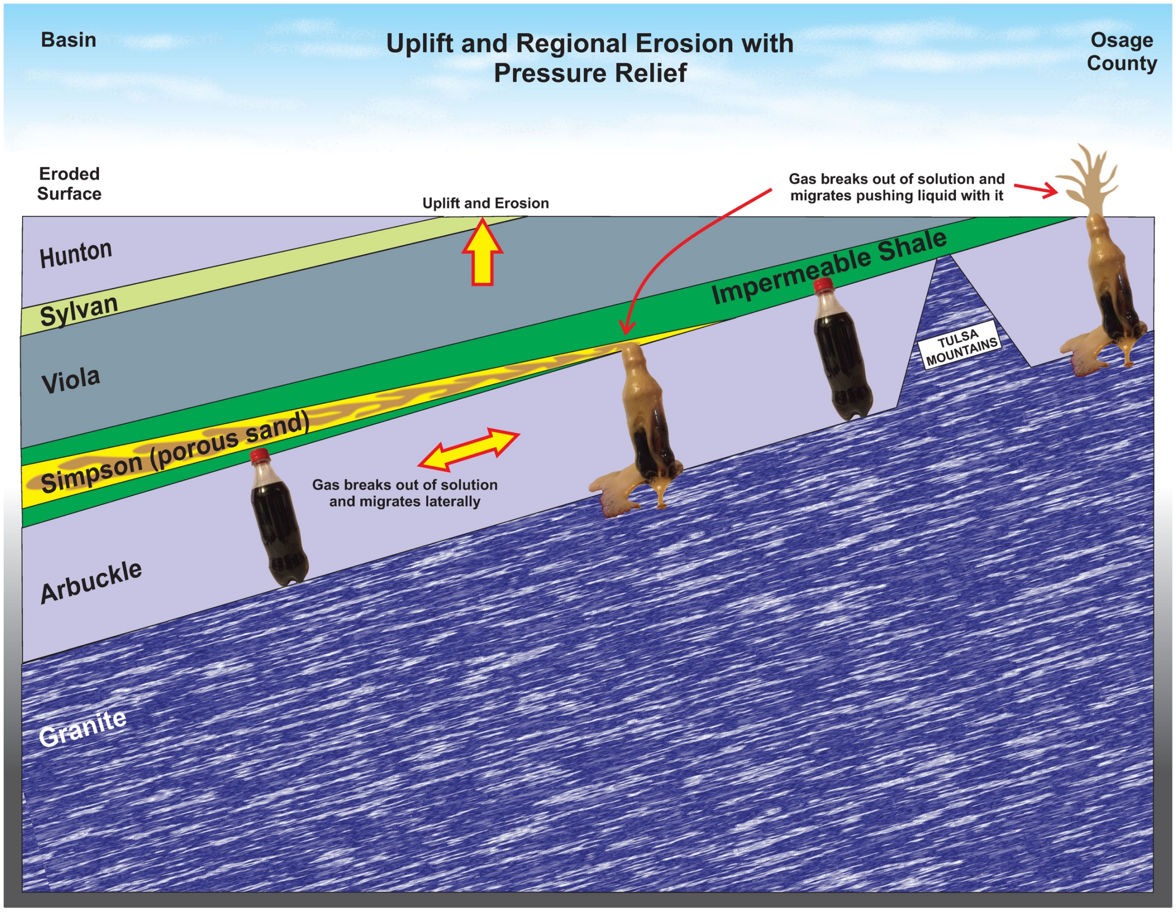

Figure 41: Schematic cross section illustrating the uplift and erosion of sediments overlying the Arbuckle. Pressure release occurs from parts of the Arbuckle at this time.

Figure 43 represents a second stage of uplift and erosion of overlying sediments. The sediments that are now being removed include primarily the Pennsylvanian (Springer, Morrow, Atokan, Chester) and Mississippian, and in some places, the Woodford Shale. This uplift probably represents a second phase of pressure loss within the Arbuckle. These series of figures suggest that the Arbuckle has a repeated history of being buried and uplifted with overlying sediments eroded. Due to fluid loss from the pressure relief of the Arbuckle and the lack of makeup fluids, the Arbuckle was probably underpressured at this time.

Figure 44 represents a period of renewed subsidence and deposition of the middle and late Pennsylvanian strata. This deposition probably resulted in the greatest depths of burial for the Arbuckle, but as has been previously suggested, the formation pressures for the Arbuckle may have

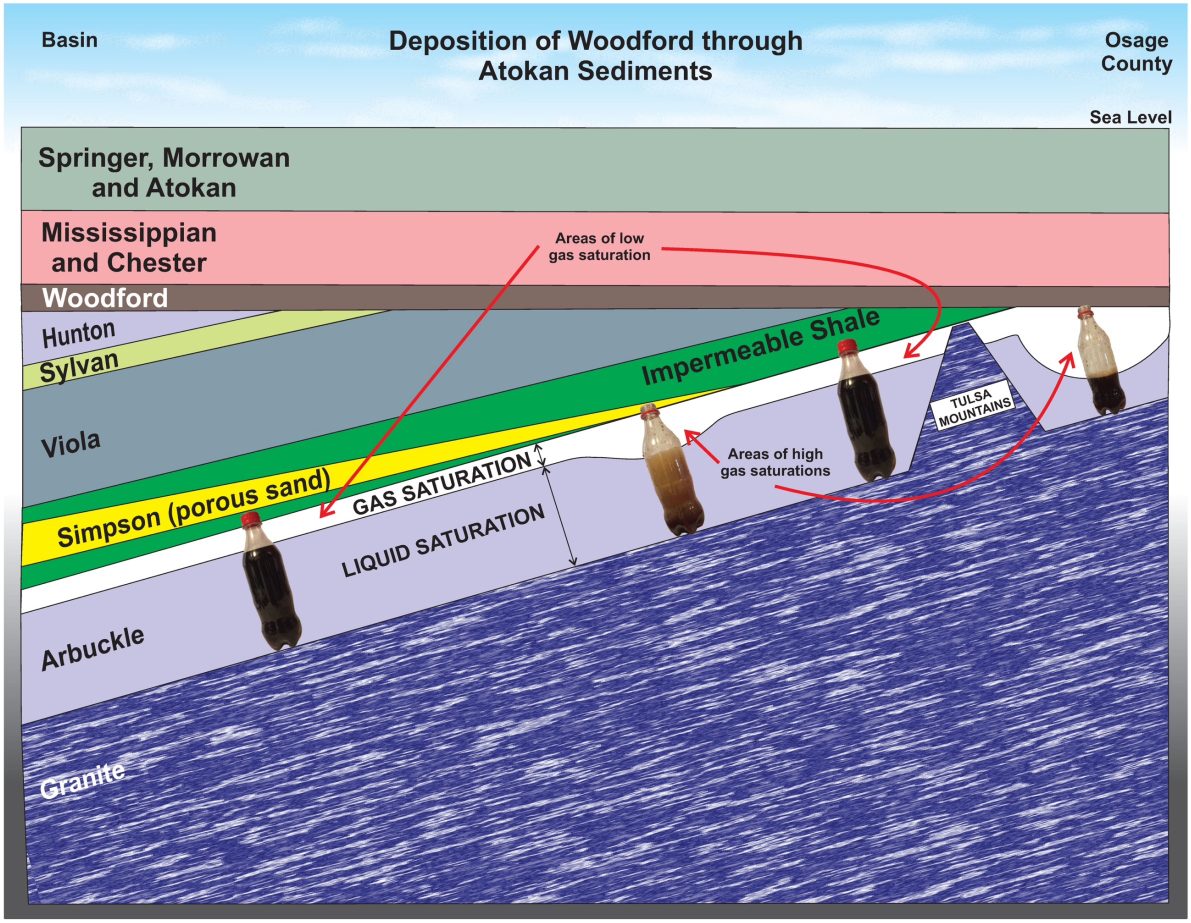

Figure 42: Reburial of the Arbuckle with subsequent deposition of Woodford through Atokan sediments.

been at their greatest degree of underpressure. Dolomitization, the subject of next section, probably occurred during this period.

4 - Post-Arbuckle Deposition and Erosion and Effects on Formation Pressure

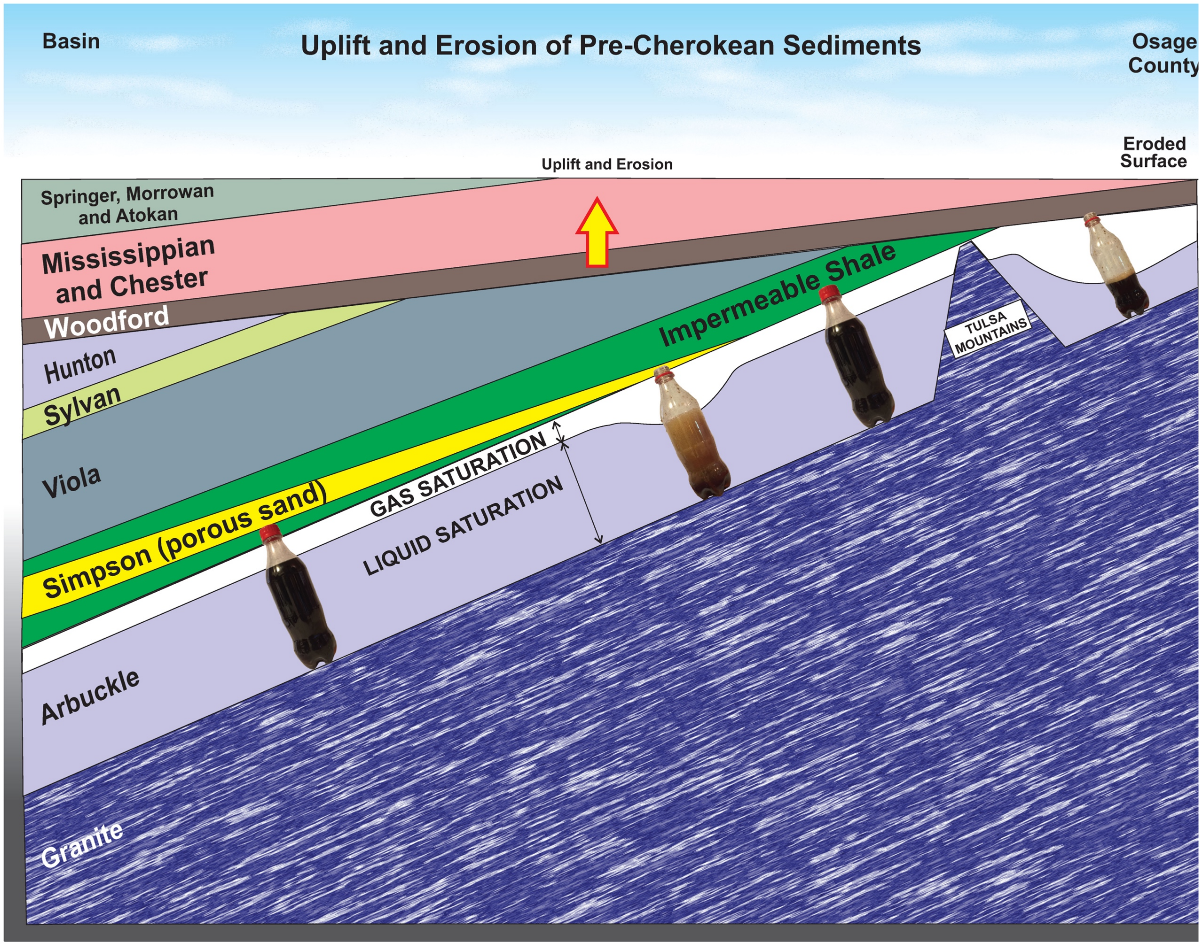

Figure 43: Uplift and erosion of Woodford through Atokan sediments. This period represents a second opportunity for pressure relief from the Arbuckle.

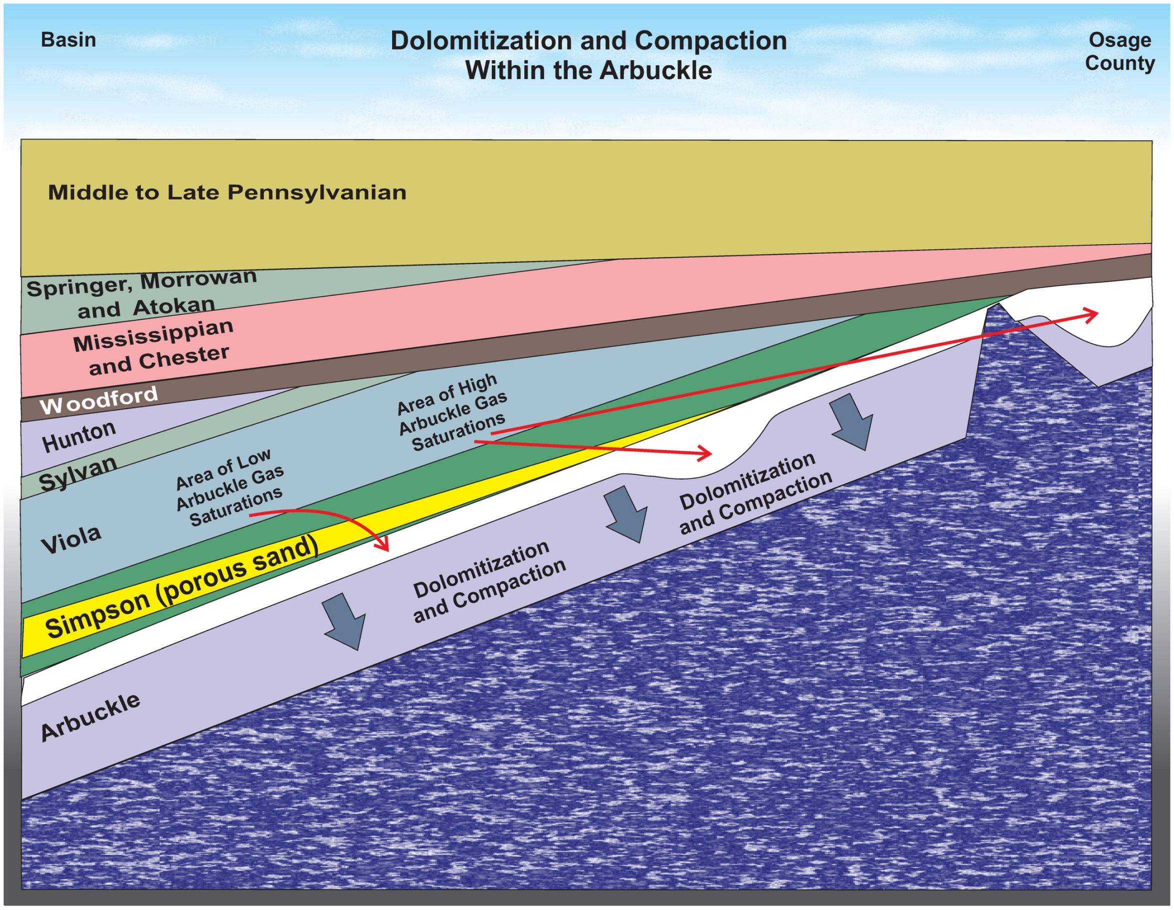

Figure 44: Deposition of Middle to Late Pennsylvanian sediments. During this burial phase, dolomitization and compaction probably occurred within the Arbuckle.

5 – Deep Burial Dolomitization of the Arbuckle Group

Jones and Xiao (2005) have suggested that the diagenetic alteration of limestone to dolomite within the Arbuckle, along with the resultant decrease in volume of the crystal lattice could account for the under pressured conditions of the Arbuckle by increasing the porosity of the rock. The following section will address this scenario, showing that the thickness variations of the Arbuckle in some areas strongly suggests that burial dolomitization was accompanied by or followed by additional compaction of the section, reducing the total volume change significantly.

Figure 45 is a structure map, from Rountree (1991), of the top of the Arbuckle in parts of Osage and Pawnee Counties, Oklahoma, including three fields previously studied by the author (highlighted in the figure). The structures are almost exclusively steeply dipping domal closures. A comparison of these structures with the Arbuckle Isopach of Figure 15 shows that these structures are superimposed on the areas of thin Arbuckle section in that figure. The thin sections of Figure 15 are themselves deposited on the Precambrian erosional features described in the section on Basement Geomorphology.

Figure 46 is a structure map, also from Rountree (1991), on the top of the Pink Lime for the same area as Figure 45. The vertical relief on the structures is almost exactly the same as that for the vertical relief on the Arbuckle and that the location of the Pink Lime structures is superimposed on the Arbuckle structures

In 1926, Merritt and McDonald (1926) recognized the superposition of the Pink Lime and Arbuckle structures on top of the Precambrian erosional features. Figures 47 a) and b) are modified from the illustrations they used to explain this structural relationship. In Figure 47 a), two deposits occurred on the top of the granite in areas of low and high granitic relief. They assumed no compaction of sediments throughout deposition. Figure 47 b) illustrates compaction that follows the deposition of sediment 2 with both sedimentary units being compacted by 50%. A 50% value for compaction of shale sediments is reasonable and has been documented in the Woodford of western Oklahoma (Rottmann, 2000)

With the thickness differential from the top of the granite to the erosional valley floor being 200 feet, a compaction factor of 50% would result in both sediments 1 and 2 having structural closures of 100 feet. The structural closures for this example reflect what was seen for the structural relationships observed in Osage and Pawnee Counties.

However, they knew that compaction did not occur after deposition as illustrated here, but occurred penecontemporaneously with deposition. Merritt and McDonald (1926) also published a set of figures similar to Figures 48 a) through d). These figures were an attempt to predict what the actual structural closures for various sequences of strata would be using a 50% compaction factor for each horizon at the time of deposition or shortly afterwards. In Figure 48 a), sediment 1 was deposited around the Precambrian geomorphic features. At this horizon there was a maximum of 200 feet of deposits for sediment 1 and 0 feet for sediment 1 over the apex of the pre-Cambrian feature.

In Figure 48 b), sediment 2 was deposited on top of sediment 1, which has been compacted by 50% from the weight of the overburden from sediment 2. This compaction resulted in a structural closure of 100 feet at the top of sediment 1. Notice how sediment 2 acted as a fill over the compacted parts of sediment 1. Figure 48 c) illustrates how the deposition of sediment 3 now compacts sediment 2 with a subsequent structural closure of 50 feet at the top of sediment 2. This series of deposition and compaction events results in a 50% reduction in the amount of closure for each succeeding section.

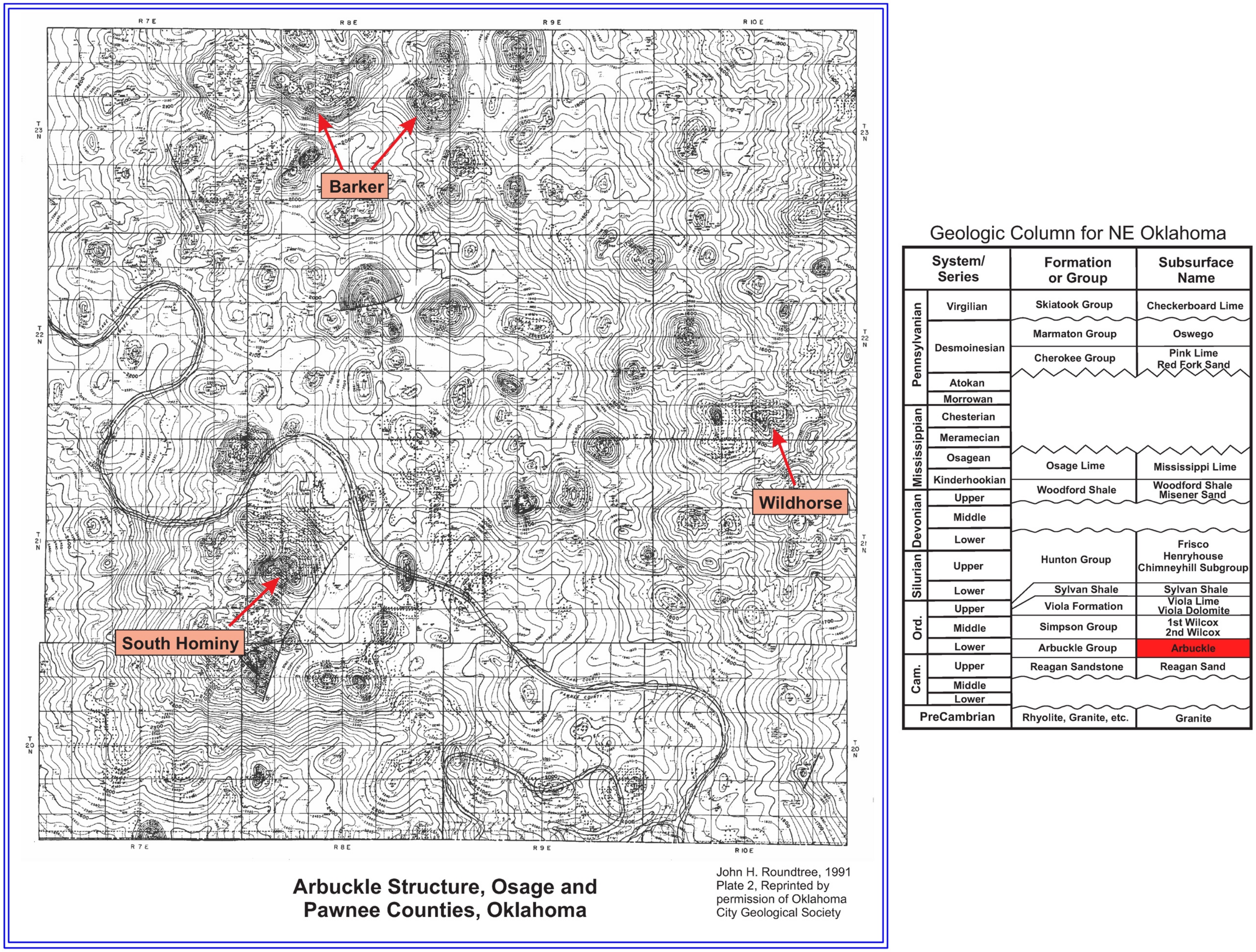

Figure 45: Arbuckle structure map in parts of Osage and Pawnee Counties, Oklahoma. Contour interval is 20 feet. Red box within stratigraphic column illustrates age of the Arbuckle.

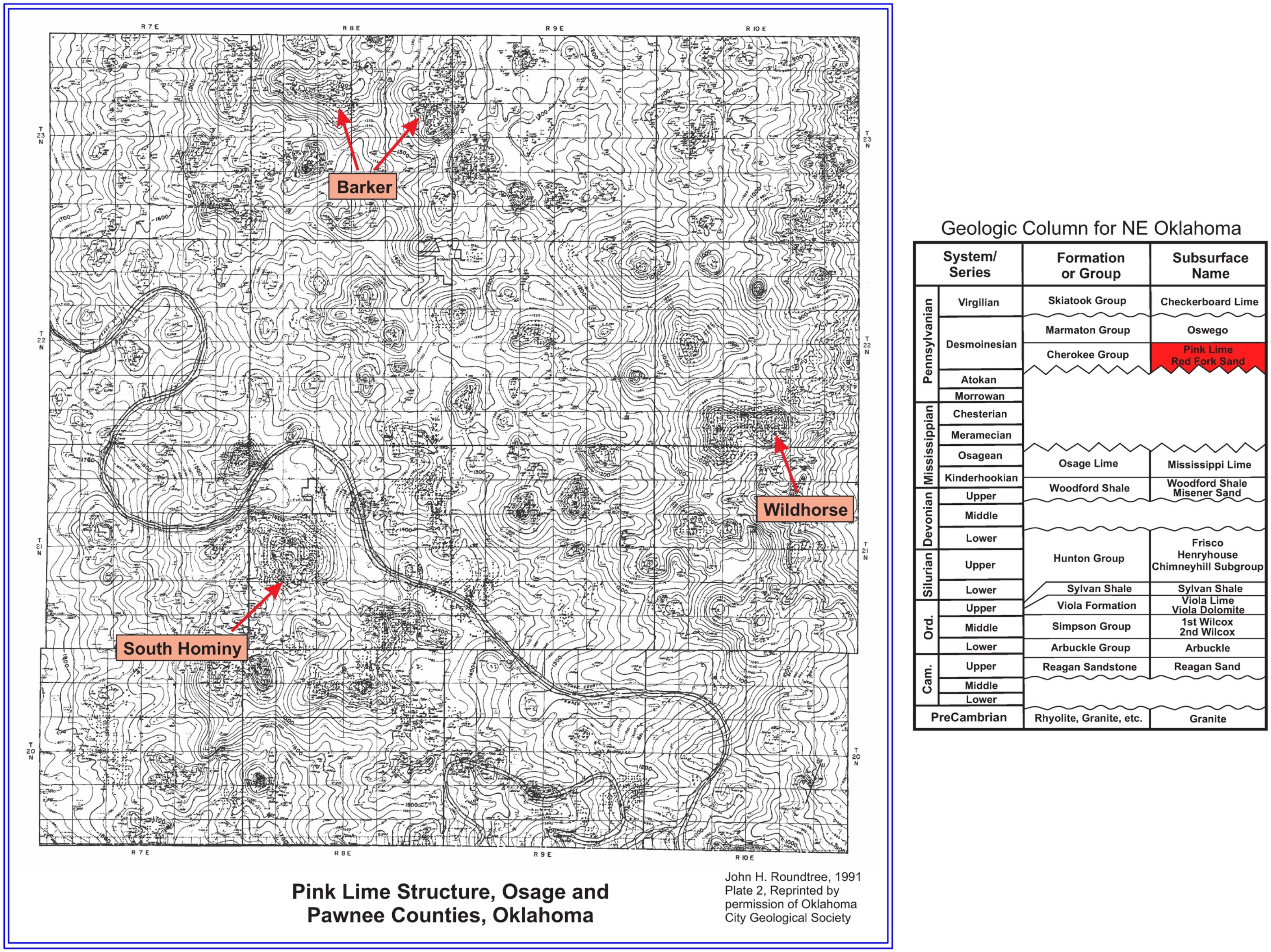

Figure 46: Pink Lime structure map in parts of Osage and Pawnee Counties, Oklahoma. Contour interval is 20 feet. Red box on stratigraphic column illustrates age of the Pink Lime.

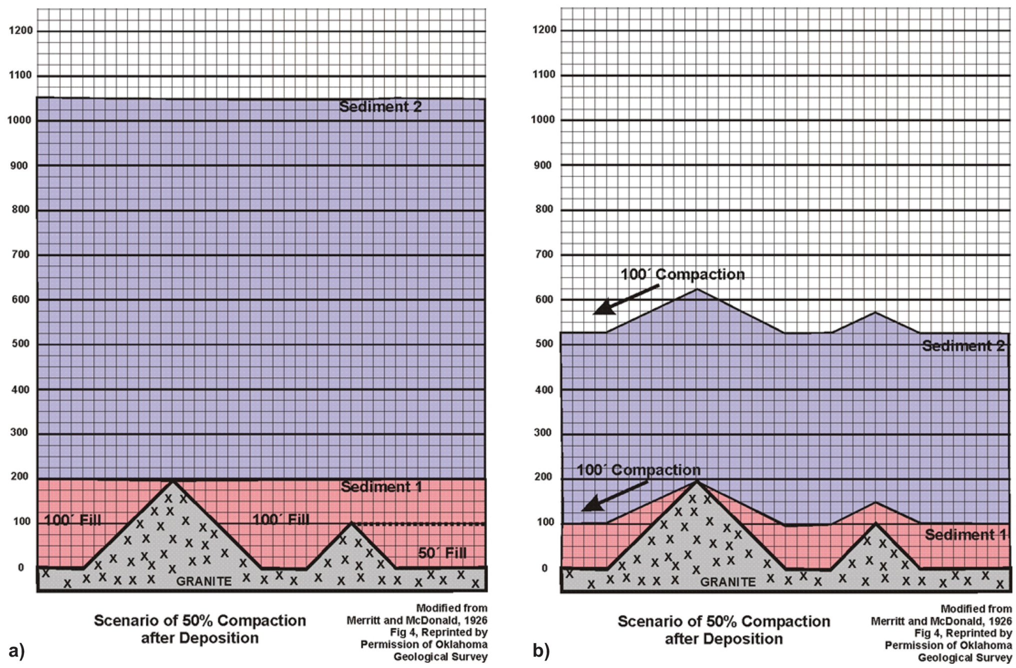

Figure 47: a) Sediment deposition prior to compaction; b) compaction of sediments after deposition.

Thus, in Figure 48 d), the structural closure at the top of sediment 8 is ½ the closure seen at the top of sediment 6. Likewise, the structural closure for sediment 7 is ½ that found at the top of sediment 6. This relationship occurs all the way to sediment 1. The anticipated closures for these eight sediments is shown on Figure 48 d).

These hypothetical closures were used by Merritt and McDonald to estimate what the structural closure should be at various horizons given the amount of closure observed at the top of the Arbuckle. They assumed sections 1 through 8 were composed of shale and would compact by a factor of 50%. However, if the sections were composed of sand or limestone, the compaction factor would be considerably less. In fact, the results for Figure 48 d) would be optimistic if the section contained sand or limestone.

Figure 49 compares the hypothetical closures predicted by Merritt and McDonald and the actual closures observed for the Wildhorse Field of Osage County. The actual map and closures for the Wildhorse Field will be discussed in the following sections. The sediment names of 1-8 have actually been replaced by formation names found in Osage County.

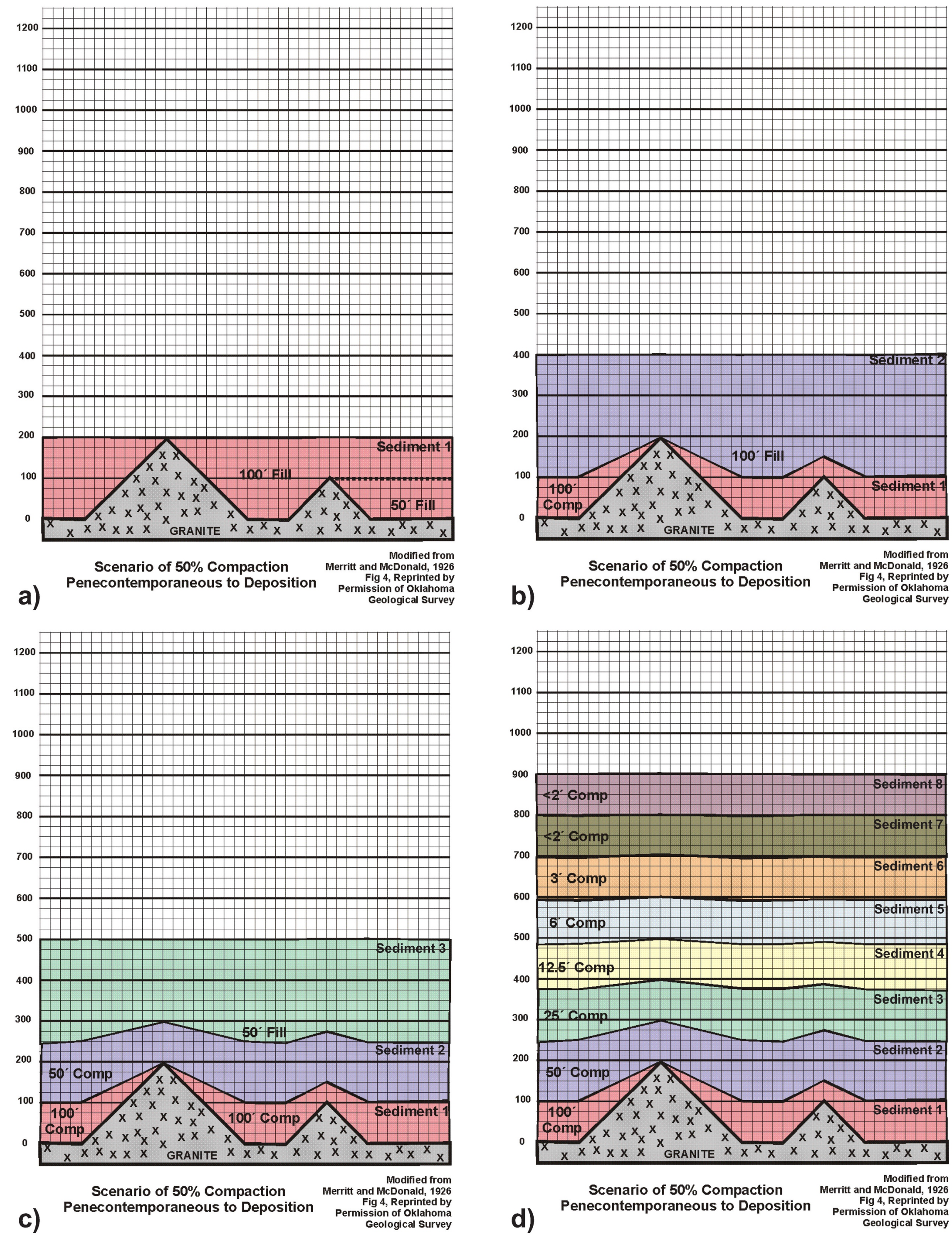

Figure 48: a) Deposition of sediments on Precambrian geomorphic features; b) Compaction of lower sediment with deposition of upper sediment; c) Continued deposition and compaction of sediments; d) Deposition and compaction of final elements of sedimentary section.

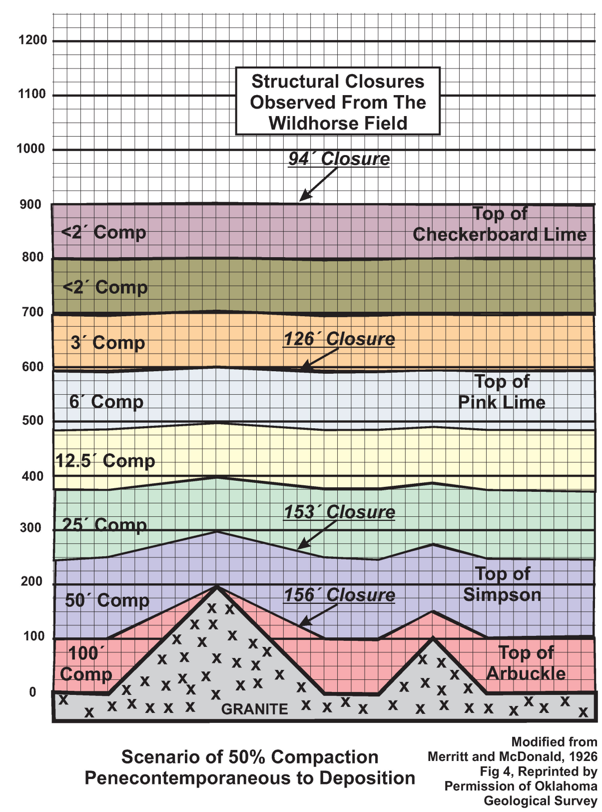

Figure 49: Comparison of predicted closure amounts with observed closure amounts.

What is important to understand is that the hypothetical model indicates very small structural closures at the top of the Pink Lime and the top of the Checkerboard Lime. However, actual shallow structural closures are over 30 times that predicted. This relationship holds true for the South Hominy and the Barker Fields also studied by the author. The shallow structural closures for those fields are also in the range of 25 to 30 times that predicted in the model of Merritt and McDonald. Therefore, compaction as the source for those closures observed in the field was ruled out and they had to explain the source of the structural relationships by other means.

The Wildhorse Field is an elongated closure with two separate structural apexes. The Arbuckle is absent on the left side of the closure. Figure 50 is a structure map contoured on the top of the Arbuckle. This figure illustrates the two wells on the right side of the structure that show the vertical relief for the closure at those points. The structural relief between those two points is 156 feet.

Figure 51 is a structure map contoured on the top of the Simpson Group for the Wildhorse Field. The same two wells of Figure 50 have a structural elevation difference of 153 feet at this horizon. Figure 52 is a structure map contoured on the top of the Desmoinesian Pink Limestone. The same two wells from Figures 51 and 52 have a structural difference at this level of 126 feet at this horizon.

Figure 53 is a structure map contoured on the top of the Virgilian Checkerboard Limestone. The contour elevation difference between the two wells is 94 feet. This illustrates that the structural closure at the Checkerboard is 2/3 of that at the top of the Arbuckle. The amount of closure at the top of the Checkerboard should have been less than 2 feet from compaction only as predicted from Figure 48d.

This is what Merritt and McDonald observed about the structures in Osage County. They dismissed compaction as the source and assumed the structures formed by another mechanism. However, coincidence of all of the structures with the underlying Precambrian geomorphic features needed to be accounted for. Compaction was known to Merritt and McDonald. What they didn't recognize was the possibility of a second compaction event through diagenetic alteration, porosity enhancement, and subsequent partial collapse of that pore space. Dolomitization of the Arbuckle Group provides a section thick enough to undergo a second phase of compaction that would allow for the magnitude of structures in this area.

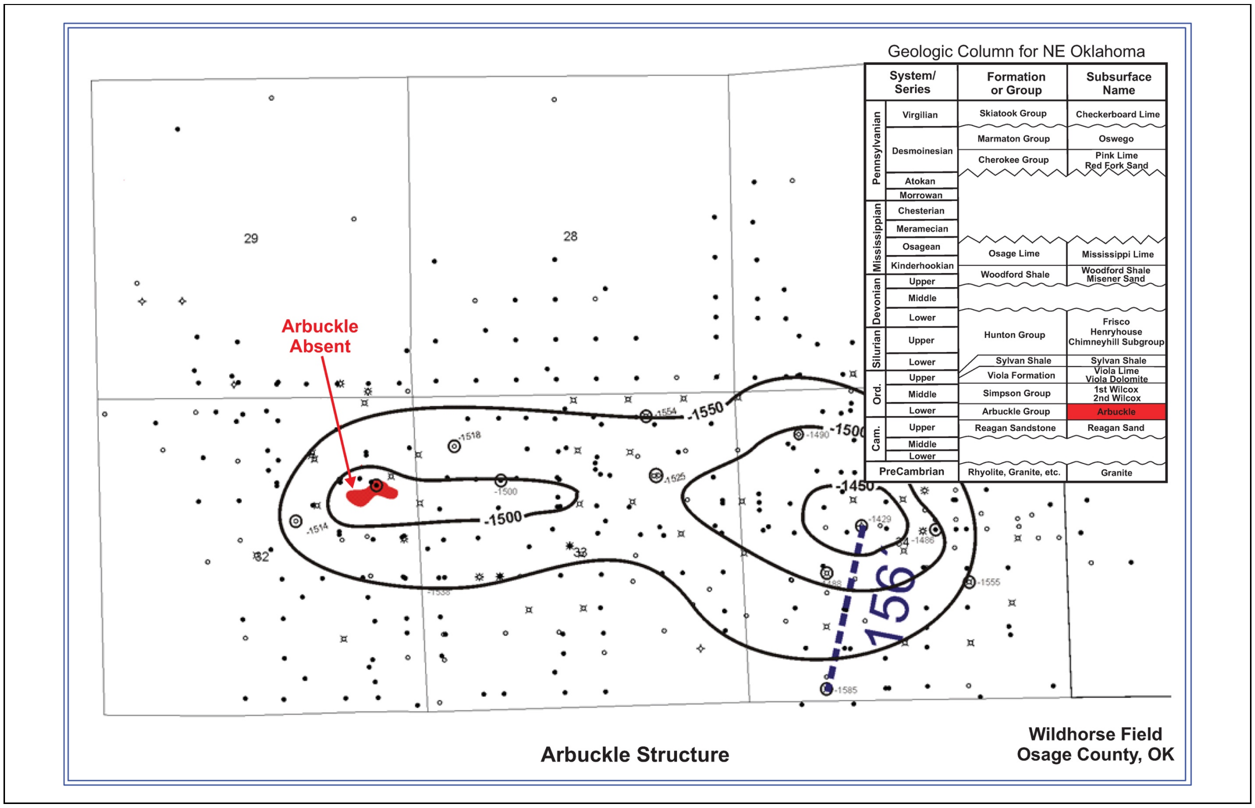

Figure 50: Structure map on top of the Arbuckle. Wildhorse Field is in T. 22 N., R. 10 E., Osage County, Oklahoma. Red box within stratigraphic column illustrates age of horizon mapped.

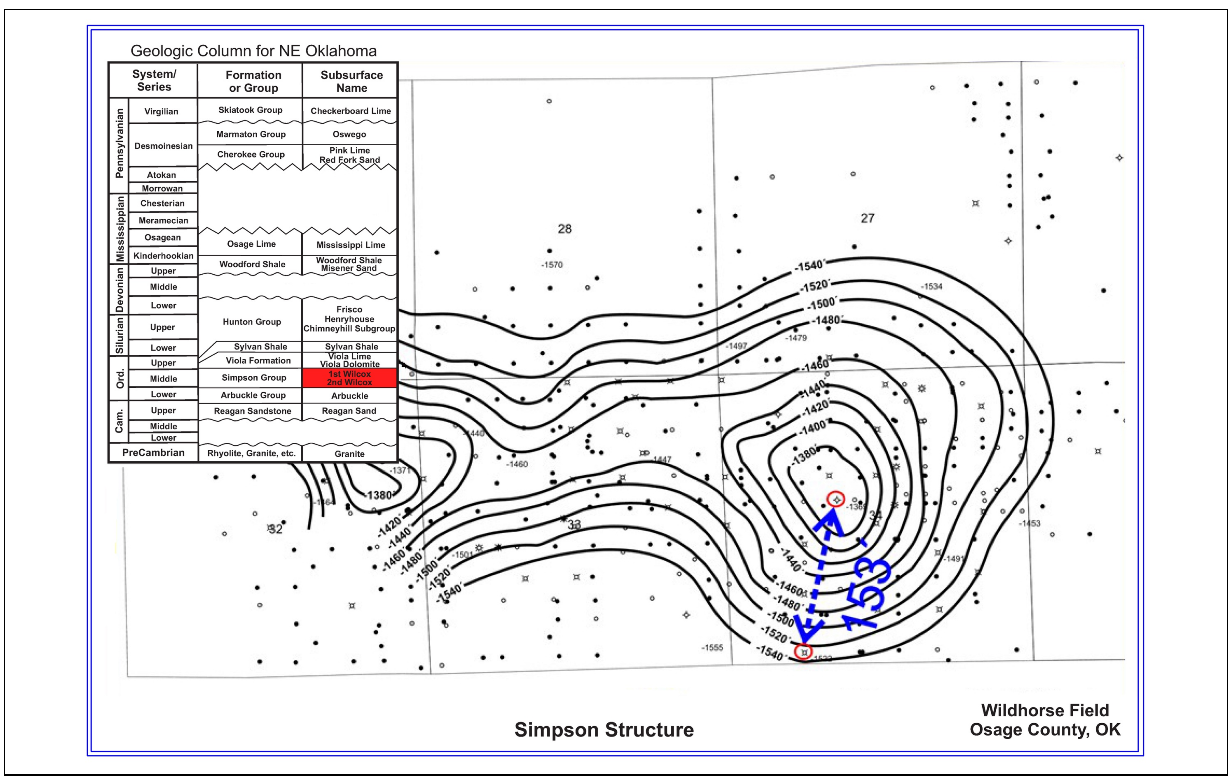

Figure 51: Structure map on top of the Simpson. Wildhorse Field is in T. 22 N., R. 10 E., Osage County, Oklahoma. Red box within stratigraphic column illustrates age of horizon mapped.

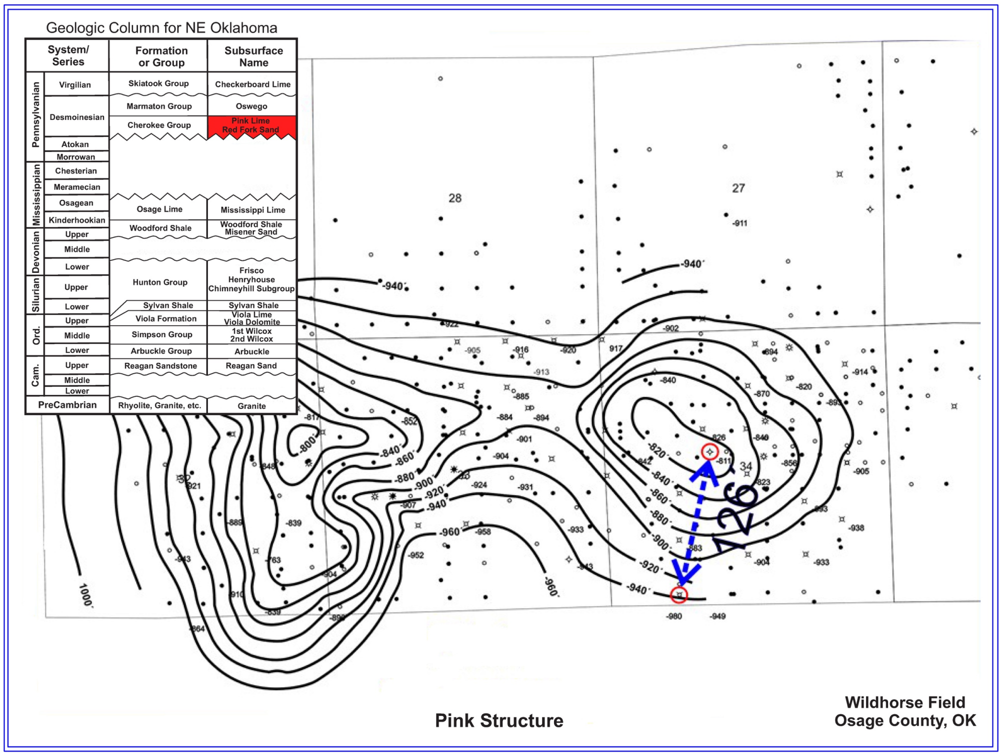

Figure 52: Structure map on top of the Pink Limestone. Wildhorse Field is in T. 22 N., R. 10 E., Osage County, Oklahoma. Red box within stratigraphic column illustrates age of horizon mapped.

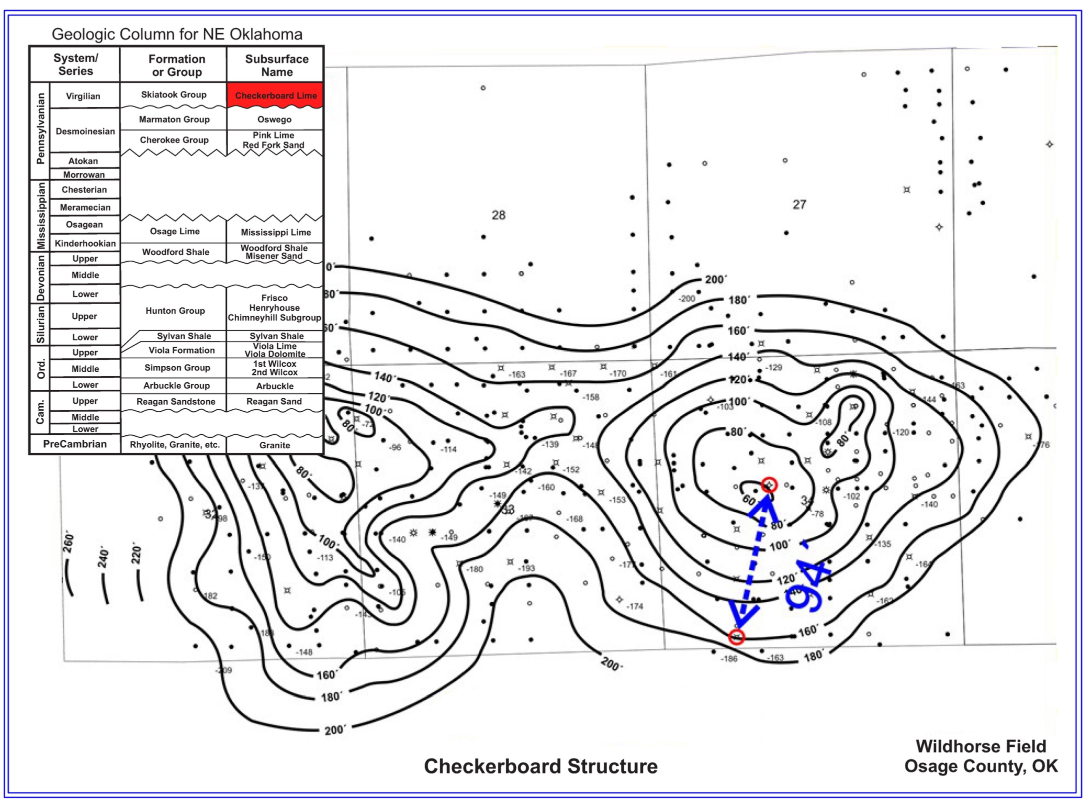

Figure 53: Structure map on top of the Checkerboard Limestone. Wildhorse Field is in T. 22 N., R. 10 E., Osage County, Oklahoma. Red box within stratigraphic column illustrates age of horizon mapped.

5 – Deep Burial Dolomitization of the Arbuckle Group

Figure 54 is a stratigraphic schematic that illustrates the geologic section at post-Checkerboard time in the Wildhorse Field area. The structures of Osage and Pawnee Counties would have had to occur after Checkerboard time.

The concept proposed here is that the Arbuckle, at post-Checkerboard time, was composed almost entirely of limestone. With burial, the Arbuckle could have entered a window of pressure/ temperature conditions where deep burial dolomitization could have occurred (Mattes, 1980). Alteration of calcite (density 2.71 g/cc) to dolomite (density 2.86 g/cc) would result in an approximately 12.8 percent molar volume decrease, and therefore an equivalent pore volume increase (Althoff, 1977). This pore volume increase from the diagenetic alteration of limestone to dolomite was the mechanism Jones and Xiao (2005) used to explain the regionally underpressured nature of the Arbuckle. This decrease in pressure may have occurred, but re-compaction of the Arbuckle also appears to have occurred subsequent to dolomitization, as indicated by the age and amount of closure observed at various horizons for the structures of the Tulsa Mountains in Osage and Pawnee Counties, Oklahoma. This compaction would dramatically alter the pore volume of the Arbuckle and might, if verified, challenge their conclusions.

Figure 55 is a schematic cross section that illustrates the effect that late term dolomitization and subsequent compaction had on the Arbuckle Group in the Tulsa Mountains area of Osage and Pawnee Counties, Oklahoma. In those areas where the isopach of the Arbuckle is thickest, the resultant compaction would be the greatest. Where the Arbuckle is thinnest (or absent) compaction would be the least. This type of compaction from dolomitization would explain why the structures at the shallow horizons would, in some places, almost equal the amount of structural closure observed close to the Arbuckle. It would also explain why the apex of almost all of the structures for Osage

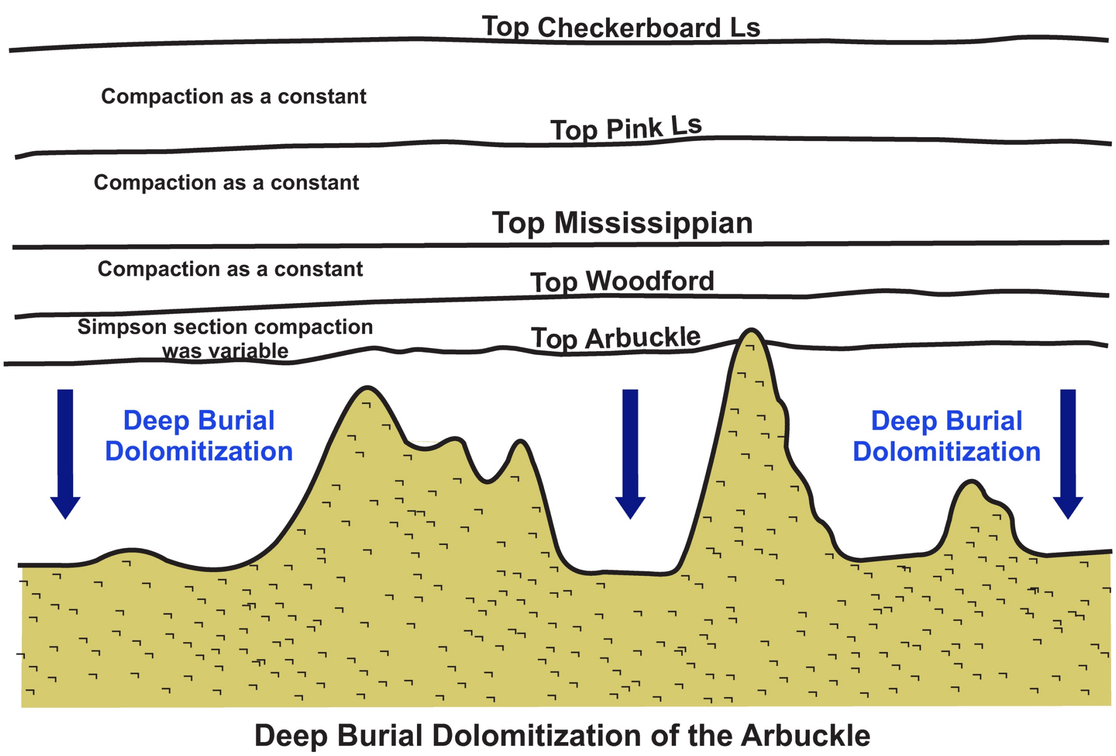

Figure 54: Schematic cross section indicating role of sediment compaction after deposition of the Checkerboard Limestone.

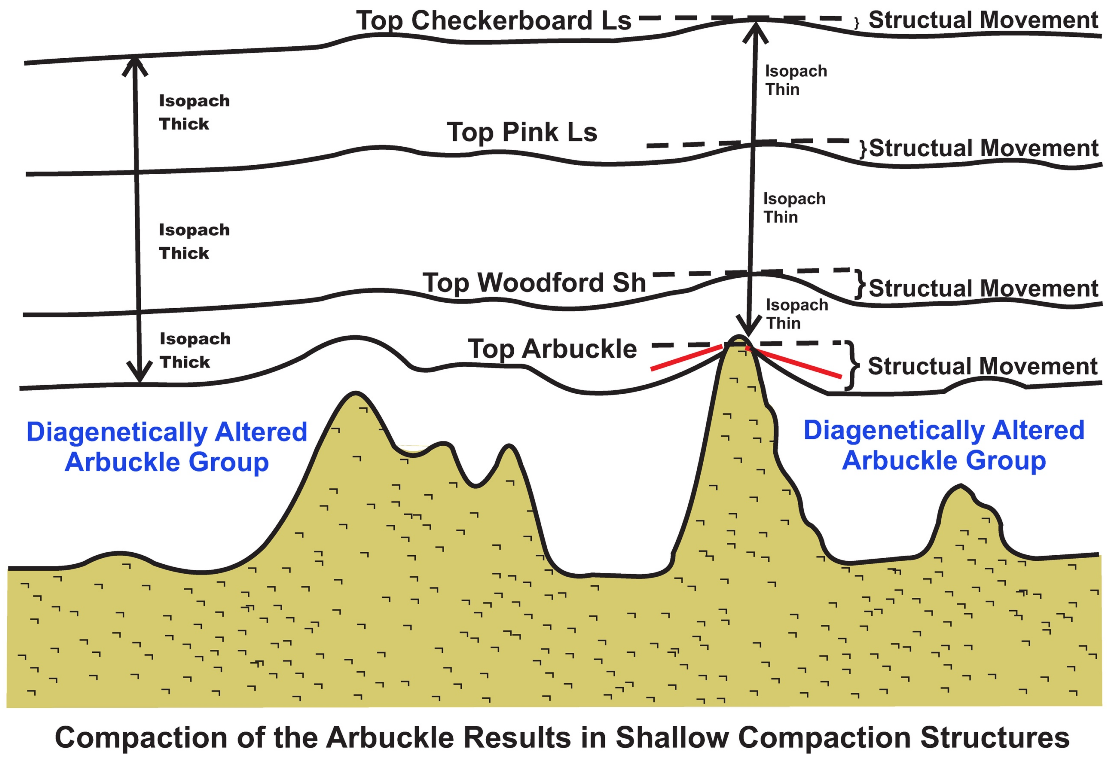

Figure 55: Compaction of the Arbuckle Group following burial dolomitization. Red line represents compaction following deposition of the Simpson.

and Pawnee Counties were directly superimposed on the highest point of the Precambrian granitic geomorphic features.

Also, with compaction, the formation pressures would have increased due to the loss of pore volume from the compaction. The conclusions by Jones and Xiao (2005) would need to be modified to account for subsequent compaction of the Arbuckle following dolomitization. Due to the density of wells and the depth of the Arbuckle and granite, Osage and Pawnee Counties may represent a unique window into the age and mechanism for dolomitization of the thick carbonates for this area and the mid-Continent as a whole. Without the topography of the Precambrian erosional surface, the impact of this process of dolomitization followed by compaction might not have been observed.

Of importance to this report however, is the probability that the lower hydrostatic pressures of the Arbuckle are not solely a function of dolomitization, because the compaction that occurred subsequently increased the formation pressures by reducing the pore volume of the Arbuckle. If the scenario of higher gas saturations in those areas where the cap rock facies of the Arbuckle consists of porous and permeable strata or where the Arbuckle had been exposed through uplift and erosion, the formation pressures of the Arbuckle should be affected as well. The issue of formation pressures and their implications for salt water injection is the subject of the next section.

6 – Arbuckle Underpressure and Saltwater Injection

This section discusses pressure gradients in the Arbuckle and other formations to indicate the degree of underpressure in the Arbuckle. Figure 56 illustrates the calculated pressure gradient of 257 final shut-in pressures from Arbuckle Drill Stem Tests (DSTs). These DSTs or the DSTs described on the next two pages, were not culled to exclude those DSTs within or near partially depleted Arbuckle production. These figures only display pressure gradients that exceed 0.34 psi/foot.

A pressure gradient was arbitrarily selected as a minimum value for the DST's used for this comparison. The value of 0.34 was chosen by the author as a minimum value for DST pressure gradients to still have sufficient permeability to make a valid comparison. The value of 0.397 psi/ft was chosen as a midway point between pressure gradients considered low and those considered high for the Arbuckle DST's. This same value was then used for the Second Wilcox and Misener/Hunton for comparative purposes.

Table 1: Arbuckle Well DST Pressure Gradients		
Wells Inside Impermeable Area	60 (24%)	
Gradient ≥0.397 psi/ft		26 (43%)
Gradient ≤0.397 psi/ft		34 (57%)
Wells Outside Impermeable Area	197 (76%)	
Gradient ≥0.397 psi/ft		36 (18%)
Gradient ≤0.397 psi/ft		161 (82%)
Total Wells		257

Table 1 summarizes the results for the pressure gradients both within and outside of the impermeable area described in section 5. This figure and the next two will compare the pressure gradients for the Arbuckle, Second Wilcox and the Misener/Hunton within the study area. Two important features of the pressure gradient in the Arbuckle are illustrated on Table 1. These features are:

1. Only 18% of the wells outside the impermeable area have a pressure gradient ≥0.397 and
2. Only 24% of all the pressure gradients exceed 0.397.

The percentages are reported for the pressure gradient for the Second Wilcox and Misener/Hunton in subsequent tables. The two values mentioned above will be compared with the other pressure gradients.

Figure 57 illustrates the location and pressure gradients for the Second Wilcox. This zone was chosen because it is generally quite porous and permeable and should contribute reliable data for the pressure gradient comparison with the Arbuckle. For the Second Wilcox (see Table 2), the percentage of wells outside the impermeable area with a value of ≥0.397 psi/foot is 44%, and the total wells with a pressure gradient ≥0.397 psi/foot is 38%. These values suggest a marked increase for the pressure gradient of the Second Wilcox over the Arbuckle, indicating substantially lower degree of underpressuring in this shallower horizon.

Table 2: 2nd Wilcox Well DST Pressure Gradients		
Wells Inside Impermeable Area	425 (35%)	
Gradient ≥0.397 psi/ft		150 (35%)
Gradient ≤0.397 psi/ft		275 (65%)
Wells Outside Impermeable Area	240 (62%)	
Gradient ≥0.397 psi/ft		106 (44%)
Gradient ≤0.397 psi/ft		134 (56%)
Total Wells		665

6 – Arbuckle Underpressure and Saltwater Injection

Figure 58 represents the wells that have a pressure gradient ≥0.34 for the Misener/Hunton. This zone was chosen also due to its high probability of having sufficient porosity and permeability to provide reliable pressure gradients. As in Table 1 and 2, the data in Table 3 show that pressure gradient for those wells outside the impermeable area exceeds 0.397 psi/ft in 51% of wells, and 51% of all wells exceed 0.397 psi/ft. Thus, the degree of underpressure in this next shallower zone is still less than for the Second Wilcox.

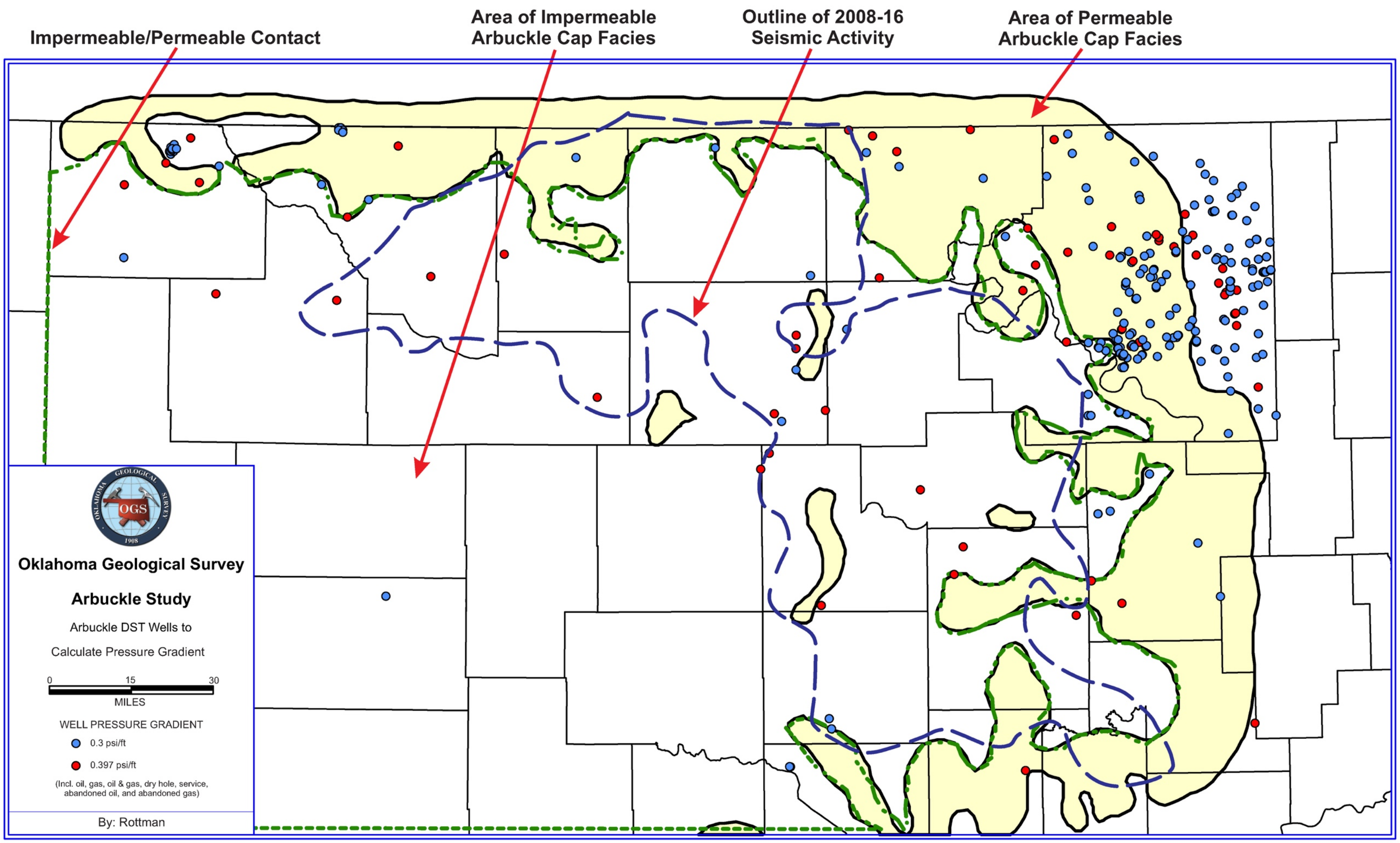

Figure 56: Location of Arbuckle DST wells to calculate bottom hole pressure gradient.

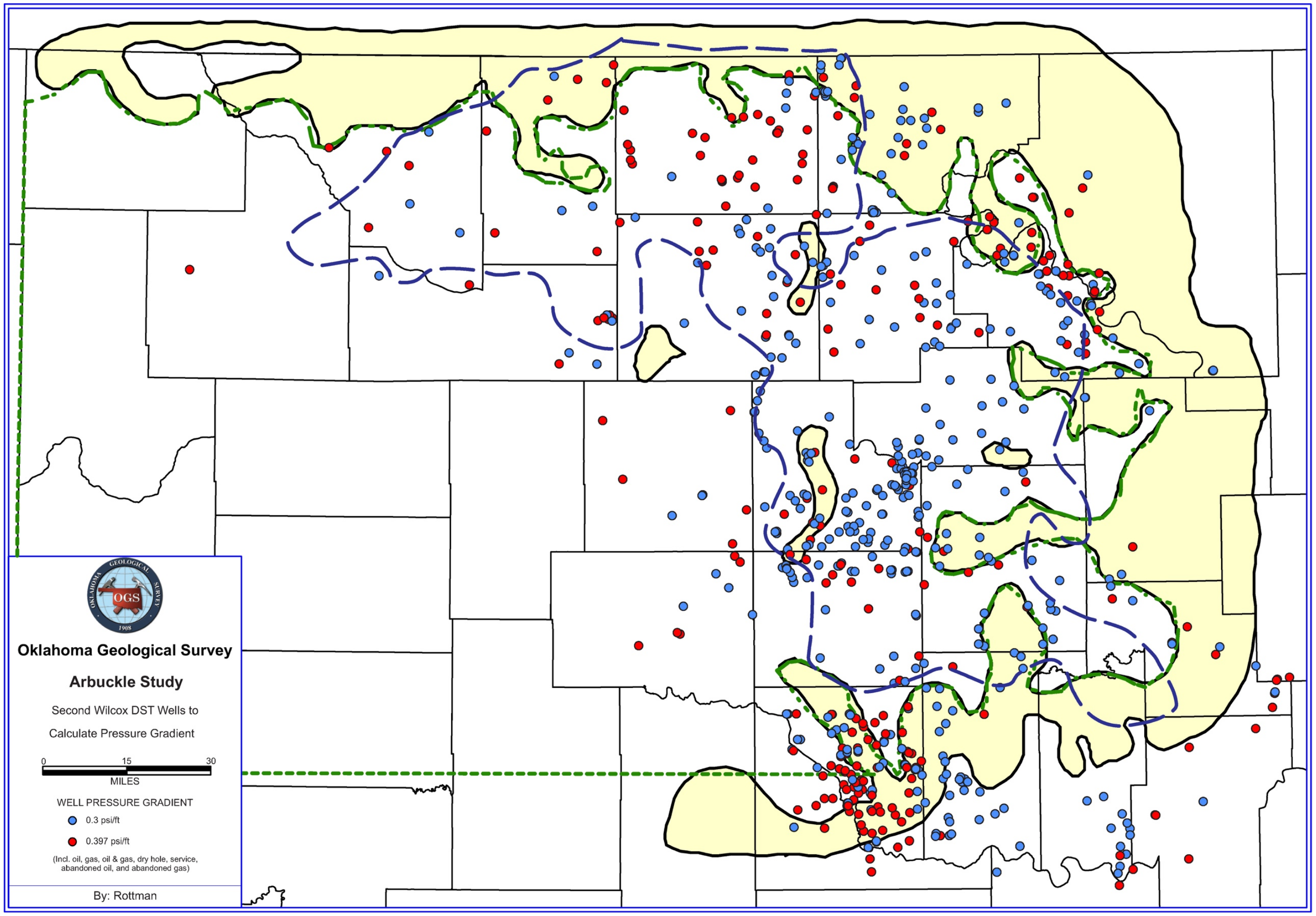

Figure 57: Location of Second Wilcox DST wells to calculate bottom hole pressure gradient.

Table 3: Hunton/Misener Well DST Pressure Gradients	
Wells Inside Impermeable Area	425 (35%)
Gradient ≥0.397 psi/ft	150 (35%)
Gradient ≤0.397 psi/ft	275 (65%)
Wells Outside Impermeable Area	240 (62%)
Gradient ≥0.397 psi/ft	106 (44%)
Gradient ≤0.397 psi/ft	134 (56%)
Total Wells	665

These values represent a large increase over the same Arbuckle pressure gradient values. The variations in the occurrence of gradients above 0.397 psi/foot suggest that the gradient in the Arbuckle was affected by the repeated uplift and erosion of the overlying sedimentary units, which should have reduced pressure through fluid loss and increased the gas saturation within the pore spaces.

Table 4 is a summary of the DST results for the Arbuckle, Second Wilcox, and Misener/Hunton as shown on Tables 1 through 3. The table illustrates the percentage of wells that are either less than or exceed a pressure gradient of 0.397 psi/ft. for the three zones within the impermeable Arbuckle cap rock area and outside the impermeable cap rock area (the area where the Arbuckle cap rock is porous and permeable).

For the Arbuckle, the total number of DST wells with a pressure gradient that is equal to or less than 0.397 psi/ft is 76%. For the Second Wilcox it is 62% and for the Misener/ Hunton it is 40%. This is a significant drop in the number of wells with low pressure gradients and possibly reflects the number of times the Arbuckle has been subjected to uplift and subsequent pressure relief as opposed to the Second Wilcox and Misener/ Hunton.

For the total DST wells, the second column shows the results for the all Arbuckle, Second Wilcox, and Misener/Hunton DST's that have a pressure gradient that equals or exceeds 0.397 psi/ft. As can be seen the Arbuckle has a low number of wells (24%) that have a pressure gradient that equals or exceeds 0.397 psi/ft. as opposed to the Second Wilcox and the Misener/ Hunton. The proportion of Misener/ Hunton wells that equal or exceed pressure gradients of 0.397 psi/ft. is almost 3 times as high as for the Arbuckle. After burial and pressure buildup in the Misener/Hunton, these zones were not exposed to the degree of uplift and pressure relief as was the Arbuckle which is potentially the reason the number of wells whose gradient exceeds 0.397 psi/ft. is so high. The decreasing degree of underpressuring upward in the stratigraphic section at least indicates significant isolation of these units from one another. This result may be critical in determining whether injection may need to be limited in units above the Arbuckle to reduce

Table 4: DST Pressure Gradient Comparison for Arbuckle, 2nd Wilcox, and Hunton/Misener Wells

	≤0.397 psi/ft	≥0.397 psi/ft
Inside the Impermeable Area		
Arbuckle	57%	43%
2nd Wilcox	65%	35%
Hunton/Misener	38%	62%
Outside the Impermeable Area		
Arbuckle	82%	18%
2nd Wilcox	56%	44%
Hunton/Misener	38%	51%
Total		
Arbuckle	76%	24%
2nd Wilcox	62%	38%
Hunton/Misener	40%	60%

seismicity. The ability to dispose of produced formation water in shallower horizons may be critical to the oil and gas industry.

Figure 59 illustrates what is proposed to occur when saltwater disposal wells are drilled into various areas whose Arbuckle section is subjected to varying degrees of gas saturation. As described previously, these variable gas saturations are the result of uplift and depressurization of the Arbuckle. Where the Arbuckle was overlain by a porous and permeable stratum, the gas saturations within the Arbuckle are highest due to the fluid and gas loss from the depressurization. Where the Arbuckle is overlain by an impermeable stratum, the gas saturations in the Arbuckle are lower due to the prevention or hindrance of fluid and gas loss from the Arbuckle. These observations are suggested by the pressure gradient study of the Arbuckle.

Because the gas is significantly more compressible than the fluid, injection into zones with higher gas saturation would be able to accept larger volumes of injected water with lower pore pressure increases than areas without gas saturation. The gas saturations of the Arbuckle would then have a direct correlation to the amount of water injected into the Arbuckle to generate a given pore pressure rise. Thus, these wells could accept greater disposal volumes before increased pore pressure transmitted through the basement fracture network and induced seismic events on deep-seated basement faults.

Figure 60 displays seismic activity from the beginning of 2009 through May 2017 and the areas of porous and permeable Arbuckle cap facies. It is readily apparent that the most seismic activity is located in those areas where the cap rock is composed of impermeable material. In these areas, the gas saturation within the Arbuckle should be lower, as previously described, thus less water can be injected into the Arbuckle before seismic activity occurs. In those areas where the gas saturation is higher, due to the processes of depressurization, more water can be injected before seismic activity occurs.

Figure 61 illustrates the location for the Arbuckle injection wells monitored by the OCC or, in Osage County by the EPA. Notice that the injection wells are located in both the porous and permeable cap rock area (yellow) and the impermeable cap rock (white area). Comparison of this figure and that of Figure 60 illustrates that injectors located where the cap rock is porous and permeable shows far less recent seismic activity.

Figure 62 illustrates cumulative water injection volumes from 2009-2014. Notice that in the northern part of the state, around the area of interest, that the water injection volumes are very high. Again, comparison of the Arbuckle injection volumes and the seismic locations of Figure 62 shows the injection of large amounts of water into the permeable cap rock facies areas has not resulted in significant seismic activity. In the southern part of the map (exception area), a large amount of water has been injected into this permeable cap rock facies area and a considerable amount of seismic activity has occurred. This can possibly be explained by the total cumulative injection of water having exceeded the available pore volume of the Arbuckle, which has then influenced the critically stressed fault and fracture planes at depth.

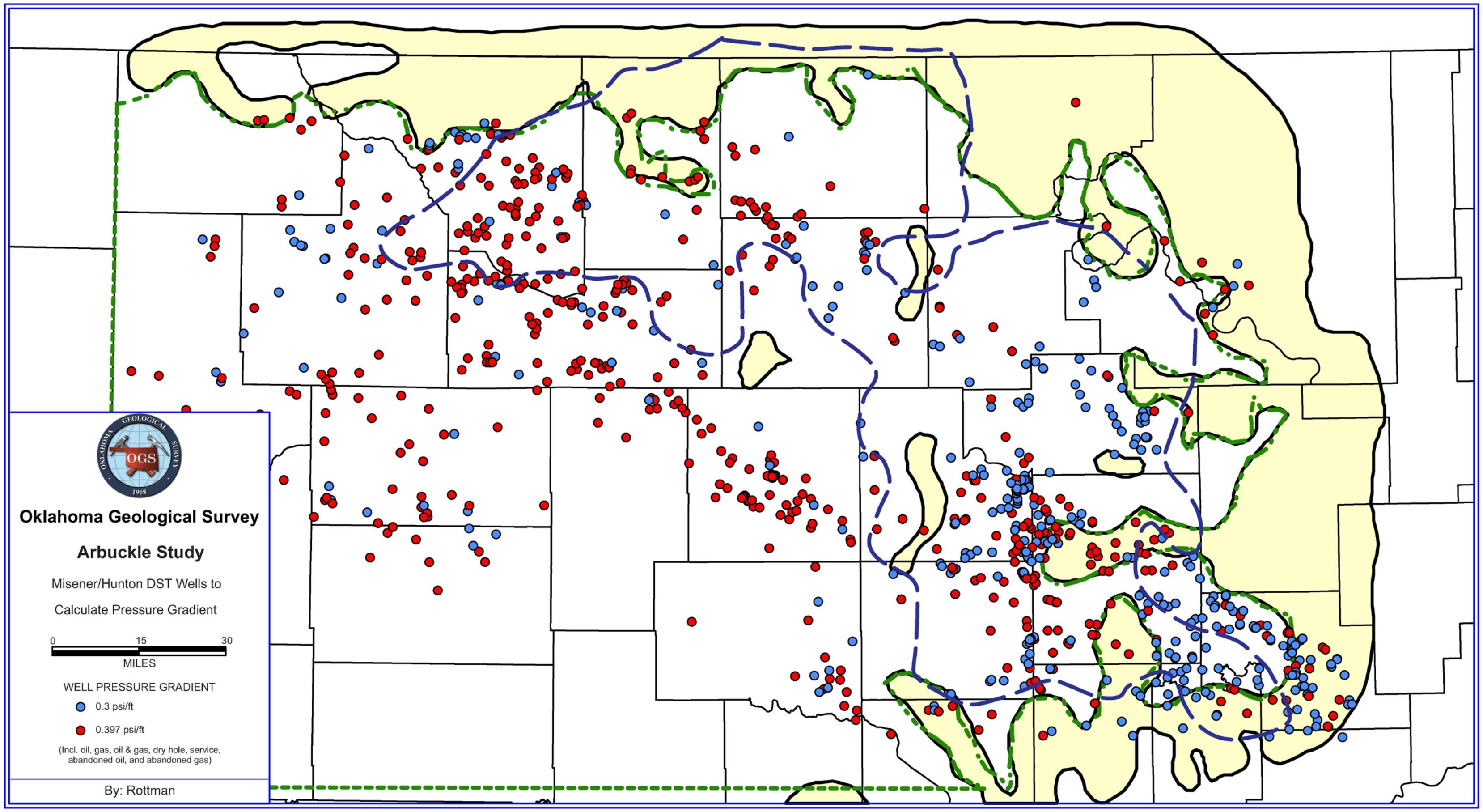

Figure 58: Location of Misener/Hunton DST wells to calculate bottom hole pressure gradient.

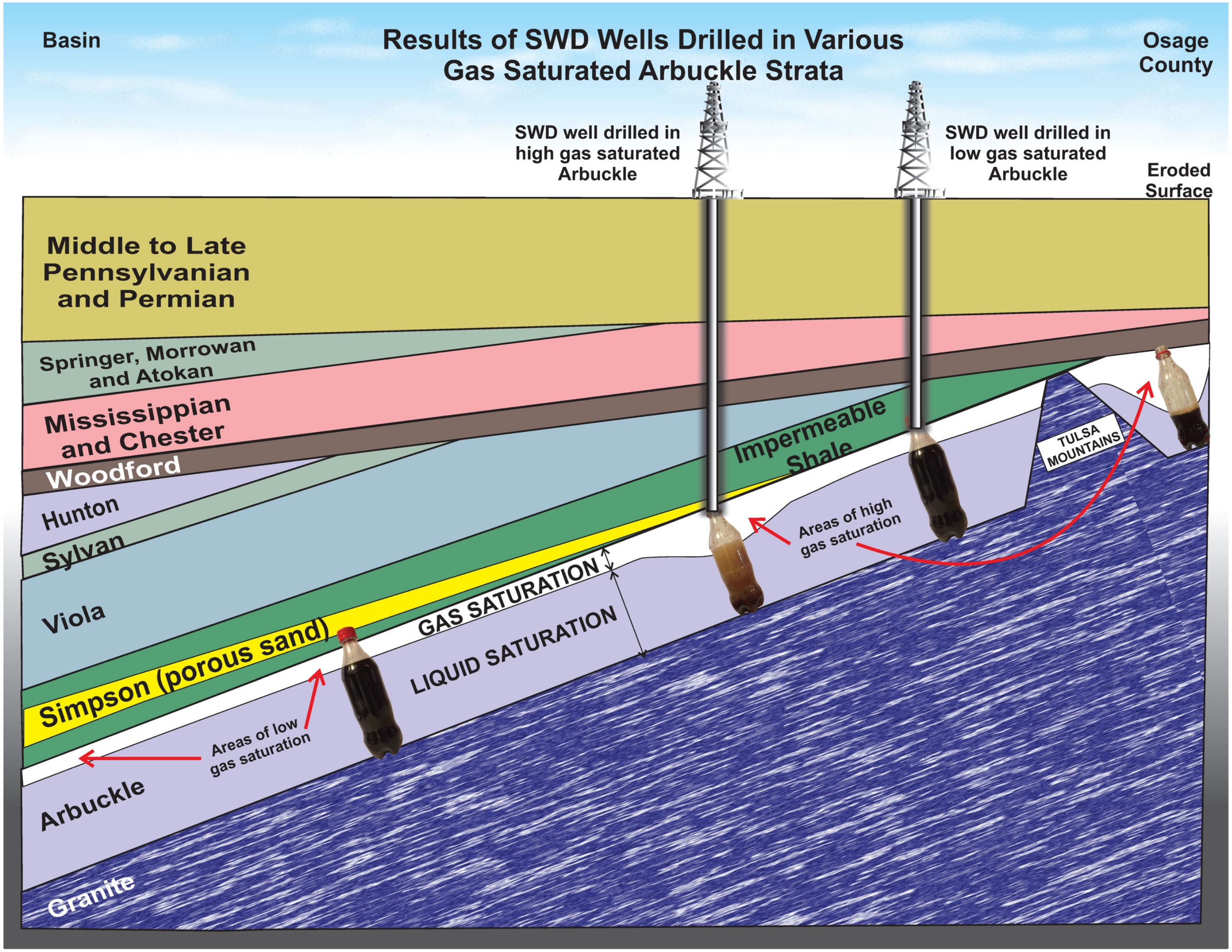

Figure 59: Injection of saltwater into the high and low gas saturated sections of the Arbuckle.

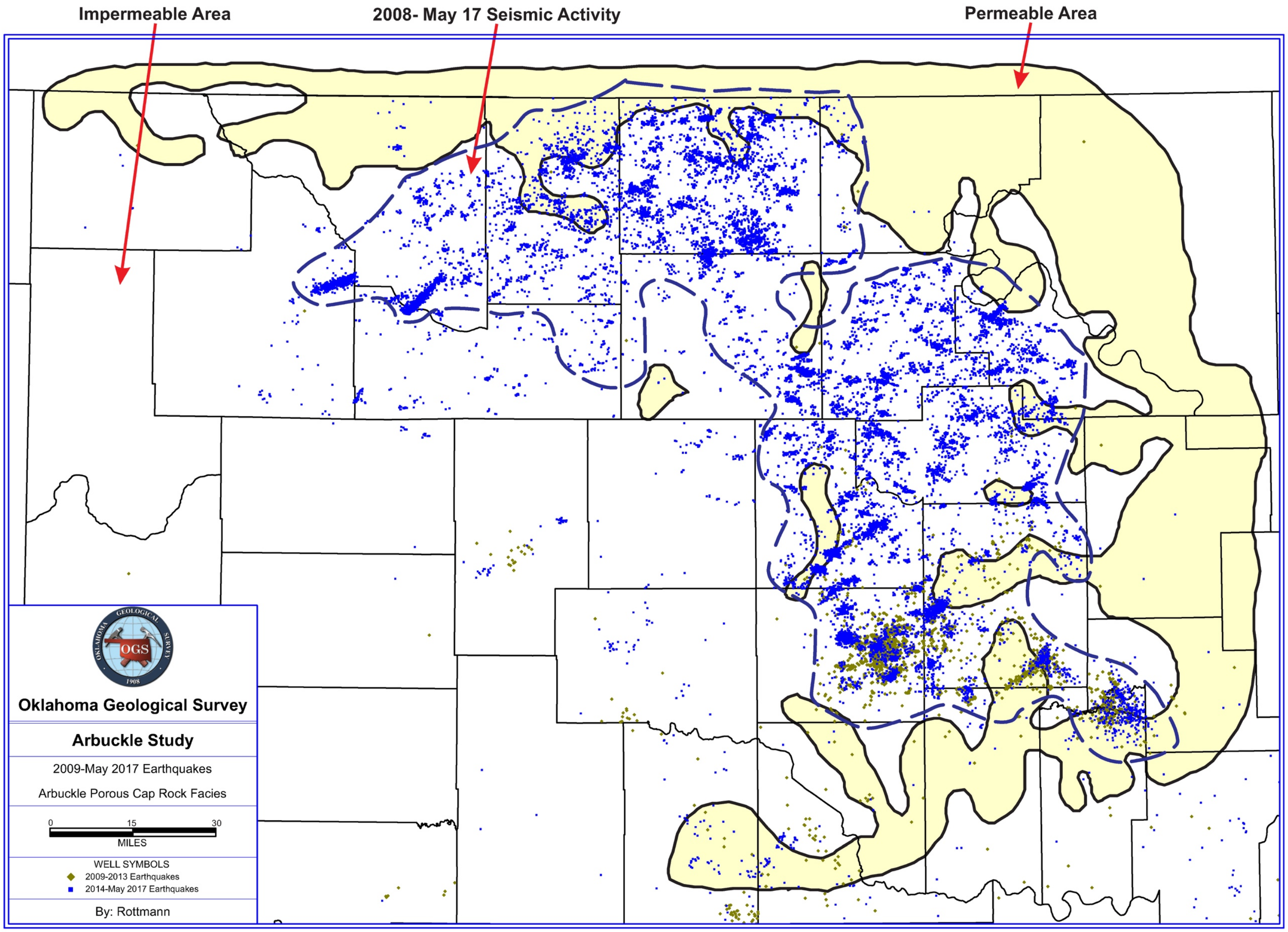

Figure 60: Comparison of the 2009 through May 2017 seismic events compared to the porous Arbuckle cap facies.

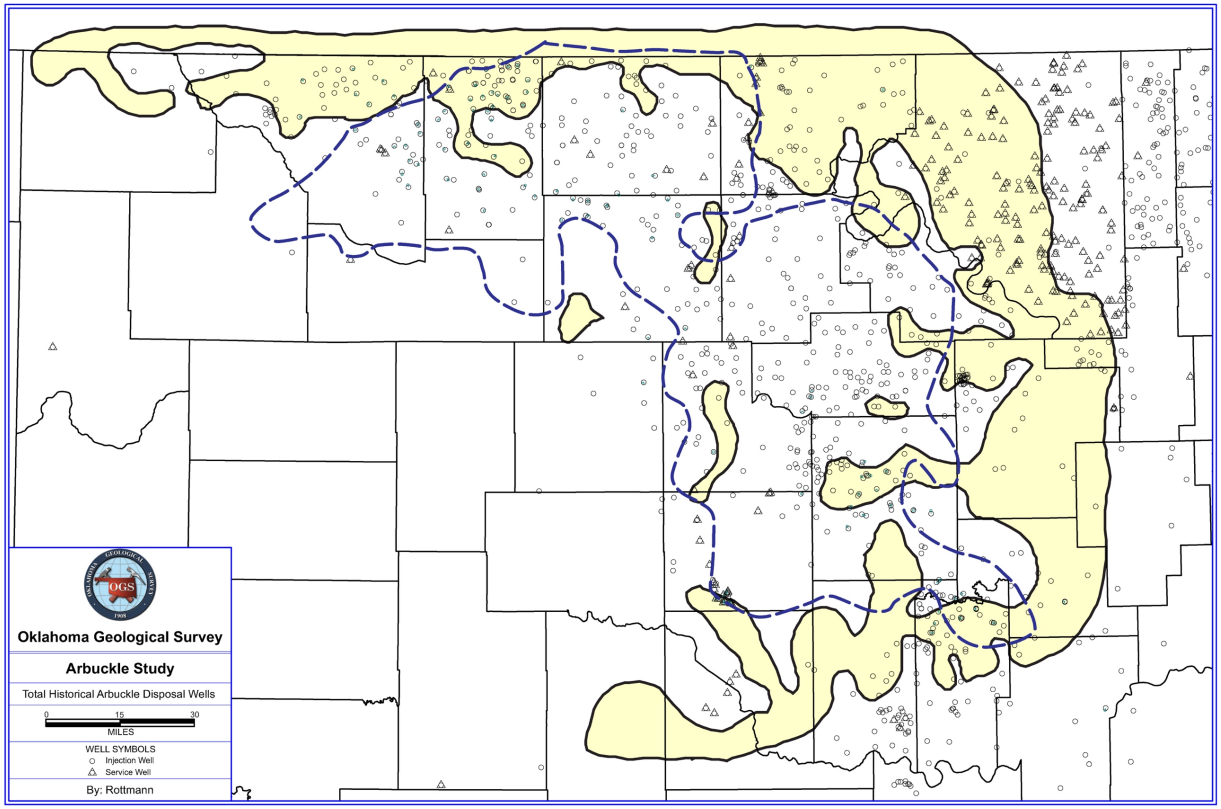

Figure 61: Location of the Arbuckle saltwater disposal wells compared to the porous Arbuckle cap rock facies. Dashed blue line represents author's outline of significant seismic events.

6 – Arbuckle Underpressure and Saltwater Injection

Figure 63 illustrates the 2009-14 cumulative water injected volumes for the Arbuckle from the Oklahoma Corporation Commission monitored injection wells and the seismic activity locations from 2008-2016. Seismic activity is low in those areas where large volumes of water have been injected into the Arbuckle that is overlain by the permeable cap rock facies. Dr. Kyle Murray, of the Oklahoma Geological Survey is currently compiling an historical cumulative Arbuckle water injection database. When this database is completed, this figure should be updated.

A number of other authors have proposed an alternative mechanism for underpressure in the Paleozoic sedimentary section of the mid-Continent. Nelson and others (2015), Umari and others (2018), and Sorenson (2005) have documented widespread regional underpressure across Colorado, Kansas, Texas and Oklahoma, with coherent gradients across the region. They attribute these gradients to post-Laramide uplift in the Rocky Mountain Front, exposure of Paleozoic formations in eastern Kansas, and drainage of fluids across the region in response to these events.

These papers do not discuss the potential effect of earlier episodes of pressure relief and reburial on the pressure conditions in the Arbuckle Group. For example, Nelson and others (2015) develop a single potentiometric surface for the Cambrian, Ordovician, and Silurian Section. This would suggest that hydraulic connectivity exists between the Arbuckle Group (Cambro-Ordovician), Simpson and Viola Groups (Ordovician), Sylvan Shale (Ordovician) and Hunton Group (Silurian to Lower Devonian).

We have argued above that significant differences occur in the degree of underpressure between these groups. In addition, evidence from pressure monitoring of Arbuckle injection wells idled in response to seismic activity in Oklahoma give informal indications of a lack of connection between Arbuckle and 2nd Wilcox (Simpson) zones and suggest that, while local lateral continuity is common in the Arbuckle, the Group does not constitute a laterally continuous hydrogeologic unit on the regional level (Murray, personal communication). It may be that, on the largest regional scale, these lower Paleozoic units show an overall hydrologic gradient controlled by the uplift and drainage mechanism described by Nelson and others (2015, 2016) and Sorenson. This model might indicate a stepwise decline in underpressure across a series of somewhat isolated hydrogeologic units. Each of these might then be influenced by older features of their geologic history. This issue certainly warrants further examination before the hypothesis detailed here can be fully accepted.

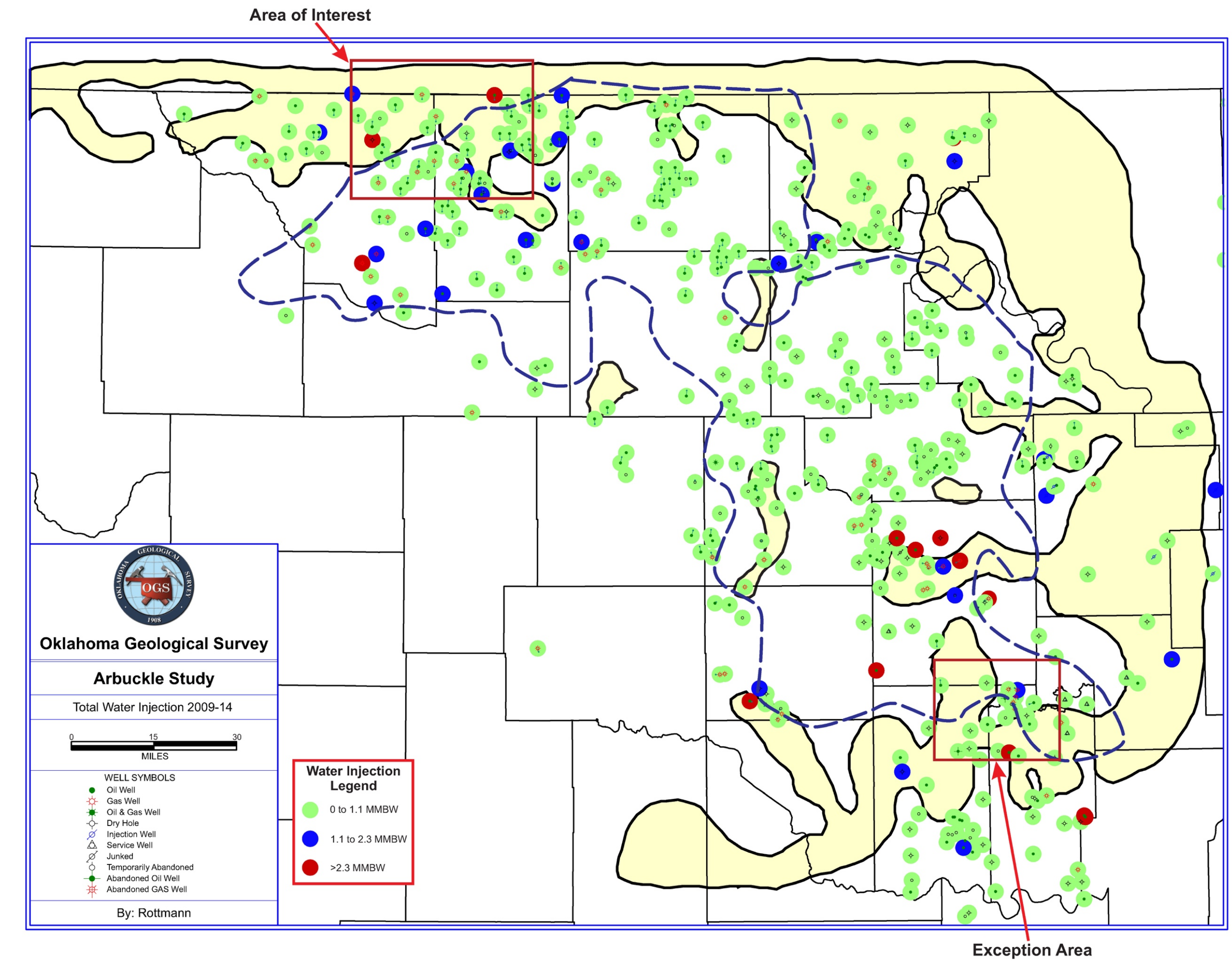

Figure 62: 2009 through 2014 cumulative saltwater injection volumes compared to the porous Arbuckle cap rock facies (area outlined in yellow). Dashed blue line represents author's outline of significant seismic events. White area of map represents area that Arbuckle cap rock facies is impermeable.

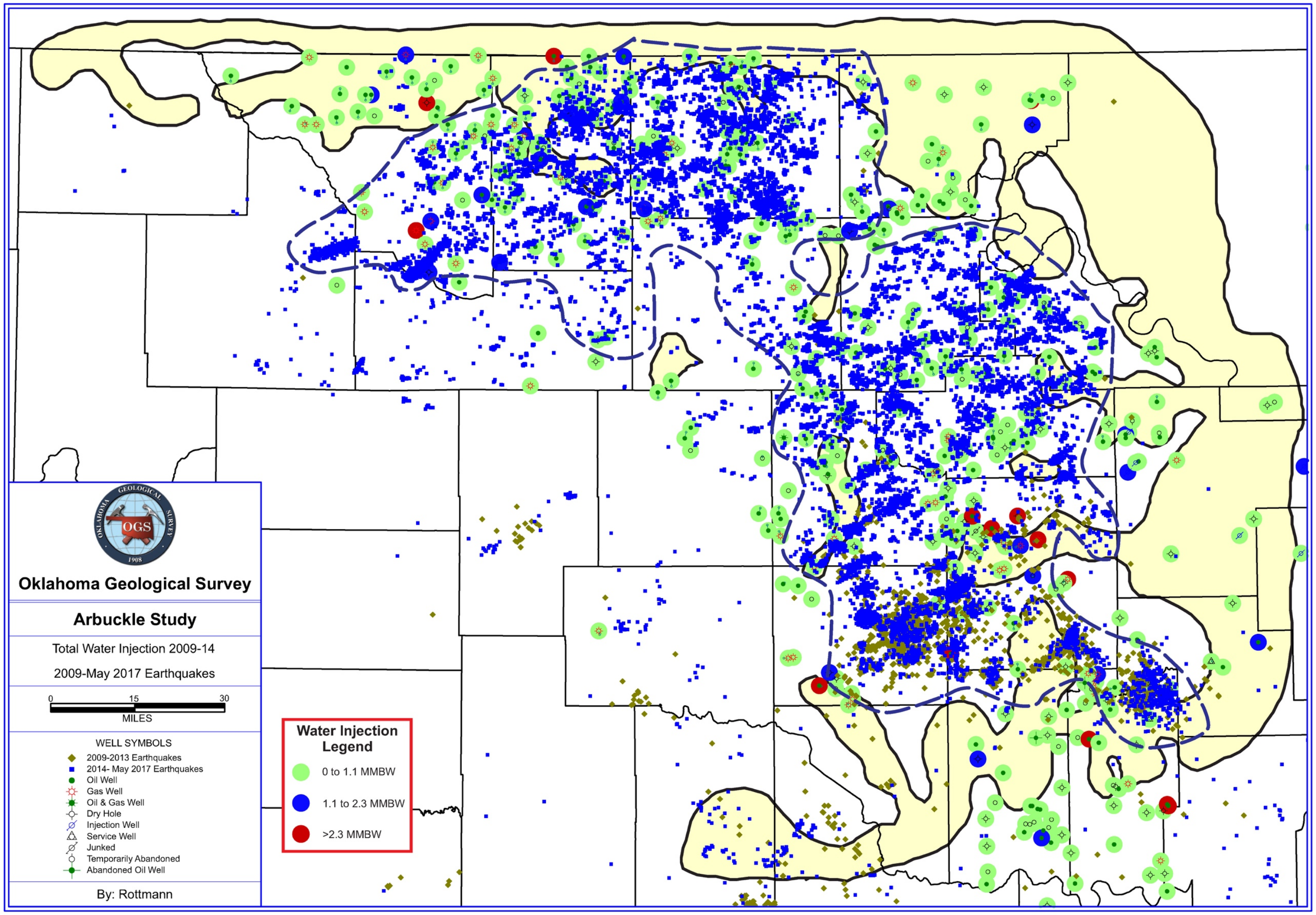

Figure 63: 2009 through 2014 water injection volumes compared to 2009 through May 2017 seismic events and the area of the porous Arbuckle cap rock (area outlined in yellow). Dashed blue line represents author's outline of significant seismic events. White area of map represents area that Arbuckle cap rock facies is impermeable.

7– Conclusions

It is apparent that understanding of the origin, stratigraphy, depositional, diagenetic and petroleum generation history, and reservoir properties of the Arbuckle remains preliminary at best. This is understandable because the Arbuckle is the deepest of the potentially productive stratigraphic horizons. The common view of explorationists has led them to believe that production only occurs at the top of the Arbuckle; therefore, very few wells have actually penetrated the entire section. Correlations of the various formations that comprise this group is currently challenging without biostratigraphic data, sample descriptions and core studies. However, this report has attempted to shed some light on the Arbuckle, its depositional and diagenetic history, and its potential for injection of produced water.

The following are the main conclusions of this report:

1. Arbuckle data, including tops and formation boundaries from public sources show significant inconsistency, and should not be relied upon without verification. These data are essential to understanding structure and stratigraphy of the Arbuckle.
2. Precambrian erosional topography was widespread across the mid-Continent region. Topographic features had vertical relief that probably approached 2000 feet. These features were preserved by the onlapping fill of Cambrian and Early Ordovician sediments of the Arbuckle Group. The Tulsa Mountains of Osage and Pawnee Counties, Oklahoma and the "buried hills" of central Kansas are some of the areas where these erosional features are preserved by Arbuckle sedimentation.
3. Formation pressure, increased by burial, was reduced several times during the depositional history of the Arbuckle. This pressure relief was due to the uplift, which caused the Arbuckle Group to become overpressured for its depth. The characteristics of the overlying cap rock facies influenced the amount of pressure release from the Arbuckle during uplift and erosion. Those areas where the cap rock facies on the top of the Arbuckle is composed of porous and permeable sand or where the Arbuckle was exposed to the atmosphere from the uplift resulted in the greatest amount of pressure relief. Those areas where the cap rock facies is impermeable probably had a relatively lower amount of pressure relief.
4. Dolomitization most likely occurred late in the history, probably as a result of deep burial. The dolomitization process would initially have created secondary porosity due to the higher density of dolomite than calcite. Dolomitization may have led to a collapse of the Arbuckle as a unit, reducing this secondary porosity. Collapse would have increased formation pressures that had been lowered by the pore volume gained from dolomitization. The dolomitization scenario suggested for the Tulsa Mountain area may explain the origin of the massive dolomites of the Mid-continent region.
5. The decreasing degree of underpressuring upward in the stratigraphic section from the Arbuckle through Simpson (2^{nd} Wilcox), and Hunton/Misener indicates significant isolation of these units from one another. This result may be critical in determining whether injection may need to be limited in units above the Arbuckle to reduce seismicity. The ability to dispose of produced formation water in shallower horizons may be critical to the oil and gas industry.
6. Gas saturations within the Arbuckle probably vary widely and were dependent on the facies type that overlies the Arbuckle. The increase in gas saturation pore volume allows the Arbuckle to accept a larger amount of injected saltwater before processes that create seismic activity occur. Arbuckle strata that contains lower gas saturation pore volumes accept considerably less injected saltwater before those processes occur that create seismic activity.

7. The Arbuckle cap rock facies map offers the Oklahoma Geological Survey and the Corporation Commission of Oklahoma an opportunity to understand why some areas of Arbuckle saltwater injection are prone to high seismic activity and why some areas of similar saltwater injection are in areas of low seismic activity.
8. The Arbuckle cap rock facies map offer the Oklahoma Geological Survey and the Oklahoma Corporation Commission a means to predict potential areas where injected saltwater in the Arbuckle could have a high probability for seismic activity and those areas where injection may not result in seismic activity for pre-determined total volumes of saltwater injection. This facies map could also influence decisions on permitting, reworking, and/or modifying injection permits.
9. The basement is complex and very few wells have significantly penetrated it in these areas. For those that did, open hole geophysical logs suggest that there are features within the basement complex that may be intrusive in nature, similar to those found from the Wichita Uplift granitic exposures. These intrusive events, whether they are dikes, sills, or vents, may be composed of material that is conducive to an enhanced degree of diagenetic alteration compared to their surrounding rock types and if so, may provide avenues for injected saltwater entry to the depths of the recent seismic activity.

8 – Recommendations

This report makes five main recommendations for the continuation of this study:

1.) Complete the Arbuckle cap rock facies map. This map would include a complete evaluation for the cap rock facies of the Arbuckle in the seismically active areas as well in those areas adjacent to them.

2.) Study the temporal variation of salt water injection and seismic activity (especially the first occurrence of seismic activity) in the vicinity of Arbuckle disposal wells in the permeable and impermeable Arbuckle cap rock facies areas. This study could potentially determine how much water could be expected to be injected in the Arbuckle whose cap rock consists of either impermeable or permeable strata before seismic activity could be anticipated to occur. This effort will need to proceed in conjunction with studies aimed at understanding the lag time between pressure rise in the Arbuckle and pressure rise in the basement.

3.) Review available core and petrographic data on Arbuckle rocks for evidence of collapse of secondary porosity created by dolomitization.

4.) Continue the study of the basement intrusive features. This study would include such topics as sample descriptions for those wells that significantly penetrated the basement. It would also include a study of these features in the outcrops of northeastern and southern Oklahoma. The purpose of the work would be to determine the possibility that diagenetically altered intrusive units could be conduits for injected disposal water to great depths. It should also enhance our understanding of the nature of fracture systems in the basement, to better characterize the response of basement faults to pressure rise in the Arbuckle.

5.) Evaluate fully the complex mechanism for creation of gas saturation in the Arbuckle rocks overlain by porous and permeable rock types to determine whether sufficient differences in gas saturation could be created by this mechanism. The degree of isolation of areas where pressure relief occurred from areas where it did not occur will be important to defining these relationships. It will also be important to further validate the conclusion that sedimentary units overlying the Arbuckle show lower degrees of underpressuring, suggesting a significant degree of isolation from the Arbuckle and hence from the basement. In addition, it will be necessary to examine other interpretations of the underpressuring of these formations in the light of the observations presented here.

9 – Acknowledgements

First, the author would like to express his gratitude to the State of Oklahoma and Governor Mary Fallin for their support and funding for this study.

He would like to thank Mr. J. P. Dick, reservoir engineer and manager of Pinnacle Energy Services, for his welcome support, critique, contributions, and advice for this project.

He would like to extend a special thank you to Merle and Kent Gatewood and the Lloyd Gatewood family for their generosity and support in donating their father's Arbuckle Study to the Oklahoma Geological Survey's Legacy Collection. This study can be used by researchers for years to come when trying to understand this complex geological group.

The author would like to thank the Oklahoma Geological Survey for allowing him the opportunity to undertake this study, Richard Andrews for recommending him for this study and for his guidance and support during the study period, and Dr. Jeremy Boak, Director of the Oklahoma Geological Survey, for his support, direction, and advice for this study.

And lastly, I would like to thank my wife Reba for her work on the graphics and for her many hours of patience while I was working on this study. Cover graphics designed and created by Kurt and Reba Rottmann.

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