Report for the Arbuckle-Simpson Hydrology Study:

Analysis of Bit Cuttings, Wire-Line Logs and Flow Tests from a Deep Test Well in the Arbuckle-Simpson Aquifer, Johnston County, Oklahoma

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FINAL REPORT

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October 5, 2009
Stillwater, Oklahoma

Submitted to:

Oklahoma Water Resources Board
3800 North Classen Blvd.
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Cover: Photograph of Drilling at Spears Ranch Site

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1.0 Executive Summary

This report presents the results of the examination of the bit cuttings from the United States Geological Survey (USGS) Spears #2 well that was drilled to collect data on the character of the Arbuckle Group and Timbered Hills Group portion of the Arbuckle-Simpson Aquifer. The original intent was to drill the entire carbonate aquifer section contained in the Arbuckle-Simpson Aquifer, determine the controls on porosity and permeability development, sample to determine water chemistry, conduct flow tests of water volumes at various positions in the aquifer and to survey the hole with a suite of modern wireline-electrical logs. Difficulties encountered during drilling, in particular high-water volumes, prevented the drilling and sampling of the entire carbonate aquifer. The initial well, which was known as the Spears #1, was abandoned at a depth of 628 feet. The second well, the Spears #2 was drilled to a total depth of 1820 feet before excessive water volume and hole conditions forced an end to drilling. Bit cuttings collected from surface to total depth were examined to determine lithology and characteristics of the pore network. These results were compared to reported water volume tests provided by the USGS and Oklahoma Water Resources Board (OWRB) and wireline-log data provided by Dr. Randall Ross, U.S. Environmental Protection Agency (EPA).

The comparison by depth of lithology, rock and wireline-log porosity indicators and water flow tests provides evidence that a relationship exists between void-rich zones as indicated by secondary cements, silicification, and vuggy porosity, and water flow volumes. These void rich zones were confirmed by the electrical log surveys that indicated enlarged hole diameter and increased travel time across these intervals. Subsurface stratigraphy was estimated by comparing the lithotypes represented in the bit cuttings and the gamma-ray log character with the descriptions and wireline logs of a recently drilled deep petroleum exploration well and published descriptions of the Arbuckle and Timbered Hills groups. The volume of water entering the borehole increased when discrete zones of porosity were drilled. The largest increase in water volume came from a porous zone located in the lower part of the West Spring Creek Formation. The USGS reported that all water encountered was fresh and low salinity.

2.0 Introduction

The characterization of the lithology, pore network and water types in the Arbuckle Simpson aquifer in the core of the Hunton Anticline tectonic subregion is hampered by the lack of a recently drilled, deep penetrating wells that sample the bulk or all of the strata comprising the aquifer. Several wells drilled in exploration for oil and gas penetrate the entire aquifer (Figure 1), but these are decades old and were not logged with modern types of wireline tools that provide the aquifer data needed for this characterization, nor did they adequately sample rock fluids to document the type of fluids encountered at depth within this thick aquifer. These vintage wells did provide a record of aquifer lithology as recovered bit cuttings.

In an attempt to provide a modern data set consisting of cuttings, modern wireline logs, and downhole measurements of water flow and type, the Arbuckle-Simpson aquifer study proposed that a new well be drilled on the Hunton Anticline. This well was contracted to the United States Geological Survey (USGS) and a drillsite was chosen near the Blue River west of the small community of Connerville, OK in Johnston County. The well drillsite is located on the Spears Ranch in the SW 4, Section 23, T.1S., R.6E (Figure 1).

2.1 Surface Geology and Physiography

The Spears Ranch drillsite is situated on a gentle northerly facing slope that extends to the Blue River. The outcropping strata are flat-lying, thinly bedded dolomitic limestones and dolostones of the Ordovician West Spring Creek Formation, Arbuckle Group (Figure 1). The Simpson Group is missing from the core of the Hunton Anticline and the drillsite as a result of uplift during the Carboniferous and subsequent erosion. Several meters north of the drillsite surface beds dip at high angles, which are believed to be the result of epikarstic dissolution and collapse of cavern passages. This pattern of rapidly changing attitudes of the outcrop bedding is common across the Arbuckle Mountain uplift where Arbuckle Group carbonates are exposed.

2.2 Spears Ranch Wells

The dataset contained herein is from the Spears Ranch #2 well. The Spears Ranch #1 well began drilling September 14, 2005, was drilled to a total depth of 628 feet (191 meters) and was abandoned as a result of drilling difficulties. The Spears Ranch #2, which is located approximately 160 feet from the Spears #1, began drilling September 25, 2005 and was drilled to a total depth of 1820 feet (555 meters) (Christenson and others, 2009). The Spears Ranch #2 was logged using a suite including natural gamma-ray, spontaneous potential, normal resistivity, lateral resistivity, single-point resistance, 3-arm caliper, P-wave sonic, acoustic televiewer, fluid temperature, fluid resistivity, and borehole flowmeter tools (Osborn, 2006).

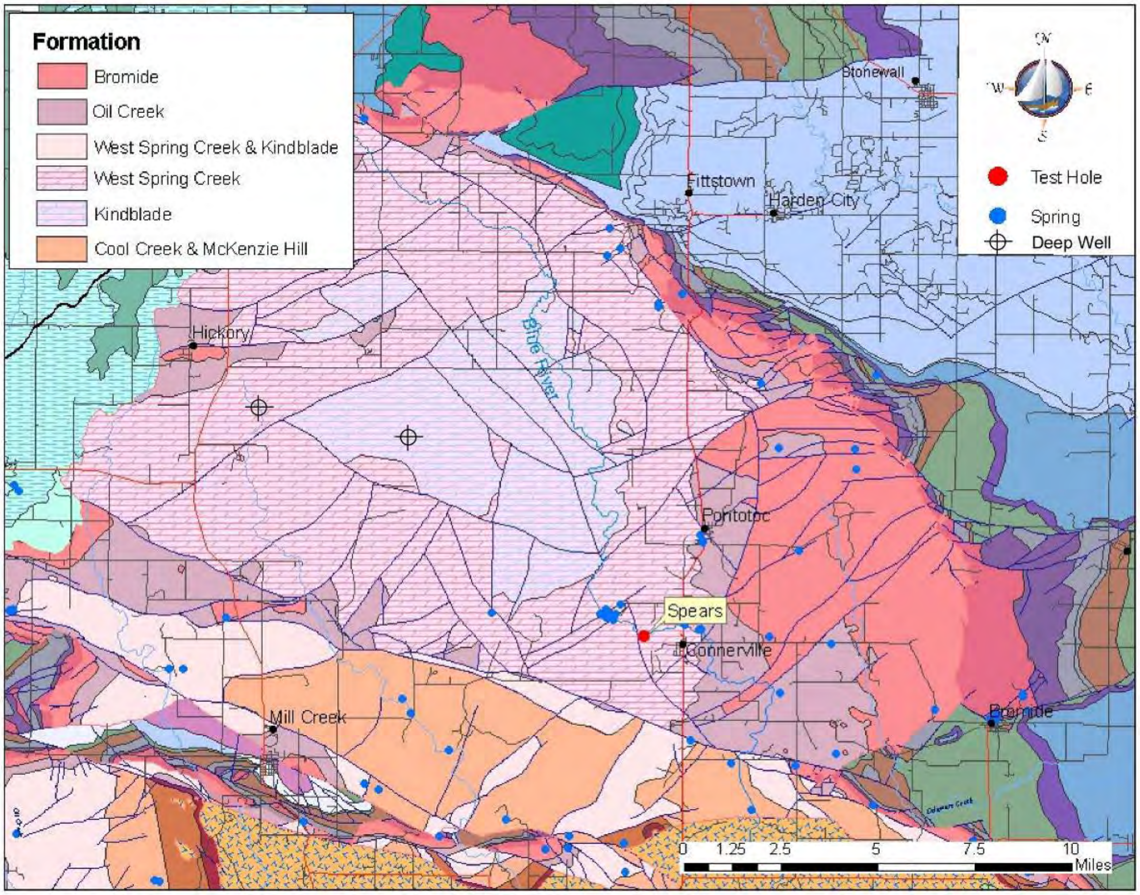


Figure 1. Geologic map of the Hunton Anticline showing location of the Spears well, springs, and petroleum exploration wells (deep wells) that penetrated the base of the Arbuckle aquifer (after Osborn, 2006).

3.0 Lithologic Record of Drilled Strata

Dolomitic limestone, dolostone, sandstone, sandy dolostone, and limestone were identified in cuttings from the Spears #2 borehole. Chert or silicified carbonate was common in certain intervals. Calcite cement occurs as another important constituent. As a result of the recrystallization during dolomitization , sedimentary grains were difficult to identify. However, several post-depositional features were recognized by changes in mineralogy and texture. Dissolution features such as enlarged fractures and vugs are evidenced by planar seams or veins of calcite cement (Figure 2), patches of calcite cement and larger crystals of baroque or saddle dolomite (Figure 3). Dissolution and conduit fill is evidenced by the presence of oxidized material deep in the section. These types of features have been documented in outcrop (Musselman, 1994; Puckette et al., 2009) and subsurface samples from oil and gas exploration wells (Lynch and Al-Shaieb, 1991).

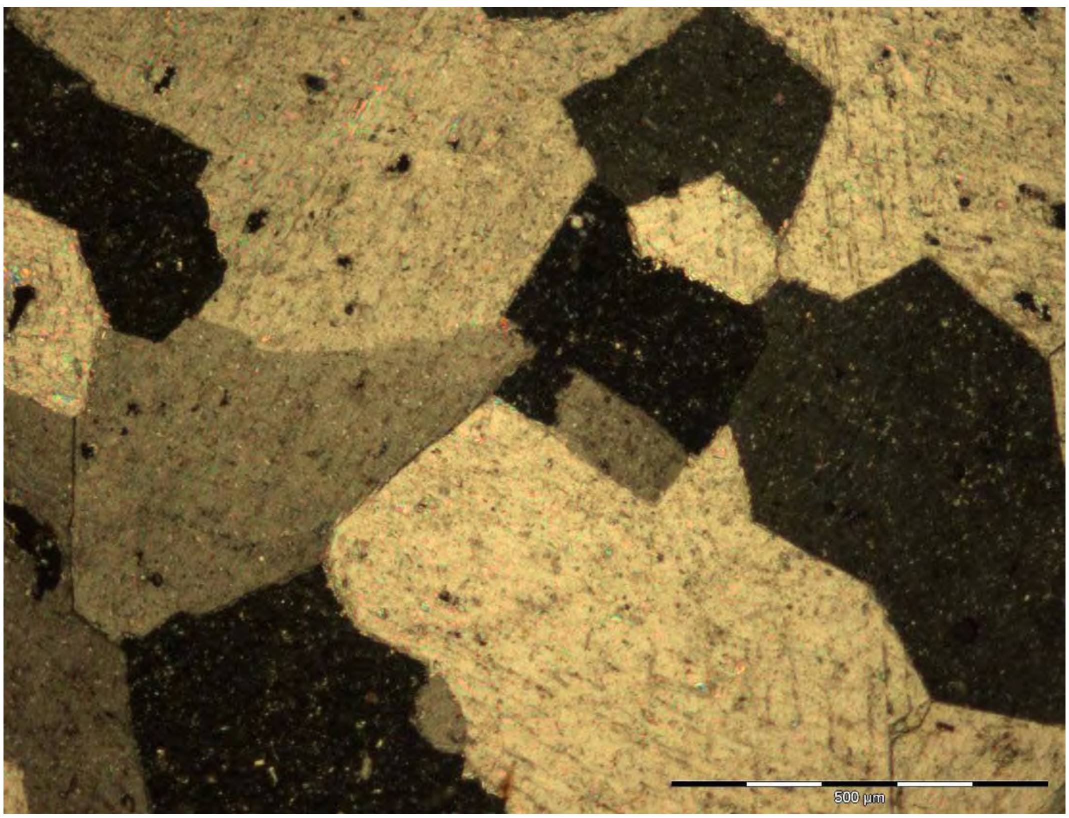


Figure 2. Photomicrograph of calcite cement that infilled a fracture or dissolution feature. Spears #2, depth 790 feet. Cross-polarized light (CPL).

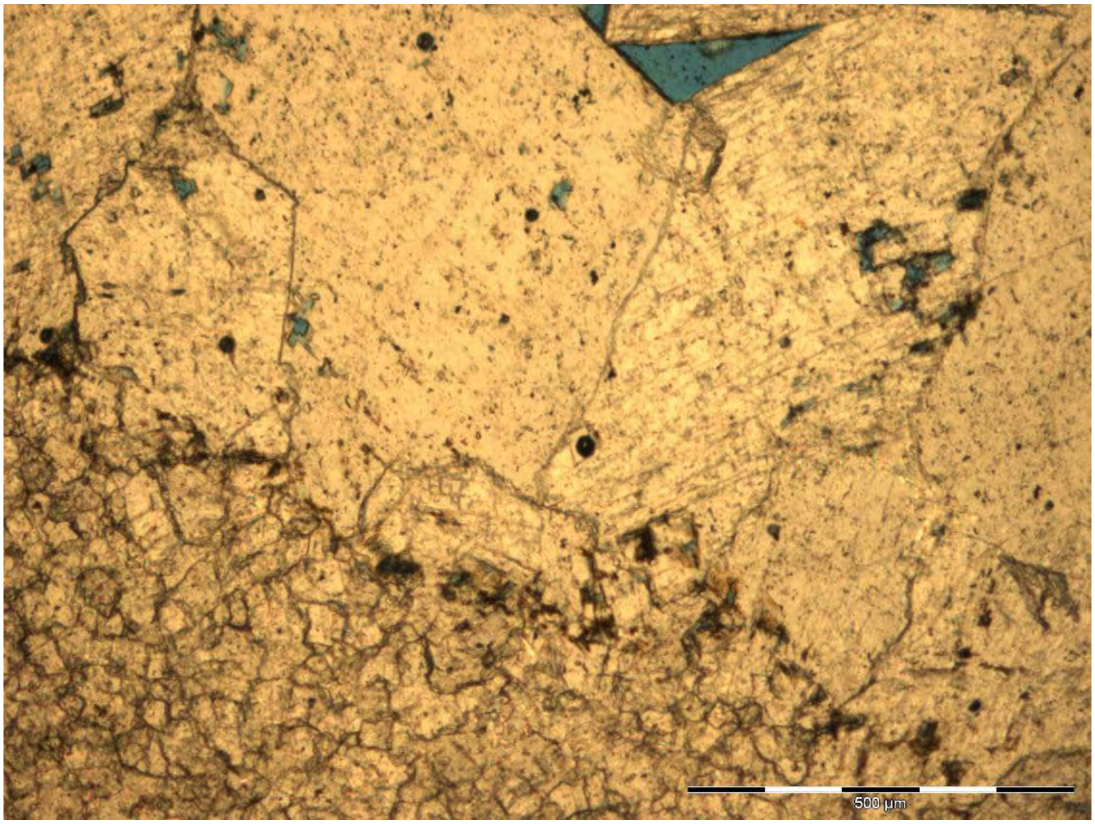


Figure 3. Photomicrograph showing contact between dolomitic host rock (lower left) and void filling saddle dolomite cement (upper right). Blue is epoxy filled porosity. Spears #2, depth 790 feet. Plane-polarized light (PPL).

4.0 Determination of Stratigraphic Boundaries

Stratigraphic boundaries or formation boundaries within the Arbuckle Group were determined based on changes in lithology and gamma-ray log character. These boundaries were selected based on premises: (1) that sandier zones in the carbonate represent events that should have affected the entire region, (2) shalier or more argillaceous carbonates represent cyclic changes in water depth that should be expressed across the region, (3) oxidized zones evident in outcrop sections should correlate to the subsurface as the conditions to produce these are caused by regional processes, and (4) silica-rich or cherty zones have value as marker beds in some instances and may be used with reservation. Employing rock descriptions by Ham (1955) and Ham et al., (1964) for the Tishomingo Uplift tectonic subregion, Fay (1989) for the Interstate 35 corridor through the Arbuckle Anticline tectonic subregion, stratigraphy provided by Allison (2008) for the recently drilled section on the Lawrence Uplift tectonic subregion, and previous work in the region by Allen (2008), generalized formation boundaries were determined. The description of the bit cuttings and the interpreted stratigraphy are shown on a petrolog, which is Appendix A.

4.1 West Spring Creek Formation

The West Spring Creek Formation extends from the surface to approximately 1200 feet below surface (Appendix A). The first approximately 130 feet consist of fine to medium crystalline dolostone (Figure 4) with occasional vuggy porosity (Figure 5). The first occurrence of sandy dolostone appears around 130-140 feet. Around 170 feet calcite cement that infills vugs or fractures becomes evident. Calcite cement is commonplace for the next 100 feet. The dolostone matrix is relatively uniformly finely crystalline down to 300 feet (Figure 6; see also Appendix A). From 300 to 390 feet the dolostone displays a range of crystalline textures from very fine to medium, and a color range from cream to brown. Vuggy porosity is evident, but secondary calcite cement is not. A water volume test in the Spears #1 conducted around 365 feet yielded approximately 300 to 350 gallons per minute (Osborn, 2006).

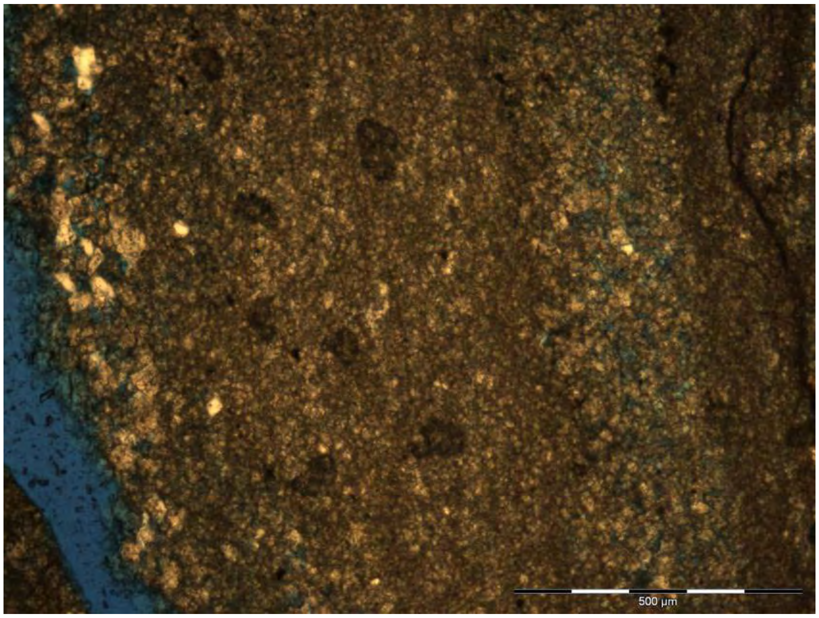


Figure 4. Photomicrograph of finely crystalline dolostone with thin bands of medium crystalline dolostone containing interrhombic intercrystalline matrix type porosity. One band is above the scale bar. Intercrystalline porosity is apparent between rhombic dolomite crystals along the left side of the image. Larger patch of blue is relic of thin sectioning process and not a rock feature. West Spring Creek Formation, Spears #2, 110 feet. PPL.

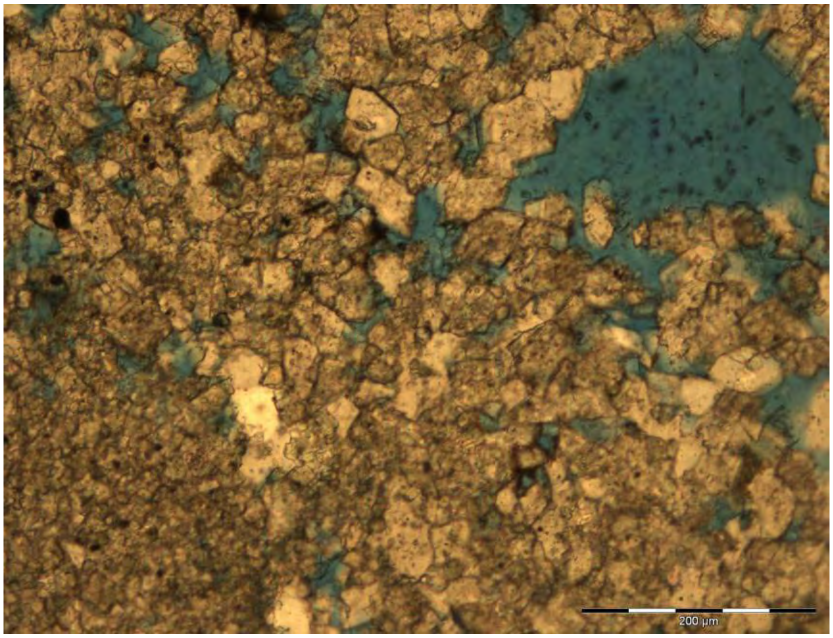


Figure 5. Photograph of small vug developed in medium crystalline dolostone with intercrystalline matrix porosity. West Spring Creek Formation, Spears #2, depth 110 feet. PPL.

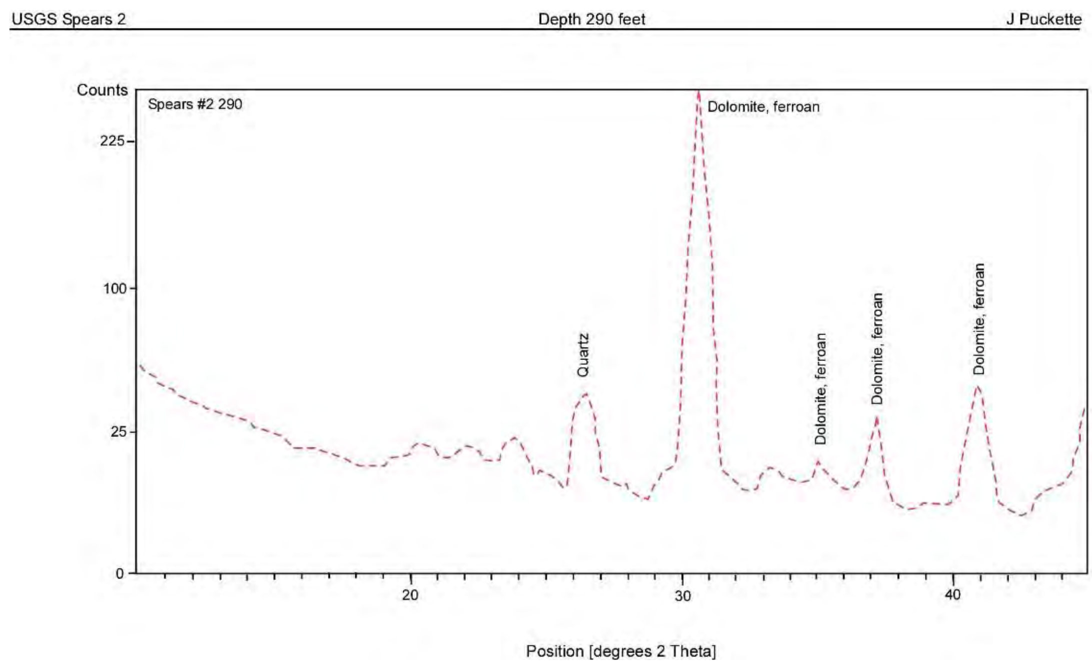


Figure 6. Powder x-ray diffractogram of a typical powdered bit cutting sample from the USGS Spears #2. The principal components are dolomite, iron-rich (ferroan) dolomite, and quartz. Dolostone and sandy dolostone dominate West Spring Creek Formation lithology from surface to around 390-400 feet in the Spears #2 well. With the exception of the thin limestone located approximately 390-400 feet deep, all samples from surface to total depth were dominantly dolomite or ferroan dolomite.

A rather thin, light gray colored, clayey limestone was identified around 390 to 400 feet (Figure 7; Appendix A). This was the only limestone recognized in cuttings and its preservation may be due to the clay content and low permeability to dolomitizing fluids.

From 400 to 480 feet the dolostone continues to display a range of texture and color. Medium to coarse-grained sandstone (Figure 8) occurs around 400 feet and white chert is evident in the sample caught at 410 feet. From 470 to 490 feet iron oxide stained, silty carbonate and clay occur. This iron-oxide stained zone is likely analogous to “red” zones identified by Fay (1989), Musselman(1994), and Puckette et al.(2009). The dolostone remains fine uniformly crystalline until 680 feet and features in this interval are largely post depositional. White chert including silicified ooids occurs from 510 to 530 feet. A thin very to fine grained sand-rich zone occurs at 560 to 570 feet. A well test at this depth in the Spears #2 yielded approximately 300 gallons per minute (USGS, 2005). Oxidized rock returns from 570 to 580 feet and vuggy porosity and saddle dolomite by 600 feet. Around 600 feet deep the rock becomes cherty, fractured and vuggy. Chert is apparent from 600 to 660 feet. Saddle dolomite crystals up to 1mm in length are noticed in cuttings from 590 to 690 feet. Interestingly, a well test extending

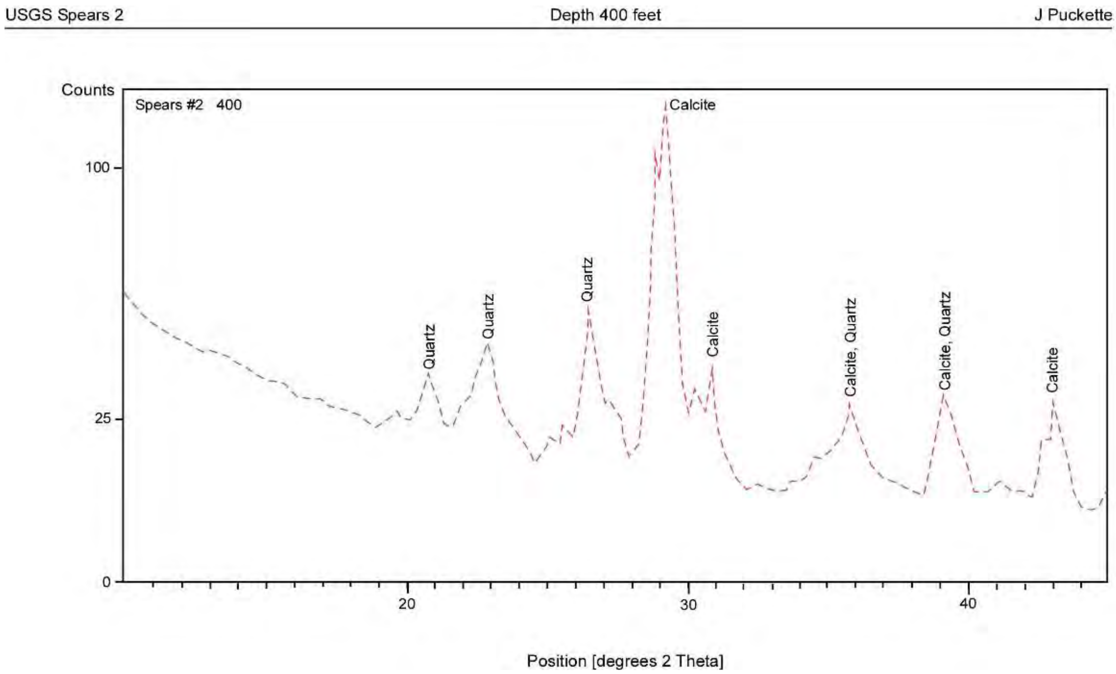


Figure 7. Powder x-ray diffractogram showing the presence of calcite matrix in the bit cutting sample collected for 390-400 feet interval. This sample contains the argillaceous limestone shown on the petrolog in Appendix A.

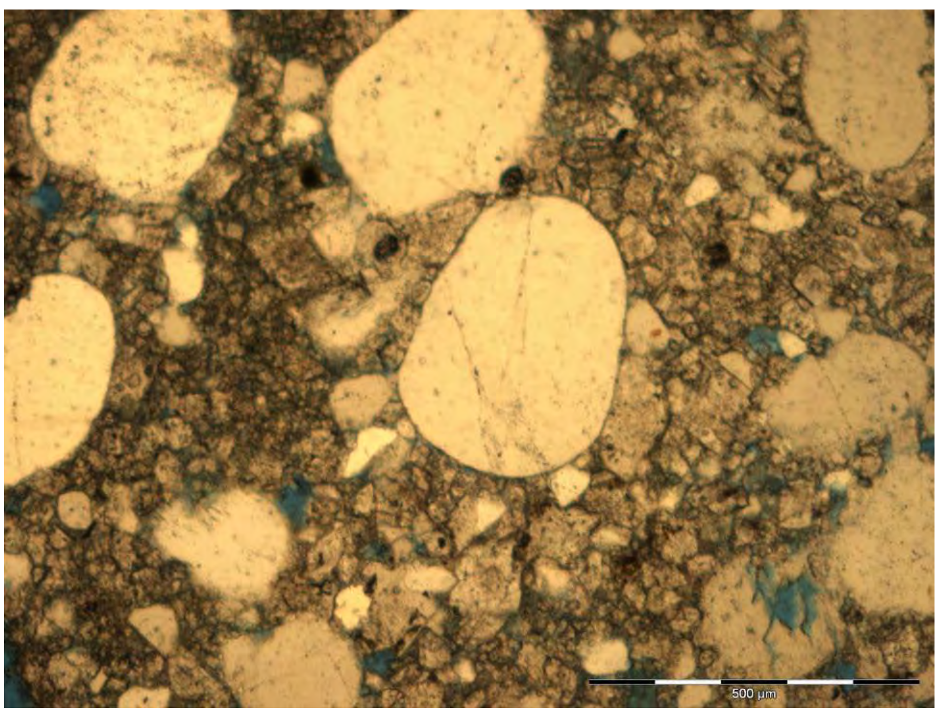


Figure 8. Medium-grained sand in a dolomitic matrix typical of sandy dolostones in the West Spring Creek Formation. Spears #2, depth 360 feet. PPL

from 645 to 700 feet yielded 800 to 1000 gallons per minute (Osborn, 2006), a several fold increase over the volume recovered at 560 feet. A similar porous zone in southern Oklahoma oil fields is called the “Brown Zone” by the petroleum industry.

The dolostone is sandy from 700 to 720 feet and 770 to 790 feet (Figure 9). Very fine-grained sandstone and dolomitic sandstone occur from 790 to 820 feet. This sandstone is interpreted as being the base of the West Spring Creek Formation. Saddle dolomite (Figure 10) fractures and microfractures (Figure 11) occur sparingly across this interval.

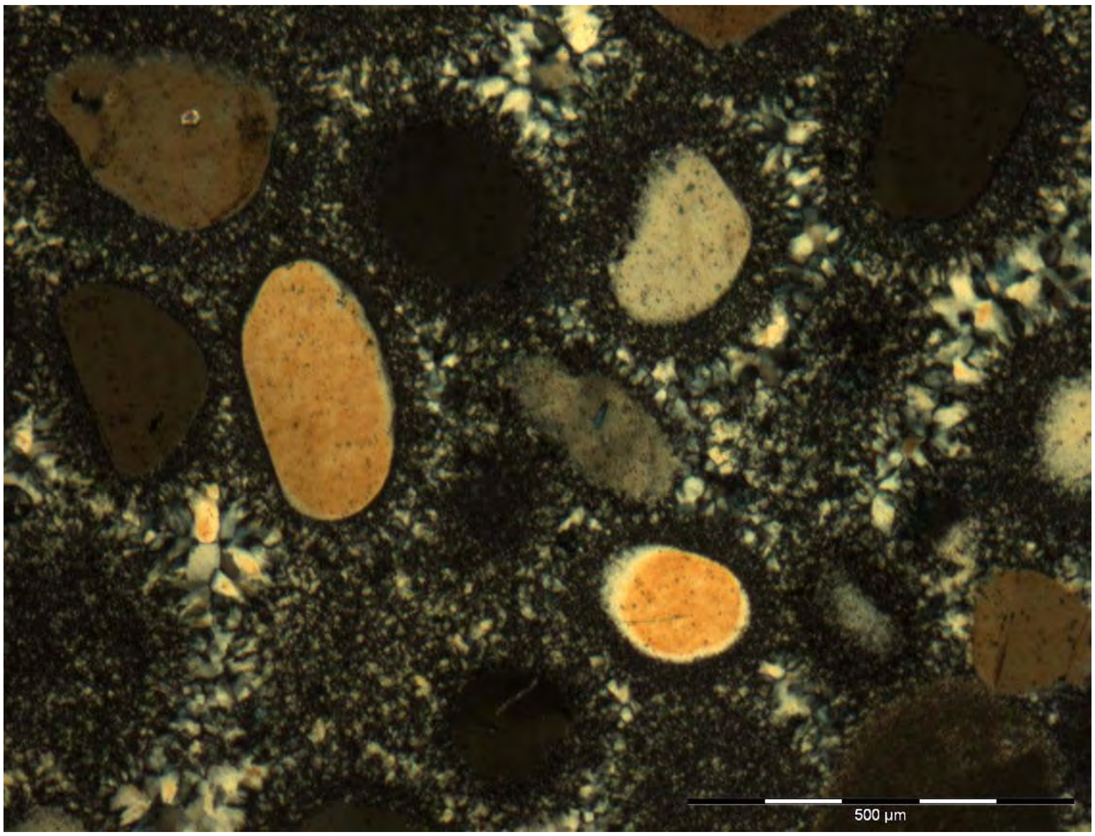


Figure 9. Fine- to medium-grained sand nucleating ooids. Finely crystalline black, gray and white material surrounding the sand grains is chert, which replaced original carbonate. Concentric banding of sand grains reflects ooid growth lines. Sand grains (black to yellow brown color) are rounded, which is typical of the Ordovician sandstones in southern Oklahoma. Carbonate-nucleated ooid ghosts are also evident in the West Spring Creek Formation. These ooids were also silicified to form chert. Spears #2, depth 710 feet. CPL

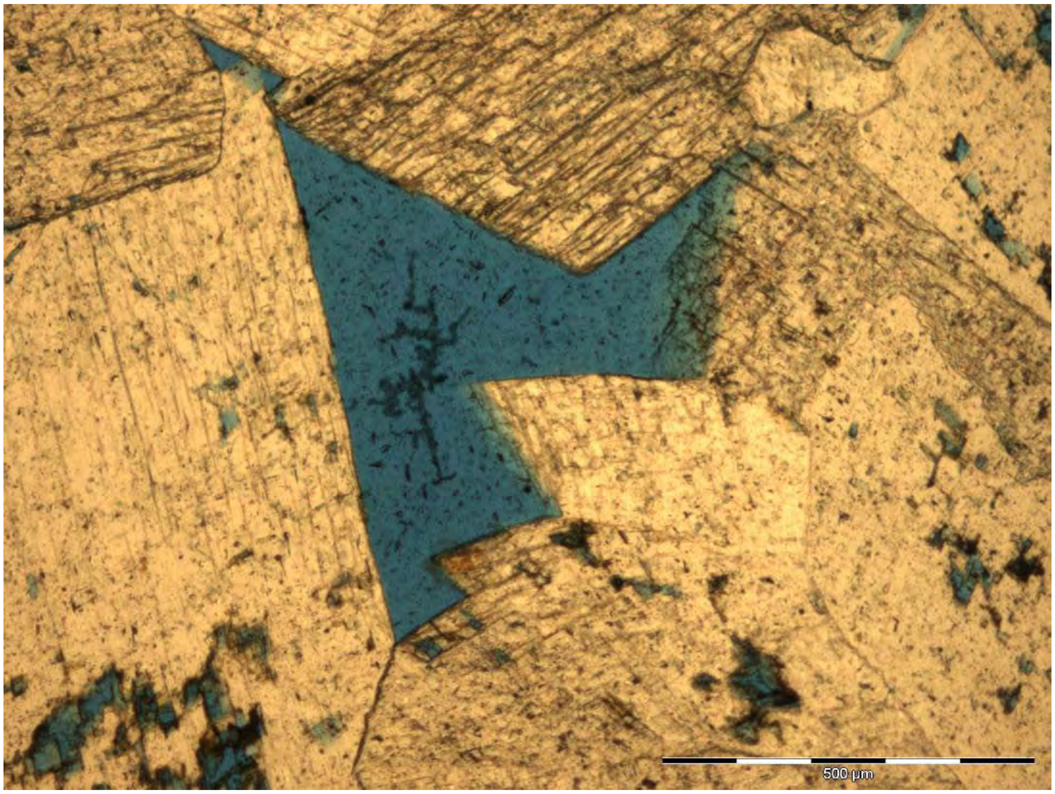


Figure 10. Photograph of baroque or "saddle" dolomite crystals that grew into a fracture or dissolution feature. Porosity is indicated by blue epoxy. West Spring Creek Formation, Spears #2, depth 790 feet. PPL

4.2 Kindblade Formation

The finely crystalline dolostone from 820 to 870 feet marks the top of the Kindblade Formation. Baroque or saddle dolomite is common from 840 to 910 feet. From 910 to 980 feet the dolostone is fine and medium crystalline with a thin sandy zone around 950 feet. Saddle dolomite increases in frequency from 980 to 1180 feet. Two zones of oxidation occur at 1090-1000 feet and 1160-1170 feet, respectively (Appendix A). The interval between 980 and 1180 feet has abundant saddle dolomite and vuggy porosity, but lacks chert and sand. A thin very fine to fine-grained sandstone occurs at 1230-1240 feet.

4.3 Cool Creek Formation

Dolostone dominates the remaining strata drilled in the Spears #2 well. Beginning around 1280 feet, the dolostone is consistently finely crystalline (Figure 12), which marks the top of the Cool Creek Formation. Secondary saddle dolomite crystals are common down to 1340 feet. Vuggy porosity is common across the same interval, and oxidized zones occur 1280-1290 feet, 1340-1350 feet and 1360-1370 feet. An increase in water flow was recorded by the driller at a depth of 1300 feet, but a measurement was not reported. From 1360 to 1410 feet saddle dolomite is not evident, but it appears again around 1410 feet and is common until a depth of 1580 feet. Chert and sandstone are not common in the interval between 1280 feet and 1580 feet. Chert is evident from 1415 to 1425 feet and 1480 feet. This relatively pure, evenly fine crystalline dolostone (1280 to 1480 feet) (Figure 12) is believed to represent the Cool Creek Formation (Appendix A).

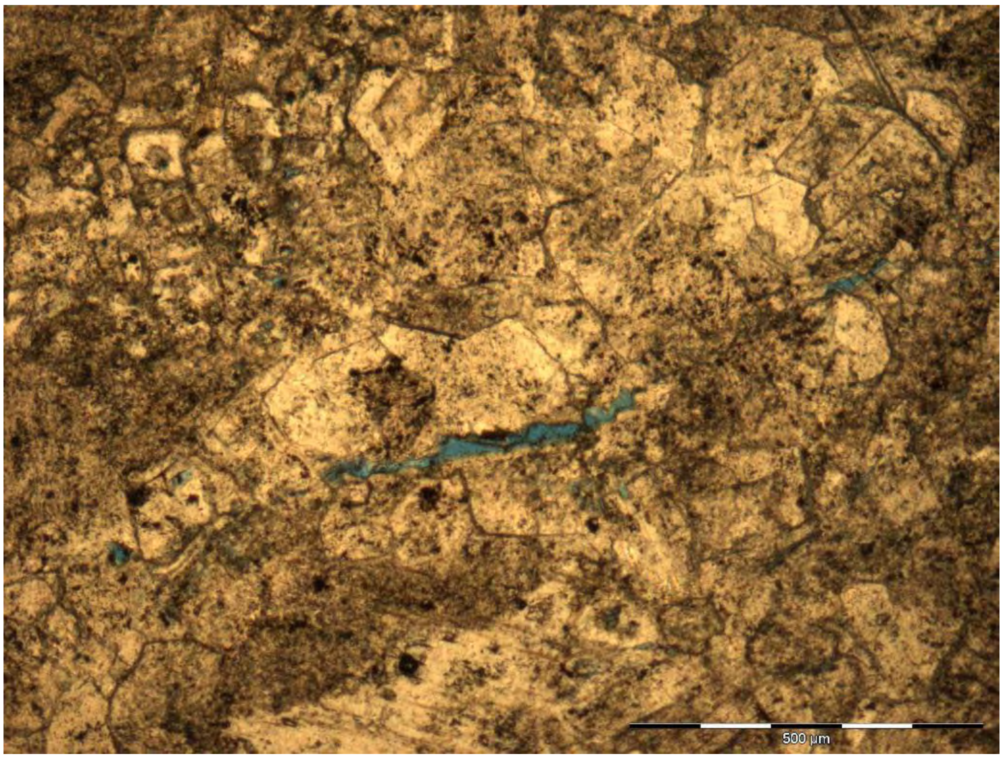


Figure 11. Photomicrograph of microfracture porosity in medium crystalline dolostone. West Spring Creek Formation, Spears #2, depth 790 feet. PPL

Around 1580 feet dolostone crystal size becomes more variable and ranges from very fine to medium crystalline, and the dolostone contains chert and interbedded sandstone. Sandstone and dolomitic sandstone are the dominant lithotype from 1580 to 1610 feet. Evidence of fracturing, dissolution and chert is very common from 1620 to 1650 feet (Figures 13 and 14), around 1685 feet, 1705 feet, 1720 to 1740 feet, and 1745 to 1755 feet. Thin chert beds occur around 1785 and 1815 feet; thin sandstone was evident 1820 feet. Saddle dolomite is abundant from 1660 to 1780 feet and an oxidized zone is evident around 1790 feet. A water volume measurement at the total depth of 1820 feet yielded an estimated 1000 to 1200 gallons per minute (Osborn, 2006).

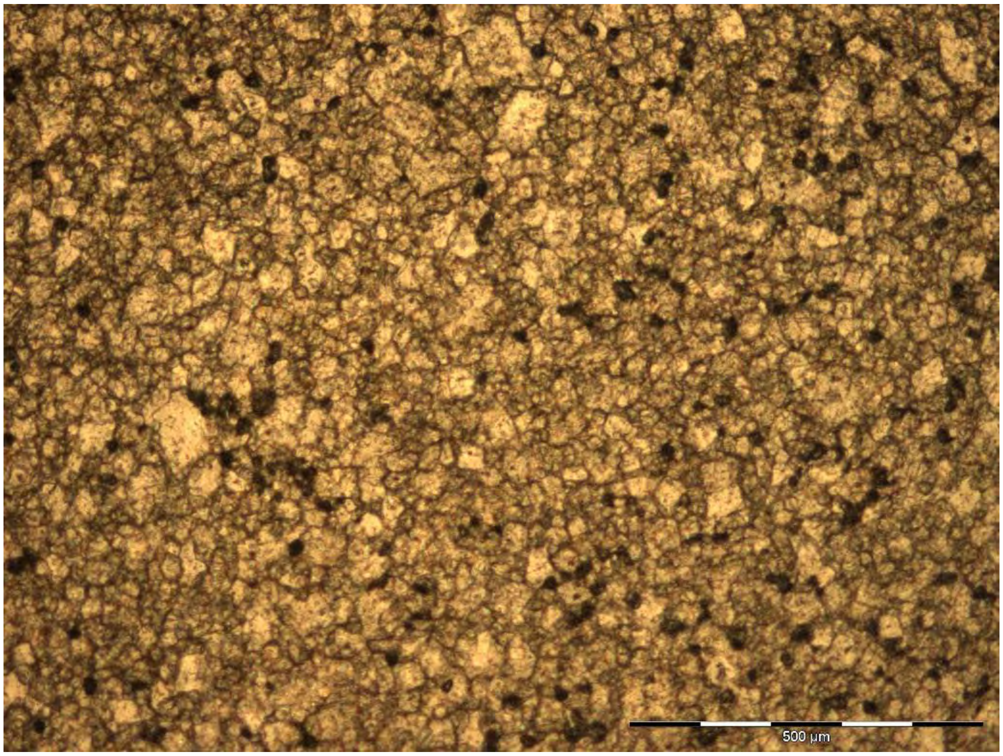


Figure 12. Photomicrograph of finely crystalline dolostone consisting of microspar (dolomitized carbonate mud) and occasional larger rhombs. Cool Creek Formation, Spears #2, depth 1340 feet. PPL

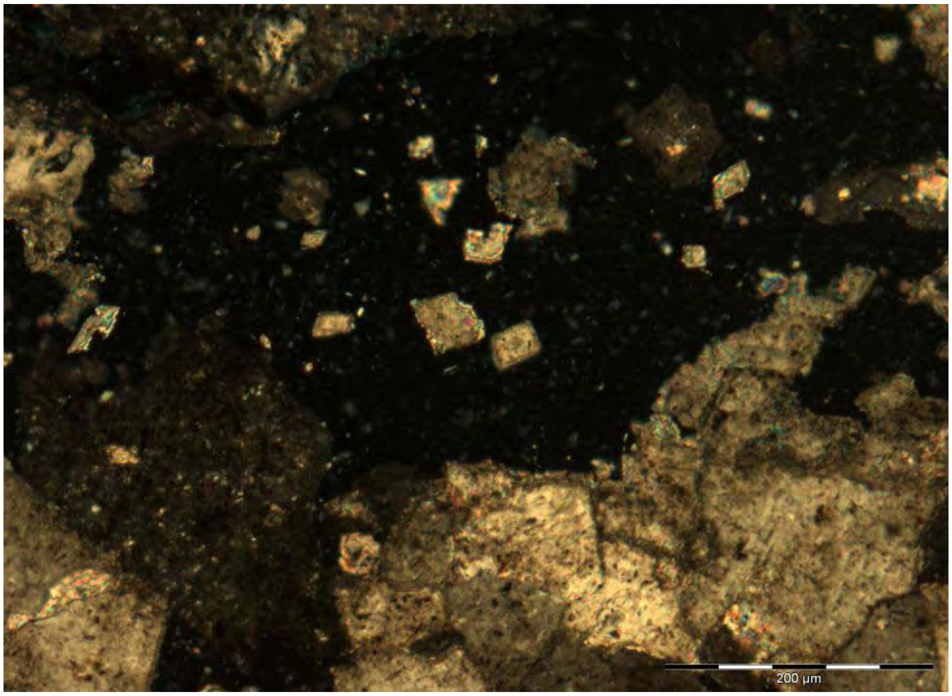


Figure 13. Photomicrograph of chert (dark) being replaced in part by dolomite. Cool Creek Formation, Spears #2, depth 1650 feet. CPL

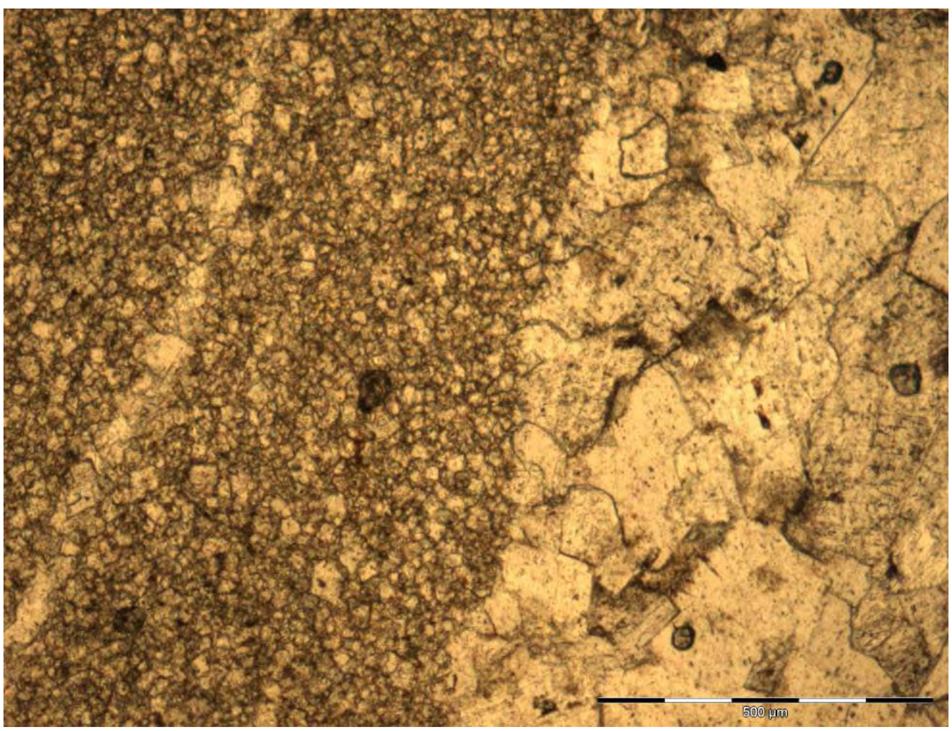


Figure 14. Photomicrograph of planar boundary between finer crystalline host dolostone and coarser crystalline dolomite that likely represents fracture-filling cement. Cool Creek Formation, Spears #2, depth 1650 feet. PPL

5.0 Water Flow Measurements and Porous Zones

The drilling crews for the Spears #1 and Spears #2 wells documented water-bearing zones when they were encountered. A percussion type air-rotary bit was used to drill most of both wells. When water was encountered it was blown back to the surface and if the volume sufficiently high, reduced the efficiency of the percussion bit. Several times it was necessary to increase air volume to continue drilling the Spears #2 well. Eventually the water volume became too great to continue drilling. Based on the correlation of reported occurrences of water and lithology, a relationship between water flow and lithology was noted. The intervals of reported water test and estimates of volumes are shown on the petrolog in Appendix A.

In the shallowest part of the Spears #1 and #2 wells, from surface to depths down to approximately 360 feet and 560 feet respectively, flow of around 300 gallon per minute was noted (Osborn 2006; USGS, 2005). The Spears #2 encountered a zone from around 590 feet to 690 feet that contained iron oxide staining, abundant saddle dolomite and calcite indicating fracture or vug filling cements, vuggy porosity and chert. Following the drilling of this interval containing this evidence of vuggy and fracture/solution-enlarged fracture porosity, the well was tested to produce 800 to 1000 gallons per minute. An increase in water was noted again around 1300 feet (USGS, 2005) after an iron oxide-containing zone, a zone with abundant saddle dolomite and a zone of vuggy porosity were drilled. Several additional porous zones were drilled before total depth was reached, where the final flow measurement was estimated around 1000 to 1200 gallon per minute (Osborn, 2006).

The increase in water flow after the drilling of porous zones separated by zones of relatively low porosity and permeability is similar to the results of drilling of water supply and oil- and gas-exploration wells on the Hunton Anticline (Puckette et al., 2009). Well records from air rotary or cable-tool drilled wells and wells logged with microresistivity tools provide evidence that supports the premise that the Arbuckle carbonates can consist of thick intervals of relatively low permeability rock that are punctuated by thinner zones of permeable rock. These thin zones were called water crevices by some drillers, which by their description may indicate solution-enlarged fractures of cavernous porosity.

6.0 Wireline Log Responses

6.1 Introduction

Open hole wireline logging tools were run by Dr. Randall Ross, U.S. EPA, Robert S. Kerr Laboratory to generate a record of the petrophysical properties of the strata drilled in the Spears #2. General types of tools used were: (1) natural gamma ray, (2) caliper, (3) resistivity/conductivity, (4) spontaneous potential, (5) acoustic/sonic porosity, (6) borehole fluid flow direction and rate, and (7) temperature. The suite of wireline logs run in the Spears #2 contains tools that were specifically applicable to characterizing aquifer properties. The applicability of these tools to the project is summarized. As a result of hole collapse, the logging tools were only able to reach about 1335 feet deep.

6.1.1 Natural Gamma-ray

The natural gamma ray log provided a measure of the degree of shaliness in the carbonate. Shaliness or clayey carbonate is the result of deposition al or diagenetic processes. Clay is a common component in open marine, subtidal or tidal flat carbonates. In contrast, intertidal deposition typically results in cleaner carbonates with minimal clay. Clay is often a component in cavern-filling sediments and as a result, oxidized fill in dissolution cavities can be reflected by an increasing gamma-ray count. The natural gamma-ray curve is displayed on the petrolog in Appendix A.

6.1.2 Caliper

The caliper tool measures hole diameter, which is typically near bit size in dense low porosity rocks in boreholes drilled with air or water. The Spears #2 was drilled with air, so hole enlargement due to turbulent flow of liquid is minimal. Likewise, as clay-based drilling mud was not used, mudcake/filtercake buildup across zones with matrix porosity did not occur. Enlarged hole indicated by the caliper is a response to dissolution porosity. As salt or sulfates are rare in the Arbuckle Group, logged increases in hole diameter were interpreted to represent dissolution cavities.

6.1.3 Resistivity/conductivity

The resistivity/conductivity logs change character across the drilled interval display generalized trends. Resistivity and conductivity curves display the expected inverse relationship. In less porous intervals, resistivity tends to increase; conductivity decreases. The inverse is true for porous intervals as resistivity decreases and conductivity increases. This relationship is believed to reflect the relative ratio of pore space to rock, with zones of increased rock to pore ratio exhibiting higher resistivity.

6.1.4 Spontaneous Potential

The spontaneous potential curve reflects the electrical potential that develops between the downhole environment (rock and pore water) and the fluid in the borehole. In the Spear #2 well, the difference in electrical potential between the drilling fluid and freshwater that filled the well was minimal. As a result, the spontaneous potential curve for the Spears #2 well exhibits little meaningful character over most of the logged interval. In zones with increased clay content such as argillaceous carbonates or zones of dissolution with clay infill, spontaneous potential deflection somewhat mimics the gamma-ray curve.

6.1.5 Acoustic Imaging

The acoustic/sonic porosity imaging log (ATV uSec on Figures 15, 16, 16, and 18) is displayed using false color that reflects acoustic travel time and consequently rock density and porosity. The acoustic sound wave exhibits slower velocities and longer travel times in microseconds (uSec)) (red) in porous zones. In contrast the sound wave speeds up and exhibits shorter travel times (green) in denser, low porosity zones. The sonic amplitude track (ATV Ampl) mirrors the travel time track in the red hues in the ATV uSec track correspond to magenta/purple hues in the ATV Ampl track.

6.2 Log Expression of the Spears #2 Section

The acoustic/sonic (ATV uSecs) log for the Spears #2 is dominated by light green hues that are indicative of low porosity/low permeability rocks from the surface to 180 feet (Figure 15). The caliper across this interval shows relatively few indications of hole enlargement. The amount of red color (ATV uSecs log) increases around 130 feet and remains relatively consistent until approximately 390 feet deep. Green dominates from 390 to 410 feet. At 410 feet, a solid red band starts that extends to around 450 feet (Figure 16). Interestingly, the green interval from approximately 395 to 410 feet corresponds to the argillaceous limestone evident in

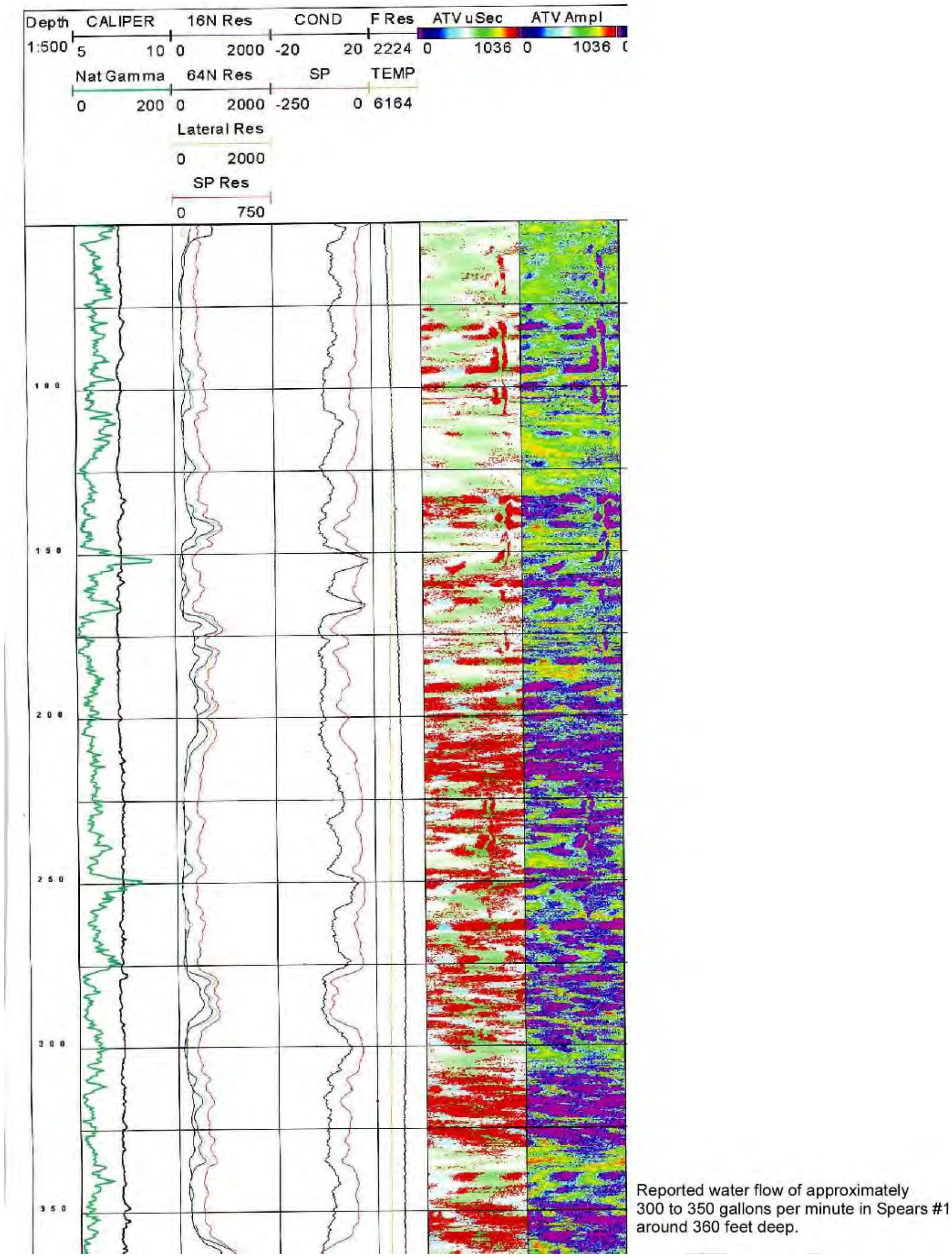


Figure 15. Composite wireline-log diagram showing from left to right: depth, natural gamma-ray (green), caliper (black), resistivity (RES), conductivity (COND), spontaneous potential (SP), temperature (TEMP), acoustic televiewer travel time (ATV uSec), and acoustic televiewer amplitude (ATV Ampl). Red hues in the ATV uSec track reflect porosity and slower acoustic travel time. Green to white colors indicate denser rock and faster travel times.

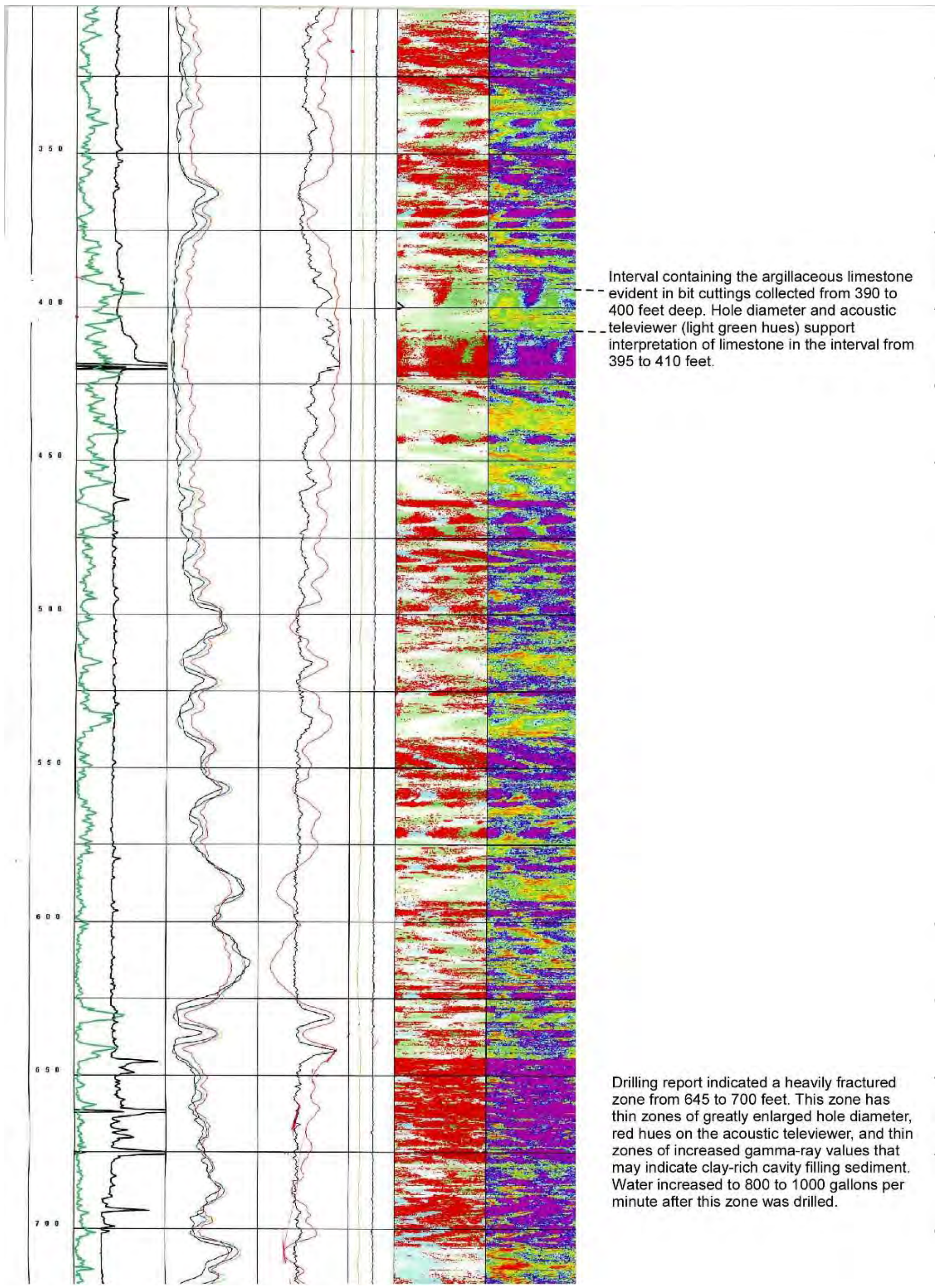
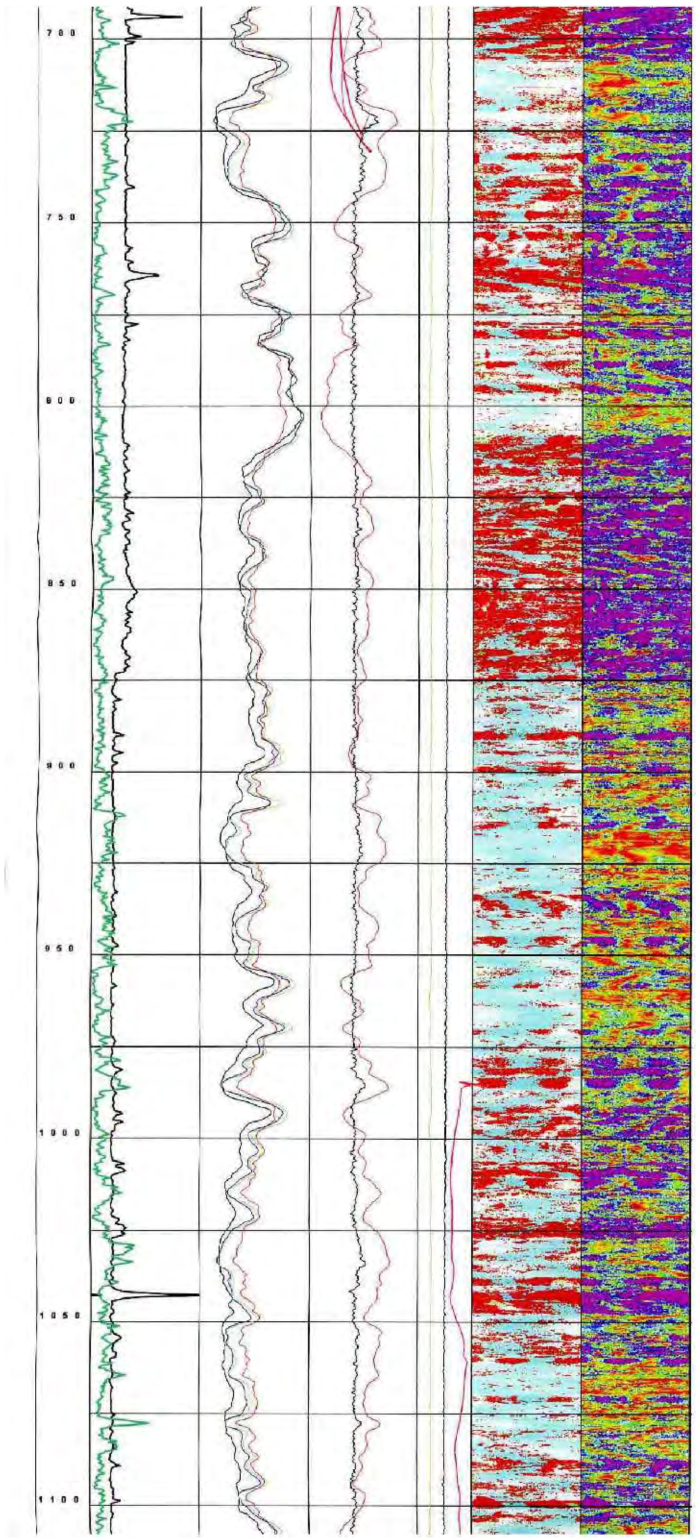


Figure 16. A portion of the section within the lower part of the West Spring Creek Formation. The correspondence between enlarged hole (larger caliper) and red hues (slower travel times indicating voids) is striking. Pump tests confirm the relationship between zones of dissolution or fracturing and the volume of water entering the borehole (after Ross, 2007).



Increased hole size evident on caliper log is reflected by a dominance of red color on the acoustic televiewer.

Figure 17. Composite wireline-log section across the West Spring Creek (810 feet base), and Kindblade (810 to 1280 feet) formations. Sandstone at base of West Spring Creek Formation may be illustrated by white to green zone from 795 to 810 feet (after Ross, 2007).

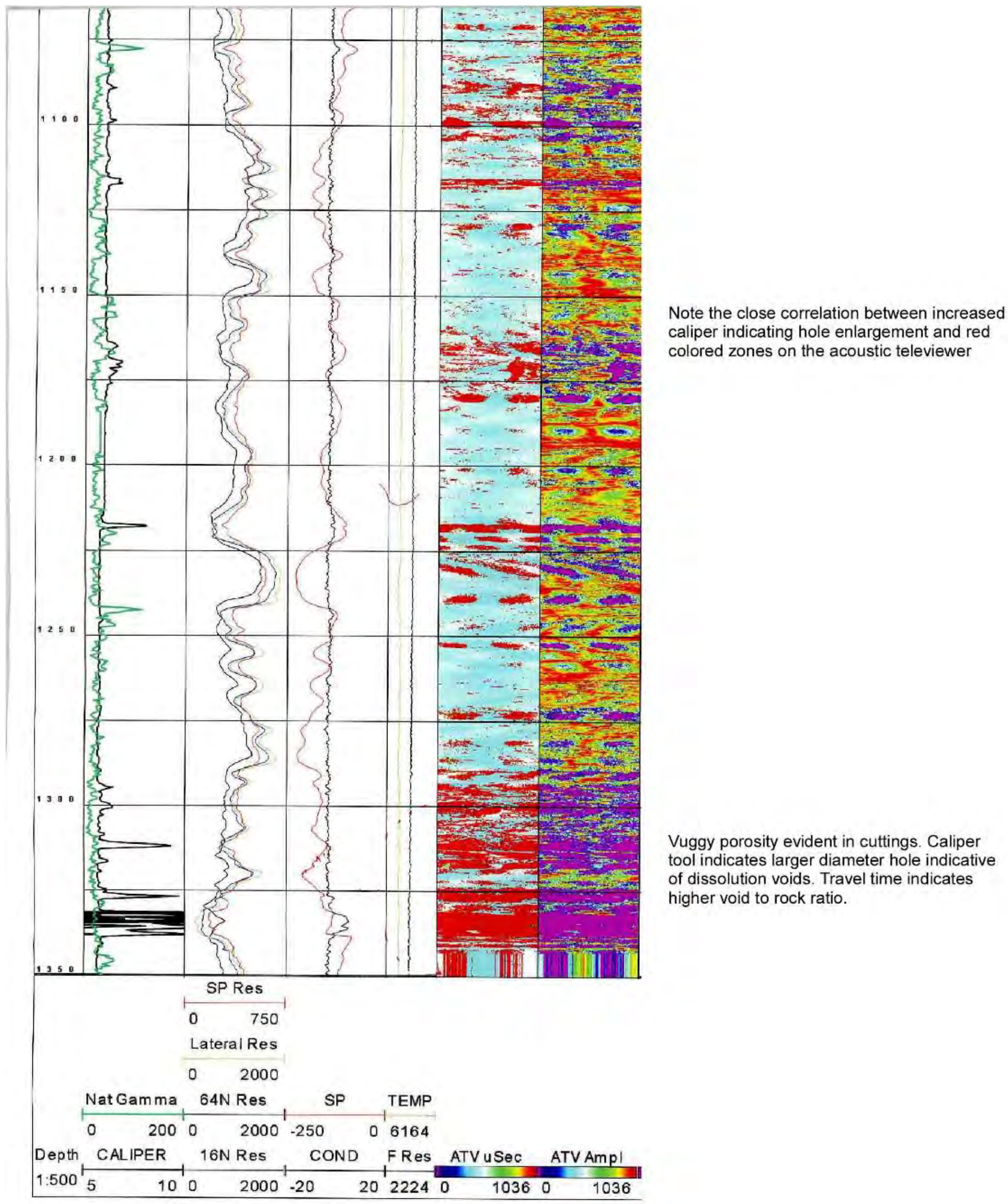


Figure 18. Composite wireline-log representation of the lower part of the Kindblade Formation and uppermost Cool Creek Formation. The porous zone between 1280 feet and 1340 feet may correspond to paleokarst developed along the Kindblade/Cool Creek boundary (after Ross, 2007).

in the cuttings. The red band from 410 to 450 feet corresponds to an enlarged hole as indicated by the caliper. Bit cuttings were missing from 420 to 450 feet, but samples from 400 to 420 contained vuggy porosity and chert.

Green dominates from 450 feet to 475 feet (Figure 16). A mixed zone of approximately 50% green and 50% red extends from 475 to 510 feet. A thin green zone at 530 to 540 feet corresponds to a zone of increased gamma-ray intensity. Another mixed zone from 540 to 645 feet is approximately 30% red. At 645 feet a zone of 90% red begins that extends to 680 feet. The red-dominated zone that is approximately 70% red continues from 680 feet to 710 feet. The red-dominated zone from 645 to 710 feet corresponds to an enlarged hole as indicated by the caliper log. Bit cuttings across this interval contained evidence of fracture/vug filling cements and abundant chert. The driller reported an increase in water in this interval and a flow test at 700 feet was reported as yielding 800 to 1000 gallons per minute (USGS, 2005) (Appendix A).

The interval from 710 feet to 760 feet begins mostly green and becomes increasingly red with depth (Figure 17). Concurrently the caliper indicates the hole is in gauge around 710 feet and remains so until 760 feet. A few thin spikes on the caliper log coincide with streaks of red between 725 and 760 feet. Red becomes dominant again around 760 feet and begins to taper off to 785 feet. This interval coincides with enlarged hole size as indicated by the caliper. Green hues begin increasing around 785 feet and continue to 810 feet. A prominent green zone from 795 to 810 feet appears to correspond to a dolomitic sandstone (Figure 17; see Appendix A).

A prominent red zone begins around 810 feet and extends to 875 feet. A corresponding zone of hole enlargement is evident on the caliper. Bit cuttings through this interval contain evidence of vuggy porosity and saddle dolomite that infilled vugs or fractures. At 875 feet, green becomes the dominant color and remains so until 975 feet. The caliper indicates that the hole through this interval contains thin zones of enlargement, but for the most part, the hole is in gauge. Bit cuttings across this green interval are mostly low porosity dolostone with minor amounts of dolomite cement around 900 feet. This zone of possible porosity is represented by thin streaks of red on the acoustic imager at a depth 890 to 900 feet.

A mixed zone of red and green begins around 975 feet and extends until 1120 feet. Within this interval red-colored zones correlate to thin zones of hole enlargement indicated by the caliper. Scattered zones of vuggy porosity were noted in bit cuttings from this interval; saddle dolomite is pervasive as well. At 1120 feet green begins to dominate and continues until 1290 feet (Figure 18). The upper sixty feet of this interval contains saddle dolomite, but it is mostly absent in the lower one-hundred feet.

A prominent red zone begins at 1290 feet and extends 1340 feet (Figure 18). This zone corresponds to an interval of hole enlargement and evidence of porosity in the bit cuttings. From1280 to 1350 feet, the dolostone contains vuggy porosity and abundant saddle dolomite cement. Furthermore, intercrystalline pores in this interval are 0.3 to 0.4 mm in diameter and saddle dolomite crystals are up to 2 mm in width and length, which suggests larger pores.

7.0 Discussion

Increases in water flow as reported on the drilling reports of the Spears wells indicate that water entered the borehole from discrete intervals (USGS, 2005) (Osborn 2006). These increases in water volume appear to be associated with carbonate intervals containing vuggy porosity, fractures, void-filling cements, chert, and in some cases oxidized rocks. Porous zones located several hundred feet below the surface are similar to features described in cores and outcrops as paleokarst by Musselman (1994) and Lynch and Al-Shaieb (1991). Evidenced of paleokarstic features in the bit cuttings correlated to the evidence of voids as indicated by the wireline logs. For this reason it seems logical that water bearing zones or hydrostratigraphic units in the Arbuckle Group correlate to specific stratigraphic intervals. Preliminary correlation of the Arbuckle Group across the Hunton anticline using gamma-ray signatures (Appendix B) indicates that the largest increase in water occurred around 700 feet below the surface (Osborn, 2006) during the drilling of the lower part of the West Spring Creek Formation. This zone of high porosity and permeability may correspond to the “Brown Zone” recognized by the petroleum industry in a similar stratigraphic position in the West Spring Creek Formation in oil fields in southern Oklahoma. Water flow tests also confirm wireline log and rock evidence that large intervals of the Arbuckle Group carbonate are relatively low porosity/low permeability and contain negligible volumes of water.

While the separation of more porous zones by low porosity/permeability ones is supported by the wireline log, well test and rock evidence, there is no evidence in the Spears #2 that water quality and type change across the drilled interval. The USGS collected water samples from five (5) discrete zones to determine if water chemistry varied across the Spears #2 well. Christenson et al. (2009) report that water was fresh, water chemistry was remarkably uniform and that the range in total dissolved solids was 322 to 332 mg/L. There was no indication of saline water detected and the deepest tested interval in the Spears #2 had the lowest sodium concentration (Christenson et al., 2009).

8.0 Conclusions

The deep aquifer characterization project provided the unique opportunity to drill a fresh borehole, collect representative rock samples, conduct water flow measurements and log the borehole with a modern suite of wireline logs. Although the final depth of investigation by drilling did reach the original objective and hole collapse further limited the depth of wireline log investigations, the various types of data analyzed in this project were integrated to formulate the following conclusions concerning the deep Arbuckle Group aquifer.

1. Bit cuttings provided a representative sample of the subsurface strata and the mode of drilling (air and water) facilitated the recovery of clean and close to true to depth cuttings.

2. The bit cuttings examined visually, tested chemically and x-rayed were found to be overwhelmingly dolomitic and that limestone is limited to a very thin zone around 400 feet below surface. Thin sandstones and sandy dolomites also occur.

3. Rock fabrics were evident in the cuttings that supported the interpretation of fracture-filling calcite and dolomite cements, void-filling calcite and dolomite cements, vuggy porosity, intercrystalline (interrhombic) porosity, silicification of oolites, oxidized zones, and lithology. Original limestone fabrics were difficult to interpret as a result of the extensive and pervasive dolomitization.

4. The carbonate section exposed in the Spears #2 consists of intervals of relatively low porosity/permeability rock and thinner intervals of porous and permeable rocks. The latter type contains rock fabrics indicative of zones of dissolution and cementation. Some of these zones contain evidence of oxidation.

5. Tests conducted during drilling indicated increases in water volume that corresponded to the discrete intervals of porosity and permeability identified in bit cuttings.

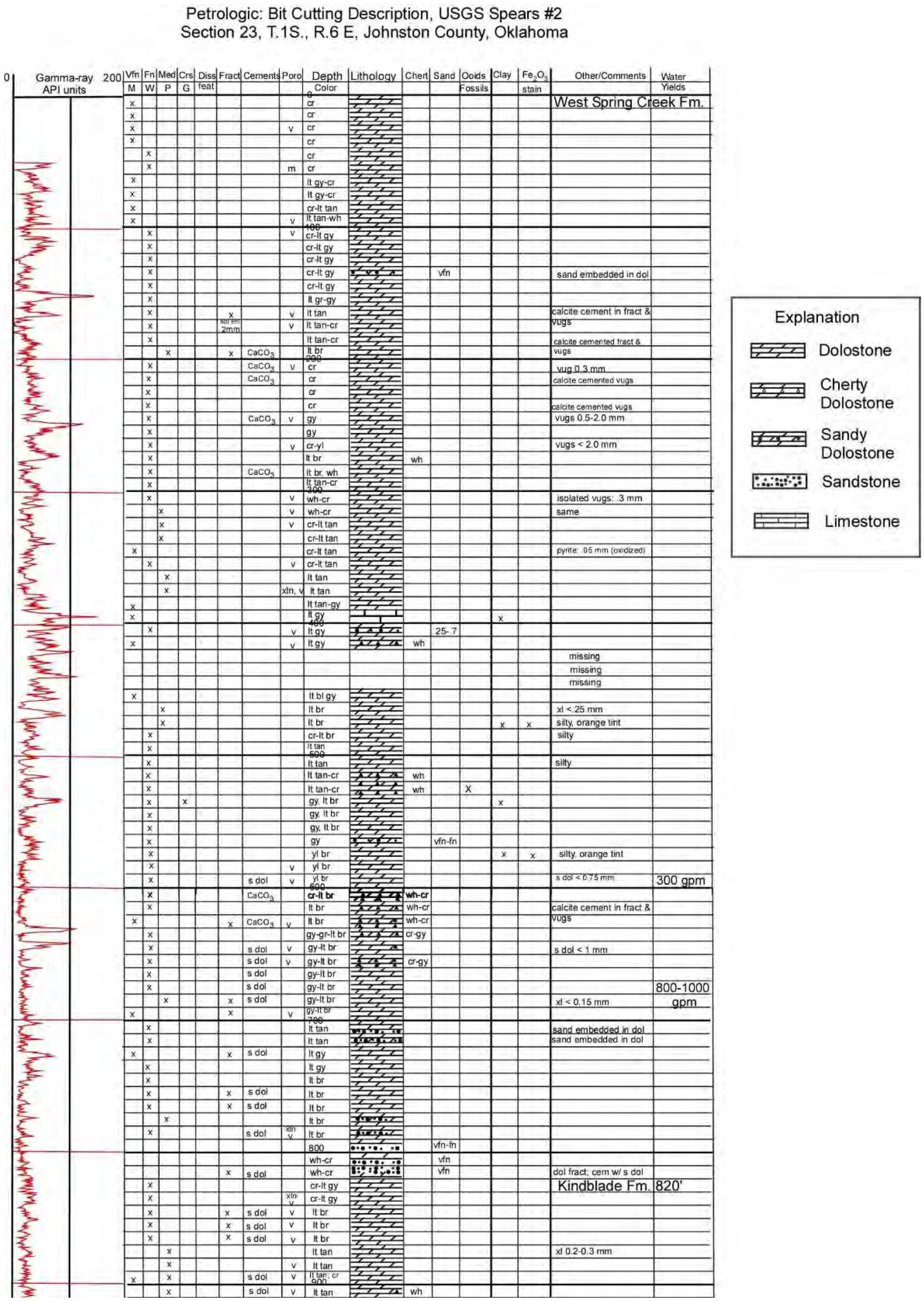
6. Wireline log curves confirmed these discrete porous and permeable intervals by identifying hole enlargement and slower acoustic log travel times. The false color images of the acoustic televiewer (ATV uSecs) confirmed the caliper-indicated voids and supported the interpretation of rock fabrics attributed to dissolution features.

7. The drilled section contains strata of the West Spring Creek Formation, Kindblade Formation and part of the Cool Creek Formation. The stratigraphy was established using the natural gamma-ray log characteristics and lithology.

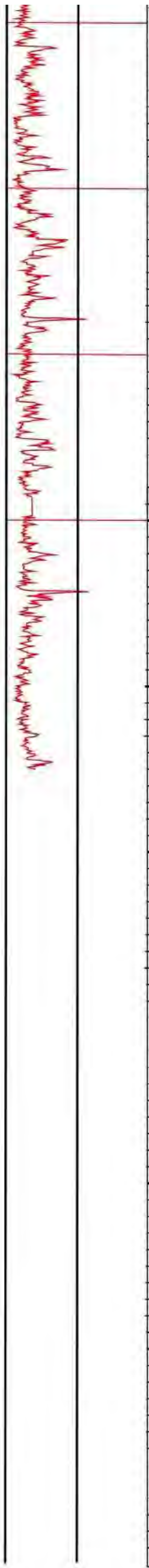
9.0 Appendices

Appendix A: Petrologic Log of the USGS Spears #2 well

Appendix B: Regional Correlation of the USGS Spears #2 to other Deep Gamma-ray Logged Wells



Appendix A. Petrologic Log of the USGS Spears #2 Well



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		x				s dol	v	lt tan	wh						
	x	x						lt tan							
x								lt gy							
x								lt gy				x	x	orange tinted	
x								lt gy-cr							
		x						lt tan-cr		vfn-fn					
		x						lt br							
		x					xln, v	lt br							
	x	x				s dol		cr-lt br							
x								gy,gr-lt tan 1000							
	x	x				s dol		cr-lt br							
	x	x				s dol	v	cr-lt br							
	x	x				s dol		cr-lt br							
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	x	x				s dol		cr-lt tn							
	x					s dol	v	cr							
	x					s dol	v	cr							
	x					s dol	v	cr							
	x					s dol	v	cr-lt tn							
x	x	x				s dol		1100					x	orange tinted	
	x					s dol		cr-br+wh							
	x	x			x	s dol		lt br							
		x				s dol		lt br							
		x				s dol	v	lt br							
	x					s dol	v	lt br							
		x				s dol	v	lt br						trace of sand grains	
	x					s dol		lt br				x	x	orange tinted fill between	
	x	x				s dol		cr-lt br						s dol xls	
	x	x						cr-lt br dk gy-br						xl < .5 mm	
	x							1200							
														missing	
	x							dk gy-cr							
	x					s dol		dk gy-cr							
	x					s dol		cr-tan							
	x							lt gy-lt br							
	x	x						lt gy-lt br							
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	x	x					v	cr-lt tan							
	x	x						cr-lt tan	wh						
	x	x						cr-tan	wh						
		x						lt br	wh						
x	x							cr-lt tan							
x	x					s dol		cr-lt tan gy-br							
	x					s dol		gy br-lt tan							
	x					s dol									
	x					s dol		1700							
		x				s dol			wh						
		x				s dol			wh						
	x	x				s dol			wh		o				
x	x					s dol		br-cr	wh						
						s dol			wh		o				
	x					s dol									
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x	x					s dol calcite								abundant saddle dol	
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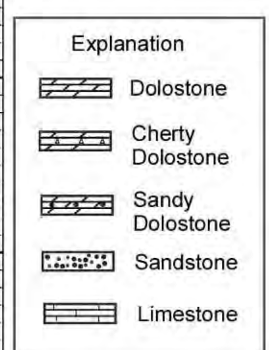
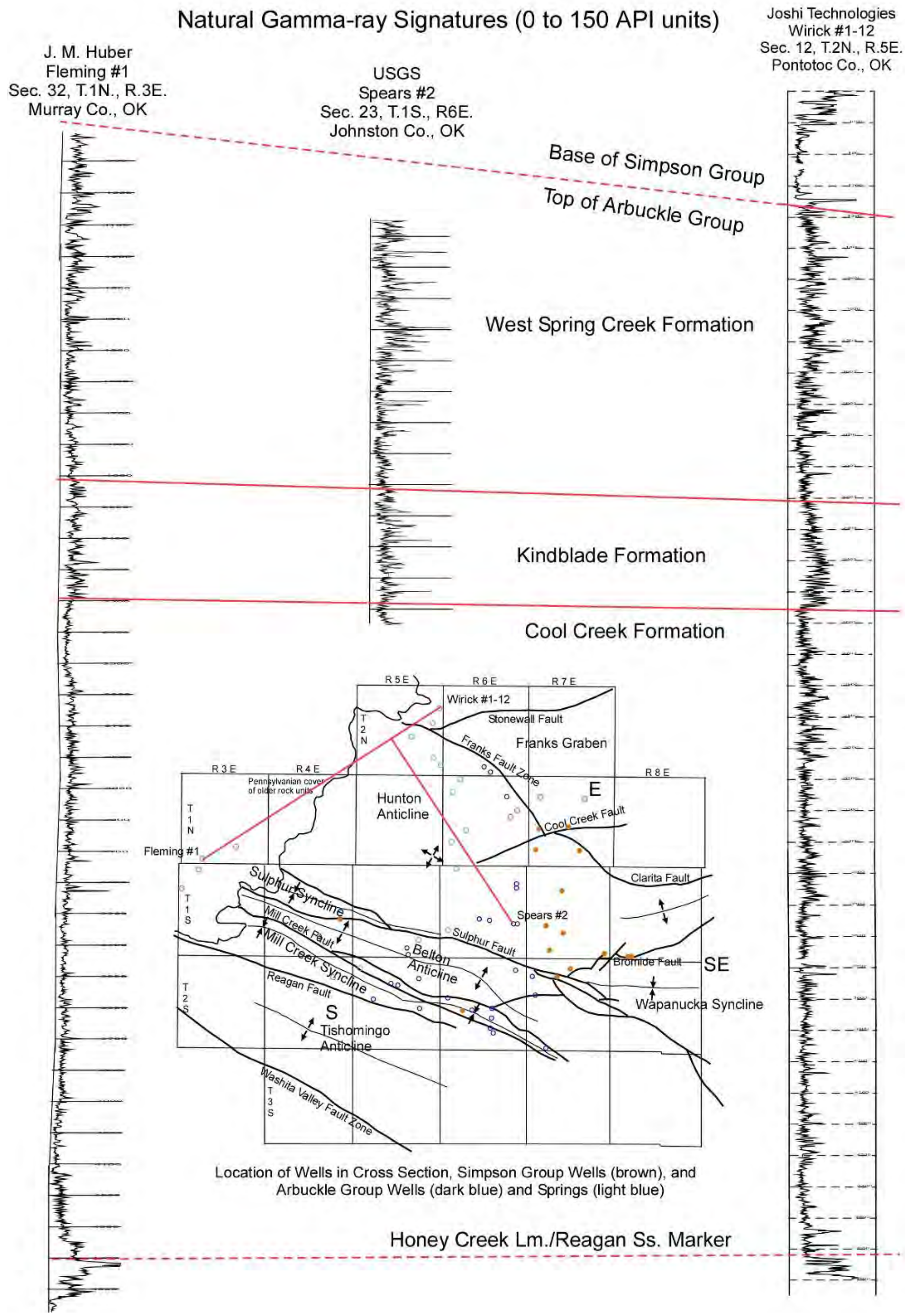


Appendix A. Continued



Appendix B: Correlation of Spears #2 to other Deep Wells with Natural Gamma-ray logs

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