Characterizing Small-Scale Permeability of the Arbuckle Group, Oklahoma

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Preface:

This Open-File Report consists primarily of undergraduate thesis research project work completed in 2014 by the first author, B. Chance Morgan. At present, B.S. thesis projects are filed in hard-copy or electronic form with the supervising professor and Department at the University of Oklahoma, but may not be readily available. The second author, Kyle E. Murray, supervised the thesis research and chose to make some additions and modifications so that valuable information about the Arbuckle Group can be documented and made publicly available.

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Abstract

The Arbuckle Group (i.e., Arbuckle) was formed during the late Cambrian and early Ordovician when the mid-continent was covered by a shallow sea. The Arbuckle underlies nearly the entire state of Oklahoma and is comprised of the Fort Sill Limestone, Royer Dolomite, Signal Mountain Formation, Butterly Dolomite, McKenzie Hill Formation, Cool Creek Formation, Kindblade Formation, and West Spring Creek Formation. Outcrops are present in the Arbuckle Uplift geologic province in south-central Oklahoma where it forms part of the Arbuckle-Simpson Aquifer. In contrast, the top of the (upper) Arbuckle is more than 30,000 ft below land surface in the Anadarko Basin and is a petroleum producing zone in other geologic provinces. Presently, the Arbuckle is primarily used as a saltwater disposal (SWD) zone because it readily accepts wastewater without applying pressure at the wellhead.

Despite its importance to industry, the properties of the Arbuckle have not been well characterized or documented in the literature. Therefore, the objectives of this research were to examine, characterize, and describe Arbuckle material from core and outcrops, while measuring small-scale permeability of the Arbuckle Group. Vertical (normal to bedding planes) matrix, horizontal (along bedding planes) matrix, and fracture permeability measurements were taken in four Arbuckle core using a handheld air permeameter. In the core that were examined, the median vertical matrix permeability was <0.16 mD, median horizontal matrix permeability was 6.62 mD, and median fracture permeability was 18.97 mD. These measurements indicate that the anisotropy ratio (vertical/horizontal) of the Arbuckle should be on the order of 0.01–0.10. Horizontal matrix permeability measurements were taken from outcrops in the Slick Hills of southwestern Oklahoma and the Arbuckle Mountains in south-central Oklahoma, with median being 115.87 mD and 20.34 mD, respectively. These small-scale matrix permeability measurements represent the lower end of permeability for the Arbuckle Group.

Cave and karst features are present in the Arbuckle Mountains of south-central Oklahoma where the Arbuckle is present at the land surface. Presumably, the Arbuckle is highly fractured and karstified in the subsurface in other parts of Oklahoma, and features zones of high permeability that are not recovered while coring. Completion intervals of SWD wells must include fractured or dissolved/karstified sections that have orders of magnitude higher permeabilities than the small-scale matrix permeabilities measured in this study, which allows the Arbuckle SWD wells to accept saltwater on a vacuum (i.e., underpressured).

1. Introduction

The Arbuckle Group (i.e., Arbuckle) was formed during the late Cambrian and early Ordovician when the mid-continent was covered by a shallow sea. The El Paso Group in west Texas, the Ellenburger Group in central and north Texas, the Knox Group in the eastern United States, and the Beekmantown Group in the northeastern United States are equivalent lithostratigraphic units (Loucks, 2006; Murray and Holland, 2014). The Arbuckle underlies nearly the entire state of Oklahoma and is comprised of the Fort Sill Limestone, Royer Dolomite, Signal Mountain Formation (carbonate), Butterly Dolomite, McKenzie Hill Formation (carbonate), Cool Creek Formation (dolostone and sandstone), Kindblade Formation (carbonate), and West Spring Creek Formation (carbonate) (Ham, 1973). The Arbuckle outcrops in the Slick Hills in the Wichita Uplift geologic province of southwestern Oklahoma and in the Arbuckle Uplift geologic province of south-central Oklahoma where it forms part of the Arbuckle-Simpson Aquifer. In contrast, the top of the Arbuckle is more than 30,000 ft below land surface in the Anadarko Basin and is a petroleum producing zone in the Anadarko Shelf, Cherokee Platform, Ardmore Basin, and other provinces. When the Arbuckle is relatively shallow, it is used as a saltwater disposal (SWD) zone because it readily accepts wastewater without applying pressure at the wellhead.

1.1. Co-Produced Water and SWD

Petroleum production has increased in Oklahoma since about 2006, when the Mississippian and Woodford zones were more heavily developed. Concurrent with petroleum production has been a higher annual statewide co-production of water, which was estimated to range from 811–925 million barrels (MMbbl) from 2000–2011 (Murray, 2013). Because SWD volumes in Oklahoma have steadily increased from ~877 million barrels (MMbbl) in 2010 to >1066 MMbbl in 2013 (Murray, 2014), it is important to study the hydrogeologic and geomechanical properties of zones used for SWD. The Arbuckle Group has been the predominant target disposal zone, receiving from 51–62% of the saltwater volumes in Oklahoma from 2010–2013 (Murray, 2014).

1.2. Geologic and Hydraulic Characteristics of the Arbuckle

Bottom-hole pressure data from over 1100 drill-stem tests collected over several decades indicates that the Arbuckle was underpressured (i.e., pressure that is less than hydrostatic) when drilling exploration and production wells (Carrell, 2014). Sixty percent (60%) of the Arbuckle SWD wells operating in Oklahoma from 2010–2013 were reportedly functioning with negative wellhead pressure, which indicates that the majority of the Arbuckle is still underpressured (Murray, 2014).

There are a number of unanswered questions regarding the geologic and hydraulic characteristics of the Arbuckle, such as *What is the capacity for the Arbuckle to accept fluids?*, *Is the pressure in the Arbuckle changing as a result of SWD?*, and *Why is the Arbuckle underpressured?* Several mechanisms may explain how a deeply buried reservoir can be underpressured including the diagenetic alteration of limestone to dolomite, which can increase volume of porosity (Jones and Xiao, 2005).

1.3. Objectives

The objectives of this study are to examine, characterize, and describe Arbuckle material from core and outcrops, while measuring small-scale permeability of the Arbuckle Group. This contributes to our understanding of the Arbuckle, and consequently, our ability to model changes that may occur in reservoir pressure as a result of fluid production or injection.

2. Methods

This study focused on characterizing four cores, available at the Oklahoma Petroleum Information Center (OPIC) managed by the Oklahoma Geological Survey (OGS), containing parts of the upper Arbuckle from Kay and Osage Counties, from outcrops in the Slick Hills in Comanche County, and from outcrops in the Arbuckle Mountains of south-central Oklahoma along the I-35 corridor in Carter and Murray Counties (Figure 1). Lithology, texture, grain size, cement mineralogy, and fracture condition were observed and recorded. Permeability was measured in various directions (i.e., horizontal or vertical) relative to the natural bedding planes of the rock using a hand-held TinyPerm II air permeameter (New England Research, White River Junction, VT).

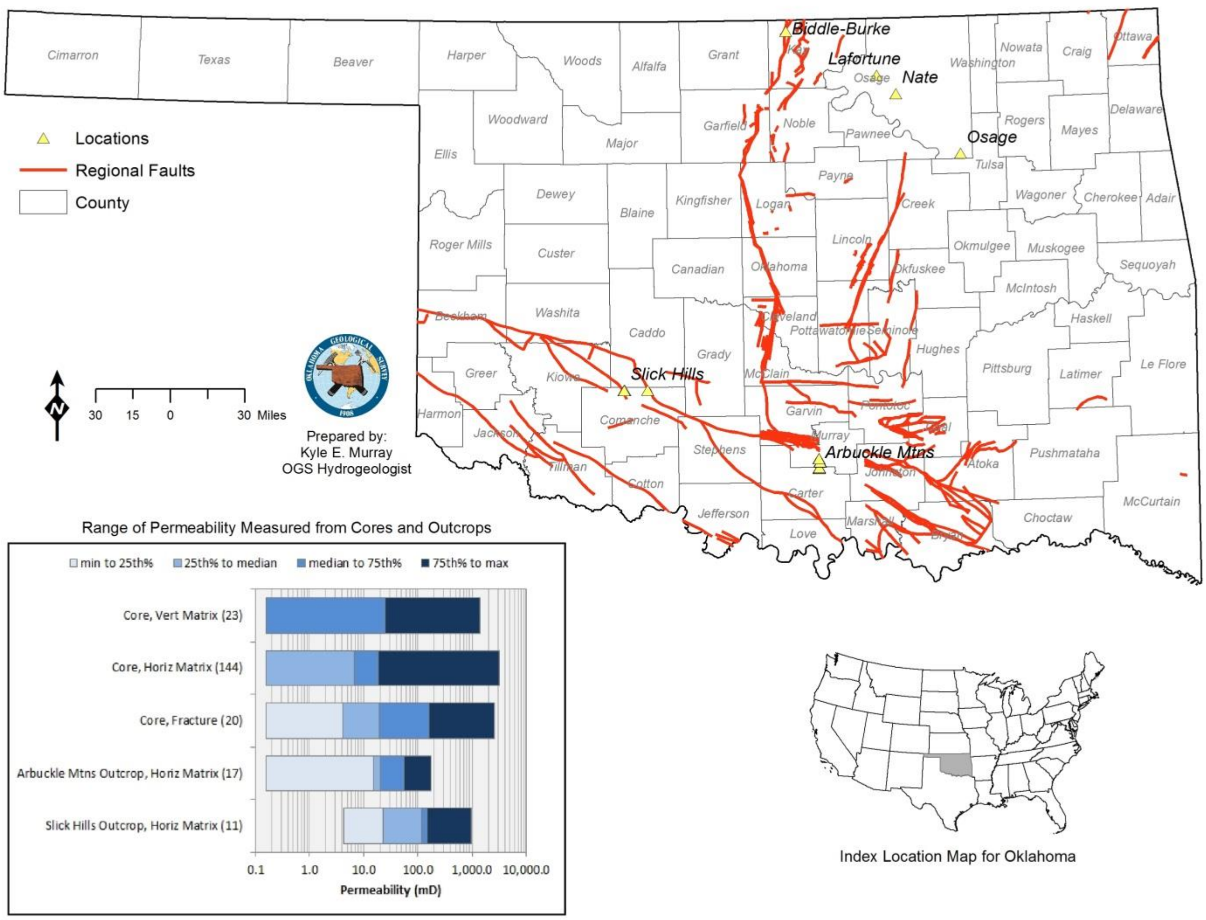

Figure 1 Map showing locations of Arbuckle cores and outcrops examined in this study, with chart for various permeability measurements of cores and outcrops.

2.1. *Core Measurements*

Boxes containing slabbed (1/3 and 2/3 diameter) sections of the four cores were laid out on a viewing table at OPIC. Cores were examined and described using a worksheet that was based on methodologies described in the OGS Arbuckle core workshop (Lynch and Al-Shaieb, 1991).

Lithological boundaries were noted and descriptions were then recorded including lithology, textures which included grain size and sedimentary classification, cement and/or matrix material, any fossils or accessories, sedimentary structures, porosity type, and type and orientation of fractures. Permeability was then measured using a handheld TinyPerm II air permeameter. When measuring permeability, a seal was created between the TinyPerm II nozzle and the core surface by exerting a "bodyweight" force onto the core surface, the TinyPerm II plunger was then fully depressed, and a stopwatch was immediately started. The stopwatch was stopped when the TinyPerm II reading was complete and then the TinyPerm II reading and elapsed time were recorded. TinyPerm II readings were converted to permeability in milliDarcy (mD) using Equation (1):

$$Permeability\ (mD) = 1E34\ \times TinyPerm\ II\ Reading^{-30.53} \qquad \text{Equation (1)}$$

If the TinyPerm II reading was not complete after 600 sec (10 min), then the measurement was aborted and permeability was recorded as <0.16 mD. Horizontal matrix permeability was measured about once every foot of the core, while vertical matrix permeability was measured when a break in the core material allowed for measurement normal to the bedding planes. Notable fractures were measured with the TinyPerm II to estimate fracture aperture using Equation (2):

$$Fracture\ aperture\ (mm) = 10^{\frac{(TinyPerm\ II\ Reading - 8.2887)}{-1.5022}} \qquad \text{Equation (2)}$$

2.2. *Outcrop Measurements*

Because core from the lower Arbuckle are seldom available, measurements were taken in two areas that provided access to outcropping sections of the lower Arbuckle Group. The Arbuckle Group outcrops in its entirety in the Slick Hills north of the Wichita Mountains (Donovan, 1986) and in the Arbuckle Mountains in south-central Oklahoma.

Lithological boundaries were noted after arriving to the field location. Loose sand or carbonate grains were removed from the face of the rock and a clean surface was created by using a rock hammer to break into the weathered surface. Outcrop descriptions were taken including lithology, texture or grain size, sedimentary classification, cement and/or matrix material, presence of fossils or accessories, sedimentary structures, porosity type, type of fractures, and fracture orientation. Permeability was measured on the outcrop surface using the same procedure described for core measurements. Measurements began in the oldest Arbuckle rock and continued into the younger rock. Formation boundaries were not discernible, but were previously described as part of the lower Arbuckle (Donovan, 1986). At least one measurement was taken every 30 ft (vertically), in addition to measurements taken at lithological contacts and fractures.

3. Results

Full descriptions of the core and outcrop materials are available in a University of Oklahoma undergraduate thesis (Morgan, 2014); however, a summary is given in this report with emphasis on permeability measurements.

3.1. *Oliphant LaFortune – 3 Core*

About 24 ft of core were available from 3334.0–3363.2 ft depth for the Oliphant LaFortune – 3 core from Osage County, northern Oklahoma, with a section missing from 3338–3344 ft depth. The core material is a very fine-grained, micritic, dolomitized, unfossiliferous limestone. Horizontal matrix permeability was measured at 17 locations on the core with permeability ranging from <0.16 mD to 309 mD, while the median horizontal matrix permeability was <0.16 mD because 12 measurements were <0.16 mD. Vertical matrix permeability was measured at three locations on the core and ranged from <0.16 mD to 197 mD, with two measurements being <0.16 mD. Fracture aperture measurements ranged from <0.3 μm to 4.5 μm with respective permeabilities of <0.16 mD to 19.23 mD, and median permeability of 3.77 mD.

Figure 2 Dry Oliphant LaFortune – 3 Core from 3334–3335 ft, showing the contact of the overlying Simpson Group with the underlying Arbuckle Group at about 0.35 ft on the measuring tape

3.2. *Oliphant Nate – 1 Core*

About 16 ft of core were available from about 2822–2830 ft and 2860–2868 ft depth for the Oliphant Nate – 1 core from Osage County, northern Oklahoma. Upper parts, 2822–2830 ft and 2860–2861 ft depth, of the core were comprised of the Simpson sandstone, which had a visible contact with the underlying Arbuckle at 2861 ft depth.

The Simpson core material is a very fine-grained sandstone. Horizontal matrix permeability was measured at four locations on the Simpson core material and ranged from <0.16 mD to 950.48 mD, while the median horizontal matrix permeability was 247.61 mD. Vertical matrix permeability was measured at four locations on the Simpson core material, ranging from <0.16 mD to 181.53 mD with a median of 169.39 mD. No fractures were visible for measurement of fracture aperture or permeability.

The Arbuckle core material is a very fine-grained, micritic, dolomitized, unfossiliferous limestone (Figure 3). Horizontal matrix permeability of the Arbuckle was measured at seven locations on the core ranging from <0.16 mD to 49.93 mD, while the median horizontal matrix permeability was <0.16 mD because four measurements were <0.16 mD. Vertical matrix permeability of 10.67 mD was measured at one location on the Arbuckle core material. Fracture aperture measurements ranged from 27.2 μm to 65.2 μm with respective permeabilities of 527.27 mD to 2610.04 mD, and median permeability of 1568.65 mD.

Figure 3 Dry Oliphant Nate - 1 Core from 2862.2 to 2862.9 ft, showing a bituminous vein with apparent fracturing and vuggy porosity

3.3. *Biddle-Burke – 6 Core*

About 77 ft of core were available from about 3318–3403 ft depth for Wedgewood Biddle-Burke – 6, which was drilled in Kay County, northern Oklahoma, with a section of core missing from 3371–3379 ft depth. The core material is a medium or medium-coarse grained, dolomitized grainstone (Figure 4). Horizontal matrix permeability was measured at 76 locations on the core and ranged from <0.16 mD to 3.089 Darcy, with a median of 13.35 mD. The highest permeability measurement was collected from a core interval having large vuggy porosity. Vertical matrix permeability was measured at eight locations on the core and ranged from <0.16 mD to 1407.83 mD with a median of 24.31 mD. Nine fracture aperture measurements ranged from 2.9 μm to 701.5 μm with respective permeabilities ranging from 9.02 mD to 527.27 mD, and median permeability of 103.57 mD.

Figure 4 Dry Wedgewood Biddle-Burke – 6 Core from 3365 to 3365.9 ft, showing a porous carbonate section with a visible stylolite

3.4. *Osage C-1 Core*

About 77 ft of core were available from about 3397–3445 ft depth for Osage C-1 from Osage County, northern Oklahoma. The Osage C-1 core material is a fine- to medium-grained, dolomitized grainstone. Horizontal matrix permeability was measured at 40 locations on the core and ranged from <0.16 mD to 119.17 mD, with a median of 2.64 mD. Vertical matrix permeability was measured at seven locations on the core and ranged from <0.16 mD to 3.10 mD with a median of <0.16 mD. One fracture aperture measurement of <0.3 μm with a respective permeability of <0.16 mD was taken from the Osage C-1 core.

3.5. *Slick Hills Outcrops*

A total of 11 measurements were taken over a large area in the Slick Hills (Figure 5), all of which were taken parallel to bedding planes or visible laminations. Horizontal matrix permeability ranged from 4.23 mD to 977.53 mD with a median of 115.87 mD.

Figure 5 Slick Hills outcrop where permeability readings were taken. This outcrop is predominantly comprised of the Fort Sill Formation within the lower Arbuckle Group.

3.6. *Arbuckle Mountains Outcrops*

Measurements in the Arbuckle Mountains were taken along I-35 and Highway 77 in south-central Oklahoma. A total of 17 horizontal matrix permeability measurements were taken throughout the entirety of the Arbuckle Group, and ranged from <0.16 mD to 171.63 mD with a median of 20.34 mD. Because this area was cleared using explosives, the rock (Figure 6) was not highly weathered and more closely resembled the OPIC cores than the Slick Hills outcrop.

Figure 6 Arbuckle Mountains outcrop material along I-35 in south-central Oklahoma

4. Discussion and Summary

The Arbuckle Group (i.e., Arbuckle) is late Cambrian to early Ordovician in age and underlies nearly the entire state of Oklahoma. Outcrops of the lower Arbuckle are accessible in the Slick Hills of southwestern Oklahoma and in the Arbuckle Uplift geologic province in south-central Oklahoma. The upper Arbuckle is a petroleum producing zone in other geologic provinces, where it is only accessible from core material. The Arbuckle is widely used as a SWD zone because it readily accepts wastewater without applying pressure at the wellhead. Despite its importance to industry, the properties of the (subsurface) Arbuckle have not been well characterized or documented in the literature, making it difficult to model lateral or vertical propagation of reservoir pressure in the subsurface.

Core and outcrop Arbuckle materials were examined, characterized, and described, while measuring horizontal (along bedding planes) matrix, vertical (normal to bedding planes) matrix, and fracture permeability using a handheld air permeameter. Four Arbuckle cores were examined including Oliphant LaFortune – 3, Oliphant Nate – 1, and Osage C-1 from Osage County, northern Oklahoma, and Wedgewood Biddle-Burke – 6 from Kay County, northern Oklahoma. In the cores that were examined, the median value was lowest for vertical matrix permeability at <0.16 mD, followed by horizontal matrix permeability with a median of 6.62 mD, and fracture permeability with a median of 18.97 mD (Table 1 or Figure 7). Fracture aperture ranged from <0.3 μm to 701.5 μm for the 20 fractures that were measured in the Arbuckle cores (Table 1 or Figure 8). Measurements of lower Arbuckle permeability in outcrops of the Slick Hills of southwestern Oklahoma and the Arbuckle Mountains in south-central Oklahoma indicate that median horizontal matrix permeability is 115.87 mD and 20.34 mD, respectively (Table 1 or Figure 7). Because median horizontal matrix permeability measurements from the upper Arbuckle (core) are lower than median horizontal matrix permeability measurements from the Lower Arbuckle (outcrop), it is likely that the matrix of the lower Arbuckle has a higher permeability.

Table 1 Summary of permeability and fracture aperture measurements from Arbuckle core and outcrops

Category	Minimum	25^{th} %	Median (50^{th} %)	75^{th} %	Maximum
Core, Vertical Matrix Permeability (mD), (n=23)	<0.16	<0.16	<0.16	24.31	1407.83
Core, Horizontal Matrix Permeability (mD), (n=144)	<0.16	<0.16	6.62	18.83	3088.61
Core, Fracture Permeability (mD), (n=20)	<0.16	4.06	18.97	161.73	2610.04
Arbuckle Mtns Outcrop, Horizontal Matrix Permeability (mD), (n=17)	<0.16	15.37	20.34	55.86	171.63
Slick Hills Outcrop, Horizontal Matrix Permeability (mD), (n=11)	4.23	22.62	115.87	145.95	977.53
Core, Fracture Aperture (µm), (n=20)	<0.3	1.9	4.4	14.3	701.5

The range of permeability measured in this study, Figure 7, indicates that the Arbuckle is highly heterogeneous and anisotropic and varies by five or more orders of magnitude. Because the Arbuckle is believed to be highly fractured and karstified in the subsurface, these small-scale matrix measurements represent the lower end of permeability for the Arbuckle Group. Sections of Arbuckle core that are missing or were not recovered during drilling may represent dissolution or karst features, and may be worth inventorying as a proxy for high permeability zones in the deep subsurface. Completion intervals of SWD wells must include these fractured or dissolved/karstified sections that have orders of magnitude higher permeabilities than the small-scale matrix or fracture permeabilities measured in this study. Our measurements indicate that vertical matrix permeability is orders of magnitude lower than horizontal matrix permeability or fracture permeability; therefore, when modeling fluid flow through the Arbuckle the anisotropy ratio (vertical/horizontal) should be on the order of 0.01–0.10. Additional research is required to process drill-stem and shut-in tests so that larger-scale permeability of the Arbuckle can be characterized.

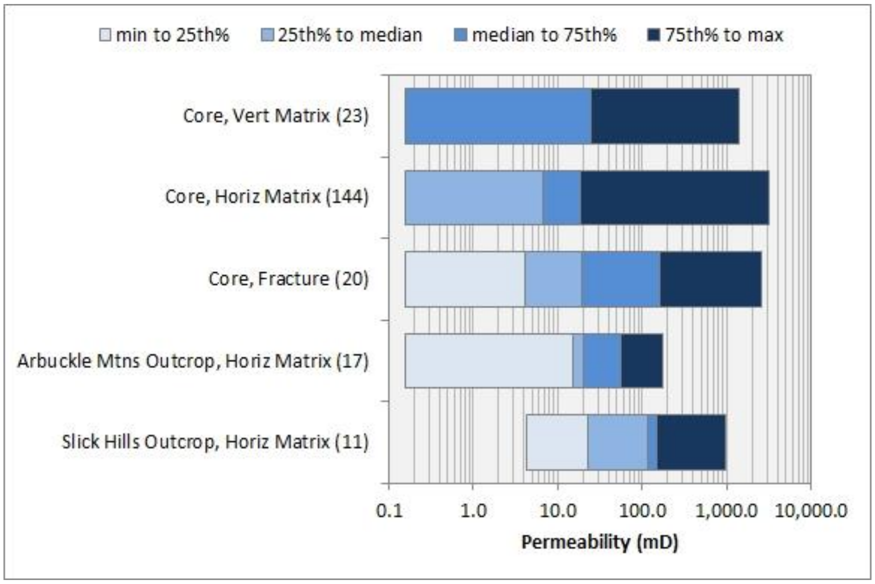

Figure 7 Range of permeability with (n) indicating number of measurements taken for each category

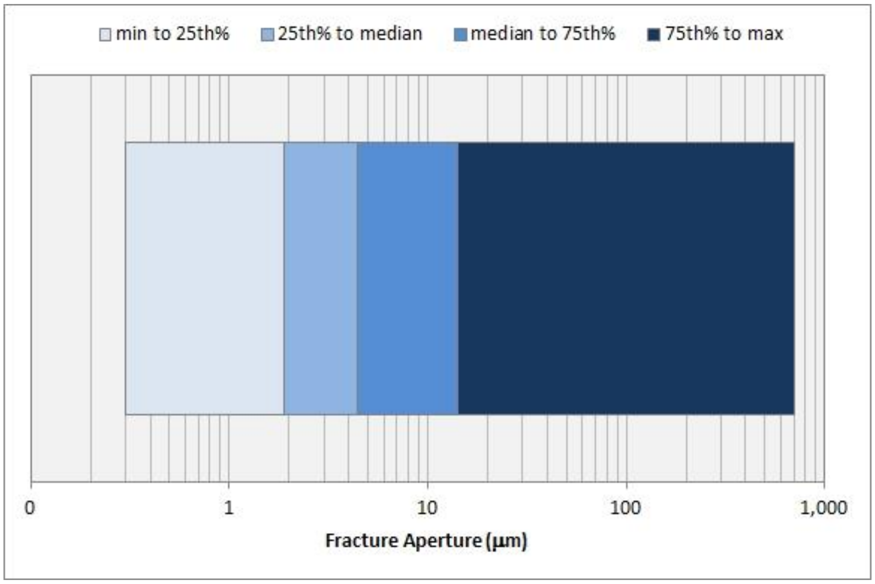

Figure 8 Fracture apertures measured from Arbuckle cores

5. Acknowledgements

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