Report for the Arbuckle-Simpson Hydrology Study:

Characterization of the Arbuckle-Simpson Aquifer

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Characterization of the Arbuckle-Simpson Aquifer

FINAL REPORT

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Cover: Photograph of Turner Falls

Table of Contents

List of Figures

List of Figures (con't)

List of Tables

1.0 Executive Summary

1.1 Background

The Arbuckle-Simpson aquifer is a primary source of water for a number of spring-fed streams, as well as domestic, livestock, industry and municipal water wells located in southern Oklahoma. As a result of rugged and rocky terrain overlying the aquifer, tillable land is scarce, irrigation minimal, and groundwater withdrawal from the aquifer for all uses is low. However, the growth of metropolitan areas in northern Texas and central Oklahoma, in combination with drought conditions and water shortages, has focused attention on the Arbuckle-Simpson aquifer as a possible source of water for these urban areas. In response to the recent and widespread interest in the aquifer, a study was launched with the objective to gather data and ultimately develop a numerical hydrogeologic model to help manage this valuable resource in an objective, evidence-based manner.

1.2 Purpose and Scope

The purpose of this phase of the project is to facilitate our understanding of the Arbuckle-Simpson aquifer by acquiring the necessary data concerning rock properties and the spatial distribution of hydrostratigraphic units to build a geologic model and a numerical hydrogeologic model. The internal lithostratigraphy and structural attitude of the Arbuckle and Simpson Groups were analyzed and the results integrated into a geologic model developed to illustrate the three-dimensional distribution of hydrostratigraphic flow units and define fault- and basement-induced boundary conditions. This geologic model is the foundation for and an essential component of the numerical model.

The numerical model of the Arbuckle-Simpson aquifer is the predictive tool for analyzing the impacts of recharge and discharge on the water budget and delineating potential flow paths within hydrostratigraphic units. Numerical models depend on a number of input data to produce reliable results. These include aquifer thickness, distribution, pore geometry and volume, hydraulic conductivity (permeability), hydraulic gradient and fluid properties. In this study, a variety of data sources were gleaned to find information necessary to define these variables.

1.3 Data for Geologic and Groundwater models

The essential geologic data required for the construction of valid and useful geologic and groundwater models comes from a number of sources. Stratal thicknesses and the spatial distribution of hydrostratigraphic units were determined using wireline logs and lithologic descriptions from water supply and petroleum exploration wells. Distribution of the aquifer flow units was achieved by mapping the subsurface using water and petroleum well data and surface geophysical techniques. Porosity values for the hydrostratigraphic units were derived primarily from wireline logs and core data from wells. The structural attitude of hydrostratigraphic units was established by mapping using surface and well-based data. Pore fluid types and their distributions were determined using reported well tests and fluid recoveries reported on well reports. In all, well records for over 250 water supply wells and 1150 petroleum exploration wells were examined. Data recovered from these records were essential to constructing the sound geologic and groundwater models necessary for the proper management of this valuable water resource.

1.4 Study Area

The Arbuckle-Simpson aquifer contains freshwater in an area that generally coincides with the region in southern Oklahoma known as the Arbuckle Mountain uplift (Figure 1). The Arbuckle Mountains are a large northwest to southeast trending anticlinal fold that contains exposures of Arbuckle-Simpson hydrostratigraphic units along it length. This study focuses on the Hunton Anticline, a tectonic subregion in the eastern portion of the Arbuckle Mountain uplift, and includes parts of Murray, Pontotoc, Johnston and Coal Counties, Oklahoma (Figure 1).

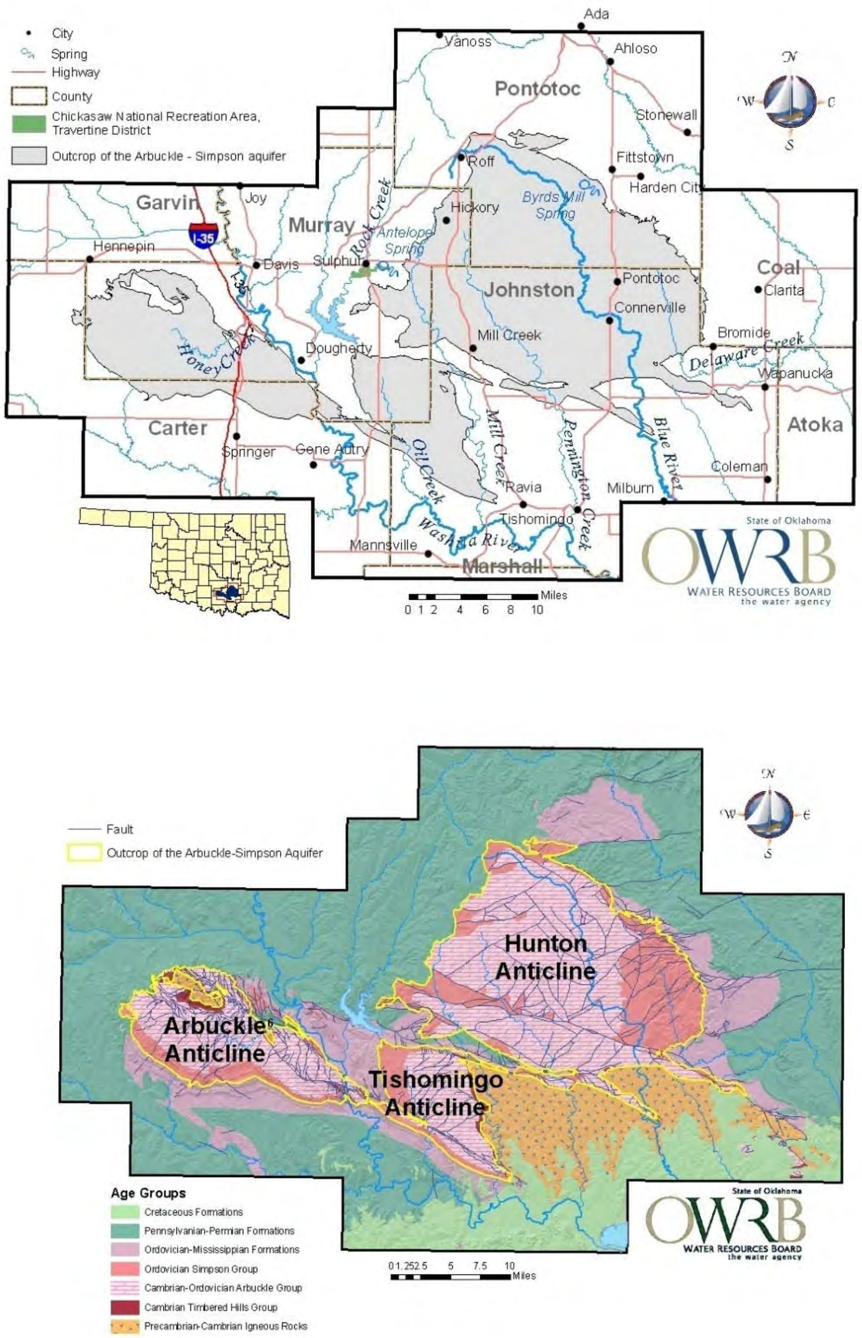


Figure 1. Generalized geology (bottom) and location of the Arbuckle Mountain uplift (top) showing the relationship of major streams with the Arbuckle-Simpson aquifer outcrop (from Oklahoma Water Resources Board (OWRB), 2008).

2.0 Introduction

2.1 Stratigraphy

The stratigraphy of the aquifer-bearing rocks that outcrop in the Arbuckle Mountains is illustrated in Figure 2. The term Arbuckle aquifer is applied to any pre-Simpson sources of water hosted in limestone or dolomitic limestone. As a result, the aquifer spans strata of the Arbuckle and Timbered Hills Groups. The Simpson aquifer coincides with the lithostratigraphic Simpson Group and includes all water-bearing strata within it. Water-bearing sandstones occur in the Bromide, Tulip Creek, McLish, and Oil Creek Formations. Well records compiled to date indicate that most completions in the Simpson aquifer produce water from sandstone within the Oil Creek Formation.

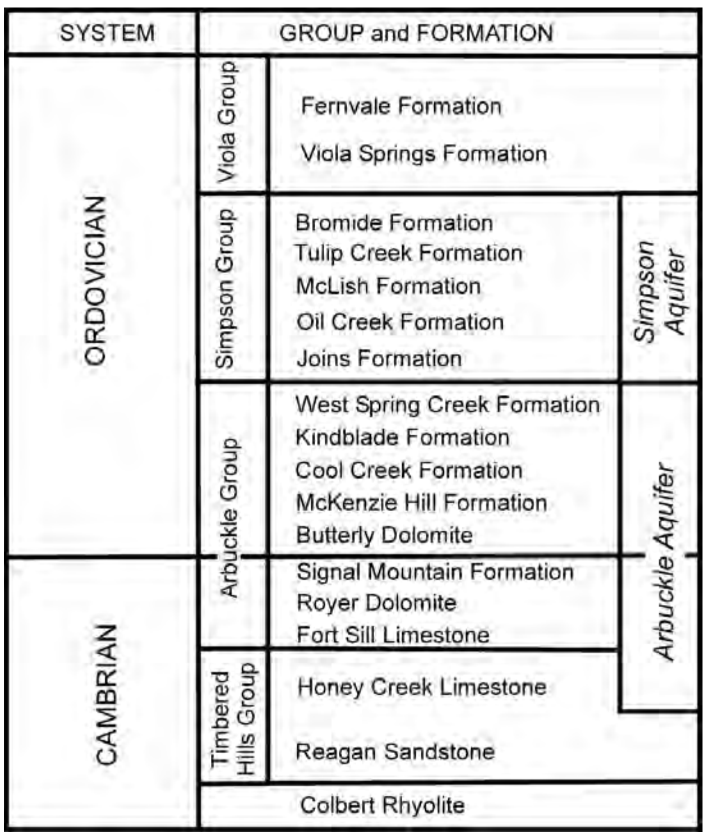


Figure 2. Stratigraphic nomenclature for the pre-Sylvan Ordovician and Cambrian rocks that outcrop in the Arbuckle Mountains. Positions of the Arbuckle and Simpson aquifers are noted (after Fay, 1989).

2.2 Thickness and Distribution of Hydrostratigraphic Units in the Arbuckle-Simpson Aquifer, Hunton Anticline, Southern Oklahoma

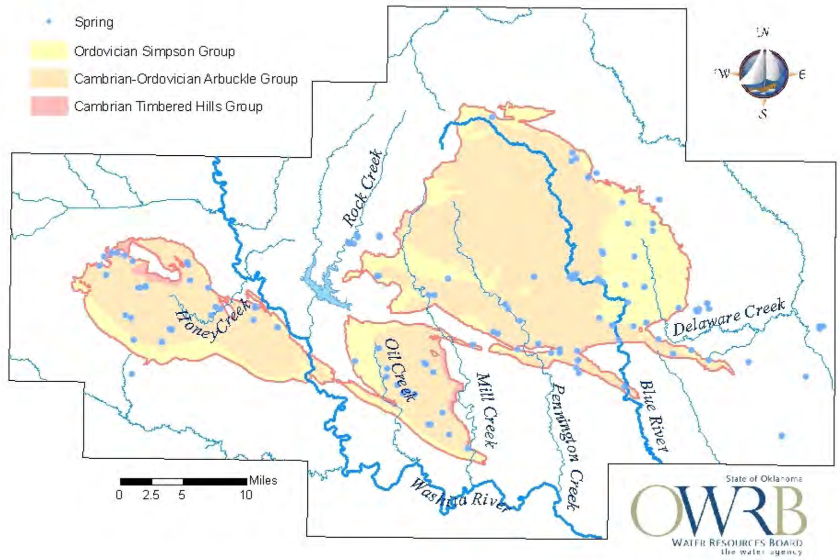
Data collected from domestic, water district and municipal water wells located on the Hunton Anticline of the Arbuckle Mountain uplift indicate that the Arbuckle-Simpson aquifer contains two prominent hydrostratigraphic units: (1) the carbonates of the Arbuckle Group and (2) sandstones of the Simpson Group. Furthermore, a survey of springs in the area revealed that a majority discharge from outcrops of the Arbuckle Group (Figure 3). Fewer large-volume springs discharge from the Simpson Group, but discharge is evident in quarries and pits that extract sand from the Bromide and Oil Creek sandstones. Well data are summarized in Table 1; spring data are summarized in Table 2.

A major task of the characterization study is to determine the thickness and distribution of hydrostratigraphic units within the Arbuckle-Simpson aquifer. To accomplish this, all available aquifer data were collected and analyzed. These included various types of data collected during the drilling of water wells and information gleaned from the examination of data collected during the drilling of oil and gas wells. This information was integrated with surface and subsurface geology to best delineate distribution and thickness of the major hydrostratigraphic units within the study area.

2.3 Aquifer Properties

Porosity, the volume of space in a given volume of rock, was determined using wireline log measurements from wells that were logged with density, neutron or sonic porosity tools. A limited number of porosity and permeability measurements were available from outcrop studies and core analyses taken from wells in oil and gas fields outside the study area. Porosity measurements from water wells and few porosity logs were available within the boundaries of the study.

Three porous and permeable sandstones occur in the Simpson Group within the confines of the study area. These are the Bromide, basal McLish, and basal Oil Creek sandstones. These three units are easily correlated and occur as isolated hydrostratigraphic units within intervals of shale and low-porosity carbonates that serve as aquitards or seals.



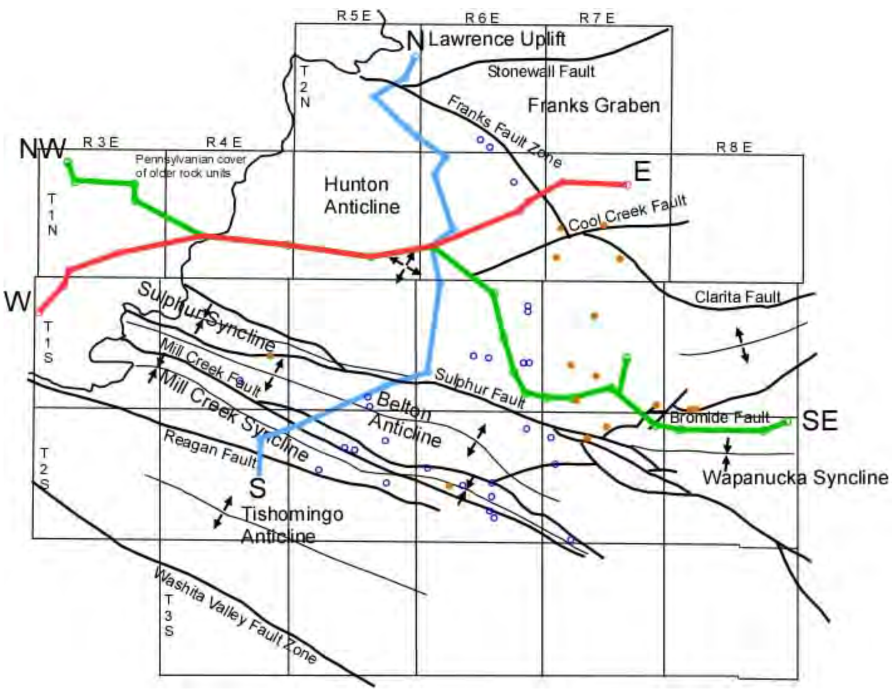


Figure 3. Locations of selected springs in the Arbuckle Mountains (top). Numerous springs discharge from the Simpson and Arbuckle Groups, but in general, larger volume springs discharge from the Arbuckle Group. In the vicinity of the Hunton Anticline tectonic subregion (bottom), many springs are associated with fault zones where hydrostratigraphic units intersect the topography. Blue circles represent springs discharging from the Arbuckle Group; brown circles the Simpson Group. Cross section lines (color) are shown in Figures 7, 8, and 9. Average and ranges of discharge rates are given in Table 2; backup data are in Appendix 2 (upper figure and spring data courtesy of OWRB, 2008)

The basal McLish and Oil Creek sandstones are widely distributed across the study area and occur on all flanks of the Hunton anticline. In contrast, the thicker Bromide sandstones are restricted to the northern and western flanks. Because of their wider distribution, Oil Creek and McLish sandstone were examined to determine Simpson aquifer properties.

Porosity in the Oil Creek Sandstone was measured from well logs for 17 wells. The average porosity for the basal Oil Creek Sandstone was 20% based on a sandstone grain density of 2.65 g/cm^3. In all wells surveyed, porosity values ranged from <10 - 26% in the Oil Creek. In comparison, the McLish Sandstone (basal) exhibited porosity values ranging from <10 - 25%, and averaged 20% (n=14). Porosity measurements for the Oil Creek and McLish sandstones are summarized in Table 3.

Hydrostratigraphic Unit	Number of wells	Range of well yields in gallons per minute (gpm)	Average yield in gpm	Source
Arbuckle Group	70	2 - 2000	140	OWRB (2008) Nord (2000)
West Spring Creek Fm	47	5 - 2000	160	OWRB (2008) Nord (2000)
Simpson Group	59	4 – 900	45	OWRB (2008)
Oil Creek Sandstone	44	4 – 150	38	OWRB (2008)
Bromide/McLish Sandstones	14	8 – 900	94	OWRB (2008)
Pennsylvanian undifferentiated	14	1 – 200	24	OWRB (2008)

Table 1 Average and ranges of yields for selected hydrostratigraphic units in wells located in the vicinity of the Hunton Anticline. All well data are from sources in the public domain. Yields for individual wells are provided in Appendix 1.

Far fewer porosity logs are available for the Arbuckle Group. Porosity in the Arbuckle carbonates is difficult to quantify as the aquifer consists of thick sections of low porosity carbonate that are punctuated by thin zones of vuggy, solution-enlarged fracture or cavernous porosity. The vertical distribution pattern of porous/permeable zones within the Arbuckle carbonates (Figure 4) reflects this phenomenon.

Permeability/hydraulic conductivity of the Simpson and Arbuckle hydrostratigraphic units was qualitatively analyzed because core samples and drill stem test charts necessary for quantification were not available. A limited number of permeability values were available for samples taken from cores from wells located outside the study area, but these data are sparse.

Hydrostratigraphic Unit	Number of Springs	Range of spring discharge in gallons per minute (gpm)	Average discharge in gpm	Average discharge excluding the two lowest and two highest rates
Arbuckle Group	30	4-8300	826	389
Simpson Group	18	4-269	54	35

Table 2. Average discharge rate and ranges of rates of discharge for selected springs located in the vicinity of the Hunton Anticline (Figure 3). Spring data are from Fairchild et al. (1990) and the OWRB (2008). Table with locations and discharge rates for individual springs are in Appendix 2.

The best indicators of permeability in the Simpson sandstones and Arbuckle carbonates came from two sources: filtercake accumulation recorded by wireline logs and the flow of fluid into boreholes as reported by well records. Examples of these two indicators are shown in Section 4.

The analysis of wireline logs and records of fluid entry into boreholes during drilling revealed that porosity and permeability are closely linked to lithostratigraphy the Simpson Group. However, this relationship within the Arbuckle Group is somewhat more difficult to predict. In areas of Arbuckle outcrops, an epikarstic aquifer zone occurs in the shallow subsurface. Beneath the shallow unit, the carbonate is typically dense and essentially void of porous zones for tens to hundreds of feet. These isolated deeper water-bearing zones can be difficult to recognize on older wireline logs that do not contain caliper, micro-resistivity or porosity measurements, but are recognized with confidence on well reports from water wells or early oil and gas exploration wells drilled with cable tool rigs.

Location	Oil Creek Total	Oil Cfeek Φ feet > 20%	Oil Creek Φ feet > 24%	Oil Creek Other	B. McLish Total	B. McLish Φ feet > 20%	B. McLish Φ feet > 24%	B. McLish Other
4-2N-3E	82	68	18		76	68	34	
19-2N-3E	116	62	32		Absent			
33-2N-3E (NW NW SE)	115	62	34		180	118	82	
33-2N-3E (NE NW SE)	108	58	2		Absent: faulted			
5-2N-4E	128	64	14		Absent			
12-2N-5E	243	130	80		90	72	56	
29-2N-6E	184	84	28		136	30	10	
31-2N-7E	252	10	0		94	60	10	
33-2N-7E	254	70	4		92	57	14	
18-1N-3E	Not penetrated				110	100	25	
20-1N-3E	Not penetrated				115	86	18	
29-1N-3E	142	123	101		Absent			
12-1N-7E	240			60' >13% Φ	Absent			
12-1N-8E	214	42		98' >18% Φ	75	12		44' >18% Φ
11-1N-8E	84+	42+			52	44		
5-1S-8E	177	83	2	139' >18% Φ				
11-1S-8E	Not penetrated				60	27	10	50' >18% Φ
34-1S-8E	330	218	54		67	44	14	54' >18% Φ
11-2S-4E	230			154' >16% Φ	160			128' >16% Φ
13-2S-4E	90 faulted			30' >16% Φ	Absent: faulted			
12-2S-8E	110+			43' >16% Φ	40			20' >16% Φ

Table 3. Porosity measurements in the Oil Creek and McLish sandstones. Values were determined from density and sonic porosity logs based on a grain density of 2.65 g/cm^3 (Φ = porosity).

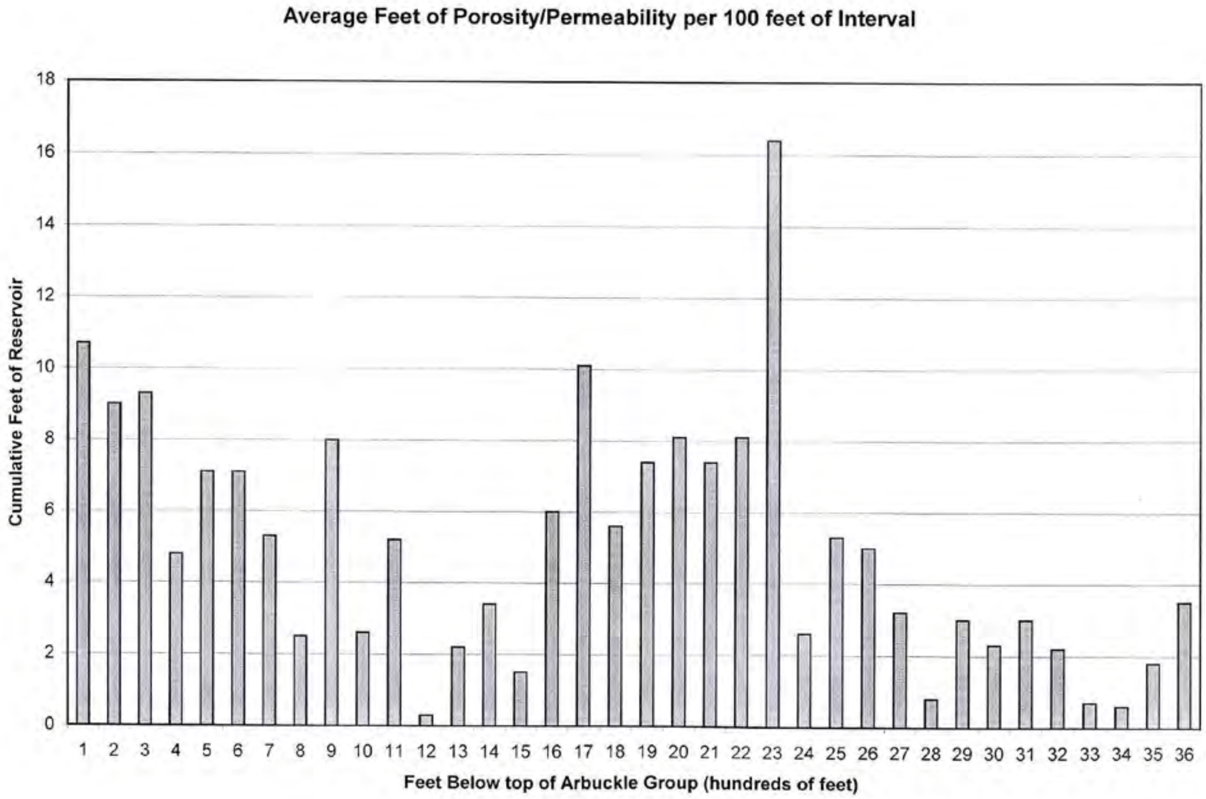


Figure 4. Distribution of porous and permeable intervals within the Arbuckle Group as determined by the analysis of wireline logs. Increased bar length indicates intervals with enhanced aquifer quality. Area of decreased aquifer thickness around 1200-1500 feet below the top could coincide with the upper part of the Kindblade Formation. Note: the number of samples decreases with depth and fewer than ten (10) porosity/permeability logs are available that measure > 2000 feet into the Arbuckle Group. (See Appendix 3 for data used to construct this graph).

3.0 Geology of the Arbuckle-Simpson Aquifer

3.1 Stratigraphy and Generalized Depositional History

Simpson and Arbuckle lithofacies reflect deposition that occurred in shallow marine environments. The Cambro-Ordovician Arbuckle/Timbered Hills carbonates are cyclic carbonates deposited on a platform setting (Ragland and Donovan, 1991). The plate configuration during the Cambro-Ordovician was such that the Laurentia (including what is now North America) was at low latitudes (Figure 5) and conditions were ideal for the proliferation of life and carbonate production. As a result of cyclic changes in sea level and very slow subsidence, thick intervals of alternating grain-rich and mud-rich carbonates were deposited. The Arbuckle/Timbered Hill carbonates gradationally succeed the Reagan Sandstone, which is relatively coarse-grained sandstone that contains abundant fragments of the underlying basement rocks. The basement is dominantly Proterozoic igneous rocks, but Paleozoic (Cambrian) rhyolite porphyry, which outcrops on the Arbuckle Anticline to the west, may underlie the sedimentary section in the western part of the study area.

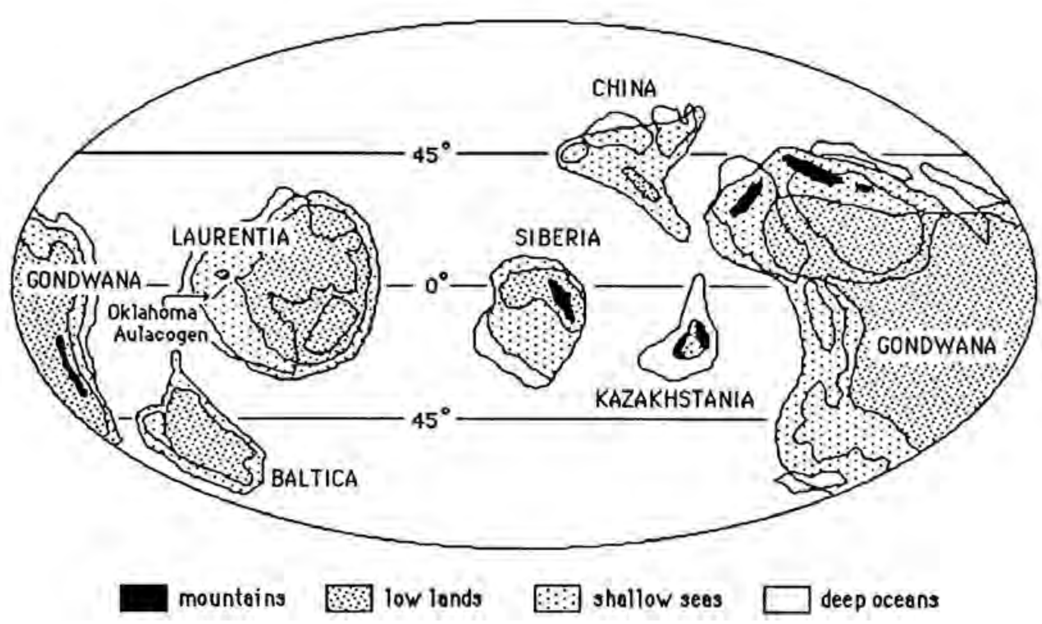


Figure 5. Global paleogeography during the Late Cambrian to Early Ordovician. Southern Oklahoma was located close to the equator where shallow and warm seas promoted carbonate deposition (from Ragland and Donovan, 1991).

A disconformity separates the Ordovician Arbuckle carbonates from the overlying Ordovician Simpson Group. The Simpson Group is dominantly siliciclastic and contains shale and sandstone with only minor carbonates. North America remained at low latitudes during Simpson deposition. Distribution and thickness patterns as well as composition and faunal evidence have contributed to the interpretation of the Simpson as shallow marine. Simpson sandstones are very mature and reflect a long history of recycling by wind and water that removed the non-quartz mineralic fraction. Shallow marine deposition continued in the Ordovician with deposition of the Viola Group carbonates, Sylvan muds and the ooid- and skeletal-grain-rich lowermost carbonates of the Hunton Group. During the Silurian and Lower Devonian, additional Hunton Group carbonates were deposited as shallow marine conditions persisted.

A profound change in depositional style occurred during the Upper Devonian (Frasnian) as the North American continent was flooded and the dark mudrocks of the Devonian black shales were deposited. In the southern Mid-continent region and other areas dark mud deposition continued into the Lower Mississippian (Tournasian/Kinderhookian). Carbonate generation resumed during the Mississippian Osagean and continued in shelf depositional settings in the Meramecian and Chesterian. During this time, southern Oklahoma was dominated by marine siliciclastic deposition. Consequently, the Mississippian section is mostly shale and siltstone. Siliciclastic dominance continued during the Pennsylvanian, which is represented by a wide spectrum of depositional environments that were influenced by the formation of the Wichita-Arbuckle-Ouachita orogenic belts and the adjacent Arkoma and Anadarko foreland basins.

3.1.1 Arbuckle-Timbered Hills Stratigraphy

Formations that compose the Arbuckle and Timbered Hills Groups were established based on lithologic and faunal evidence from outcrops in the Arbuckle and Wichita Mountains. Carbonates in these outcrop sections are mostly limestone that preserves original depositional fabrics and bioclasts. The depositional cycles in the Cool Creek, Kindblade and West Spring Creek formations of the Arbuckle Group weather to form a series of linear ridges and swales labeled “tombstone topography” where they outcrop on the south flank of the Arbuckle anticline. The shallow ramp depositional setting and cyclic nature of sea level changes were critical to the evolution of porous zones within the thick Arbuckle carbonates. Minor fluctuations in sea level subaerially exposed or inundated vast areas. As a result, intra-Arbuckle dissolution occurred when newly deposited carbonates were exposed to meteoric processes. Dissolution processes were dominantly focused flow and responsible for developing solution-enlarged fractures, enlarged bedding planes and caverns within the tightly cemented limestones. Some of these shallow dissolution features filled with mud containing oxidized iron, creating reddish-brown colored terra rosa zones within the carbonate sequences. In more extensively karsted areas, cavernous features developed including crackle breccias and cavern-filling parabreccias (Lynch and Al-Shaieb, 1991). In nearby oil and gas fields, karsted zones are recognized as important oil- and gas-bearing zones (Waddell et al., 1991). Dolomitization also played an important role in the evolution of porous zones within the Arbuckle carbonates. One hypothesis for the formation of dolomite is the mixing of meteoric and saline waters, which would occur during the repeated cyclic lowering of sea level. Outcrops in the Arbuckle Anticline tectonic subregion are mostly limestone with dolomitization somewhat restricted to two intervals of hydrothermal alteration named the Royer and Butterly dolomites (Figure 2). In contrast, Arbuckle carbonates on the Hunton Anticline are extensively dolomitized indicating the shelfal position in that area was prone to more frequent exposure and meteoric alteration. As a result, depositional features and original composition are difficult to recognize in the Arbuckle and Timbered Hills Groups, and identification on wireline logs is difficult. This difficulty is exacerbated by the vintage of the wireline logs and the scarcity of wells that penetrated the entire interval. However, in spite of these limitations, some formations such as the McKenzie Hill Limestone, the Honey Creek Limestone and the Reagan Sandstone have distinct compositions that facilitate their recognition on wireline logs or in bit cuttings.

In ascending order, the formations of the Timbered Hills and Arbuckle Groups are described in a generalized fashion as follows.

Reagan sandstone: The Cambrian Reagan Sandstone, an arkosic and glauconitic unit of marine origin, rests unconformably on the Cambrian and Precambrian igneous basement. The Reagan Sandstone thickens in paleotopographic lows and thins over highs on the basement surface. On the Tishomingo Anticline the sandstone is close to 400 feet thick. To the north on the Hunton Anticline, the maximum drilled thickness is 240 feet.

Honey Creek limestone: The Honey Creek Limestone is a glauconitic sandy limestone that is in gradation contact with the underlying Reagan sandstone. The Honey Creek becomes progressively more carbonate rich toward the top and more dolomitic northward away from the basin axis. The Honey Creek is approximately 140 feet thick on the Tishomingo Anticline and 150 feet thick on the Hunton Anticline. In the type wireline log (Figure 6) from a well drilled Sec. 12, T.2N., R.5E, the Honey Creek is present, but not drilled to the base.

Ft. Sill limestone: The Fort Sill Limestone, a relatively thin bedded limestone with occasional interbedded dolomitic limestone beds, is approximately 425 feet thick on the Tishomingo Anticline. The thickness of the Fort Sill Limestone could not be determined from wireline logs of wells on the Hunton Anticline, because of the scarcity of wells that penetrated the unit and the extensive dolomitization that obscures original depositional features.

Royer dolomite: The upper part of the Fort Sill Limestone is replaced by thermal dolomite that is locally called the Royer Dolomite. This coarsely crystalline dolomite is often considered a unit unto itself and is mappable on the surface of the Tishomingo and Arbuckle Anticlines. On the Tishomingo Anticline the Royer Dolomite is approximately 560 feet thick. The thickness of this unit was not determined on the Hunton Anticline due to the scarcity of data and inability to recognize the unit on the few logs that penetrate the interval.

Signal Mountain limestone: The Signal Mountain Limestone is a cherty and grain-rich carbonate interval that is 415 feet thick on the Arbuckle Anticline (Fay, 1989). The Signal Mountain is highly dolomitized on the Tishomingo and Hunton anticlines and included in the Butterly Dolomite.

Butterly dolomite: The Butterly Dolomite overlies the Royer Dolomite on the Tishomingo Anticline. Dolomitization of the Butterly is of thermal/hydrothermal origin and replaces the lower part of the McKenzie Hill Limestone or the upper part of the underlying Signal Mountain Limestone.

McKenzie Hill limestone: On the Tishomingo Anticline, the McKenzie Hill Limestone consists of approximately 230 feet of thinner bedded cherty limestone and 360 feet of thicker, chert free limestone. In the type log (Figure 6) section, the McKenzie Hill Limestone is 490 feet thick (Allison, 2008).

Cool Creek limestone: The Cool Creek Limestone is a cherty and grain-rich limestone that contains depositional cycles that shallow upward from shallow subtidal peloid- and bioclastic limestones to intertidal ooid grainstones and supratidal argillaceous mudstones. On the Arbuckle Anticline, the Cool Creek limestone contains a series of caverns and other epikarstic features. The Cool Creek limestone is approximately 1000 feet thick on the Tishomingo Anticline, whereas the dolomitized Cool Creek limestone is a similar thickness in the type log well located in Section 12,T.2N., R.5E., which is immediately north of the Hunton Anticline on the Lawrence Uplift.

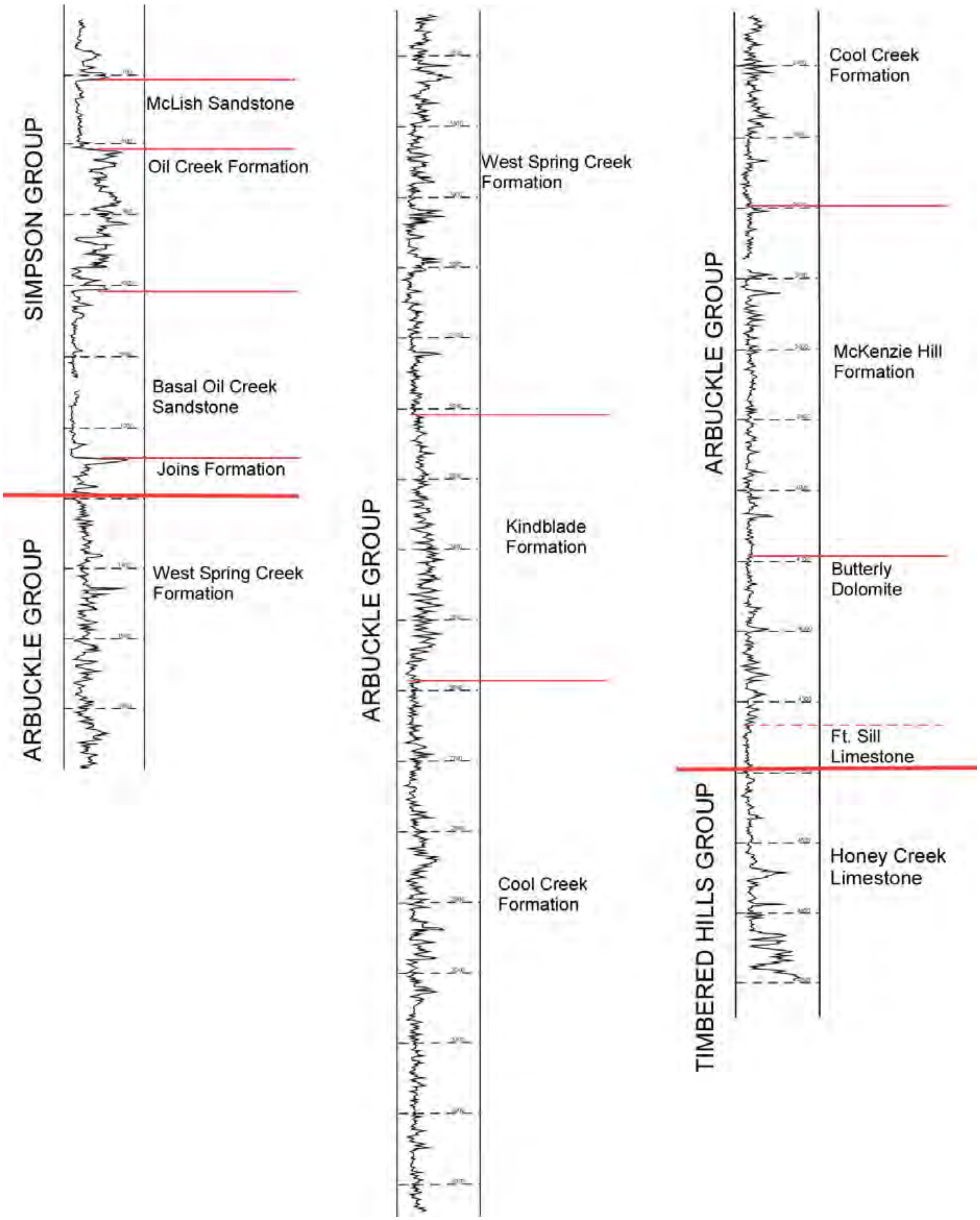


Figure 6. Type log for the Hunton Anticline showing the natural gamma-ray signatures for the identified stratigraphic units within the interval including the McLish Sandstone, Oil Creek and Joins formations, Arbuckle Group and the Honey Creek Limestone of the Timbered Hills Group. Joshi Technologies, Wirick #1-12, Section 12, T.2N., R.5E., Pontotoc Co., OK.

Based on these measurements, it is expected the Cool Creek Limestone is approximately 1000 feet thick across the Hunton Anticline, though its' boundaries cannot be determined exactly using the existing wireline log signatures.

Kindblade limestone: The Kindblade Limestone is a relatively fine crystalline and clean limestone with relatively little chert in the upper part. Ham (1964) identified spicular chert in the lower 350 feet of the Kindblade on the Tishomingo Anticline, where the total thickness is 1400 feet. In the USGS Spears #2 well the Kinblade section is almost devoid of chert and contains only a few thin sandstones. The depositional cycles evident in outcrop of the Kindblade (Wilson et al., 1991) and West Spring Creek (Mussleman, 1994) on the Arbuckle Anticline may be represented by the alternating three- to ten-feet thick intervals of higher and lower gamma-ray values that give the section a serrated appearance on wireline logs of wells drilled on the Hunton Anticline. Terra Rosa (oxidized) zones associated with paleokarstic features in the Kindblade Limestone are detected in bit cuttings of wells drilled on the Hunton Anticline, but further delineation of stratigraphic boundaries is difficult.

West Spring Creek limestone: The West Spring Creek Limestone consists of a series of grain-rich (bioclasts and ooids) intertidal to shallow subtidal carbonates that cycle upward to finely laminated, silty and dolomitic upper intertidal silty carbonates. The silty carbonates weather to form the swales between more resistant beds of grainy carbonates. Toward the base of the West Spring Creek is a karsted and dolomitized zone that is called the “Brown Zone” for the Brown oil and gas lease in Healdton oilfield. A zone of coarse crystalline saddle dolomite and dolomitic limestone with vugs was tentatively identified in the USGS Spears #2 well at a depth interval of 600 feet below surface (Puckette, 2009). If this interval is the Brown Zone, the thickness of the West Spring Creek limestone was approximately 820 feet on the Hunton Anticline. A thickness of 930 feet is indicated on the type log (Figure 6). Ham (1955) reported a thickness of 1460 feet on the Tishomingo Anticline, which would reflect expected thickening of Arbuckle Group carbonates toward the basin axis. Terra Rosa zones similar to those in outcrop (Musselman, 1994) were detected in cuttings of the West Spring Creek from the Hunton Anticline, and the serrated appearance of the gamma-ray signature is evident on wireline logs.

3.1.2 Simpson Group Stratigraphy

The stratigraphy of the Simpson Group was established from outcrops in the Arbuckle Mountains (Ham, 1969). The lithostratigraphic subdivisions are anchored on specific sandstones that mark the base of formations. Shale units in the Simpson are a conspicuous green color that allows their differentiation from the underlying Arbuckle Group and overlying units. Major sandstones are in ascending order the Oil Creek, McLish, Tulip Creek, and Bromide. The basal Oil Creek and basal McLish sandstones are more widely distributed and prominent on wireline logs from wells drilled in the Hunton anticline study area. The base of the basal Oil Creek sandstone marks the contact between the Oil Creek Formation and the subjacent Joins Formation, whereas the top of the Oil Creek Formation is placed at the base of the overlying basal McLish sandstone.

The Oil Creek, McLish and Bromide sandstones in many parts of the Arbuckle region escaped destructive diagenesis (cementation) that normally occurs during burial. Thin-section microscopy studies indicate that Simpson sandstones remain porous and uncemented when the quartz grains are coated with authigenic clay minerals such as illite that inhibit crystal nucleation and resultant cementation (Tigert and Al-Shaieb, 1990; Abdalla et al., 1997). In some areas, the top of the basal Oil Creek sandstone is cemented with calcite or dolomite causing the sandstone to grade into sandy carbonate that is low porosity, non-aquifer/reservoir rock (Springman et al., 1999).

Generalized descriptions of the formations of the Simpson Group are as follows:

Joins: The Joins Formation contains shale, limestone and sandstone. It has a distinct wireline log signature and is relatively easy to recognize and correlate in the study area. The Joins Formation is feet thick in the Wapanucka Syncline and feet thick on the western flank of the Hunton Anticline.

Oil Creek: The Oil Creek Formation consists of a basal sandstone-rich interval and overlying calcareous shale. The Oil Creek Formation is mappable using well log data as the basal sandstone and shale intervals generate distinct log responses. The thickness of the Oil Creek Formation varies on the western flank of the Hunton Anticline as the result of truncation beneath the pre-Pennsylvanian unconformity. The thickness and number of individual sandstone bodies within the sandy interval also vary from the west flank to the east flank. In the Wapanucka Syncline the Oil Creek Sandstone is as much as 340 feet thick, and the total formation >600 feet thick. On the western flank of the anticline, sections unaffected by the pre-Pennsylvanian orogeny contain up to approximately 300 feet of sandstone and reach a total thickness exceeding 400 feet.

McLish: The McLish Formation contains a prominent basal sandstone that is succeeded by a shale-dominated interval. The basal sandstone ranges in the type well (Figure 6) is approximately 100 feet thick. The overlying shale and carbonate interval is approximately 310 feet thick. The basal boundary of the McLish Formation is easily recognized on wireline logs, but the top of the formation is more difficult to identify primarily because sandstone in the overlying Tulip Creek Formation are poorly developed in the vicinity of the Hunton Anticline.

Tulip Creek: The Tulip Creek Formation is not easily identified on wireline logs and is difficult to separate from the underlying McLish Formation or overlying Bromide Formation in the study area.

Bromide Formation: The Bromide Formation is typically a sandstone dominated interval in southern Oklahoma. However, in the vicinity of the Hunton Anticline the Bromide Formation is relatively shale-rich and recognition of the Bromide/Tulip Creek contact is difficult. On the northern flank of the Hunton Anticline, thicker sandstone beds are evident in the Bromide. The Bromide Formation in the type well is approximately 330 feet thick and is similarly thick on the western flank of the Hunton Anticline, and to the east in the Wapanucka Syncline and Franks Graben.

3.2 Tectonic Modification and Pennsylvanian Orogeny

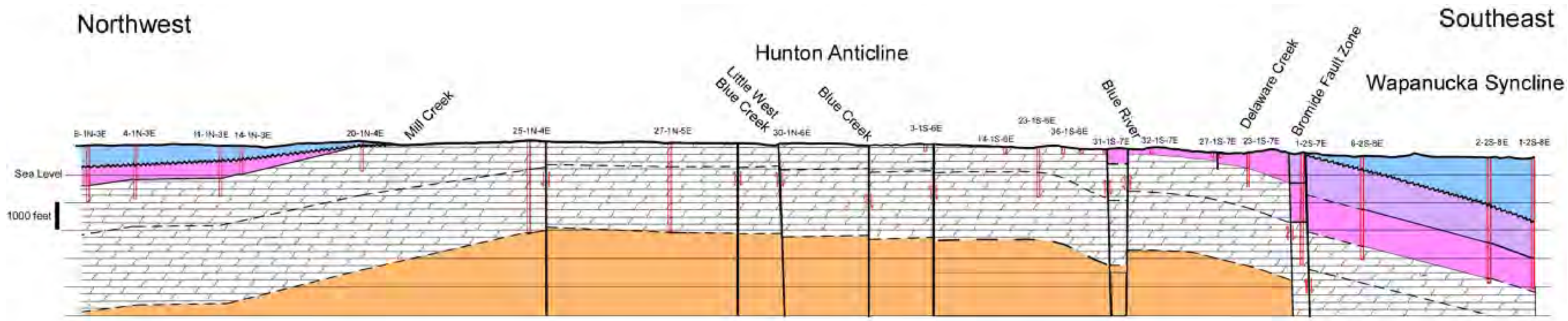
During the Early Pennsylvanian (Morrowan) the collision of Gondwana (South America/Africa) with Laurentia (North America) brought profound changes to what is now known as the southern Mid-continent of North America. This event, which is called the Pennsylvanian Orogeny, initiated inversion and uplift of the thick sedimentary section across the Amarillo-Wichita-Arbuckle Uplift and the later thin-skin tectonics that generated the Ouachita thrust belt. Concurrent with uplift, rapid subsidence and sedimentation dominated deposition in the adjacent Arkoma and Anadarko basins.

The Amarillo-Wichita-Arbuckle Mountains became a positive feature as evidenced by the Morrowan fan deltas that prograded northward from the uplift (Puckette et al., 1996). By the Desmoinesian (Middle Pennsylvanian), the Arbuckle Mountains were positive topographic features with steep stream gradients capable of transporting boulders and cobbles that form the Collings Ranch and Vanoss conglomerates. The Collings Ranch Conglomerate fills narrow grabens within the Arbuckles and rests unconformably on steeply dipping lower Paleozoic strata, indicating that the major folding of the Arbuckle anticline and erosion occurred prior to deposition of Desmoinesian sediments. Petroleum-impregnation and preservation of aragonite mollusk shells in Pennsylvanian shale indicate that petroleum was being generated concurrently in the basin adjacent to the uplift.

As a result of uplift and erosion, Middle Pennsylvanian rocks rest unconformably on Arbuckle and Simpson strata in the subsurface beneath the northern part of the study area (Figures 7 and 8). This unconformity, which is given the operational name of pre-Pennsylvanian unconformity by the oil and gas industry, may coincide with the pre-Atokan unconformity that is evident in the adjacent Franks Graben and eastern Lawrence uplift.

Faults and folds that form the major tectonic features (Figures 7, 8 and 9) in the Arbuckle region occurred during the Pennsylvanian Orogeny. Pre-folded lower Paleozoic strata were eroded prior to deposition of Middle Pennsylvanian sediments. Conglomerate deposits that fill the interior grabens and flank the north side of the Arbuckle Mountains clearly indicate the positive topography of the Arbuckle area during the Middle Pennsylvanian. The Franks fault zone (Figure 8) along the eastern margin of the Hunton Anticline separates exposed Arbuckle Group on the uplift from Pennsylvanian strata in the adjacent Franks Graben. Pennsylvanian strata are preserved in the Mill Creek Graben/Syncline, whereas Cambro-Ordovician strata are exposed on the adjacent Belton Anticline to the north and Precambrian granitic basement outcrops on the Tishomingo Anticline to the south (Figure 9). The preservation of the complete Lower Pennsylvanian through Cambrian section in graben areas is evidence that these units were stripped from the crest of the Arbuckle Mountains during the orogeny. The western flank of the Hunton Anticline consists of deformed (faulted and folded) pre-Pennsylvanian strata that are covered by flat-lying Pennsylvanian (Desmoinesian) strata (Figure 8).

The Pennsylvanian Orogeny slowed from the west and the western end of the uplift was onlapped by Permian sediments. Erosion of the exposed parts of the Wichita and Arbuckle Mountains continued during the Permian and likely through the Mesozoic, though evidence of Mesozoic erosion is scarce.



Northwest (NW) to Southeast (SE) trending cross section (green on index map) across the Hunton Anticline. Additional detail shown on Plate 2 in Appendix 7.

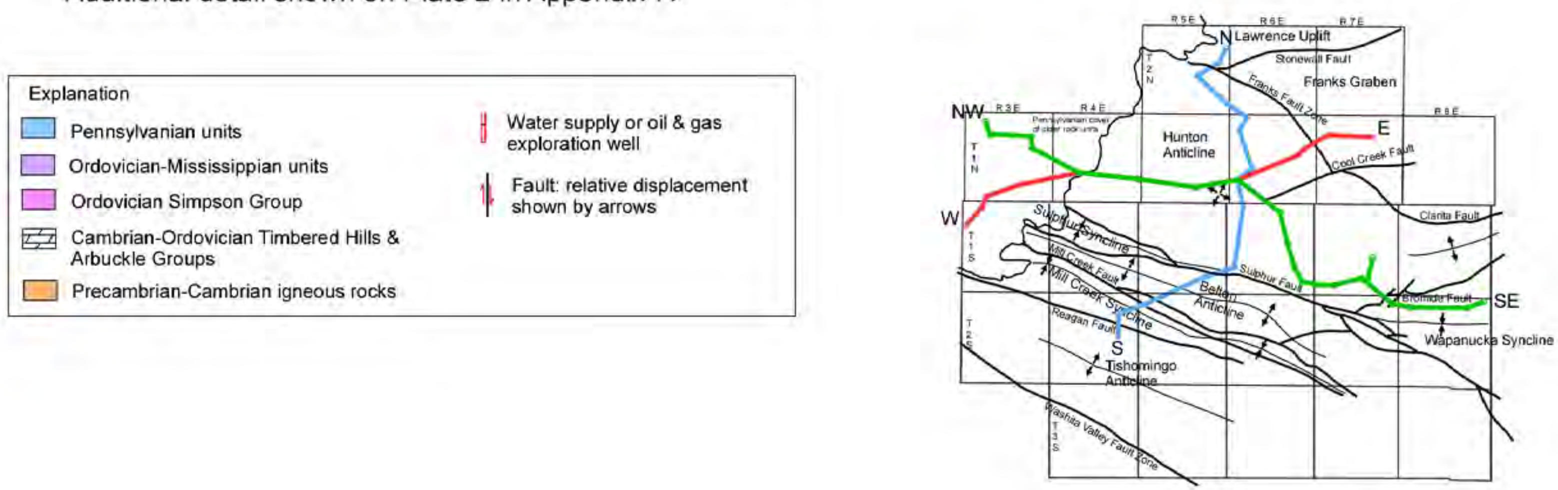
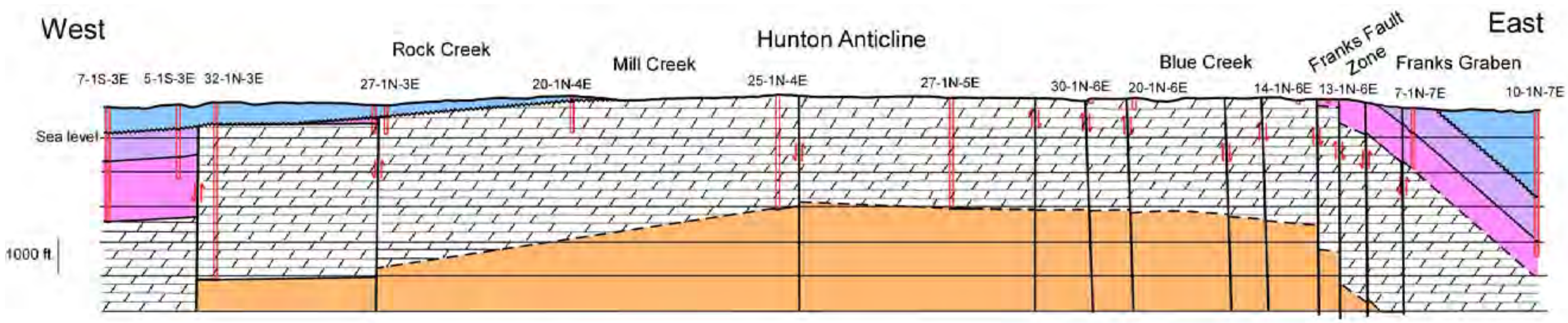


Figure 7. Northwest to southeast trending cross section (Green) across the Hunton Anticline. Note the eastern dip into the Wapanucka Syncline and the Pennsylvanian cover on the eastern and western margins of the uplift. Surface fault locations are from Ham and McKinley(1954).



West (W) to East (E) trending cross section (red on index map) across the Hunton Anticline.
Additional detail shown on Plate 1 in Appendix 7.

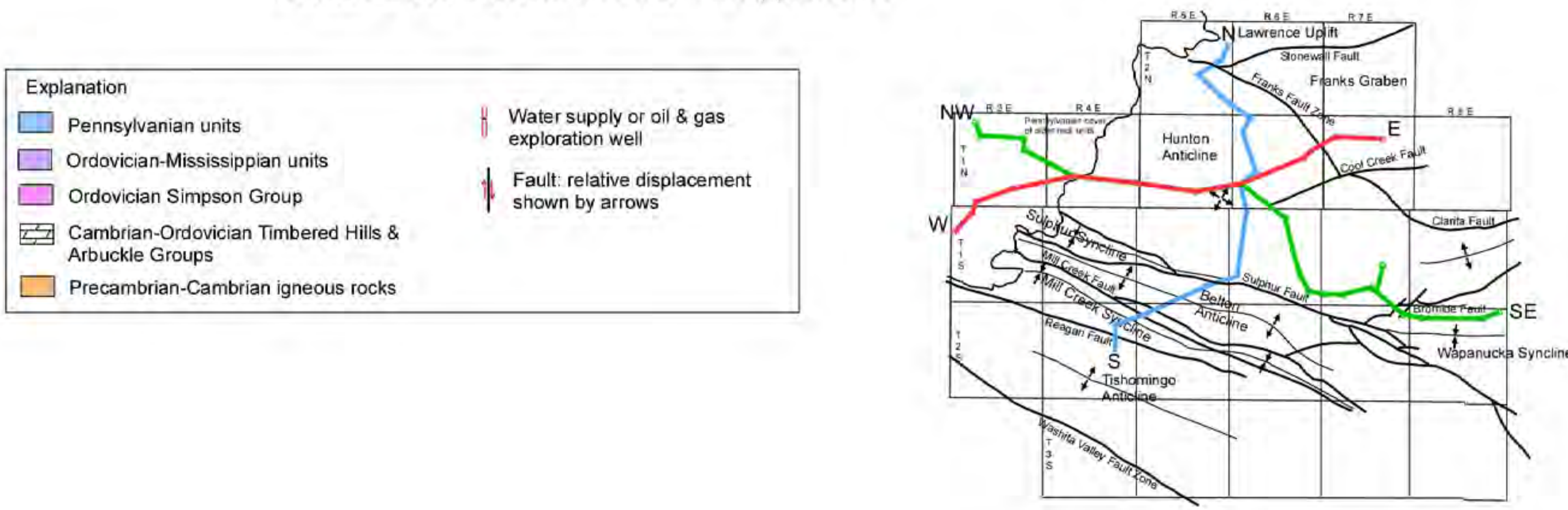
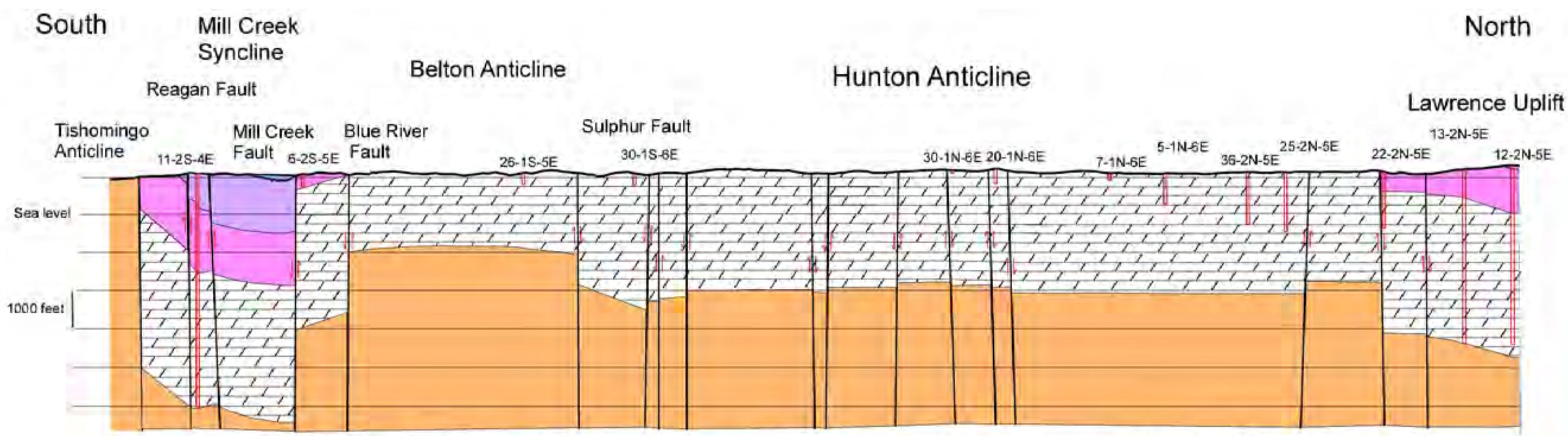


Figure 8. Northern cross section (Red) across the Hunton Anticline. Note the eastern dip into the Franks Graben and Pennsylvanian cover over the faulted Arbuckle-Simpson Aquifer on the western margin of the uplift. Surface fault locations are from Ham and McKinley (1954). Locations of faults beneath Pennsylvanian cover are from mapping of subsurface and geophysical surveys.

3.3 Post Laramide Uplift and Erosion

The Laramide Orogeny, which formed the Rocky Mountains, profoundly affected the southern Mid-continent. The central part of the North American continent began rising toward the end of the Mesozoic and the resulting uplift and erosion in central and northern Oklahoma removed a minimum of 1000 meters of strata. During the Cenozoic, most Mesozoic rocks were stripped from central and northern Oklahoma, and the Arbuckle, Wichita and Ouachita Mountains were reduced further. Offset and tilted speleothems in caves on the Arbuckle Anticline and tilted bedding planes of sediments infilling sinkholes are evidence that slow uplift and erosion continue in the present as the Laramide epeirogeny.

As erosion breached the Arbuckle Mountains, the exposed Simpson and Arbuckle Groups were altered by meteoric processes. The carbonates weathered to form epikarstic features and freshwater infiltrated aquifer/reservoirs that previously contained petroleum and brine. Freshwater occurs in conjunction with petroleum saturation in the Oil Creek Sandstone located south of the community of Sulphur, Oklahoma. The high values of hydraulic conductivity/permeability in the Arbuckle/Timbered Hills Groups contributed to the extensive flushing of petroleum and brine from the Arbuckle carbonates on the crest of the Hunton and Arbuckle anticlines. On the northwest flank of the Hunton anticline, freshwater occurs in flushed Oil Creek and Arbuckle hydrostratigraphic units beneath shallower Pennsylvanian beds containing oil, gas and brine.



South (S) to North (N) trending cross section (blue on index map) across the Hunton Anticline. Additional detail shown on Plate 3 in Appendix 7.

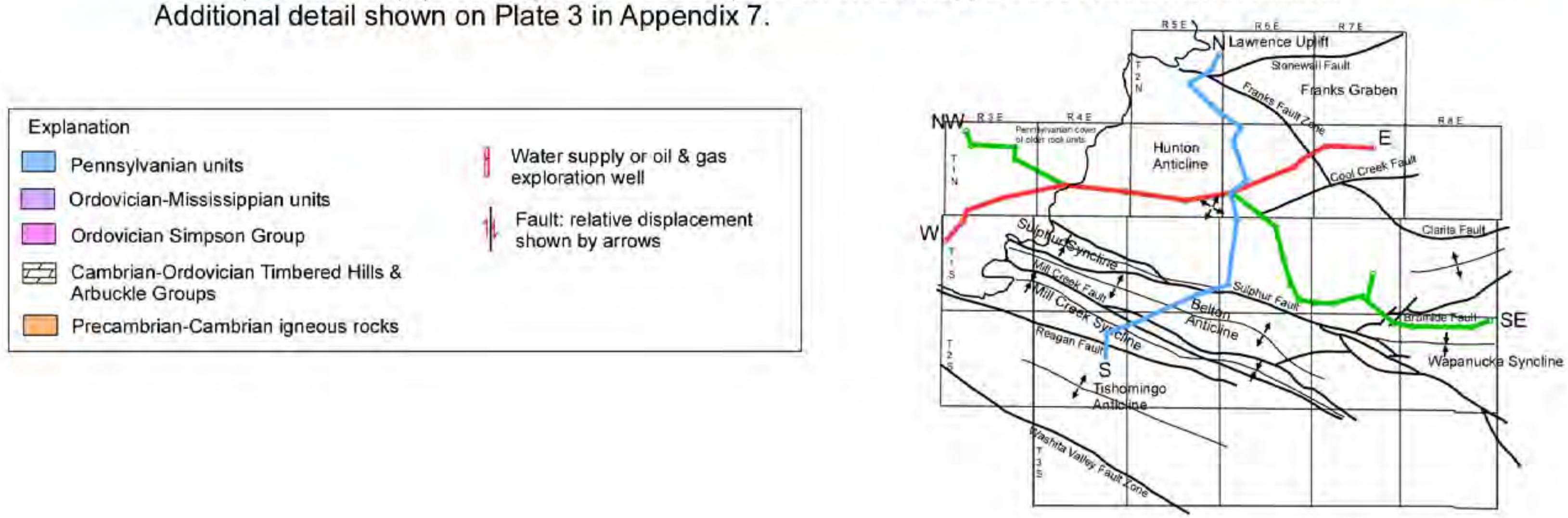


Figure 9. South to north trending cross section (Blue) across the Hunton Anticline. Note the northeastern dip on the Lawrence Uplift and the fault bounded Mill Creek Syncline toward the southern end of the section. Surface fault locations are from Ham and McKinley (1954).

4.0 Spatial Distribution of Hydrostratigraphic Units

4.1 Recognition of Hydrostratigraphic Units in Water Supply Wells

Hydrostratigraphic units were initially identified by examining well records of domestic, municipal and rural water district water supply wells (Table 1). A total of 150 well records, analyzed in conjunction with the map of surface geology, provided evidence that established the Arbuckle Group carbonates as the principal hydrostratigraphic unit in the region and the Simpson sandstones as a secondary unit. Well yields in the Arbuckle Group carbonate aquifers reached 2000 gallons per minute (OWRB, 2008). Maximum well yields for the Oil Creek Sandstone hydrostratigraphic unit exceeded 200 gallons per minute. Spring discharge data (Table 2) were analyzed and showed similar results. Large-volume Arbuckle springs such as Byrd's Mill and the Washington group, have static flow discharge volumes that average several thousands of gallons per minute. In contrast, spring discharge volumes from the Oil Creek Sandstone reported by Fairchild and others (1990) reach a maximum of 269 gpm and average approximately 54 gallons per minute (Table 2). Groundwater flow into sand quarries and pits in the Bromide and Oil Creek sandstones confirm the importance of Simpson Group hydrostratigraphic units.

A number of water wells penetrate the entire Oil Creek sandstone, but the deepest water supply wells in the Arbuckle aquifer only penetrate the upper one-third of the Arbuckle/Timbered Hills section. In an effort to properly characterize the thickness of the hydrostratigraphic units within the Arbuckle-Simpson aquifer, the large volume of data collected during the drilling of oil and gas exploration wells was analyzed.

4.2 Importance of Petroleum Industry Data to Aquifer Characterization

The Arbuckle Mountains have intrigued the petroleum industry since the United States Geological Survey (USGS) surveyed the lands for the Chickasaw Nation in 1890 (Taff, 1904a). The region contains a number of prominent oil seeps and asphalt-impregnated sandstone and carbonate outcrops (Taff, 1904b). These deposits and seeps attracted the petroleum industry to the area and resulted in the drilling of wells across the region. Oil- and gas-exploration companies quickly learned that the rock column on the crest of the uplift was fresh-water bearing and as the result of "freshwater flushing" of the reservoirs, that the prospect of finding significant oil deposits there was minimal. The disappointing results of drilling in the Arbuckle Mountains discouraged drilling in the adjoining basins and, as a result, discoveries were delayed. As an example, the Fitts Pool, which is located in the Franks Graben in T.2N. R. 6E. and R. 7E., Pontotoc County (Figure 10), was not discovered until 1933 (Dott and Swindell, 1935).

Records for wells drilled in the search for oil and gas (petroleum wells) provide information that is essential to the proper characterization of the Arbuckle and Simpson aquifers. This includes aquifer lithology, thickness, structural attitude, porosity and types of pore fluids. Petroleum wells also provide information that is used to characterize the thickness and spatial distribution of aquifer confining units.

Petroleum wells are typically drilled to greater depths than ground water supply wells, and consequently penetrate more of the stratigraphic column. There are 23 known wells in the Arbuckle uplift that penetrate the entire sedimentary column and reached total depth in the Proterozoic (Precambrian) or Cambrian basement rocks. These wells are critical to establishing the thickness of the Simpson, Arbuckle and Timbered Hills Groups, identifying the stratigraphic positions of zones of porosity and permeability within these groups, and interpreting fluid types and their distribution. Petroleum wells penetrate the marker beds used to establish the structural attitude of the Arbuckle and Simpson aquifers. The spatial distribution of aquifers, coupled with potentiometric data, provide the basis for a sound estimation of directions of ground water flow and determining the thickness of the freshwater saturated zone.

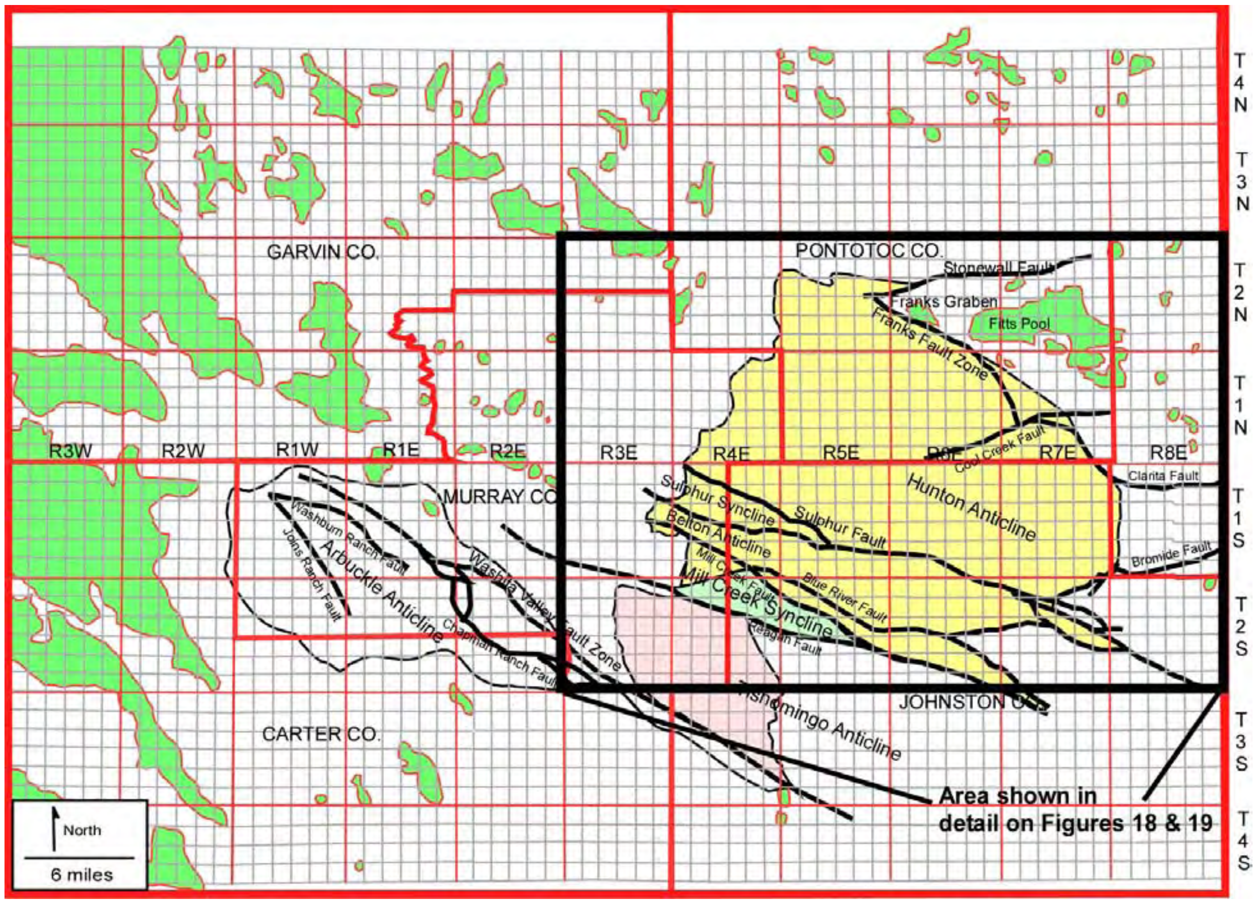


Figure 10. Oil and gas fields (shown in green) in the vicinity of the Arbuckle Uplift. Black box outlines areas shown in detail in Figures 18 and 19.

4.3 Data Sources, Quantity and Type

The primary source of information concerning oil and gas wells in the Arbuckle Mountain region is standard, petroleum-industry data located in the Oklahoma City Geological Society (OCGS) Geological Library in Oklahoma City. The OCGS Library was the source for a variety of useful information, including wireline logs, completion cards with stratigraphic and fluid data, completions forms (State of Oklahoma Corporation Commission 1002A), and drillers logs. These data were supplemented by information from the Oklahoma State University School of Geology geological library and contributions from industry professionals. Mr. Robert Allen of Ardmore, Oklahoma graciously contributed stratigraphic columns published by the Ardmore Geological Society and his personal interpretations of specific areas. Mr. Michael Allison of the North Texas Sample Library contributed data and expertise necessary for establishing the internal stratigraphy of the Arbuckle and Timbered Hills groups. Published and unpublished studies, which are listed in the literature review (Halihan et al., 2004), provide the stratigraphic and structural context in which petroleum data were analyzed. Information on available cores and bit cuttings was obtained from the Oklahoma Geological Survey Oklahoma Petroleum Information Center in Norman (OGS, 2004).

This appraisal of the Arbuckle and Simpson aquifers in the Arbuckle Mountains focuses on the Hunton Anticline subregion (Figures 1 and 10). Petroleum data are referenced to the U.S. Public Land Survey System and reported by section, township and range. Portions of townships that are located in adjacent basinal areas that contain densely drilled oil fields such as Fitts Pool in the Franks Graben, were excluded. All or part of the following townships are included in the dataset: T.1S., R.1E. through R.8E., T. 2S., R.1E. through R.8E., T. 3S., R.1E. through R.8E., T.1N., R.2E. through 6E., and T.2N., R.2E. through R.6E. The numbers of well records by township and the data types they report are summarized in Appendix 4, Table 1.

Multiple data types are provided by oil and gas exploration. Some are the result of the direct sampling or measuring of lithology and pore fluids. These include coring, bit cutting sampling and drill stem tests or bailing tests. Others result from indirect processes and require interpretation to recover the desired information. These include open hole and cased hole wireline logs, with the former being much more common.

4.3.1 Fluids Recovered During Drilling with Cable Tool Rigs

Petroleum wells completed prior to the 1930s were commonly drilled with cable tool rigs. This technology requires minimal liquid drilling medium. When fluid-saturated rock is encountered, the fluid moves freely from the rock's pore network into the borehole. Consequently, the penetration of porous or permeable zones results in increased fluid in the hole and the position of these units and the type of fluid they contain are determined during drilling. More than 50 wells located on the eastern part of the Arbuckle uplift report fluid recovered during drilling of the Arbuckle and Simpson sections (Table 1, Appendix 4). Fluid recovery data, including well location, stratigraphic interval and depth of fluid recovery, and type of fluid are reported in Appendix V.

4.3.2 Lithologic or Driller's Logs from Cable-Tool-Drilled Holes

As there is no fluid circulation to bring bit cuttings to the surface, cable-tool holes must be cleaned frequently by bailing. This process results in a very detailed lithologic record. Furthermore, cable-tool rigs drill non-deviated holes, facilitating the interpretation of the thickness of strata and the recognition of dipping beds. These detailed lithologic logs and reports of fluids encountered during drilling provide reliable data for establishing the depths of porous and permeable zones, and the spatial distribution of generalized fluid types.

4.3.3 Drill Stem Tests

The use of rotary rigs and freshwater-mud-based drilling-fluid systems eliminated the unrestricted flow of fluid into the borehole. Consequently, it became necessary to develop technology to isolate suspected porous intervals and evaluate their ability to transmit fluid. To accomplish this, the drill stem test or DST was developed. The DST uses a system of packers, valves and perforated pipe to isolate an interval in the borehole and permit flow of saturating fluid from the rock into the drill pipe. During this testing process, it is normal procedure to record the volumes and types of fluids recovered. If water is recovered, it is usually tested for salinity and total dissolved solids. In addition, a qualitative assessment of the salinity of recovered water based on taste and odor is often noted. This information is reported to oil industry data collection organizations and state regulatory agencies. More than 340 wells located on the eastern part of the uplift report drill stem test results. Well records indicate nearly 300 drill stem tests were conducted in these wells that resulted in high-fluid recoveries from Arbuckle and Simpson intervals (Appendix 4, Table 1). The results of these tests are reported in Appendix 5.

4.3.4 Wireline Electrical Logs

Most wells drilled after the mid 1930s were logged with open-hole wireline surveys. These electrical surveys or “logs” are interpreted to determine the lithology of the strata penetrated during drilling and establish stratigraphic correlations. Wireline logging tools capable of identifying porous and permeable zones were developed in the 1950s. These porosity surveys provide the necessary data to quantify porosity, calculate estimated water resistivities, and establish the stratigraphic and structural positions of porous water-bearing zones. The summary of wireline logs located to date in the detailed study area is shown in Appendix 4, Table 2. The wells listed in Table 2 that drilled large intervals of the Arbuckle and Timbered Hills Groups and were logged with porosity detecting tools are critical to establishing the stratigraphic framework and distribution of porous and permeable zones in the Arbuckle aquifer.

4.3.5 Cores

Cores are the most useful source of lithologic, pore geometry, and fluid property data. Though there is no record of coring in the Arbuckle or Simpson aquifer intervals on the Hunton

Anticline, a number of cores are located in adjacent areas of more intense oil- and gas-exploration Figure 11 and Appendix 4, Table 3. These cores were examined and correlated to wireline logs to establish the origin and spatial distribution of the pore network in the Arbuckle Group. Calibration of wireline log signatures to cores allowed for inferences concerning rock properties from wireline-log signatures of wells in areas where cores are not available.

4.3.6 Bit Cuttings

Bit cuttings recovered during the drilling process are an important source of lithologic data. Cuttings or “samples” as they are often called, are available for over 60 wells located on the Arbuckle uplift (Figure 12 and Appendix 4, Table 4). Eight of these wells are located on the Hunton Anticline and outcropping Simpson or Arbuckle Group strata. In addition to providing lithologic data, cuttings provided evidence used to interpret types and sizes of pores.

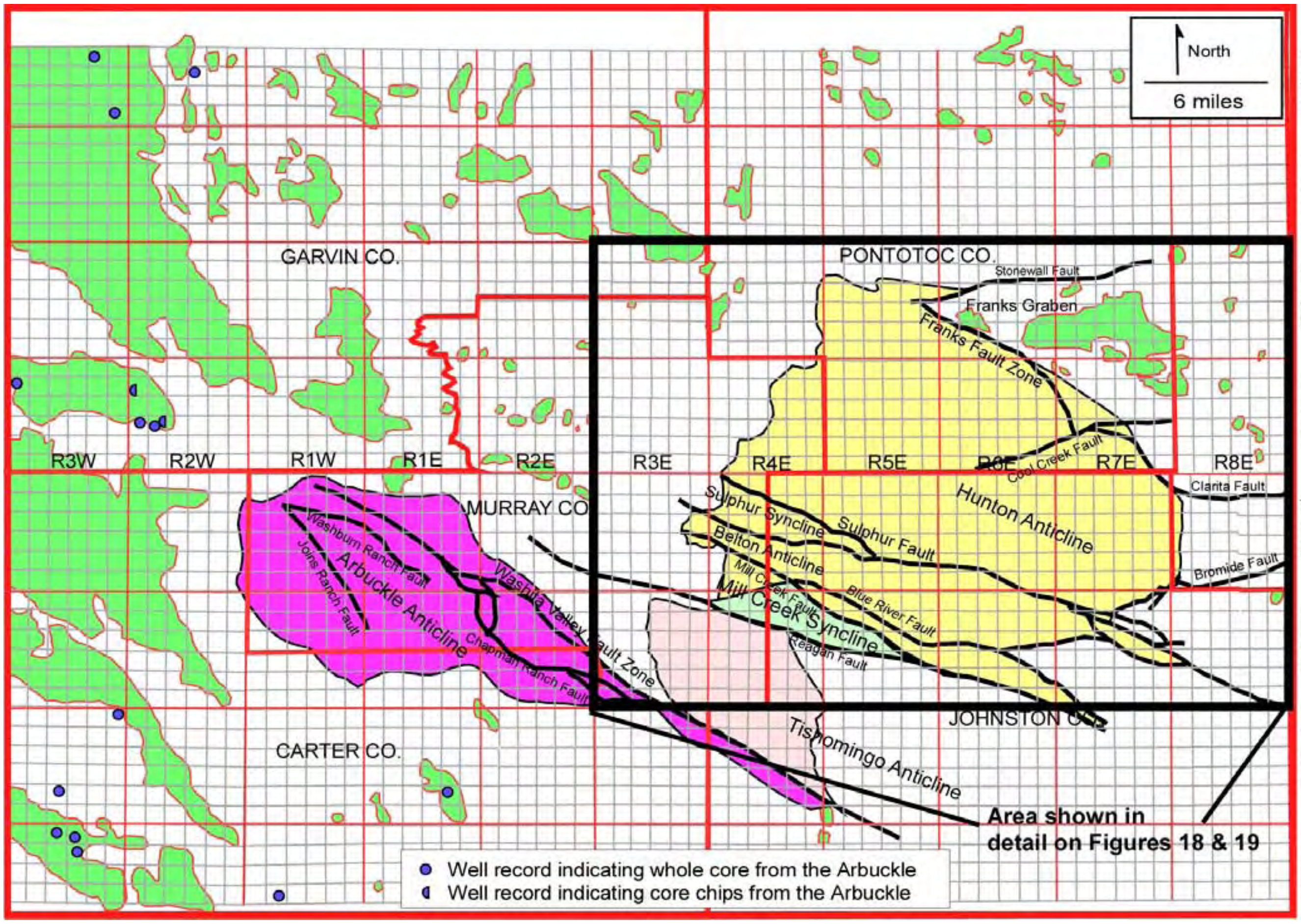


Figure 11. Locations of wells with records indicating cores were taken in the Arbuckle section. Area outlined by black box is shown in detail in Figures 18 and 19.

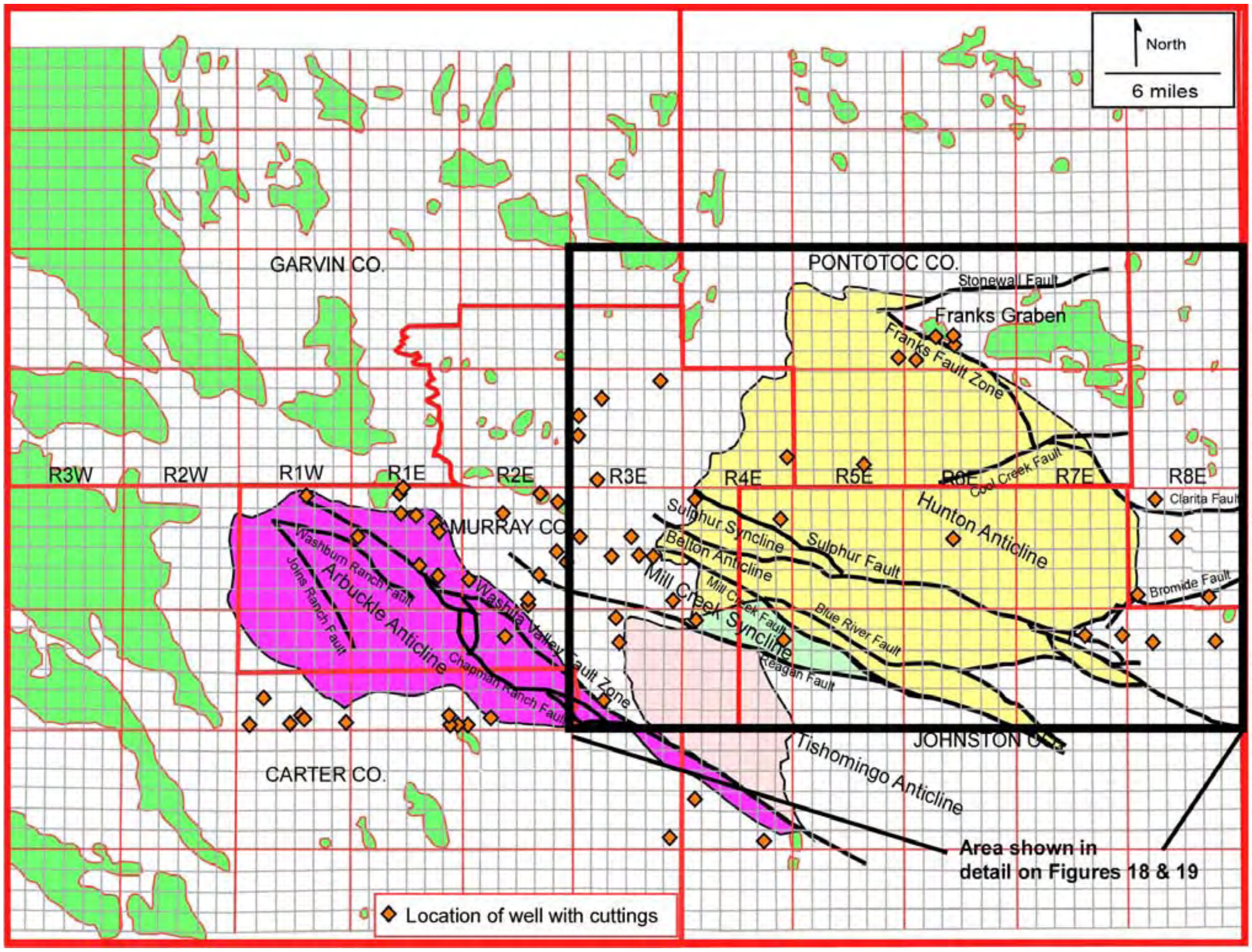


Figure 12. Wells with bit cuttings stored at the Oklahoma Geological Survey, Oklahoma Petroleum Information Center (OPIC) in Norman, Oklahoma. Locations of wells with a set of bit cuttings are indicated by orange-colored diamonds.

5.0 Porosity Types and Stratigraphic Distribution

5.1 Simpson Group

The Bromide, McLish, and Oil Creek sandstones of the Simpson Group are classified as quartz arenites (Folk, 1974), which means that the rock framework of each sandstone is composed of greater than 95% detrital quartz grains. Quartz sandstones have a propensity to become tightly cemented during burial as silica cement generated at grain-to-grain contacts by compaction moves into the adjacent pore space. Porosity decreases with depth of burial and does not increase because these sandstones do not contain metastable mineralic grains that can dissolve to form secondary porosity once primary porosity in occluded. However, Simpson Group sandstones are commonly friable and so poorly indurated that they disaggregate easily into loose sand. Sand quarries in the vicinity of the communities of Mill Creek and Hickory, Oklahoma use water pressure to disaggregate the sandstone, which has porosity exceeding 30% and permeability in the 2000 to 2500 millidarcy range (McPherson et al., 1988). Oil and gas wells completed in the Simpson sandstones at depths of 2500 to 3000 meters often produce sand along with formation fluids, and sand is frequently recovered from the drill string following drill stem tests of the Oil Creek and other Simpson sandstones.

Examination of thin sections confirms that the porosity in Oil Creek samples from the study area is primary and that the sandstone is greater than 95% quartz grains. However, primary porosity is preserved because most individual quartz grains are coated with illite clay (Figure 12) that inhibited the nucleation of silica cement during burial. Secondary porosity was not evident and is not believed to contribute significantly to the total porosity volume.

Oil Creek porosity values were collected from 17 wells logged with density, or density/neutron or sonic wireline tools. These values, which are shown in Table 3, are reported in porosity feet and compared to the total thickness of the sandstone exposed in the well. In some cases, more consolidated, porous sandstone accumulated drilling fluid filtercake, which indicates mud filtrate invasion and permeability. In other cases, poorly cemented Oil Creek sandstone eroded during drilling, forming a small cavity in the sandstone. Both filtercake accumulation and washout are evidence that the Oil Creek Sandstone is porous and permeable. Forty five (45) water well records with yields report screened intervals across the Oil Creek Sandstone. The Bromide and McLish sandstones are aquifers of secondary importance with screening reported in <10 wells that report yields (OWRB, 2008). These sandstones are lithologically similar to the Oil Creek Sandstone, highly porous and permeable. Porosity values for the basal McLish sandstone are reported in Table 2.

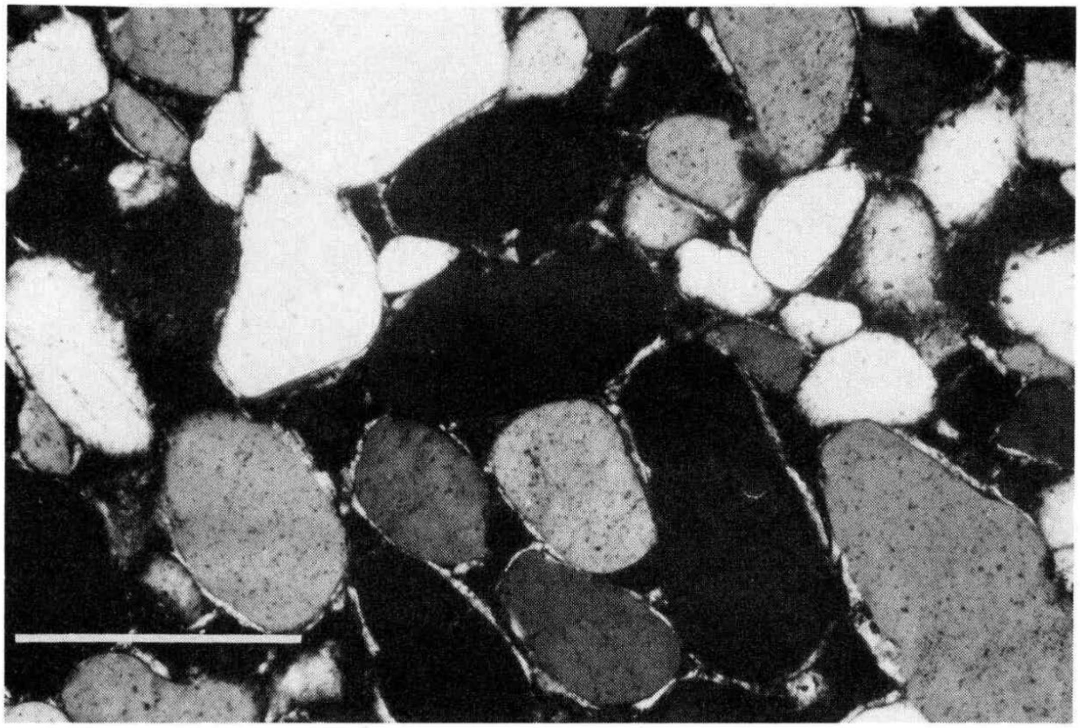


Figure 13. Photomicrograph of the basal Oil Creek Sandstone from a sand quarry near Mill Creek, Oklahoma. Highly birefringent (light colored) illite grain coatings on dark colored (gray to black) sand grains. Grain coatings are not evident on light-colored quartz grains due to the lack of contrast between the color of grains and clay coats.Scale bar equals approximately 0.25 mm. (Cross-polarized light image from McPherson et al., 1988)

5.2 Arbuckle Group

Previous studies of the Arbuckle Group by Lynch and Al-Shaieb (1991) show that paleokarstic processes and dolomitization are important to the generation of porous reservoirs/aquifers. Dolomitization, which is more prevalent in the northern part of the study area, can create a porous crystalline rock matrix that affects flow and storativity.

Focused-flow paleokarstic and epikarstic features are inferred from drilling records of wells located on the Hunton Anticline. The drilling records of many water-supply wells indicate that drilling encountered near-surface water flow followed by intervals of non-water-producing strata before the reaching next zone of flow. Zones of flow are frequently named “water crevices” or “sands” (Figure 14). Water saturation within surficial rocks may reside in epikarstic features. Within deeper wells, these water-producing zones may be separated by intervals of rock several hundred feet thick (Figures 14 and 15) for which there is no record of water flow (Figure 14).

Data from oil and gas wells located in fields in the Ardmore basin on the southern margin of the Arbuckle uplift also provide evidence to suggest that the Arbuckle Group is not a single homogeneous reservoir. Instead, oil and gas accumulated in thinner porous and permeable intervals that are separated by thicker zones of low-permeability rock (Latham, 1970). Some zones of enhanced porosity and permeability in these petroleum fields correlate to specific stratigraphic intervals such as the “Brown Zone” near the base of the West Spring Creek Formation.

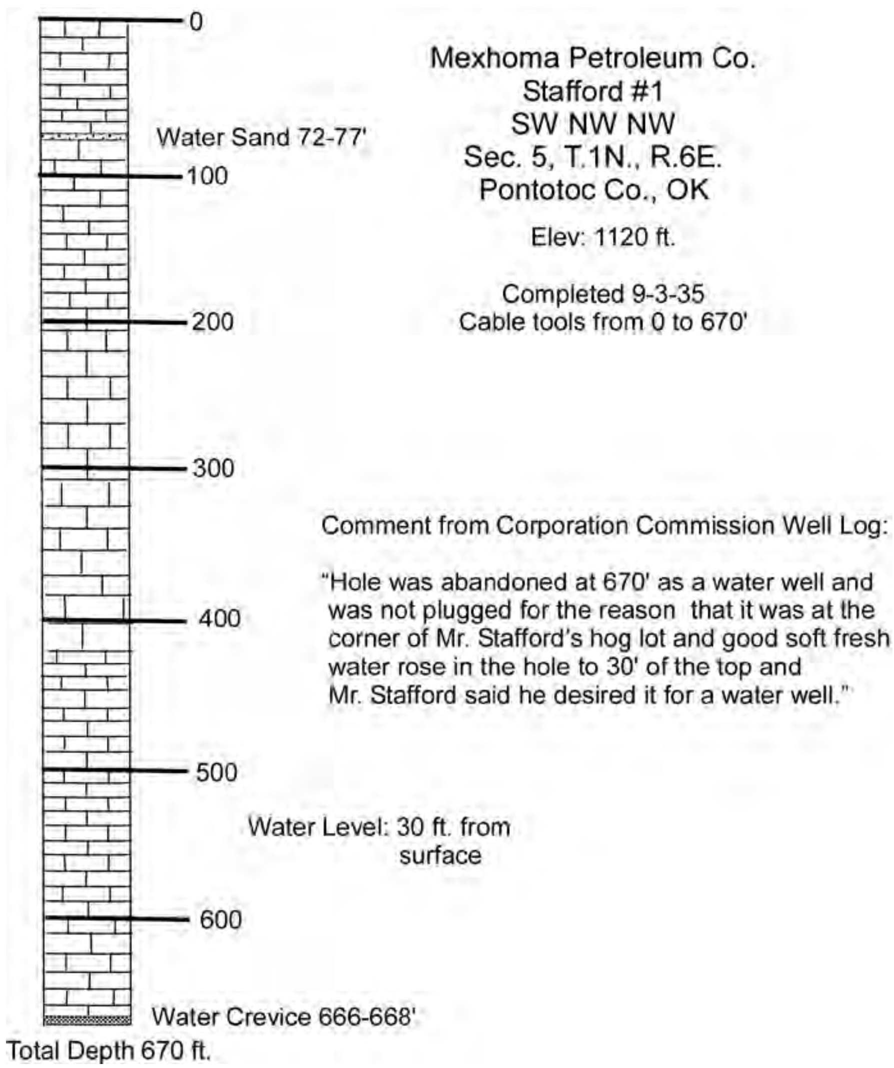


Figure 14. Lithologic log constructed for cable-tool-drilled well. Note “water sand” and “water crevice” separated by a thick interval of apparently non-water producing strata. Well data from the Oklahoma Corporation Commission.

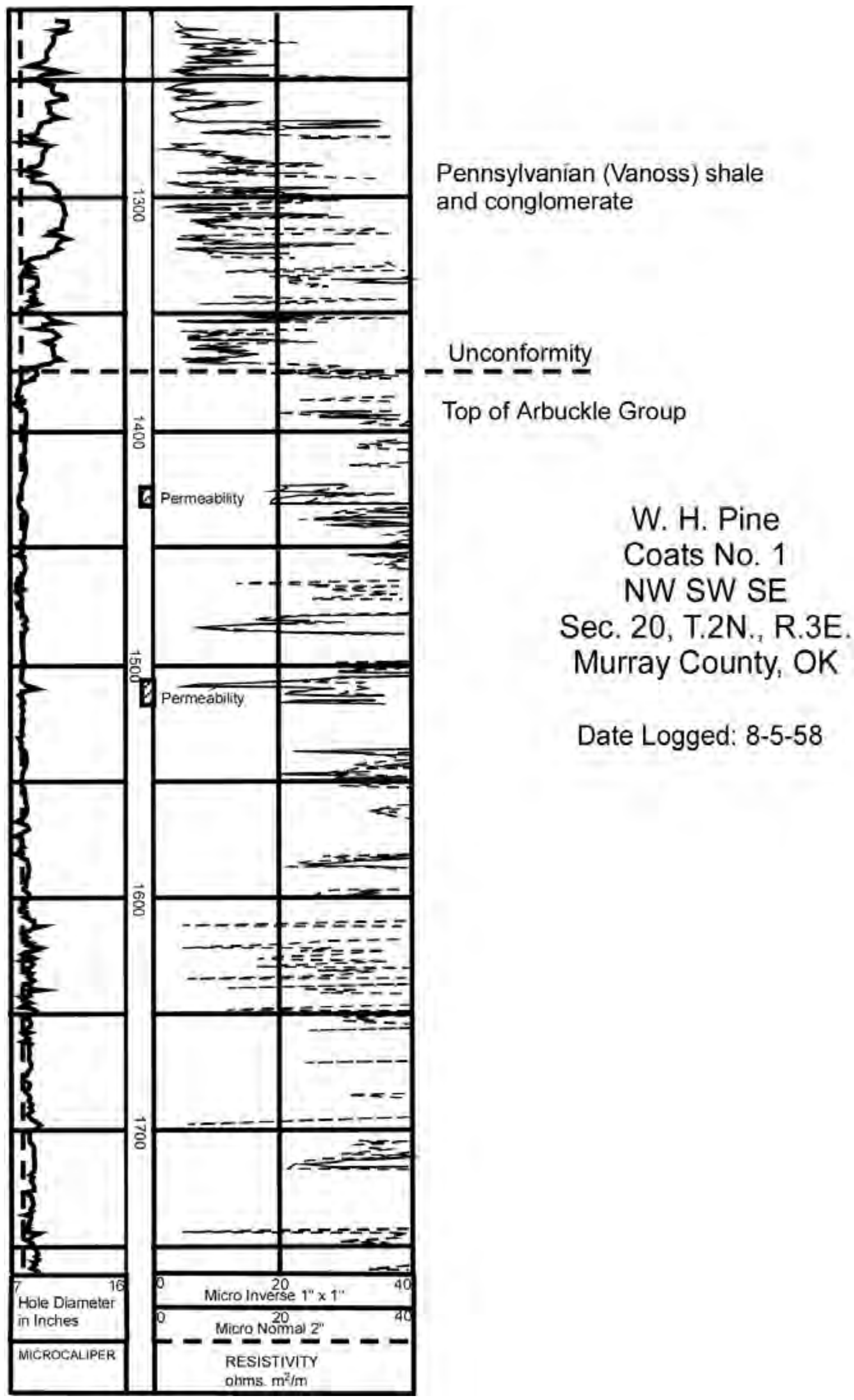


Figure 15. Microresistivity wireline log that indicates zones of permeability in the Arbuckle section that are separated by zones of low-permeability rock.

5.2.1 West Spring Creek and Kindblade Formations

The West Spring Creek and Kindblade Formations represent a major portion of the outcropping strata on the Hunton anticline. These units are mostly flat-lying to gently dipping and contain evidence of meteoric dissolution. Solution-enlarged fractures, disappearing streams, large springs and small caverns are all evidence of karstic processes. Records of water wells also support the occurrence of isolated porous zones within thicker low porosity carbonate intervals. The examination of bit cuttings from oil and gas exploration wells and the recently drilled USGS Spears #2 well near Connerville, Oklahoma, provide further evidence that focused flow dissolution processes were responsible for the porosity network in the Arbuckle carbonates. Pore- and fracture-lining baroque dolomite crystals (Figure 16) occur on curved faces that resemble vugs and along planar surfaces that are consistent with fractures. During drilling, reddish-brown mud was encountered at depth in conjunction with the inflows of large volumes of water. This mud, which may represent terra rosa zones (Figure 17) similar to those seen in karst terrains and in West Spring Creek/Kindblade outcrops along Interstate (I-35) on the Arbuckle Anticline, is indicative of sediment infill in solution features. Based on the work of Ham (1955) and Ham et al., (1964) immediately to the south on the Tishomingo Anticline, it is anticipated that the West Spring Creek should be approximately 400-500 meters (1200-1500 feet) thick on the Hunton Anticline. Wireline log surveys of the upper few hundred meters (1000 feet) of the Arbuckle Group identify permeable zones based on filtercake accumulation. However, since solution-enlarged fractures, enlarged bedding planes and small caverns are typically encased in low porosity rock, the overall wireline-measured-porosity values remain low. A summary of the vertical distribution of permeable zones determined from wireline logs is shown in Figure 4.

5.2.2 "Brown Zone" Data from Southern Oklahoma

Several oil fields in southern Oklahoma contain a porous and permeable zone near the base of the West Spring Creek Formation that is named the "Brown Zone" for an oil-producing lease in Healdton Field, Carter County, Oklahoma. The "Brown Zone" consists of karsted and dolomitized Arbuckle limestone that occurs at a relatively similar stratigraphic position in a number of oil and gas fields in southern Oklahoma. Correlating the "Brown Zone" from oil fields to nonproducing areas is problematic in that few wells penetrate the Arbuckle Group deeply enough to encounter the "Brown Zone" in areas where it is not expected to produce.

In the Cottonwood Creek field, Carter County, Oklahoma, the discovery well encountered a solution-enlarged-fracture or cavern during drilling and it is reported that the bit dropped eighteen feet. The Arbuckle Group was cored in Cottonwood Creek field, but the only recovery was low porosity carbonate from above the productive interval. It is believed that the rubbly nature of the

cavern-filling breccia within the productive zone prevented rock recovery in that interval.

Cores identified in Figure 11 were examined and described for lithology, rock fabric and dissolution features. A summary of these cores with their petrologs are in Appendix 6. Several

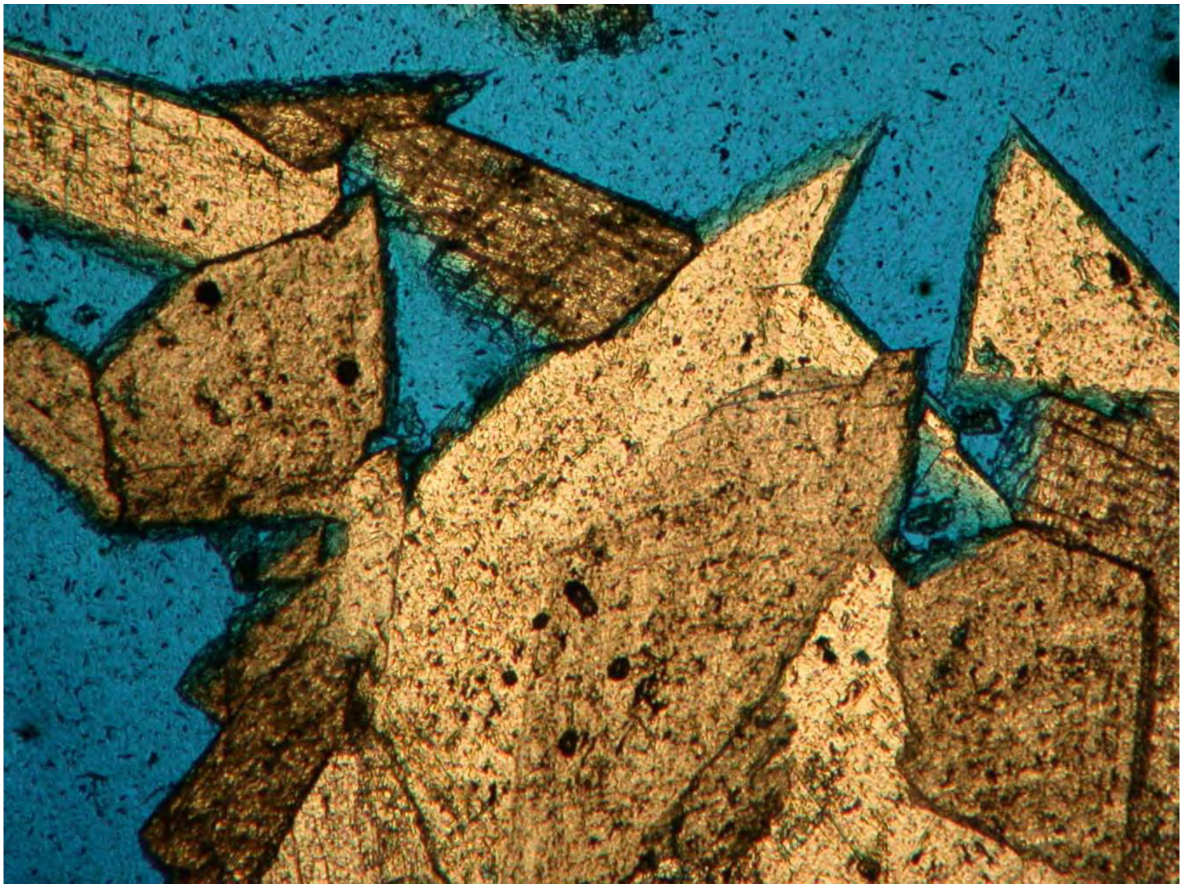


Figure 16. Baroque (Saddle) Dolomite crystal growing into a solution cavity or fracture. West Spring Creek Formation, USGS Spears #2 well.

Figure 17. Oxidized or "terra rosa" zones in the West Spring Creek Formation along I-35 in the Arbuckle Mountains (from Musselman, 1994).

rock fabrics were recognized including: (1) dense, low porosity argillaceous limestone, (2) dense, micritic to grainy limestone, (3) thinly bedded, porous dolomitized limestone and dolostone, and (4) porous sucrosic dolostone. The thinly bedded dolomitized limestone and sucrosic porous dolostone appear to be peritidal carbonates and represent deposition at the culmination of a shallowing-upward cycle. The dense argillaceous limestone represents open-marine subtidal deposition, whereas the dense micritic to grain-rich limestone is characteristic of shallow subtidal envinronments. The dolomitic fabrics (3 and 4) contain intercrystalline porosity and are considered reservoir/aquifer rock. The dense, but clean fabric 2 is susceptible to fracturing and dissolution and could develop vuggy to solution-enlarged porosity if subjected to corrosive fluids. Fabric 1 is not a candidate for porosity development because the argillaceous nature discourages dissolution and its depositional setting is one that is not prone to subaerial exposure during cyclic sea level declines.

6.0 Generalized Structure of the Hunton Anticline

The Hunton anticline tectonic subregion is a broad anticlinal fold that is fault bounded on the northeast and east by the Franks Fault Zone and the south and southwest by the Sulphur Fault (Figures 7, 8 and 9). The northwestern and southeastern flanks of the fold dip gently westward and easterly, respectively (Figure 7). Arbuckle Group carbonates of the West Spring Creek and Kindblade Formations outcrop in the central part of the fold. On the southeastern flank, progressively younger strata outcrop toward the Arkoma basin. The lower Paleozoic strata on the northwestern and western flanks dip westward beneath Middle Pennsylvanian cover (Figures 7 and 8). Ham and McKinley (1954) mapped a series of dominantly northwestern and southeastern trending faults that subdivide the anticline into a series of blocks. Some faults juxtapose Simpson and Arbuckle rocks, whereas others juxtapose Kindblade Formation against the West Spring Creek Formation. These faults have minor amounts of displacement compared to faults in the Bromide (Figure 7), Franks (Figure 8) or Sulphur (Figure 9) fault zones.

As a result of tectonics and erosion, the highest topographic elevation for the aquifer is located in T.1N., R.4E. The primary Simpson Group (Oil Creek sandstone) outcrops are located along the eastern, northern and western margins of the Hunton Anticline. The Simpson Group dips to the southeast and northwest along the gently dipping flanks and westerly beneath the Pennsylvanian cover. Steeply dipping Simpson Group is encountered in the Franks Fault Zone.

6.1 Structural attitude of the Arbuckle Group on the Hunton Anticline, Mill Creek Syncline and parts of the Tishomingo Uplift

A generalized structural contour map was constructed for the top of the Arbuckle Group to determine structural configuration of the aquifer. This representation (Figure 18) is a necessary tool to help determine the direction of groundwater flow in the study area. The structure map indicates that the aquifer is segmented by major faults that separate it into distinct blocks.

Seven distinct blocks are evident along the western margin of the mapped area. These are the (1) Tishomingo Anticline, (2) Mill Creek Syncline, (3) Belton Anticline, (4) Sulphur Syncline, (5) Hunton Anticline (southern block), (6) Hunton Anticline (central block) and (7) Hunton Anticline (northern block). Faulting further segments several of these blocks.

The mapped area of the Tishomingo Anticline is primarily located in T.2S., R.3E. and 4E. (Figure 18). The Tishomingo Anticline is bounded on the south by the Washita Valley Fault

Zone and on the north by the Reagan Fault. The highest structural and topographic position for the Arbuckle aquifer is centered in Sec. 16, T.2S., R.4E. This area represents a drainage divide between surface water flow toward Mill Creek to the east and Oil Creek toward the west. The westerly dip rate is approximately 750 to 1000 feet per mile (Figure 18).

The Mill Creek Syncline tectonic subregion is a faulted and folded downthrown block between the Reagan Fault on the south and the Mill Creek Fault on the north (Figures 9 & 18). The structural attitude of the Arbuckle Group is not defined within most of the synclinal area due to a scarcity of data. The western end of the syncline, including Sections 28 to 33, T.1S., R.4E. and Sections 25 to 29 and 32-36, T.1S., R.3E. was mapped. Here, the aquifer dips to the west at a rate of approximately 1000 feet per mile.

The Belton Anticline subregion is the horst-like feature located between the Mill Creek Fault on the south and the south fork of the Sulphur Fault on the north (Figures 9 & 18). Mill Creek crosses the anticline in Sections 21 and 28 of T.1S. R.3E., but its topographic expression is subtle and consequently its impact on groundwater flow may be minor. The Pennington Creek drainage crosses the anticline in T.1S., R.5E. and T.2S., R.5E. As a result, the western end of the Belton block may receive recharge from an area including parts of Sections 19 through 28, 35 and 36 in T.1S., R.4E. The aquifer is flat-lying to gently west dipping in T.1S., R.4E. Dip increases in T.1S, R.3E. to approximately 600 to 1000 feet per mile.

The Sulphur Syncline is defined as the area between the north and south forks of the Sulphur Fault (Figure 9). The Arbuckle Group does not outcrop in the syncline. As a result of the scarcity of well data, the structural attitude is projected primarily from the surface geologic map of Ham and McKinley (1954). The syncline is apparently bounded on the northwest by a fault located in Sections 1, 2, and 3 of T.1S., R.3E that separates the Vendome Well in Section 3, T.1S., R.3E. from the structurally lower area to the southeast.

The Hunton Anticline is bordered by the Sulphur Fault on the south, the Franks Fault Zone to the northeast, and the Lawrence Uplift to the north (Figures 8, 9 & 18). Surface topography is influenced by the Blue River and Pennington Creek drainages to the east and south, respectively, and Mill Creek to the west. A potential groundwater divide is located primarily in the eastern part of T.1N., R.4E. and the western part of T.1N., R.5E. The aquifer dips gently westward from this divide at a rate of approximately 200 feet per mile. The northeastern margin of the Hunton Anticline is the Franks Fault Zone, which is composed of a series of high-angle, down to the northeast faults (Figure 9). The southeastern boundary of the Hunton Anticline is influenced by the Bromide fault and Wapanucka Syncline, but is less faulted than the area bordered by the Franks Fault Zone (Figures 7 & 8). The limited well control, integrated with surface geology indicate the Arbuckle Group aquifer dips to the east at approximately 100 to 200 feet per mile in T.1S., R.7E. Southeast of the Bromide Fault in T.2S., R.7E. and R. 8E., dip increases to approximately 500 feet per mile. The western and central parts of the Hunton Anticline are subdivided into the northern, central and southern blocks.

The northern block is located to the north of the arcuate-shaped fault that trends west to east through the N/2 of T.1N., R.4E., crosses the northwest corner of T.1N., R.5E and extends into T.2N., R.5E. The Arbuckle aquifer dips gently to the northwest in the unfaulted area of this block.

The central block is delineated by the previously described fault to the north, a southwest to northeast trending fault in T. 1N., R.3E. and R. 4E. to the south, and a northwest to southeast trending fault to the east. Within this block, the Arbuckle Group dips gently westward at approximately 200 feet per mile. In T.1N., R.3E., the dip increases to approximately 400 feet per mile.

The southern block is bounded by the Sulphur Fault to the south and on the north by a fault trending southwest to northeast across T.1N., R.4E. The southern block, which is terminated to the west by the intersection north- and south-bounding faults, is mostly confined to the topographically higher part of the anticline. The block extends eastward across the anticline, where it is relatively flat-lying with no clear trends in dip. Dip becomes evident along the eastern margin of the anticline in T.1S.,R.7E.

One additional block, the northeastern, is evident along the eastern boundary of the Hunton Anticline. It is located primarily in T.1N., R.6E., but includes parts of T.2N., R.6E.,T.2N., R.5E. and T.1N., R. 5E. (Figure 18). The only noteworthy trends of dip in the northeastern block are found adjacent to the Franks Fault Zone.

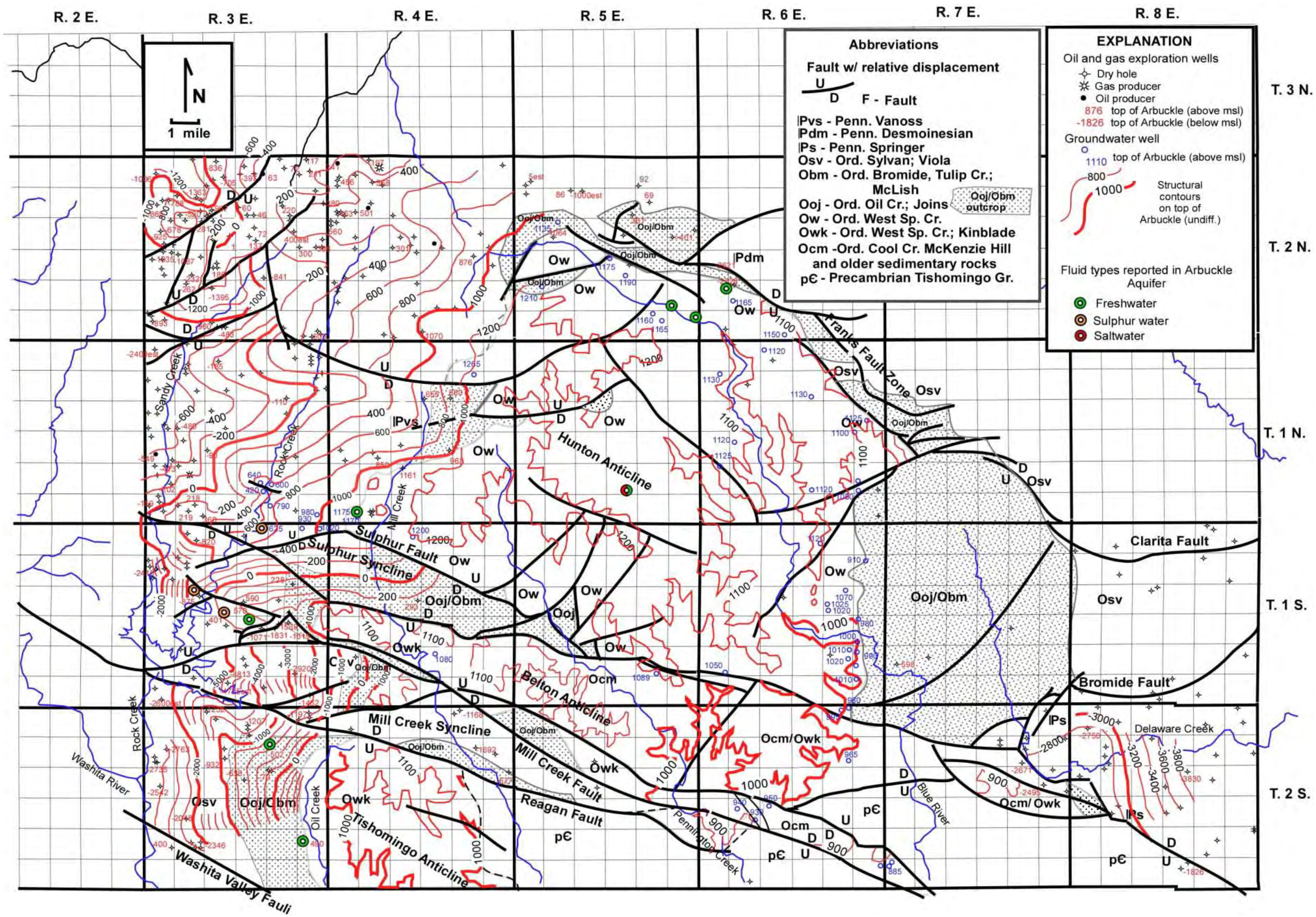


Figure 18. Generalized interpretation of the structure on the top of the Arbuckle Group: Hunton Anticline, Mill Creek Syncline and Tishomingo Anticline Tectonic Subregions, Arbuckle Uplift, Southern Oklahoma. Outcrop geology after Ham and McKinley (1954).

6.2 Structural attitude of the Oil Creek Sandstone (Simpson Group) on the Hunton Anticline, Sulphur Syncline, Belton Anticline, Mill Creek Syncline and Parts of the Tishomingo Anticline

The structural contour map for the top of the Oil Creek Sandstone (Figure 19) indicates that the attitude of the Oil Creek surface mimics the one contoured for the Arbuckle Group (Figure 18). However, as a result of erosion prior to Pennsylvanian deposition, the Oil Creek Sandstone is absent in several areas and contours are terminated against the boundaries that mark the limits of the distribution of the Oil Creek Formation. The large faults that define the tectonic subregions extend through the Oil Creek Sandstone and are delineated in the subsurface. Contour patterns define fault patterns in the subsurface that are similar to those for the Arbuckle.

Five tectonic subregions were evident in the western part of the mapped area. These are the (1) Hunton Anticline, (2) Sulphur Syncline, (3) Belton Anticline, (4) Mill Creek Syncline, and (5) Tishomingo Anticline. Mapping along the eastern part of the area defined easterly dip into the Wapanucka Syncline.

Outcrops of the Oil Creek Sandstone fringe the Hunton Anticline. Gaps in the outcrop pattern (Figure 19) result when Pennsylvanian strata unconformably overlie the Arbuckle Group and all intervening strata were removed by pre-Pennsylvanian erosion.

Contour patterns on the top of the basal Oil Creek Sandstone confirm the low values of dip gradient of around 50 ft./mile on the top of the Hunton Anticline. Dip gradients steepen on the flanks of the flanks of the Hunton Anticline and increase rapidly to the west of the Mill Creek Syncline to values >1000 ft/mile and increase to around 800 ft/mile in the Wapanucka Syncline. Steep dip gradients occur in the Franks Graben, but this area was not mapped due to its location outside the model area.

The distribution pattern of the basal Oil Creek Sandstone confirms syntectonic erosion. Fault blocks in the northwestern quadrant including T.2N., R.3E., T.2N., R.4E., T.1N., R.3 E. and T.1N., R4E. are tilted into ramps that are bounded by faults. The up sides or highest parts of these ramps are generally to the south edge of the block. Across the bounding fault on the downside is lowest portion of the adjacent ramp. The Oil Creek Formation is eroded off the upside or high part of these tilted blocks, but preserved on the downside or low end of the blocks (Figure 19).

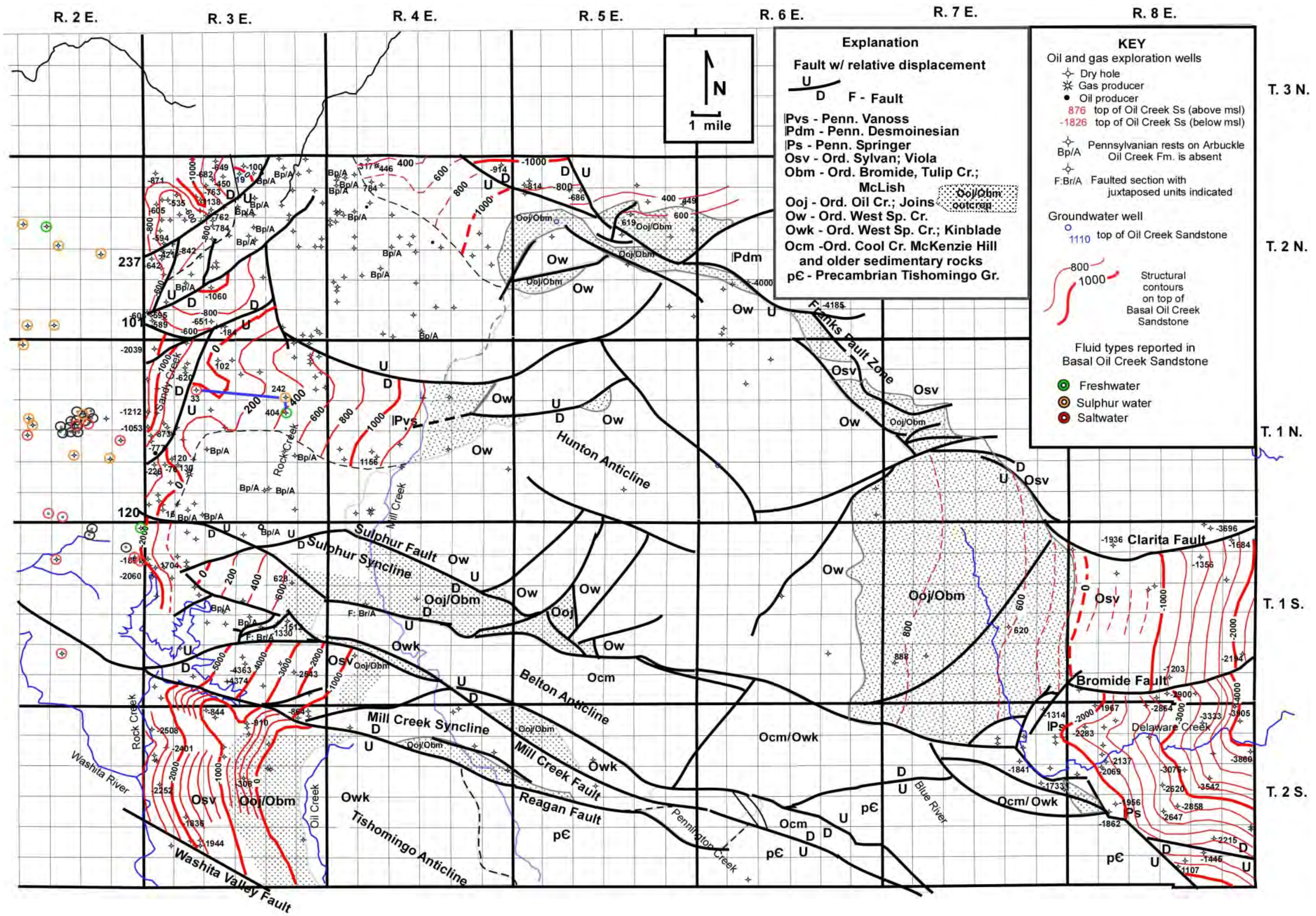


Figure 19. Generalized interpretation of the structure on the top of the Oil Creek Sandstone: Hunton Anticline, Mill Creek Syncline and Tishomingo Anticline Tectonic Subregions, Arbuckle Uplift, Southern Oklahoma. Cross section in T.1N., R.3E. is shown on Figure 20. Outcrop geology after Ham and McKinley (1954).

6.3 Generalized Distribution of Water Types (Facies)

Integrated fluid data from cable-tool-drilled wells, drill stem tests and wireline logs were used to map the generalized distribution of water types in the Arbuckle-Simpson aquifer. Water type distribution, when coupled with structural attitude, allows several inferences regarding the segmenting of these aquifers by faults and the affects of porosity and permeability networks on the downdip migration of meteoric water.

Two key deep wells report freshwater in the Arbuckle aquifer on the western end of the Tishomingo Anticline. The first and more important is located in the SW NW NW Section 11, T.2S., R.3E. (Figure 18). Reported data indicate the top of the Arbuckle at a structural position of minus 504 feet below mean sea level (msl). This well reports freshwater in the Arbuckle to a depth of 1614 feet or -686 msl. Following completion, this well was assigned to the landowner to be a water supply well. The second key well is located along the Arbuckle/Simpson Group contact in SE SW NW Section 25 (Figure 18). Reports for this well indicate that artesian freshwater flow was encountered in the Arbuckle aquifer at a depth of 760-780 feet. The total depth of this well is 780 feet, which is a 120 feet above mean sea level (+120 msl).

As a result of the paucity of data in the Mill Creek Syncline, no attempt was made to analyze the distribution of water types in that block.

Several wells located on the Belton Anticline report water types in the Arbuckle aquifer. Records indicate that two wells encountered sulphur water; 1 reported encountering freshwater. According to the drilling records, the well located in the S/2 SW SE Sec. 16, T.1S., R.3E. recovered sulphur water at a structural position of -141 msl. A well in the NE NW NE Sec. 17, T.1S., R.3E. recovered sulphur water at a position -1145 feet below mean sea level. A third well, which is located in the N/2 NE NW Section 22, reported freshwater at a depth of 1460 feet, which is -401 msl. This well is located in a small fault block within the Mill Creek Fault Zone and may not reflect generalized trends in the aquifer. All key wells are shown on Figure 17.

The distribution of water types within the Sulphur Syncline was not determined due to the lack of data. However, the Vendome Well, which is located in NW NE Sec. 3, T.1S., R.3E. (Figure 18), appears to be located within the syncline and it reported artesian sulphur water flow from a zone at 325 feet below the surface or 615 feet above mean sea level (+615 msl).

Several deep petroleum-related wells provide important water data on the Hunton Anticline. In the northeastern block, three wells report freshwater from depth in the Arbuckle section. Data for a well in the SW SW SW Section 25, T.2N., R.5E. indicates freshwater at a depth of 1421 feet or a structural position of -300 msl. A well located in the SW NE NE Section

36, T.2N., R.5E. recovered freshwater from -321 msl. Reports for a well drilled in the SE NE NE Section 30, T.2N., R.6E., indicate freshwater in the Cool Creek Formation, Arbuckle Group at a depth of 1834 feet or -644 msl. These wells are identified on Figure 18.

The southern block of the Hunton Anticline contains an enigmatic well. It is located in the SW SE Section 27, T.1N., R.5E. (Figure 18). Drill-stem-test data for this well indicate the recovery of saltwater from the Arbuckle Group at a position of -689 msl. However, a drill stem test conducted in the deeper Reagan Sandstone Formation, Timbered Hills Group, reports freshwater at a structural position of -1966 msl.

The other blocks on the Hunton Anticline lack petroleum-related wells that report water type data. However, there are municipal, water district and domestic water supply wells that provide water-type-distribution data in these areas. Water supply wells for the Murray County Rural Water District No. 1, which are located in Sec. 31, T.1N., R.4E. (Figure 18), indicate the Arbuckle aquifer in the southern block is freshwater bearing to approximately 1145 feet below surface, which is 30 to 40 feet above mean sea level.

Water supply wells in the Simpson Group aquifers attest to the presence of freshwater near the outcrop recharge zones (Figure 19). Wireline logs indicate that the Oil Creek Sandstone may contain freshwater at depth on the western flank of the Hunton Anticline (Figure 20). The erosion of the Simpson Group beneath the pre-Pennsylvanian unconformity and the scarceness of wireline logs and fluid data prevented the mapping of a definitive distribution of water types in the Oil Creek Sandstone, but generalized trends of water type distribution are evident in Figure 19. Freshwater is found closer to the outcrop, which is the primary zone of recharge. Moving downdip away from the outcrop recharge, water quality deteriorates and a transition from freshwater to sulfur water to saltwater with oil and gas is apparent (Figure 20). The occurrence of freshwater several miles downdip of the recharge zone attests to the porous and permeable nature of the Oil Creek Sandstone.

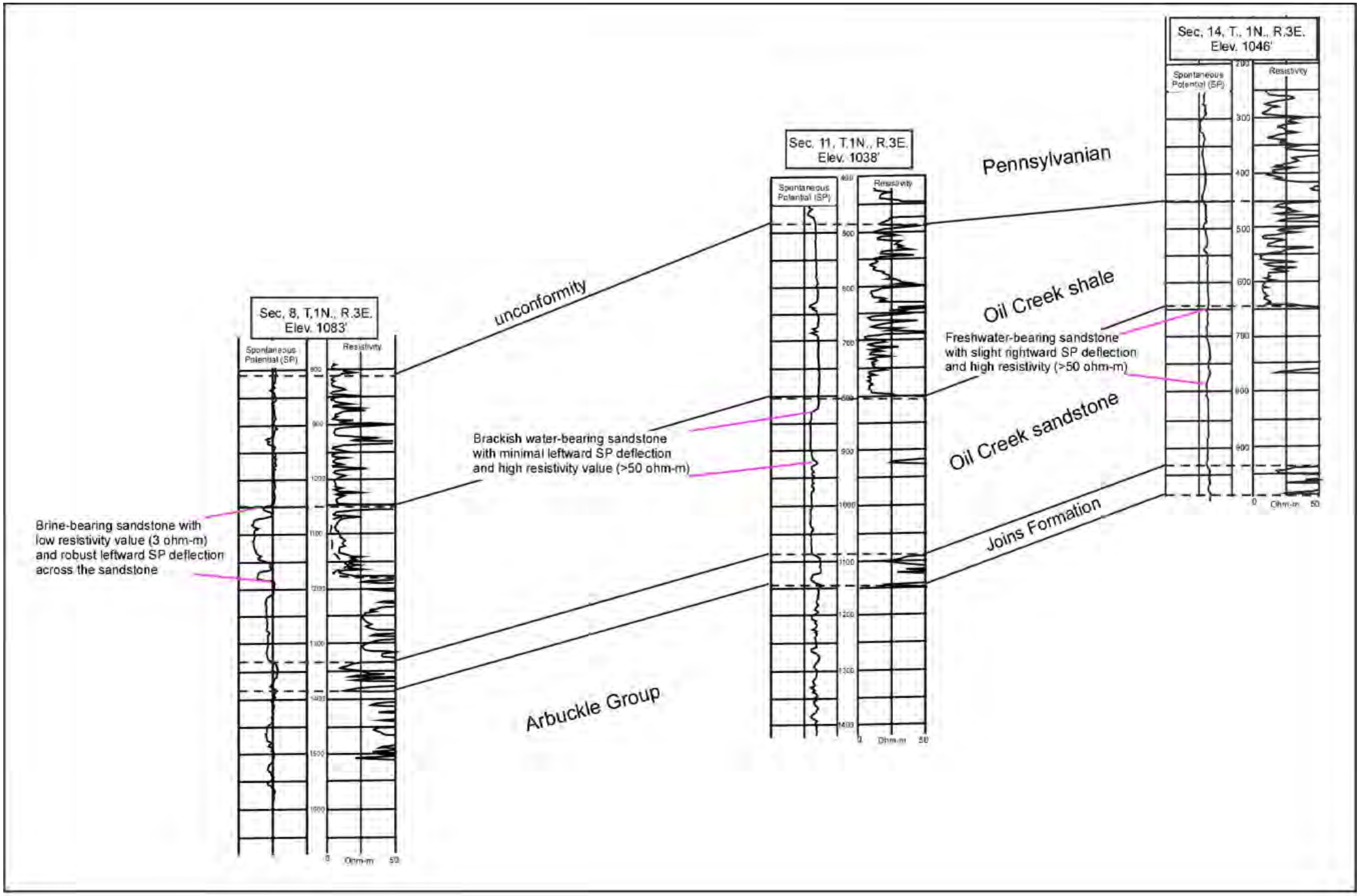


Figure 20. Transition from freshwater to brackish water to saline water in the upper part of the Oil Creek Sandstone, western flank of the Hunton Anticline Tectonic Subregion, Arbuckle Uplift. Location of the cross section is shown in Figure 19.

7.0 Discussion

The Hunton Anticline tectonic subregion of the Arbuckle Uplift is a large anticlinal fold with the Arbuckle-Simpson aquifer exposed along the crest and flanks. The aquifer dips easterly, northerly and westerly beneath younger strata. In some areas Arbuckle Group carbonates are directly overlain by Pennsylvanian rocks as the intervening strata were eroded prior to Pennsylvanian deposition.

The Arbuckle Group and specifically the West Spring Creek Formation is the principal hydrostratigraphic unit in project area. Second in importance is the basal Oil Creek sandstone in the Simpson Group. Wells producing from the Arbuckle Group and springs discharging from same have much higher yields than springs and wells producing from Simpson Group hydrostratigraphic units.

Distribution of zones of porosity and permeability in the Arbuckle Group is controlled by fracturing and dissolution. Well records from water supply and petroleum exploration indicate the Arbuckle Group contains water in the shallow (<50 feet deep) subsurface, thick sections of low permeability and discrete deeper zones of high-volume flow. Well records indicate that most flow from the Arbuckle Aquifer comes from these zones of enhanced porosity and permeability (called crevices or sands) that are separated by thick intervals of low porosity/low permeability rock. Zones of porosity and permeability in the Arbuckle Group appear to be influenced by stratigraphy and certain lithostratigraphic units, such as the West Spring Creek Formation contain more water than deeper zones. A zone of porosity and permeability in the lower part of the West Spring Creek Formation may correlate to the “Brown Zone” of the petroleum industry. The “Brown Zone” is an interval of enhanced porosity and permeability development near the base of the West Spring Creek Formation that produces oil and gas in fields located in south-central and southern Oklahoma. Cores from these fields contain features that indicate that porosity was enhance by dolomitization and paleokarstic processes. It is conceivable that these processes operated across the area and that dolomitization and dissolution of the Arbuckle Group limestones generated the porosity and permeability occurring within the West Spring Creek Formation located within the project area.

Since few water supply wells penetrate the entire Arbuckle-Simpson aquifer, much of the data concerning the aquifer was garnered from the examination of data generated during the exploration for oil and gas. Oil- and gas-exploration wells provided important data on aquifer/reservoir fluids across the project area. These data were augmented with water well data and used to develop a preliminary interpretation of the distribution of water types or facies within and adjacent to the project area. The interpretation of this information suggests that the Arbuckle aquifer in the region containing the Hunton Anticline is segmented by faults. The resulting blocks have distinct freshwater/sulphur water distributions. Freshwater is encountered in the Tishomingo block at a structural position more than 600 feet below mean sea level. A few miles to the north on the Belton Anticline, the aquifer contains sulphur water at this same structural position. Another example comes from the area near the City of Sulphur and Vendome Well. The Arbuckle aquifer in the southern block of the Hunton Anticline is saturated with freshwater to a depth that is structurally 30 to 40 feet above mean sea level. In contrast, the Vendome Well, which is located approximately 3 miles to the west, flows sulphur water from the aquifer at a structural position that is 600 feet above mean sea level.

Zones of higher permeability in the basal Oil Creek Sandstone and Arbuckle Group are found to be freshwater bearing beneath shallower (Pennsylvanian) low permeability rocks that contain brine and oil and gas. Freshwater-, sulphur water- and brine-bearing zones are detectable on wireline logs, which can be used to map their distribution in the subsurface. The integration of the structural, stratigraphic and water type/quality data provides the foundation for the proper characterization the Arbuckle-Simpson aquifer.

8.0 Conclusions

The integration of data from multiple sources, including the petroleum industry and governmental and regulatory agencies, allowed for the construction of a reasonable stratigraphic framework and the interpretation of the subsurface geology in the project area. As a result of this novel approach of utilizing multiple types of data generated by a number of different and completely unrelated sources, it was possible to formulate the following conclusions concerning the Arbuckle-Simpson aquifer.

1. The Arbuckle-Simpson aquifer contains hydrostratigraphic units within a thick column of sedimentary rock. These are in order of decreasing importance (1) the Arbuckle Group and in particular the West Spring Creek and Kindblade Formations, (2) the basal Oil Creek Sandstone of the Simpson Group, and (3) the Bromide and McLish sandstones of the Simpson Group.

2. The hydrostratigraphic units within the Arbuckle Group consist of zones of enhanced porosity and permeability that are the result of dolomitization, fracturing and dissolution. These zones of enhanced permeability/porosity are separated by thick intervals of low permeability/porosity rock that have low water yields.

3. The hydrostratigraphic units in the Simpson Group are the thick sandstones of the Oil Creek, McLish and Bromide formations that contain intergranular primary porosity. Of these, the basal Oil Creek Sandstone is by far the most utilized aquifer. These sandstones in the Simpson Group are separated by low permeability shale and limestone beds.

4. Hydrostratigraphic units of the Arbuckle-Simpson aquifer dip beneath younger strata on the flanks of the Hunton Anticline tectonic subregion of the Arbuckle Uplift.

5. The distribution of water type is somewhat mappable in the project area and influenced by the distribution and structural attitude of the hydrostratigraphic units. In areas, highly permeable hydrostratigraphic units contain freshwater in a position beneath shallower lower-permeability units that are brine and or oil- and gas bearing.

6. The Arbuckle-Simpson aquifer appears to be segmented by faults and other flow barriers. As a result, depth to the base of freshwater is not consistent across the project area.

7. The change is water type within the Arbuckle-Simpson aquifer can be traced down gradient from areas of potential recharge. These changes are recorded in fluid tests and in some cases evident on wireline logs.

8. The integration of the stratigraphic framework and structural attitude of the hydrostratigraphic units provides the foundation for the construction of geologic and aquifer models.

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10.0 Electronic Appendices

10.1 Appendix 1 – Aquifer Yields for Selected Wells

10.2 Appendix 2 – Discharge Rates for Selected Springs

10.3 Appendix 3 – Vertical Distribution of Porous and Permeable Zones in the Arbuckle Group

10.4 Appendix 4 – Summary of Petroleum Industry Data

Table 1: Formation Fluid Data

Table 2: Wireline Log Data

Table 3: Cores of the Arbuckle Interval

Table 4: Wells with Bit Cuttings

10.5 Appendix 5 – Well Data Collected from Petroleum Industry

10.6 Appendix 6 – Summary and Description of Selected Cores

10.7 Appendix 7 – Plates 1, 2, 3, 4 and 5