THE SIMPSON PLAY

(Including parts of the Arbuckle & Viola)

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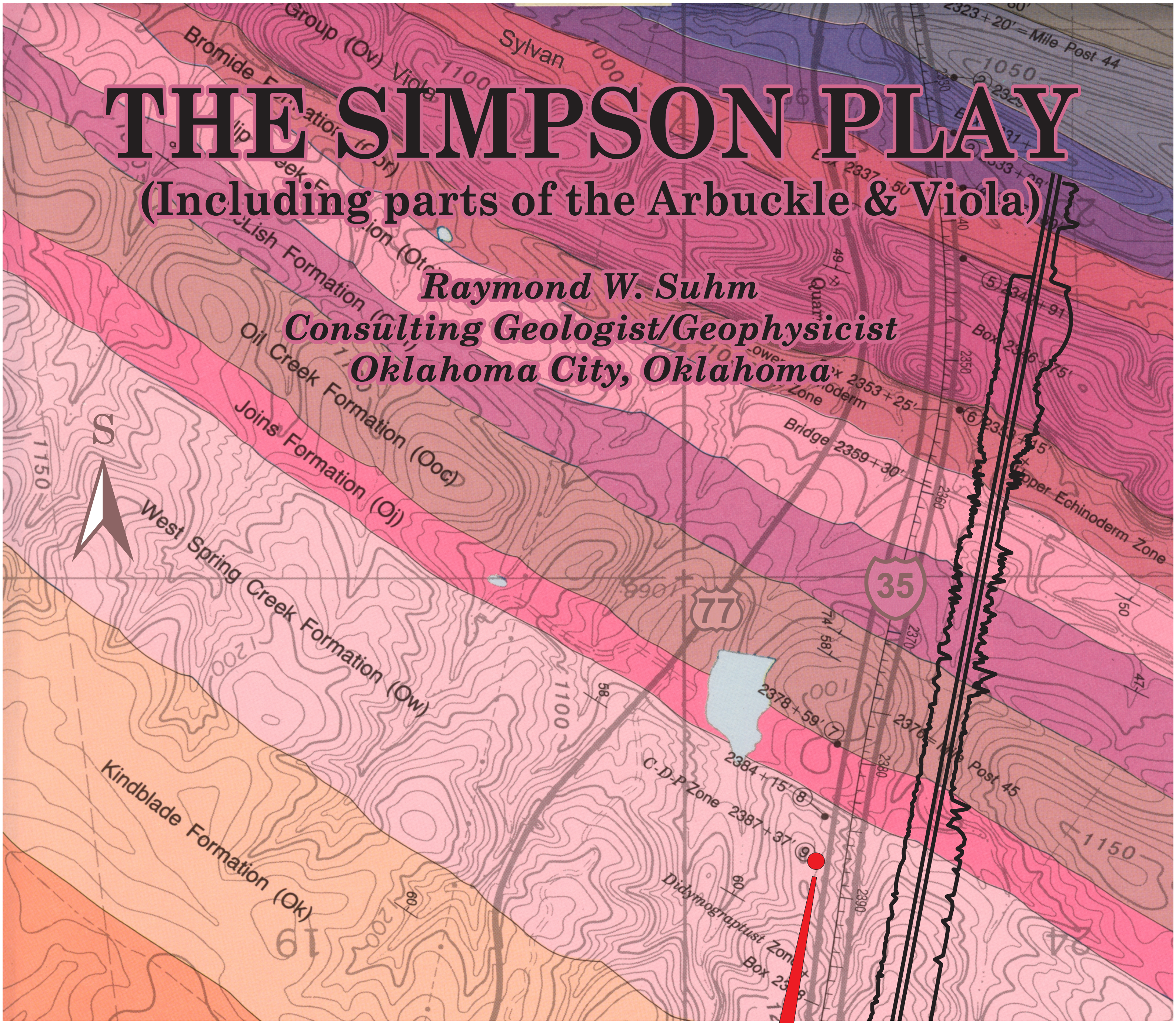

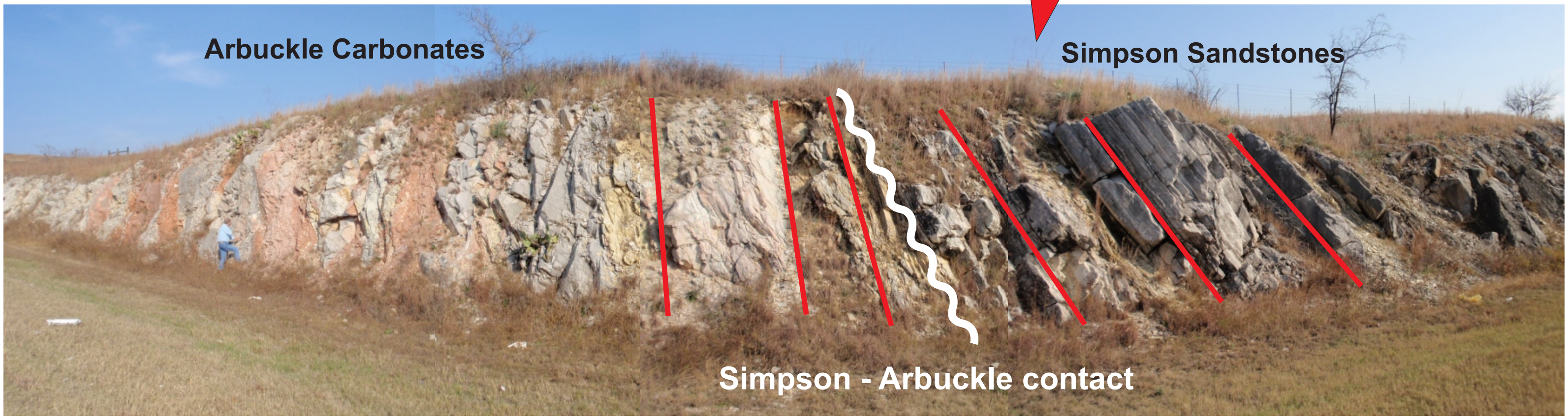

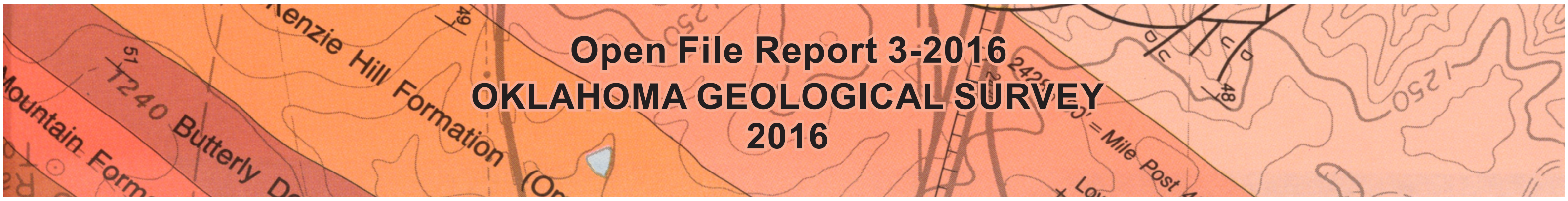

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Oklahoma Geological Survey
JEREMY BOAK, *Director*

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Stratigraphy And Petroleum Potential Of Simpson Group (Ordovician), Oklahoma

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2016

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Cover: Stratigraphy of the Simpson Group in Oklahoma and petroleum potential. Well log profile for Northern Nat. Gas #1-6A Little aligned with Interstate 35 superimposed on a geologic map for western Arbuckle Mountains prepared by Fay (1995). Red dot on the map is panoramic view of outcrops (Section 24, T2S-R1E) looking east from northbound Interstate 35 (GPS: 34°22'3.20"N; 97° 8'44.26"W) showing the contact between quartz sandstones and carbonates of the Simpson Group and carbonates and redbeds of the Arbuckle Group. Red stratal contacts suggest an angular discordance between the two groups. Ray Suhm is on left side for scale (Photo by Rick Andrews).

The Oklahoma Geological Survey is a state agency for research and public service, mandated in the State Constitution to study Oklahoma's land, water, mineral and energy resources and to promote wise use and sound environmental practices.

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ABSTRACT

Stratigraphy and Petroleum Potential of Simpson Group (Ordovician), Oklahoma

Raymond W. Suhm, Consulting Geologist/Geophysicist Oklahoma City, Oklahoma

Subsurface data acquired over the past 20 years has necessitated a reinterpretation of the stratigraphy of the Simpson Group in Oklahoma discussed by Suhm (1997). New maps and cross sections provide insightful observations on formations of the Simpson and their significance as hydrocarbon reservoirs. Simpson structure is conveyed through a state-wide Viola structure map that was prepared from well control and seismic data. This map shows outcrops, subcrop, and subsurface structure across Oklahoma including its structure beneath the thrust complex of the Ouachita Mountains. Numerous well logs exemplify Simpson characteristics and some show K-bentonites that were used to help define the Simpson/Arbuckle contact, a contact that coincides with the Tippecanoe/Sauk Sequence boundary. Isopach maps were prepared for the Joins, Oil Creek, McLish, Tulip Creek, and Bromide Formations of the Simpson Group, and Burgen Sandstone and Tyner Formation equivalents in the Ozark Mountain area. The Seminole sandstone of the Viola Group is also mapped and discussed in this report since it is an oil reservoir often classified as Simpson with the name “Wilcox sandstone.” Isopach maps display not only thickness variations in sandstones, but also show lateral facies and porosities. Each map shows locations of type sections, well control points, and production. The reader will have access to supporting digital Excel data on the enclosed DVD, including unpublished cross sections prepared by Suhm (1997).

The formations and members of the Simpson Group in Oklahoma form specific lithologic associations in distinct depositional provinces that include: (1) thin, supratidal to shallow-subtidal carbonates and initial, earliest quartz sandstones of the South Ozark Platform; (2) thin, subtidal limestone, dolomite, shale, and younger sandstone of the Oklahoma Shelf, a province that is separated from the South Ozark Platform by the Southwest Ozark Lineament, a basement feature that may merge with the Seneca and Southwest City Faults and possibly the McClain County Fault; (3) thin, intertidal to subtidal carbonates of the Texas Arch.; (4) thick, shallow to moderately deep-water limestone, shale, and sandstone of the Anadarko and Ardmore Basins that are bordered, in part, by hinge lines and/or syndepositional faults and which merge southeastward with the Fort Worth Basin; and (5) Ouachita Trough consisting of basinal lithologies, often anoxic, that represent deposition in restricted seas.

Sandstone reservoirs of the Simpson Group are primary exploration targets. Exploration strategies are discussed in context of reservoir characteristics, such as thickness, porosity, entrapment, and hydrocarbon generation relative to source beds, burial depths, and temperatures. Broader implications of basin development, paleogeography, and paleotectonics are also discussed. Deep faults, some of which are syndepositional, are discussed in reference to the boundaries of structural provinces and their role in determining oil and gas distribution. Selected oil and gas fields in the Anadarko and Ardmore Basins, Hollis Basin, Arkoma Basin, and Cherokee Platform are discussed to exemplify size and productivity of Simpson reservoirs. Equivalent reservoirs comprising the Ouachita facies in the Ouachita Mountains are also mentioned. Structural styles of all tectonic provinces are vividly illustrated on a seismically generated Viola structure map which enables tectonic interpretation and formulation of exploration strategies leading to the drilling of vertical and horizontal wells.

PART 1

INTRODUCTION

REGIONAL OVERVIEW

Stratigraphy is one of the oldest branches of geology and one that marks the beginning of modern geology. It is a study of all aspects and contents of strata exposed on the earth. However, with an increasing need for mineral resources, stratigraphic studies have shifted from surface exposures to the larger realm in the subsurface. Research for this paper, "The Simpson Play (Including Parts of the Arbuckle and Viola)" is approached in the spirit of subsurface stratigraphic relationships and distributions of facies. This study represents an expansion of an earlier study (Suhm, 1997), the purpose of which was to correlate strata of the Simpson Group throughout Oklahoma and Arkansas, utilizing all available well logs and outcrop data. In fact, names for sedimentologic provinces proposed in 1997 will continue to be used in this report. Well log data and subsurface cross sections not included in the earlier publication are included in this report, along with more well data, updated information, and new interpretations that should be useful to explorationists and earth scientists of varying specialties.

Historically, the early 1900's saw the beginning of pioneering studies of Simpson outcrops by Taff, Ulrich, Purdue, and Miser in the area of the Arbuckle and Ozark Mountains. A few decades later, "traditional" Simpson in Oklahoma was defined by Decker and Merritt (1931) as a group of sedimentary rock consisting of five "cyclic" formations, each of which may have a basal sandstone; from bottom up these are Joins, Oil Creek, McLish, Tulip Creek, and Bromide. Although this early definition does not take into account the subsurface distribution of these formations, it is a valid overview, and, with a few exceptions, such as adding members, it is adhered to in this report. Since their 1931 publication thousands of wells have been drilled across the state with the result that geophysical logs, along with cuttings, cores, production tests, etc., have enabled more detailed stratal correlation from well to well. These data show that formations of the subsurface Simpson Group possess readily identifiable well log signatures that can be traced with accuracy and relative ease from far northeastern Oklahoma to southern Oklahoma. Electric-log response can be related to specific lithofacies identified from study of drill cuttings, and be correlated and mapped as facies. Schramm (1964) and Statler (1965) are credited with published reports containing regional isopach and lithofacies maps for the subsurface Simpson in Oklahoma. Similarly, Holden (1965) extended the Oklahoma Simpson Group into Arkansas. Well logs used by these earlier investigators were incorporated into the work of Suhm (1997), along with "newer" well logs that display lithologic information, such as gamma-ray, neutron/density, and photoelectric (PE) data. Moreover, as shown in this study, sensitivity of modern logs allow recognition of thin bentonites and organic-rich shales not normally seen in drill cuttings, and provide detection of interspersed silica and clay in carbonates (similar to insoluble residues). Additionally, bentonites were found to be concentrated at the top of the Arbuckle Group, a state-wide pattern that enables separation from the overlying Simpson Group. This was previously unknown.

Quartz sandstones are emphasized in this report because they represent traditional, well-established hydrocarbon reservoirs recognized by explorationists. All Simpson sandstones share the quality of being fine to coarse grained with quartz that is well-rounded and having a frosted or pitted appearance. For that reason they are given the description, "St. Peter-like," implying that quartz grains composing formations of the Simpson Group were derived from the erosion of older preexisting sandstones from the Canadian Shield, and that quartz grains were subjected to eolian processes at some point in their history. All of these "St. Peter-like" sandstones are productive in Oklahoma with the most prolific fields developed where the sandstone is porous and on anticlines or upthrown fault blocks. Limestone and dolomite also yield oil and gas. For example, the "Great American Carbonate Bank"** over which the Simpson was deposited was selectively karstified to create cavernous carbonate reservoir systems that were, in some areas, filled with Simpson detritus. Moreover, as will be discussed in more detail later, some production assigned to the upper part of the Arbuckle has been identified in this study as Simpson, or Joins such as at Wilburton Gas Field, Oklahoma

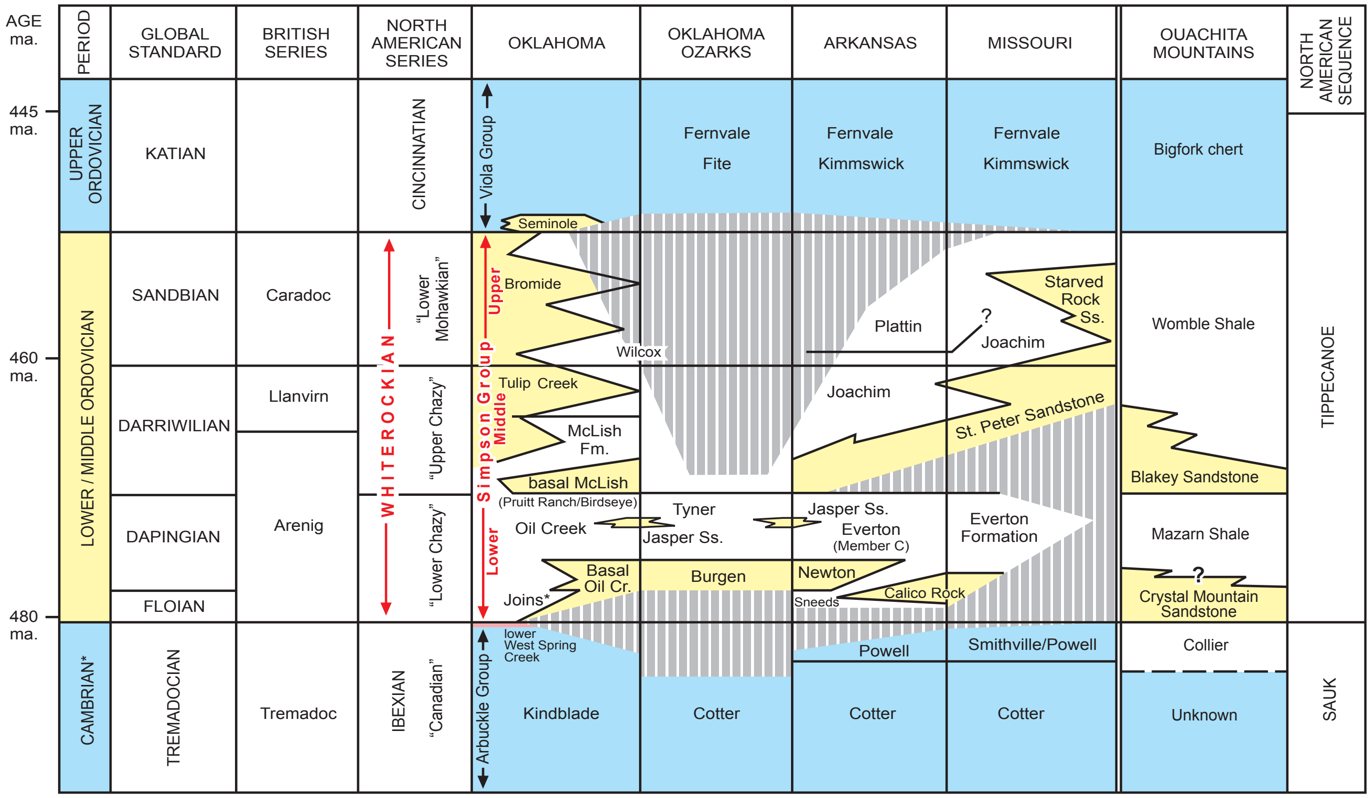


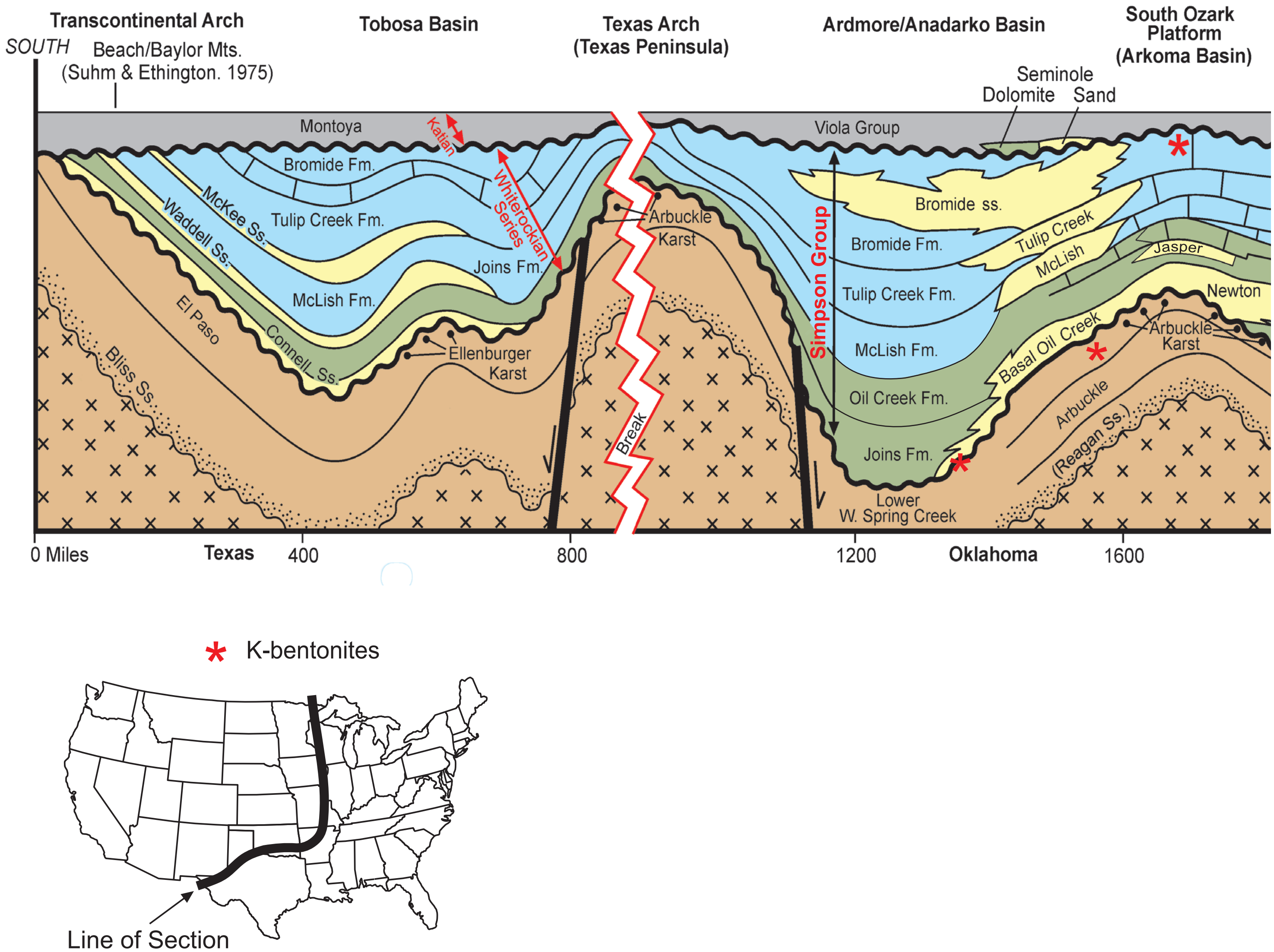
FIGURE 1. Correlation Chart: Interpreted age of the Simpson Group in Oklahoma and correlations to Arkansas, Missouri and the Ouachita Mountain area. Stratigraphic time relationships were compiled through consideration of work of Cocks, et al 2010 (who places Tremadoc with Cambrian System below Florian); Lapworth, 1879; Leslie and Lehnert, 2005; Sadler, et al 2009; Nolvak, et al 2006. Lacunas (gray vertical line pattern) reflect uplift of the Ozark Dome and South Ozark Arch. For purposes of subsurface mapping, the Simpson is subdivided into lower, middle, and upper units. The basal sandstone of the Jasper Member of the Everton Formation of the lower Simpson replaces what was called "Member C Sandstone" in earlier publications. The basal McLish sandstone in the middle Simpson is equivalent to the St. Peter Sandstone, as also supported by Ethington, et al (2012). The Joins is a facies of the basal Oil Creek sandstone. The stratigraphic position of the lower part of the West Spring Creek Formation of the Arbuckle Group is shown. The upper part of the West Spring Creek is not shown because of its inclusion with the Joins. Simpson equivalents in the Ouachita Mountains are considered from Suneson (2008), Pitt (1955), and Suhm and Campbell (2001).

**The Cambrian-Ordovician boundary in North America is placed at the top of the Tremadocian (Lapworth, 1879) and discussed in the "Nomenclature" section of this report.*

City Field, Healdton Field, and West Mayfield Field.

As will be seen, most Simpson production is concentrated on the ancestral Oklahoma Shelf of the present-day Cherokee Platform. However, accentuated and complex structures that flank the Anadarko and Ardmore Basins in southern Oklahoma have also yielded exceptionally large reserves from multiple reservoirs within the Simpson (Plates 1, 2, 3). Simpson production is meager on the ancestral South Ozark Platform, part of the present-day Arkoma Basin, with the exception of a few high-reserve fields at western extremities where porosity is better developed. Simpson equivalents in the Ouachita facies (restricted marine) in the allochthonous (transported) strata of the Ouachita Mountains are largely undrilled and have not yielded significant hydrocarbons. Simpson-equivalent in situ sandstones deposited in the "original" Ouachita Trough have not been penetrated by drilling. The Crystal Mountain and Blakely Sandstones and their associated black shales and fetid limestones (Figure 1) have exceptional hydrocarbon potential in the southeastern part of the

** Marshall Kay (1951) constructed a paleogeographic map of the craton as it appeared during Early Medial Ordovician time that was referred to by numerous geologists as an extensive "carbonate bank." To better describe it some investigators added the term "Great American Carbonate Bank."



state, albeit at depths greater than 20,000 feet.

From the point of view of an explorationist, promising Simpson structural and stratigraphic plays are yet to be discovered across most areas of Oklahoma, especially in light of the relatively few wells that have penetrated near complete sections of Simpson strata. Structural plays include many untested anticlines, fault blocks, and subthrust features. This study shows that sandstones within the Simpson Group are not necessarily blanket-like; many display stratigraphic complexities in thickness that may be favorable for stratigraphic entrapment of hydrocarbons, notably at their fringes. Additionally, Simpson carbonates where fractured and interbedded with organic-rich lithologies may prove to be economic horizontal drilling targets, similar to other proven reservoir plays. Similarly, horizontal economic viability could also be proven in areas where porous Simpson quartz sandstones grade across permeability barriers to less porous sandy carbonates. Equally important, basal Simpson brecciated sandy carbonates that rest on, or within, the irregular karsted surface of Arbuckle Group limestone are potential reservoirs and horizontal candidates, such as in the Oklahoma City Field. Carbonates at the Simpson/Arbuckle contact remain essentially untested due to the relatively small number of wells that were drilled into the Arbuckle. Because the Arbuckle and Viola share structural similarities, the Viola structure map included in this study may mirror that of Arbuckle structure as it does for Simpson structure. For example, with information contained on an Excel spreadsheet on the enclosed DVD, Viola and Simpson thicknesses can be added to Viola subseas on the Viola structure map to derive relative depths to the Arbuckle. Depths to the Arbuckle would be important for many things, including locating disposal wells, evaluating geothermal ventures, plotting exploration strategy, and

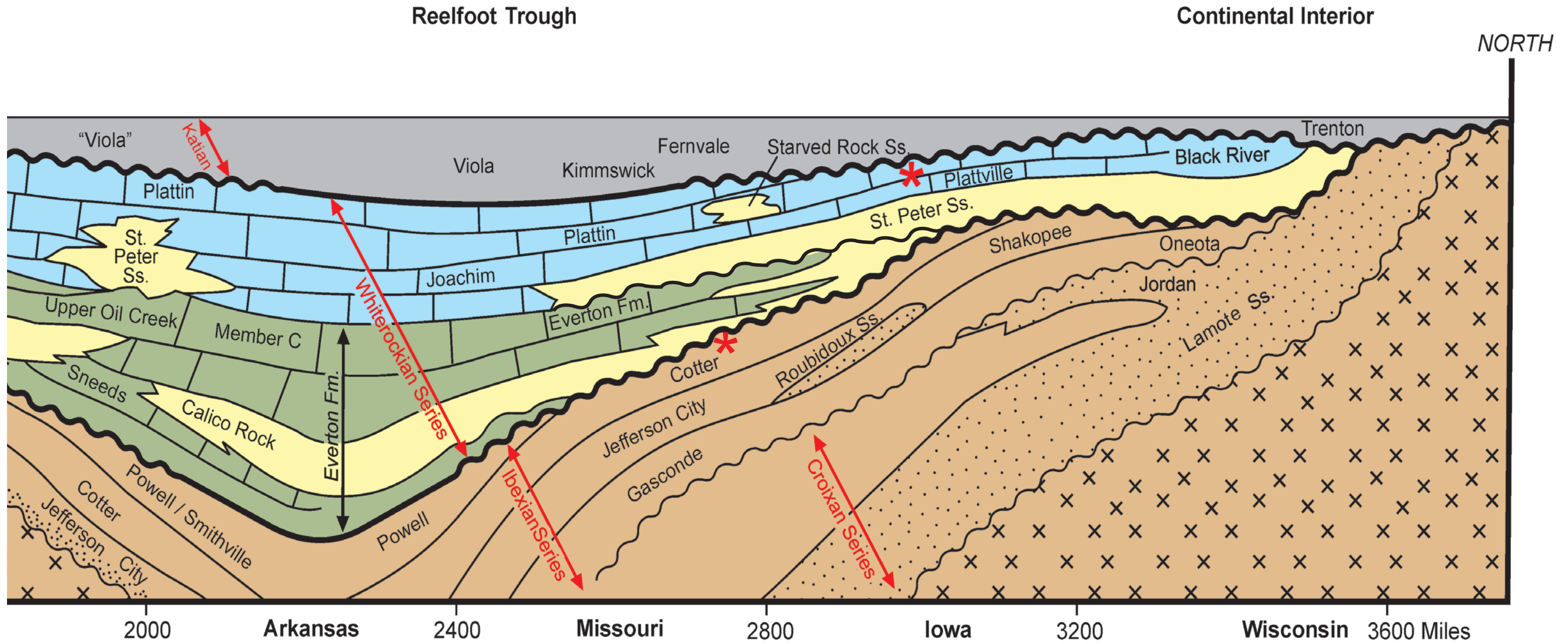


FIGURE 2. Reconstructed cross section of Simpson and equivalents from Texas to Canada. Inception of this section by Grabau, (1913) was later modified by various authors (Dake, 1921; Patterson, 1969; Templeton and Willman, 1963; Thompson, 1991; Suhm, 1997). Relative thicknesses of each formation have been altered for diagrammatic purposes. The Sauk sequence (light brown) consists of Reagan Sandstone through the Arbuckle Group (Ibexian Series). The overlying Simpson Group is within the lower part of the Tippecanoe Sequence. Supermature sandstones of the Simpson and St. Peter consist of quartz grains re-cycled from older sandstones. Limestone (blue) is common in upper Simpson; dolomite (green) is more abundant in lower parts of the Simpson Group. The Simpson is overlain by Viola Group carbonates shown in gray.

academic research among others.

In sum, subsurface studies such as this one show that geophysical wireline logs are valuable tools, which, through correlation, can lead to an understanding of facies and porosity relationships. This and other subsurface data enable reservoirs of the Simpson Group to be mapped and interpreted. Moreover, numerous isopach and lithofacies maps included here illustrate the relationship of tectonic and eustatic controls on deposition, sand-dispersal patterns, and the influence of source areas, and allow the tectonic and paleogeographic frameworks to be reconstructed. Data contained here can be used to evaluate areas of future potential economic interest and lead to a better understanding of geologic history.

NOMENCLATURE

Twenty years after Lapworth (1879) introduced Ordovician System in Wales, Taff (1902, 1904) mapped rocks exposed in the area of the Arbuckle Mountains of southern Oklahoma. He recognized a detrital-rich section of rock consisting of beds of sandstone, shale, and limestone that visibly contrasted with thick overlying and underlying carbonates. That observation enabled Taff (1902, 1904) to name and map Arbuckle, Simpson, and Viola strata in the Arbuckle Mountains. He named the Simpson from strata exposed along Little Blue Creek near Camp Simpson, Indian Territory (GPS: 34°29'18.58"N; 96°37'44.58"W, now Pontotoc, Johnston County, Oklahoma, Section 12, T1S-R6E*). Taff (1905) named and mapped Simpson-equivalent strata that he called Tyner and Burgen in the Ozark Mountains of northeastern Oklahoma. The Tyner originally included all beds between the Chattanooga Shale and Burgen Sandstone; later, Cram (1930) recognized the limestone in the upper Tyner to be Fite and Fern-

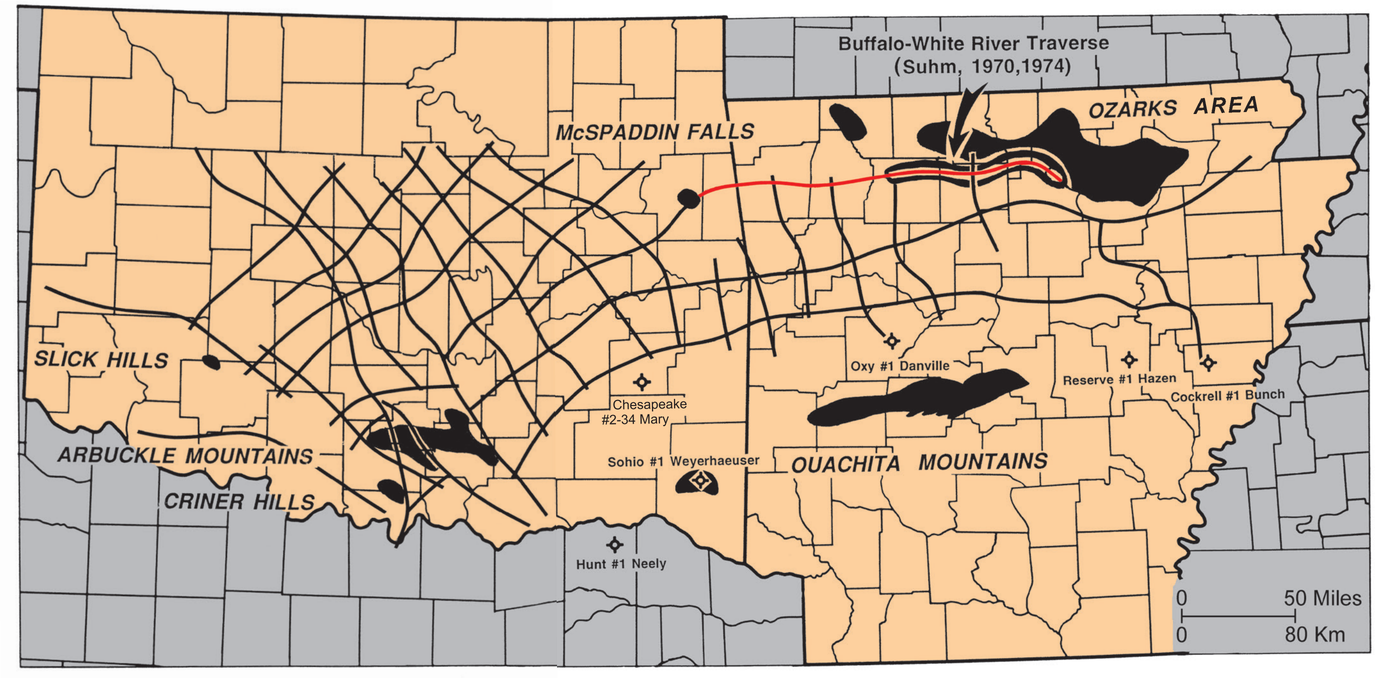


FIGURE 3. "Simpson" correlations from Arkansas to Oklahoma.

A. Surface exposures of Simpson Group (black) and lines of subsurface cross sections. Intersecting lines of cross sections were constructed for, but not included with, an earlier study (Suhm, 1997). All cross sections are accessible from a DVD included with this publication. Selected outpost wells are shown for the Ouachita frontier, such as Chesapeake #2-34 Mary (see also Plate 1). Line highlighted in red is Cross Section line BO shown in Figure 3B.

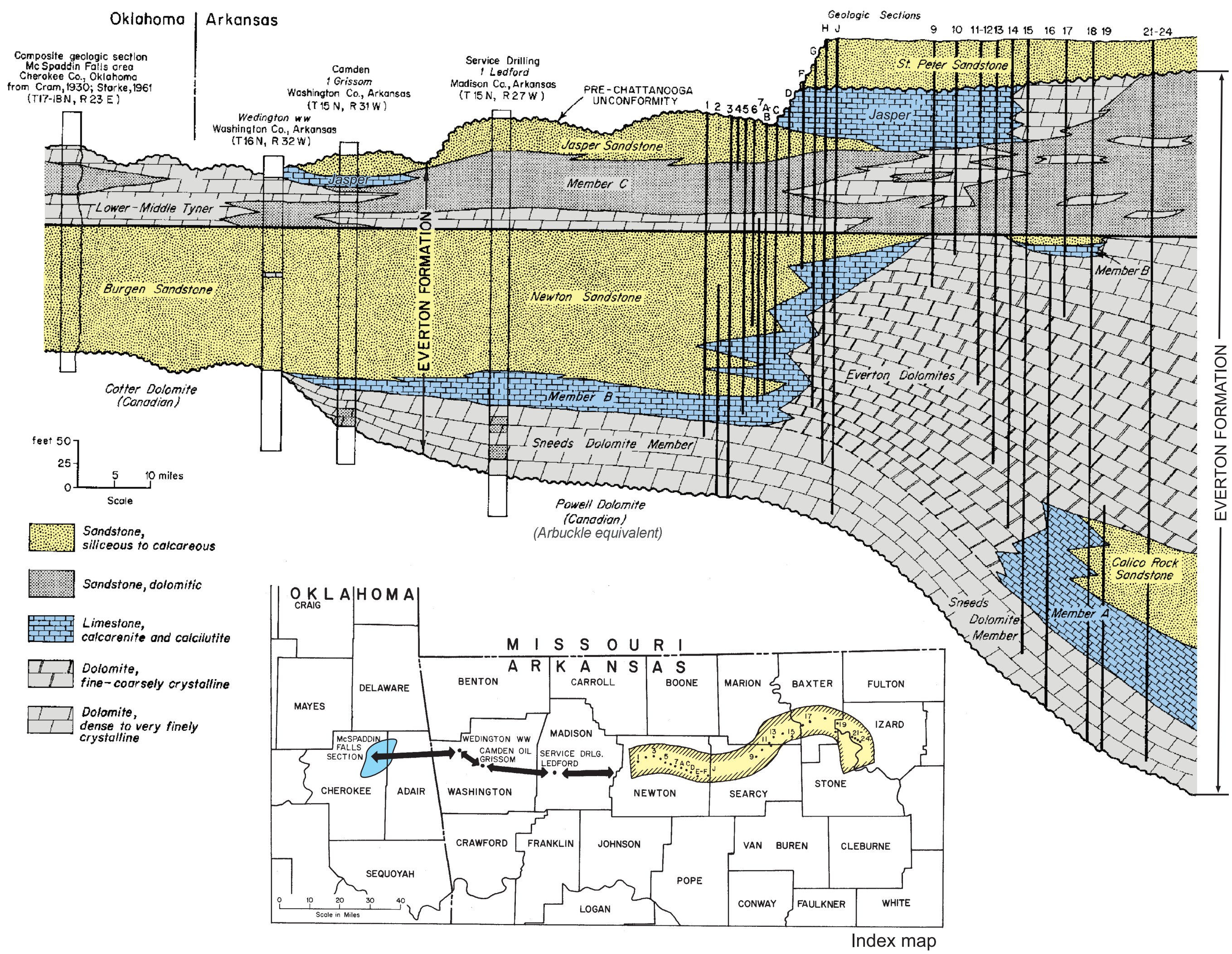
B. (*See page 7)* Simpson correlation from northern Arkansas to northeastern Oklahoma along Cross Section BO (see Figure 3A and Plate 1 for location). Datum is top of Newton-Burgen Sandstone. The section illustrates stratigraphic similarities of Newton Sandstone (Everton) with the Burgen (basal Oil Creek) sandstone of Oklahoma. Everton Members A and B, Sneeds Dolomite, and Calico Rock Sandstone are equivalent to the Joins Formation in Oklahoma; Everton Member C and the Jasper Member are correlative with the Tyner and Oil Creek shale of Oklahoma. Index map shows locations of measured sections and wells used in subsurface correlations (See also Plate 1). Illinois River outcrops are shown in blue. Modified from Suhm (1974).

vale (Viola) which he excluded from the Tyner.

Ulrich (1911, 1929) applied names to formations of the Simpson Group that crop out in the Arbuckle Mountains. From names proposed by Ulrich (1929), Decker and Merritt (1931) defined five formations to be included with the Simpson; they standardized them, and established boundaries, as summarized in Harris (1957). Their field studies, along with influential paleontological contributions published by Ulrich (1911, 1929) and Decker (1930), resulted in Decker and Merritt (1931) naming and defining the Joins, Oil Creek, McLish, Tulip Creek and Bromide Formations of the Simpson Group. Furthermore, Decker (1930, p.1494) and Decker and Merritt (1931, p. 6) specifically studied the Simpson with the stated purpose " ... to divide the Simpson into formations which would represent the natural physical and faunal subdivisions." According to them, each formation represented a sedimentary cycle, with basal sandstone or with a basal conglomerate (as with the Joins).

Early studies such as those of Decker (1929, 1930) and Decker and Merritt (1931) in the Arbuckle Mountains were not without problems, especially with correlations. This is to be expected because the Simpson thins from 2,300 ft in western parts of the Arbuckle Mountains to 630 ft in the east in a distance of 50 miles. Unknown at the time, within this short distance, the depositional setting grades from platform to basin (along the Ardmore Basin/South Ozark Platform Hinge). Lithologies changed as depositional settings changed, resulting in intricate facies relationships within Simpson formations, such as shown on well logs on Cross Section A-A' (Plate

*Ranges(R) refer to locations east or west of the Indian Meridian of Oklahoma.



3). Decker and Merritt (1931), however, did not have the benefit of subsurface well information. Their "logs" with which to correlate often consisted of incomplete measured sections. Decker and Merritt (1931, p. 96) say, " ... the Simpson is so extremely variable in its outcrops that it is impossible with the restricted time at hand to attempt any detailed correlation of the outcropping parts with the subsurface extensions to the north." Additional shortcomings about Simpson correlations can be found in Edson (1935).

Simpson formations defined by Decker and Merritt (1931) are used in this report. Decker and Merritt (1931) also recognized several "members" within those formations, but proposed none. Those are introduced in this report as informal members and recommended for formalization. For example, informal sandstones recognized by most geologists in Oklahoma include the "basal Oil Creek sandstone" of the Oil Creek Formation, "basal McLish sandstone" of the McLish Formation, and "Tulip Creek sandstone" of the Tulip Creek Formation. The 1st Wilcox sandstone is renamed "Seminole sandstone of the Viola Group" and proposed here as an informal formation or member for formalization. The above sandstones have been mapped in this report. Formalization by the Oklahoma Geological Survey and other governmental and professional geologic organizations would facilitate exploration and enable better understanding of stratigraphy. Using a regional sequence stratigraphic approach, the genetically-related Simpson is divided into three time-equivalent groups. The three units, or "cycles," are shown on Cross Section Plates 3, 11-15, and discussed below.

Lower Simpson: The Joins is the first "sedimentary cycle" of the Simpson Group, succeeded by the second cycle of the Oil Creek Formation. However, rather than the Joins being defined as stacked and discrete below the basal Oil Creek sandstone as stated by Decker and Merritt (1931), it was found that the Joins actually interfingers with, and is in facies relationship with, the basal Oil Creek sandstone. And, further, the Joins was found to have a basal

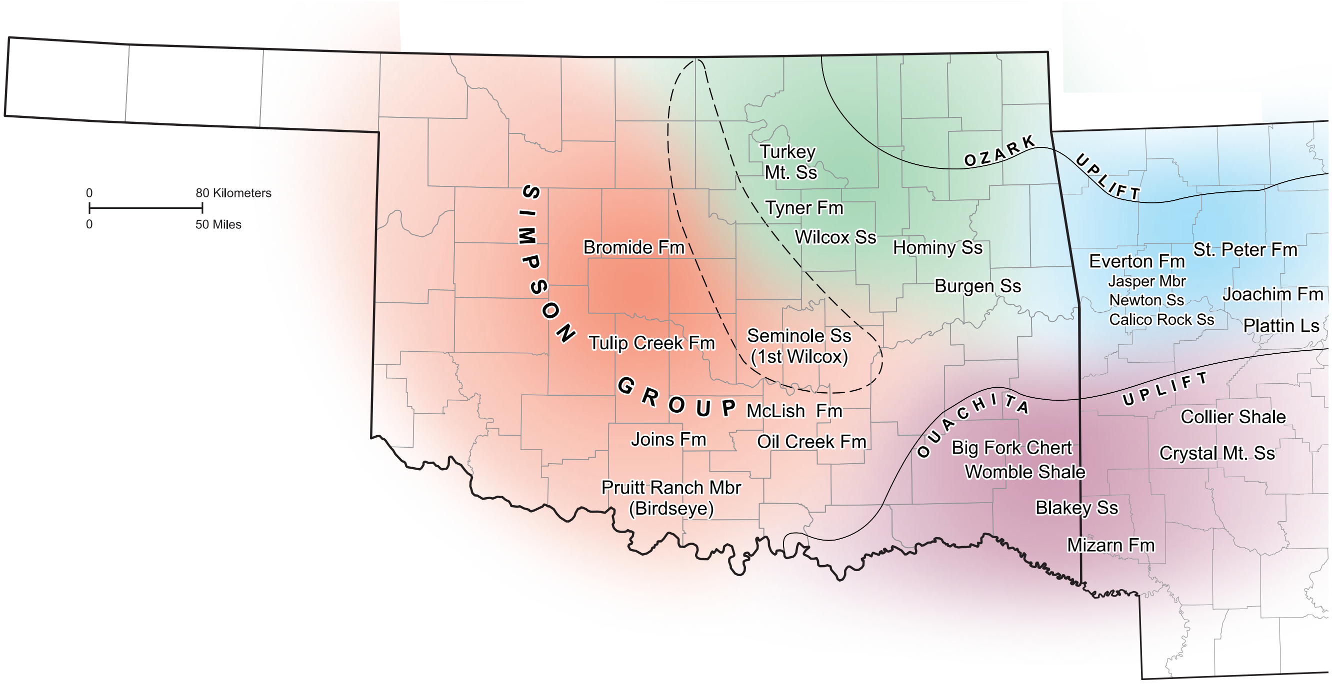
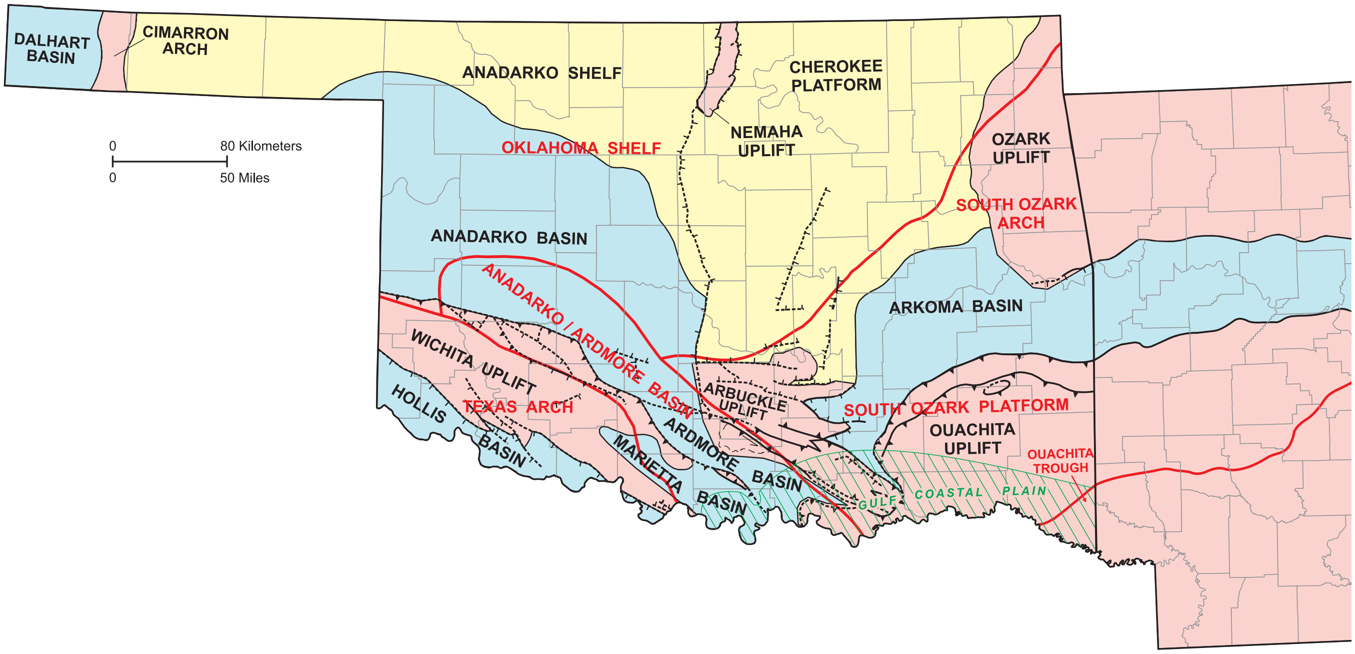


FIGURE 4. Realms of Simpson names, tectonics, and paleogeography.

A. Geographic distribution of names of formations and members of the Simpson Group was based on early outcrop studies. Purdue and Miser named most of the formations in the Ouachita Mountains (purple). They were also responsible for naming formations and members in the Ozark Mountains of Arkansas (blue). Taff and Ulrich named most of the formations exposed in the Ozark region (green) of Oklahoma. And, they, along with Decker and Merritt, named the Simpson Group and all of its formations from outcrop studies in the Arbuckle Mountain area (pink). The areas in northeastern Oklahoma and southern Oklahoma coincide with two regions of pre-1930 oil and gas activity (http://ogs.ou.edu/docs/bulletins/B40-QPI.pdf). During early shallow drilling in northeastern Oklahoma, "Simpson" rock units exposed in the Ozark area (green) were projected in the subsurface; similarly, in southern Oklahoma, the Simpson was projected into the subsurface from the Arbuckle Mountains (pink). The widely known "Wilcox" was named for a sandstone in the subsurface, as was "Seminole" (First Wilcox) sandstone named by Levorsen (1928) in Seminole County (dashed outline). The Hominy and Turkey Mountain sandstones under the Tyner Formation are infrequently used subsurface names. Because Simpson formations have log characteristics that enable accurate and widespread subsurface correlation, well-known Simpson names in the Arbuckle Mountains will likely replace those used in northeastern Oklahoma.

sandstone similar to basal sandstones of other formations of the Simpson Group. The Joins has long been viewed as the only Simpson formation without basal sandstone — an intraformational conglomerate was substituted for sandstone. The sandstone is developed in several areas of Oklahoma and is informally referred to as "basal Joins sandstone" of the Joins Formation; it needs to be mapped before it can be considered for formalization. The boundary of the Joins with the Arbuckle is discussed in Joins Stratigraphy, but, it is proposed that the traditional Joins contact in the Arbuckle Mountains be shifted downward to include the upper quartz-rich portion of the West Spring Creek Formation, that according to Derby (1969, 1973), is known to be Whiterockian age. A Whiterockian age for this interval suggests a paleotologic affinity with the Simpson Group, rather than with the Arbuckle. This revised relationship is also discussed in Figure 1. With this proposed revision, the base of the Simpson would include sandstones stratigraphically equivalent to an interval *above* the nearly ubiquitous redbed complex of the upper Arbuckle Group readily seen in Arbuckle Mountain roadcuts on the east side of northbound Interstate 35 (GPS: 34°22'3.20"N, 97° 8'44.26"W) and illustrated in the photograph on the cover of this publication. The Joins contact is repositioned above those redbeds and above a faunal horizon described by Ham (1955) and Derby (1969) consisting of *Ceratopean* gastropods and brachiopods *Diparelasma* and *Pomatotrema* known as the C-D-P Zone (named for the first letters of the three predominant



B. Ordovician depositional provinces (red) compared with structural provinces (black). Geologic (tectonic) Provinces defined by Northcutt and Campbell (1995), marked by black lines and words, represent areas of similar structural styles. Red words and lines are Simpson "Depositional Provinces." Depositional provinces are regions that share sedimentologic and stratigraphic similarities. Boundaries between the two types of provinces broadly overlap suggesting similarities or origin and interrelationships. For example, the structural basins of southern Oklahoma today once existed as one interconnected depositional basin during Simpson deposition. Additionally, the boundary between the Cherokee Platform and Arkoma Basin is similar in position to the boundary that separates the Oklahoma Shelf from the South Ozark Platform/ Arch. The boundary corresponds to the Southwest Ozark Lineament, a zone of crustal weakness resulting in thickness variations in Ordovician strata — thin, very shallow marine on the South Ozark Platform to the southeast, the opposite on the Oklahoma Shelf. Following Simpson deposition, the structural and burial history changed, not only along this "shared" boundary, but other boundaries. Depositional provinces are discussed in the first part of this paper, followed by Simpson productivity within structural provinces.

fossils) found at marker number 9 (Fay, 1989) and shown on maps and photographs in Fay (1995) and Musselman (1995). This contact also corresponds to the unconformity between the Sauk (Arbuckle) and Tippecanoe (Simpson) sequences defined by Sloss (1984, 1988). In Oklahoma, the oldest sandstones at the base of the Simpson Group are a proxy for a time when erosion was taking place on stable interiors and, therefore, represents a lowstand accumulation that marks the initiation of the Tippecanoe Sequence. Moreover, as shown on Figure 1 the Simpson is considered to be lowest Ordovician resting on an upper Cambrian Arbuckle. This revised age reassignment was proposed by Suhm, et al (1977) who state, "The Cambrian-Ordovician boundary in North America is enigmatically placed within a thick sequence of carbonates or shale termed "Cambro-Ordovician" on the basis of paleontology (Stitt, et al 1976). A stratigraphically defined boundary is suggested on the basis of natural breaks (unconformities) in the historical development on the earth as discussed by Calvert (1964), Suhm (1974), Patterson (1961, 1969) and Freeman (1949, 1953). … Although the unconformity can not be depicted in regions of continuous deposition it may be recognized by detailed surface and/or subsurface physical orientation with a degree of certainty no more than is gained by ranges or organisms that continually overlap. … The Ordovician cycle of transgression begins with a basal sandstone and shale sequence of the Everton-St. Peter, Simpson-Winnipeg-Glenogle overstepping Cambrian carbonates such as the Beekmantown, Knox, El Paso, Arbuckle, Ellenburger, and McKay. … Regional cross sections from selected locales in North American show stratigraphic relationships of the Cambrian and Ordovician with the unconformity." Additionally, Ross, et al (1977) obtained radiometric ages from bentonites in type sections in Great Britain proposed by Sedgwick (Cambrian), Murchison (Silurian), and Lapworth (Ordovician); those dates agree with more recent dates shown on the left side of Figure 1.

Sandstone thickness and porosity values for all Simpson sandstone reservoirs are included as plates in this report and on an Excel spreadsheet on the enclosed DVD. The thickness of the Joins, referred to by Taff (1904, p. 23) as "shaly and impure lime - the basal beds of the Simpson formation," is not individually specified on the DVD; instead, it is included with the "Basal Oil Creek/Joins Interval" ("OCKD Group Thickness" on an Excel spreadsheet), including strata between the informal unit of the "Oil Creek shale" of the Oil Creek Formation and strata at the top of the Arbuckle, the boundaries of which will be discussed later. This interval is the basal deposit of the Tippecanoe Sequence. The thickness for the Basal Oil Creek/Joins Interval has been calculated from well logs and is included on the DVD attached with this report. Sandstone at the base of the Joins observed on well logs is informally called the basal Joins sandstone member; its thickness and porosity are included on an Excel spreadsheet in the column marked "Calico Rock Sandstone." The Joins is discussed throughout the text in the context of being the lowest formation of the Simpson Group, with the understanding that it is in facies relationship with the informal basal Oil Creek sandstone member. In this context, the Joins will have the dual role of being separate from, yet also a facies of, the basal Oil Creek sandstone. The "Basal Oil Creek/Joins Interval" together with the informal Oil Creek shale constitutes the "lower Simpson." The Pruitt Ranch Member is in the upper part of the Oil Creek Formation (upper part of the informal Oil Creek shale). It was named by Harris and Harris (1965) for exposures in Criner Hills. It is also a petroleum-bearing reservoir with specific log attributes in southern Oklahoma where it is called the "Birdseye limestone." Lithologically similar limestones are found in the overlying McLish as discussed by Statler (1965), but without characteristic "Birdseye" log signatures.

Middle Simpson: The McLish Formation is the third "sedimentary cycle" of the Simpson Group. The basal sandstone of the McLish is widely referred to in subsurface data and publications. In this report the sandstone represents an informal member of the McLish Formation, called "basal McLish sandstone member." Traditionally, the Tulip Creek Formation is the fourth "sedimentary cycle," and in contrast to interpretations of Decker and Merritt (1931), the Tulip Creek Formation was found to have considerable geographic extent. The Tulip Creek Formation consists of basal sandstones below a sequence of shales and limestone. However, for correlation purposes and convenience the upper boundary of the Tulip Creek Formation is placed at the top of redefined "Tulip Creek sandstone," rather than within a shale sequence beneath the Bromide as defined by Decker and Merritt (1931). It may be thought of as an informal member of the Tulip Creek Formation. The designation "TPCK Group Thickness" on Excel spreadsheet represents the approximate thickness of the Tulip Creek Formation of Decker and Merritt (1931).

Upper Simpson: The Bromide is the fifth and uppermost "sedimentary cycle" of the Simpson Group. It consists of sandstones, shale, and limestone that interfinger with one another. The thickness of the Bromide Formation, along with sandstone thicknesses and porosity, are posted on an Excel spreadsheet. In this report "Bromide sandstone" is an informal member of the Bromide Formation. Bromide subdivisions, Pooleville and Mountain Lake Members, are not used because they are minor facies within a larger existing map unit and lack regional distinguishing subsurface characteristics. Similarly, the names of Viola subdivisions Viola Springs and Welling Formations are not used. Rather, the name Viola is used to include these formations in the Arbuckle Mountain region. The Viola equivalent, Fite Limestone, exposed on the Illinois River in the Ozark region of northeastern Oklahoma is referred to in this report as being part of the Viola Group. In subsurface central Oklahoma, the Seminole sandstone ("1st Wilcox"), is considered to be a part of the Viola Group, rather than a member of the Simpson as classified by Levorsen (1928), who was unaware of the unconformity between the Viola and Simpson Groups. It is recommended in this report that "Seminole sandstone" be advanced to formation status due to its formal introduction by Levorsen (1928) and because it has the property to be regionally mapped (Plate 10). Further, the name "Seminole Sandstone" would replace the name "Wilcox" (or post-"Wilcox") thereby helping to eliminate confusion with the Bromide sandstone of the Simpson.

Simpson equivalents exposed along the Illinois River in the Ozark Mountain region of northeastern Oklahoma are referred to as Burgen Sandstone and Tyner Formation (Taff, 1905). This study shows that both are equivalent to the Oil Creek Formation

(Suhm, 1974; Bauer, 1989). However, although the upper McLish, Tulip Creek, and Bromide are absent along the Illinois River due to removal by pre-Viola erosion (Bauer, 1989), they are present in the subsurface to the west where they are included with the Tyner Formation. The "Wilcox sand" is correlative with Bromide in this report. Limestone included in the upper Tyner by Taff (1905) was found to be Fite and Fernvale (Viola) by Cram (1930). The generally inclusive subsurface name "Tyner" should be replaced by names of respective equivalent formations of the Simpson Group; because, as shown in this report, lithologic and log characteristics for Simpson formations share state-wide similarities. Simpson equivalents in Arkansas and Missouri are assigned to several formations such as the Everton Formation, St. Peter Sandstone, Joachim Dolomite, and Plattin Limestone (see Figure 1). Purdue and Miser (1916) contributed to naming and mapping Cambrian and Ordovician formations in the Arkansas Ozarks, but nomenclature of this interval was refined by Giles (1930), McKnight (1935), Miser (1922), Suhm (1970, 1974, 1997), and Thompson (1991).

In a "time-stratigraphic" context, the paleogeographic setting for each of the Simpson formations described in this report is the product of specific tectonic and depositional activities taking place at the time of deposition, not only in Oklahoma but in adjacent states. A 3,600-mile cross section extending from Texas to Canada shows the regional stratigraphic placement of the Simpson Group and equivalents (Figure 2). As a final note, detailed lithologic descriptions and photographs of the formations and members of the Simpson Group are not included in this report. For this information, the reader may wish to refer to several articles in Symposium on the Simpson (Herndon, 1965) and numerous articles in the Shale Shaker (Oklahoma City Geological Society) and Oklahoma Geological Survey (www.ou.edu/ogs), in addition to those cited in this report.

PROCEDURE AND CORRELATION

Carried out in a fashion similar to Ulrich and other early Oklahoma geologists who studied Ordovician outcrops in both the Arbuckle and Ozark Mountains,

Oklahoma Shelf
Anson
No. 1-21 Northcutt
Sec 21, T. 7 N., R. 1 W.
Cleveland County, Oklahoma

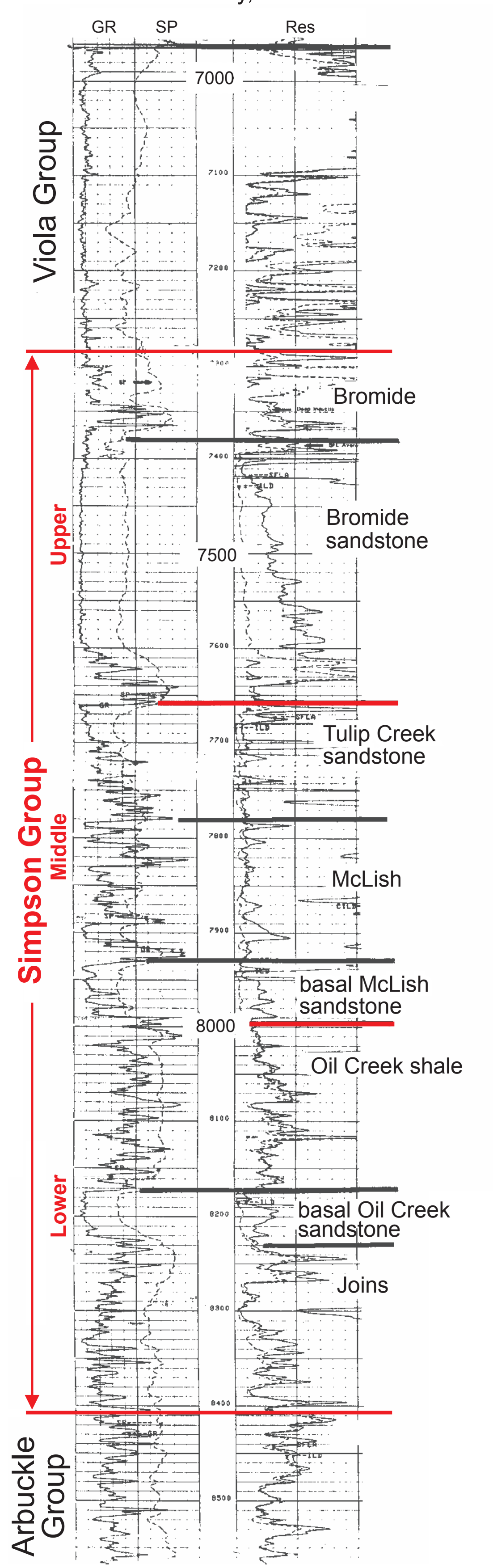


FIGURE 5. Reference induction/resistivity well log for Simpson in Oklahoma Shelf province. Anson No. 1-21 Northcutt, Section 21, T7N-R1W, Cleveland County, in central Oklahoma is a "type log" for Simpson formations in the state. It was tied with type sections of the Simpson Group in the Arbuckle Mountain area, and used to correlate those formations throughout Oklahoma.

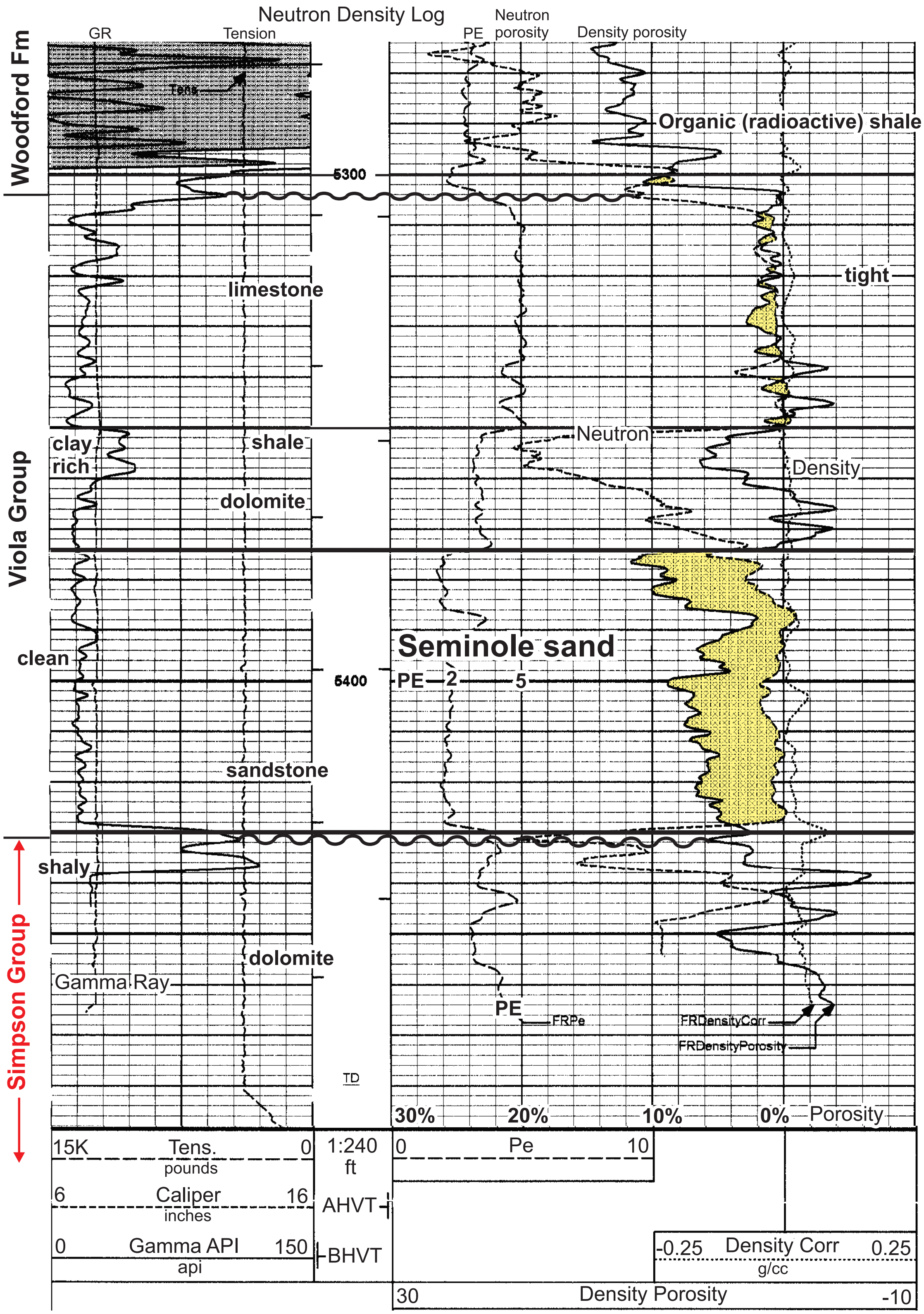
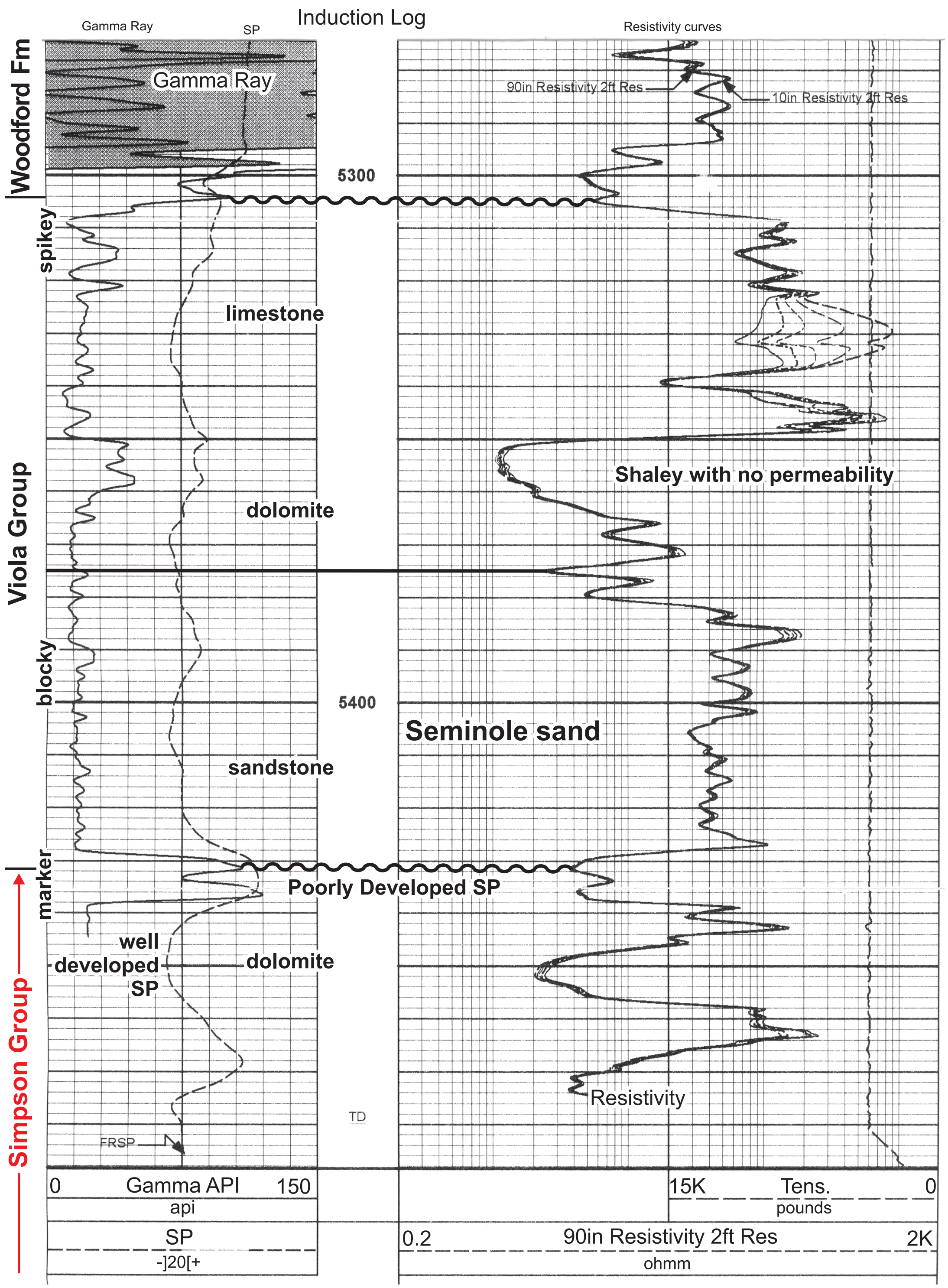


Figure 6. Wireline logs as correlation and lithology tools; an example from Section 18, T21N-R2W, Noble County, Oklahoma.

A. Lithology indicators. Gamma-ray, neutron/density and PE (photoelectric effect) curves allow differentiation of rock type and porosity. Limestone has a PE of 5; relatively low amounts of radioactive minerals in limestone cause the gamma ray curve to shift left. Limestone also displays close tracking of neutron and density curves, almost on top of one another, indicating low porosity. Sandstone has a PE of 2, clean gamma-ray, density curve crosses left of neutron curve (cross-over) with average of two curves yielding 5% porosity. Dolomite has a PE of 3-4, neutron curve is left of and separated from density curve showing 5% porosity, and gamma-ray shows slightly shaly dolomite in upper half coincident with higher porosity. Shale has relatively high gamma-ray, high porosity with neutron tracking left of density



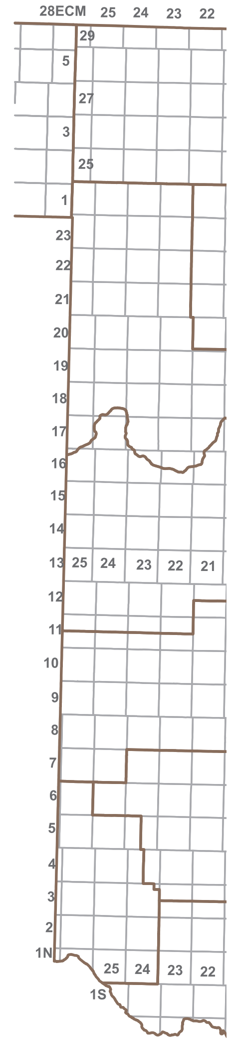
curve; gamma ray for organic shale of Woodford plots off-scale (greater than 150 API). Additional visual examples of gamma-ray and neutron responses can be seen for a variety of rock in Haun and LeRoy (1958, p. 334). The top of the Simpson Group is characteristically marked by elevated gamma-ray and subdued SP curves across several areas of Oklahoma.

B. Correlation indicators. Induction log with spontaneous-potential (SP) and resistivity curves that provide qualitative information about porosity, permeability, and fluid content. Resistivity is a function of resistance to electric flow through fluids within the rock matrix. Shales and "wet" sandstones have resistivity curves that project toward center of well log (low resistivity), whereas rocks with little matrix porosity and low permeability (commonly called "tite or tight") or oil bearing have high resistivity. Shale is represented by poorly developed SP and low resistivity. Limestone, dolomite, and sandstone are "clean" with well developed SP patterns, and since they have less fluid in pores relative to shale, they show higher resistivities. Relative high resistivities of the Seminole sandstone coincident with "favorable" density porosity verify productivity in this well and nearby wells.

my starting point for "Simpson" correlation began with outcrops in eastern parts of the Ozark Mountains (Suhm, 1965); this was followed a few years later by studies of Ordovician rocks exposed along the gorges of the Buffalo and White Rivers in the central Ozark area of Arkansas (Suhm, 1970, 1974). From river-long cross sections (Figure 3), I matched outcrop sections with nearby wells in the subsurface, first in Arkansas, then to northeastern Oklahoma where Simpson outcrops are exposed along the Illinois River (Suhm 1970, 1974, 1978, 1979). From there I correlated the Simpson south and west into the subsurface into and across the Arkoma Basin to Cleveland County in central Oklahoma, in an area that has been extensively drilled and where all the Simpson sands are well developed and flat lying (Figure 5). From central Oklahoma, I correlated the Simpson southward to exposures in the Arbuckle Mountains described by Fay (1989, 1995) among others. The Simpson was tied into the Northern Natural Gas No. 1-6 Little "A" (Section 6, T3S-R2E), Carter County, a few miles south of outcrops along Interstate 35 in the Arbuckle Mountains. The log is shown as part of Cross Section A-A' (Plate 3) and illustrated as an overlay on the cover of this report. Several well logs on Plate 3 are representative of formations in the Simpson Group because of their proximity to type sections in the Arbuckle Mountain region. Outward from these core areas, Simpson formations were identified on geophysical well logs across the remainder of the state (Suhm, 1997). In an attempt to establish later continuity of Simpson formations, the names of Simpson formations in the Arbuckle Mountains were applied across the state (Figure 4A).

For decades, the "standard" electric-log has been used in subsurface correlation. It is one that displays spontaneous-potential (SP) and resistivity; both curves relate to fluids within the rocks and their response to resistance and flow of electricity which is an indirect measure of lithology. These two curves remain useful today in formation recognition and in correlation. Preferred curves today, however, are those found on neutron/density logs including gamma-ray and photoelectric curves, in addition to neutron and density curves, which provide specific information about bed contacts, rock types, and porosity (Figure 6). The curves also provide convenient insight into the kind and amounts of disseminated terrigenous material within carbonates, and so may be a substitute, or proxy, for insoluble residue studies that were utilized for correlation purposes decades earlier (Ireland, 1944; McCracken, 1955).

Gamma-ray curves are useful in recognizing organic shales by their elevated, often offscale gamma-ray signatures. More often than not, these shales are too thin to be seen in well cutting samples, especially where they are thinly dispersed within the Simpson Group. Gamma-ray streaks are present in all formations of the Simpson Group. The areal and stratigraphic distribution of six of the larger "gamma-ray clusters" is shown on Figure 7. The origin of thin beds of fine-grained material is unknown and one that requires further study. Possibilities include deposits of organic-rich material related to biokill (brought about by oceanic anoxic activity such as in dead zones described in Karstensen, et al 2015), or deposits of extraterrestrial material or volcanic ash. Thin beds of volcanic ash rich in radioactive potassium and referred to as K-bentonites are readily seen on logs and best identified from gamma-ray and neutron density curves (Figure 8). They are commonly less than five or ten feet thick and characterized by gamma-ray spikes that kick offscale (to the right), indicative of high content of radioactive potassium and, correspondingly, possess very porous neutron and density values that kick far to the left. They are present in greater frequency near and at the Simpson/Arbuckle contact (Sauk/Tippecanoe boundary). In his discussion of Ibexian (Arbuckle) equivalents, Kolata, et al (1996, p. 51) explains. …. "notable K-bentonite in the upper part of the Knox Group ("Arbuckle") can be traced in the subsurface of eastern Missouri throughout the southern Illinois Basin into north-central Kentucky where is appears to correlate with one of two K-bentonites in the Beekmantown Formation (Arbuckle)." K-bentonites are also located at the Viola/Bromide contact where they have been more extensively studied and thought to have provided evidence for volcanism, perhaps related to tectonic activity (Leslie, et al 2008).



Suhm (1997) studied approximately 3,500 wells and wireline logs in Arkansas and Oklahoma, several of which have well-cutting descriptions. Since that time many more well logs have been studied for incorporation into this report. Simpson correlations from well to well were difficult, but manageable.

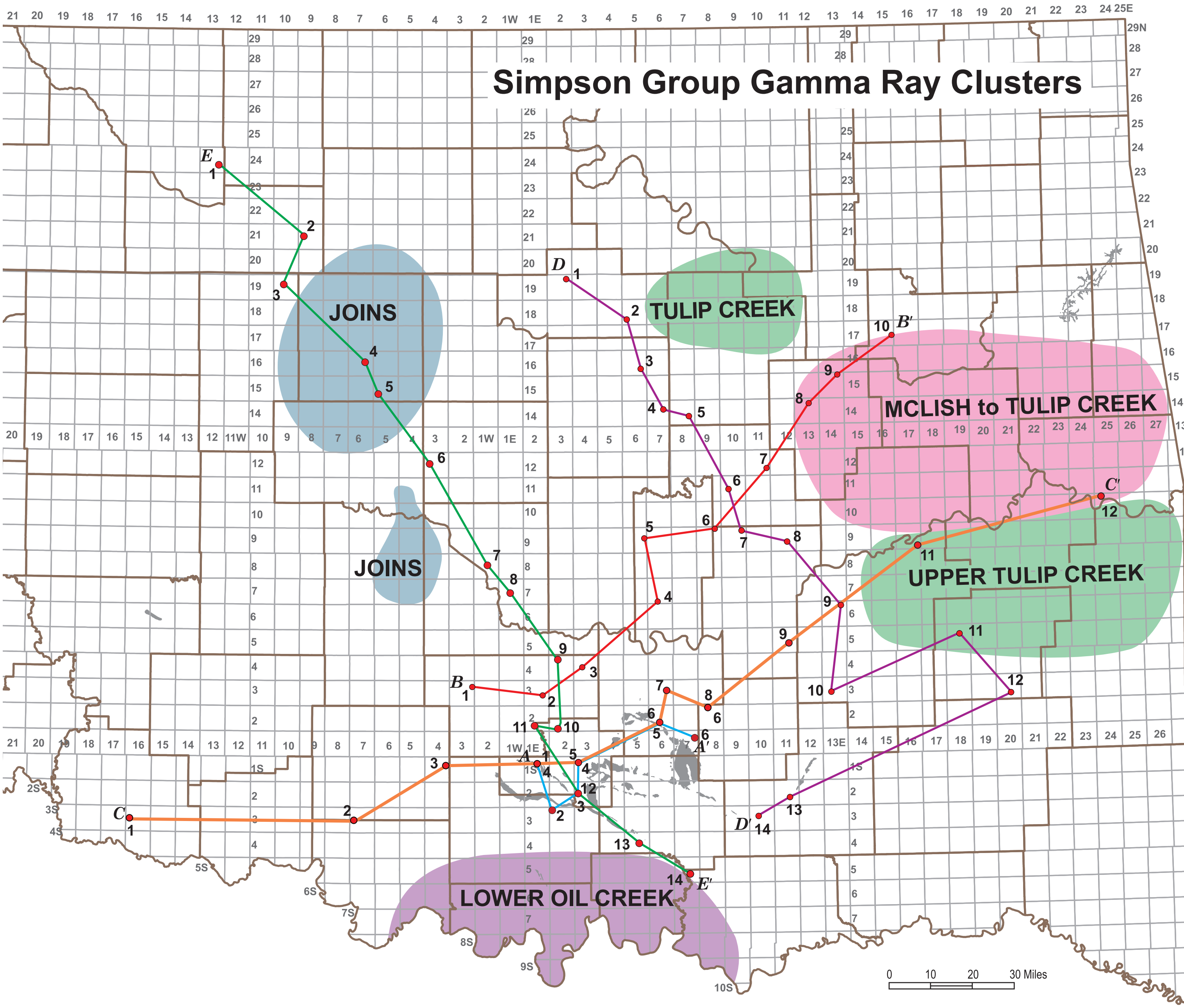


Figure 7. Geographic and stratigraphic distribution of gamma-ray anomalies in the Simpson Group. Gamma-ray curves that spike sharply to the right (offscale for some) range from 1-10 feet thick are common in the Oil Creek shale across the state, but they may be distributed within other formations of the Simpson Group. Radioactive spikes are interpreted to represent emanations from radioactive materials in organic shale (biokill), potash salts such as sylvite (KCl) deposited in evaporative salt pans, or volcanic debris.

Bed-by-bed tracing of specific lithologies within formations between wells spaced more than a mile apart was virtually impossible, so, only gross lithologic units could be compared and correlated. For regional correlation purposes the Simpson was divided into several operational map units consisting of establish formations or members, both formal and informal, that represent a specific set of depositional conditions that existed during a discrete interval of time. It would be unlikely, as this study indicates, that time-lines cross from one formational unit into another. Longitudinal (strike) cross sections are especially meaningful. For example, strata parallel to the strike form stratigraphic sets that are not only about equal in thickness but also about the same age and so may be isochronous. Therefore, the division of the Simpson into three units, or three sequence stratigraphic cycles, enabled correlation across long distances. These are shown on the cross section plates. Recognition of smaller and more refined stratigraphic cycles within formations of the Simpson Group, and their application to correlation, is possible in local areas, such as the Bromide in the Arbuckle Mountains (Carlucci, et al 2014), but such studies may be difficult due to sedimentary consequences of thickness variations brought about by the vagaries of subsidence and depositional rates, along with differences of quartz sand distribution across and within different depositional regimes. Biostratigraphic correlation was not attempted.

Twenty-two intersecting dip-and-strike cross sections across Oklahoma were constructed from well logs at a vertical scale of 1 in. to 150 ft from a previous study (Suhm, 1997); their locations are shown on Plate 1. These cross sections were not published in Suhm (1997). They are however, included on the DVD accompanying this publication. It should be noted that the older cross sections lack recent revisions that better define the base of the Simpson, and, therefore, should be viewed with skepticism. Five new sections are prepared for this report, including one for the Arbuckle Mountain region (Plates 3, 11-14). Cross sections such as these served not only to confirm statewide correlations but were found helpful in evaluating regional changes in

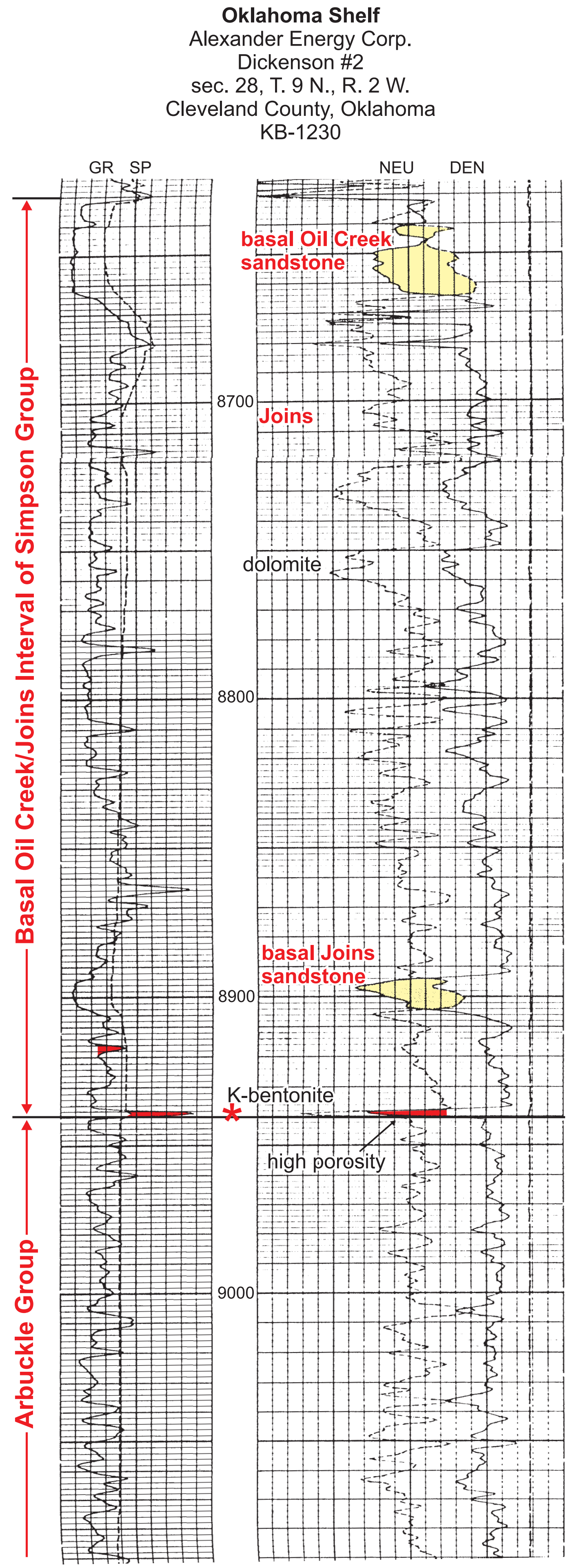


Figure 8. Log character of K-bentonites at the Simpson/Arbuckle contact in central Oklahoma. K-bentonites are represented on neutron/density logs by offscale gamma-ray spikes accompanied by high neutron/density porosity. Bentonites are interpreted to represent regional volcanic ash falls related to tectonic activity. They are also present in the interval spanning the Simpson/Viola contact. Yellow represents sandstone with density cross over of neutron curve.

thickness and lithology. In spite of facies complexity, stratigraphic position was maintained, mainly through correlation of persistent, log irregularities within or between formations, called markers. Some of these were "shale breaks" (elevated gamma-ray streaks) that maintained stratigraphic persistence on a regional scale, sometimes over a hundred miles. They proved to be useful correlation tools. Bentonites are similar markers. For example, from their study of Ordovician bentonites in the eastern and central Midcontinent regions, Huff and Kolata (1990) found that isochronous bentonites support existing lithostratigraphic correlations. A similar, but much earlier conclusion was reached by Templeton and Willman (1963), who state that lithostratigraphic correlations utilizing lithology (and well log signature) may be as chronostratigraphically accurate as biostratigraphic correlations. Because of this, subsurface correlation markers such as these have been met with widespread acceptance by paleontologists and stratigraphers.

Simpson thickness and lithologic values for each well, including porosity, are in Excel format on a DVD included with this report. Many isopach maps were prepared from this data. Some maps were not included with this report, such as an isopach map for the total Simpson thickness, because few wells across the state penetrated more than 50 ft below the top of the basal Oil Creek sandstone. Rather, it is replaced by an isopach map labeled "Middle and Upper Simpson" (Plate 2) that includes 1,500 well control points, about three times more control than a map prepared for total thickness. Lower Simpson thicknesses representing the "Basal Oil Creek/Joins Interval" are to be found on a separate column on Excel spreadsheet, and if desired, those values can be added with Oil Creek shale and values for the "Upper and Middle Simpson" to derive total Simpson thicknesses.

DEPOSITIONAL PROVINCES

GENERAL

Local and regional tectonic movements exert major influences on sedimentation. They control the rate and amount of supply of terrigenous material, the gradient across which sediment is transported, and influence accommodation rates at depositional sites. Lineaments and hinge lines, and syndepositional faults also might have been important in affecting sediment types and thicknesses. Lithologic associations are products of these relationships, and in this paper these associations are termed Simpson depositional provinces. For example, over a period of 20 million years, pre-Simpson Arbuckle deposition was a time of widespread environmental consistency and stability of both accommodation areas and source areas; however, climate and geologic conditions changed in Simpson time (Harper, et al 2015; Huff, et al 2010; Keller and Lehnert, 2010). There was an increase in structural activity, accompanied by volcanic activity that produced new source areas and new detrital products such as those composing the Simpson at the base of the Tippecanoe Sequence. Widespread detrital quartz sands became common for the first time – some as products of recycling of older sands (Figure 2). Life forms reacted to environmental changes and became more diverse.

One of the purposes of this study is to map the areal distribution of Simpson facies that were deposited under environments controlled by tectonics and changing sea levels, not only in Oklahoma, but elsewhere. Provincial associations introduced by Suhm (1997) are retained and shown on maps included here. Provinces and paleogeography are linked; paleogeographic setting will be discussed later but the reader might want to view maps on Figures 20-22 for regional paleogeographic perspective. Maps such as these are useful in evaluating the tectonic fabric, since they reflect variations in the stability of the surface on which they, the sediments, were deposited. Thicker sections of strata represent greater basin instability, relative to thinner time-equivalent strata deposited on shelves and platforms. Simpson formations show lateral continuity of log characteristics with their respective provinces. Paleogeographic and sedimentologic provinces that existed during Simpson deposition include: 1) Anadarko and Ardmore Basins, 2) Texas Arch, 3) South Ozark Platform, 4) Oklahoma Shelf, and 5) Ouachita Trough. Separation of depositional provinces from one another may take place at faults, or, in the area of Golden Trend Field, the separation between the South Ozark Platform and Anadarko Basin is arbitrary and transitional (white dashed line on Plate 2). Isopach maps, included here as plates, show reconstructed thicknesses of Simpson formations across provincial areas that existed during the Ordovician but which may have been later uplifted and eroded. Depositional provinces described below are similar in geographic position with present day tectonic provinces defined by Northcutt and Campbell (1995) to be discussed later (Plates 1 and 2, Figure 4B). Simpson "type-logs" for each of the provinces are illustrated throughout the report.

ANADARKO AND ARDMORE BASINS

The Simpson thickens to over 2,000 ft in the deepest parts of these the Anadarko and Ardmore Basins (Plate 2). Simpson exposures in the western part of the Arbuckle Mountains along Interstate 35 were deposited within this province and appear to represent a thick nearly continuous depositional succession. Further, the roadcuts are also at a position where the Anadarko and Ardmore Basins appear to have been connected, at a type of depositional and structural bottleneck. Because of this, Simpson thicknesses in this area are noticeably variable, perhaps reflective of the interplay of local tectonic activity taking place during deposition. Many well logs in this area could not be used, primarily because they had stretched sections, or fault-cut sections with repeated or missing sections of rocks brought about by stratigraphic and post-depositional structural complexities. Notwithstanding, many of the extremes in thickness are natural due to differences in depositional (subsidence) rates generated by Ordovician syndepositional loading on an irregular sea floor (Figure 9B). The presence of fill-and-spill linked basins may explain difficulties with correlation in some areas. A few of

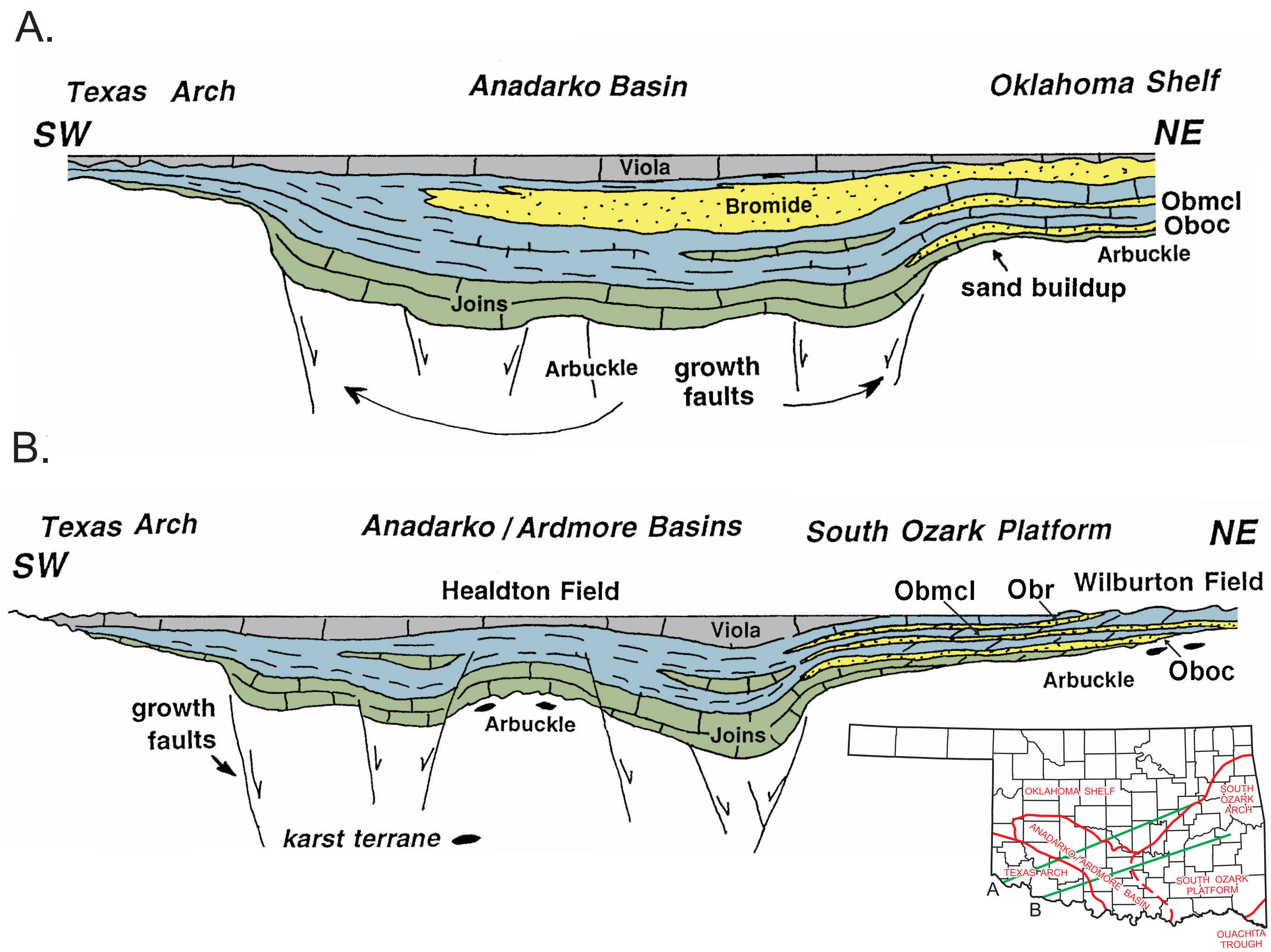


Figure 9. Schematic Simpson Cross Sections.
A. Southwest-northeast cross section illustrates the effect of hinge lines and faults on Simpson thickening into the Anadarko Basin. Basal Oil Creek (Oboc) and basal McLish (Obmcl) sands are thickest on the upthrown side of hinge and growth faults (compare with Plate 12).
B. Schematic cross section across the junction of the Anadarko Basin with the Ardmore Basin. Thickness variations in the Simpson at this junction suggest intrabasinal horsts and grabens bound by syndepositional faults. At the Wilburton Field, and possibly Healdton Field, karstification of the Arbuckle may have taken place before Simpson deposition.

the horst blocks may even have been at or slightly above sea level, creating conditions for karstification of the underlying Arbuckle, such as at Healdton Field in Carter County (Waddell, et al 1993; Latham, 1968).

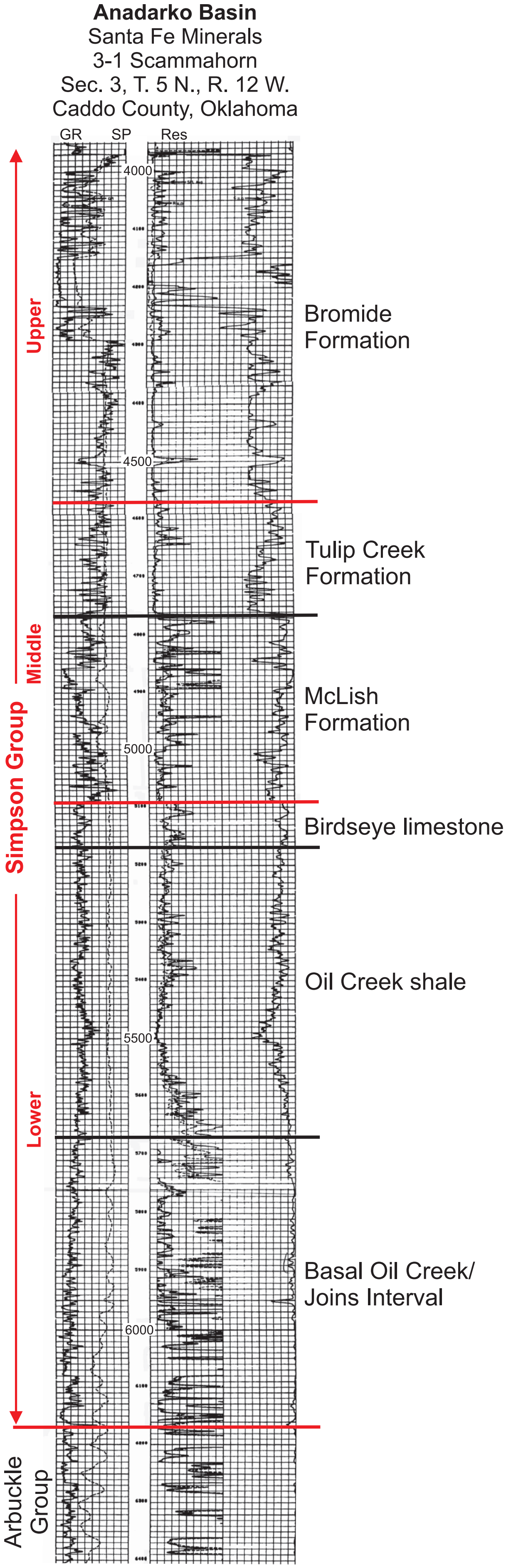
As shown on Plate 2, the separation of the South Ozark Platform from the Anadarko/Ardmore Basin is arbitrary and transitional (dashed white line), especially in the vicinity of the Golden Trend Field. Southeast of this field, two northwest-southeast hinge lines separate the east side of the Ardmore Basin from the South Ozark Platform province. Both compose what is referred to as the "Ardmore Basin/South Ozark Platform Hinge." One is identified on the enclosed plates as a solid back line that corresponds to the present day trend of the Madill-Aylesworth Flexure. The Madill and Aylesworth Oil Fields are developed along this flexure (Huffman, et al 1987). It is called the pre-Woodford "ridge" by Maxwell (1959). The other hinge is in the area of Murray and Johnston Counties where it traverses the present day northwest-southeast Arbuckle Mountain outcrop belt. It is identified by excessive thickening on isopach maps. For example, the upper and middle Simpson thickens from 800 ft on the South Ozark Platform to over 2,000 ft in the Ardmore Basin across a horizontal distance of a few miles in the vicinity of the Washita Valley Fault Zone as will be discussed later. From outcrop studies in the Arbuckle Mountains, Longman (1981) and Carlucci, et al (2014) recognize this variation as a hinge and one that represented a depositional change from shelf to basin. Sandstone isopach maps, to be discussed in more detail later, show sandstone build-ups at this hinge line. Some sand spilled into the basin a short distance westward from the hinge, but most was redirected to the northwest toward the Oklahoma Shelf by shallow-water currents. This pattern, however, contrasts with that of the Bromide which is a southward-spreading sandstone and one that appears to fill the Ardmore and Anadarko Basins. In western parts of the Anadarko and Ardmore Basins sandstone is thin to uncommon and replaced by organic-rich black shale or mudstone. Organic carbon was likely preserved in poorly oxygenated substrates of interconnected seas of the Anadarko and Ardmore Basins.

The Simpson gradually thins near the south and west margin of the Anadarko and Ardmore Basins toward the Texas Arch (Wichita Mountains) where it changes facies from thick sections of shale and shaly carbonates to dominantly thinner carbonates. The Anadarko/Ardmore Basin extends southeastward into Texas where it merges with the Fort Worth Basin, a conclusion derived from independent studies and from a north Texas isopach map of the Arbuckle prepared by Bradfield (1964). This interpretation supports the idea that the Muenster Arch, which today separates the Fort Worth Basin from the deeper Sherman/Ardmore Basin, is a Pennsylvanian structure that was not present during the Ordovician Period, or, if it were present, would have had an unimpressive bathymetric profile, perhaps similar to one of several horst blocks in the Ardmore Basin (Figure 9B). An Ardmore Basin/Fort Worth Basin connection or corridor is important in that it allowed clay derived from erosion of low-lying land areas east of the Fort Worth Basin (Texarkana Platform) to be carried into the seas of Oklahoma. The lowlands of the Texas Arch (Texas Peninsula) consisted of exposed Arbuckle carbonates; the Texas Arch was not a significant source of clay during Simpson time.

The Anadarko Basin is flanked on the north by the depositional ramp of the Oklahoma Shelf. This junction appears to be gradual and transitional and accompanied by northward thinning (shallowing) of Simpson strata. The junction of the Anadarko Basin with the Texas Arch is marked by profound differences in Simpson thickness and depositional bathymetry. For example, in the Anadarko Basin the Simpson consists of "deep-water" limestone and shale amounting to 1,700 ft thick, but thins to shallow marine carbonates about 200-300 ft thick in the short distance of 45 miles on the Texas Arch, such as in Tillman County (Figure 9A). Extremes in thicknesses along the basin margin are the result of movements associated with a syndepositional fault, perhaps related to a rift. The hinge line, or basin margin, here termed "Anadarko Basin/Texas Arch Hinge" is parallel to, but south of the trend of present-day Mountain View Fault and Meers Fault. The exact position of the Anadarko Basin/Texas Arch Hinge, however, cannot be ascertained due to sparse well control and because the Simpson has been truncated in a broad band parallel with the present-day Wichita Mountains. However, the hingeline (or fault) appears to be closely aligned with the Meers Fault (Plate 15), which is located six to ten miles south of, and on trend with, the Mountain View Fault. For example, Apache Field is located on the Wichita Uplift on the upthrown side of the Mountain View Fault, yet thicknesses of Simpson formations suggest deposition in the center of the Anadarko Basin (compare Plates 1 and 2, Figure 10). This apparent contradiction illustrates that boundaries of depositional provinces proposed here may not always agree with boundaries of structural province. Likewise, Simpson strata exposed on the Wichita Uplift in Slick Hills, Kiowa County, suggest deposition in basinal settings rather than shelfal settings of the Texas Arch discussed below.

TEXAS ARCH

The Texas Arch, originally termed the "Texas Peninsula" by Adams (1954), is a broad regional structural and paleogeographic feature capped by mostly Arbuckle/Ellenburger carbonates that extends from central Texas northwest to the Pedernal massif of New Mexico. As an exposed peninsula, the Texas Arch contributed little, if any terrigenous material to the adjacent Anadarko Basin in Simpson time. The contact of the Texas Arch depositional province with the Anadarko Basin in southwest Oklahoma is at a syndepositional fault called the Anadarko Basin/Texas Arch Hinge. The Texas Arch is interpreted to be both an Ordovician paleogeographic feature and a later structural province south of the Wichita Uplift known as the Hollis Basin. Similar to the Ozark Dome, the Simpson is absent on the Texas Arch but present on the flanks at thicknesses less than 500 ft. In contrast to high depositional rates in the more actively subsiding Anadarko Basin, diminished thicknesses on the Texas Arch are attributable to an environment of low depositional rates accompanied by higher energy environments on what is described as a stable platform. Here, the Simpson consists of mostly shallow-marine sandy platform carbonate with some shale (Figure 11). Quartz sandstone beds thicker than 10 to 20 feet are absent. From an interpretation of cores provided by Whiteside and McCommons (1991) and a well log illustrated in their figure 2, the base of the Simpson is interpreted to be



below sandy oolitic carbonates containing St. Peter-like quartz grains that they term Ellenburger "A". This interval is similar in stratigraphic position to the uppermost part of the West Spring Creek Formation which is included with the Joins in this paper. Lithologically, these beds are "Joins-like" and inferred to be unconformable on relatively non-sandy brecciated carbonates of the Arbuckle or Ellenburger. Breccias seen in cores in the underlying Arbuckle are indicative of karst processes that are related to the regression that took place at the end of deposition of the Sauk Sequence. Whiteside and McCommons (1991) and Canter, et al (1993) report common occurrences of karsted Ellenburger (Arbuckle) limestones on the west side of the Texas Arch near the Tobosa Basin.

An angular unconformity between the Simpson and Viola is interpreted on well logs by thinning (or absence) of Simpson formations. Apparently, the Texas Arch, like the Ozark Dome, experienced minor positive structural adjustment after Simpson deposition resulting in exposure and "top-down" erosion prior to deposition of the Viola. This relationship is shown on Plate 12 (Cross-section C-C'). On the west side of the Texas Arch at the edge of the Tobosa Basin, the Simpson shows similar progressive truncation of the Simpson by the Viola and Montoya limestone (Wright, 1965, see fig. 13; Jones, 2005). In this general area, Simpson stratal sections were defined and measured from outcrops in the Beach and Baylor Mountains (Suhm and Ethington, 1975). Nearby well logs show the Simpson to exhibit lithologic and electric-log similarities with the Oklahoma section (Wright, 1965). Petroleum reservoirs are termed Connell, McKee, and Waddell Sandstones (Figure 2). Quartz grains in these sandstones originated from source areas of the Transcontinental Arch to the northwest, and possibly from the Canadian Shield.

SOUTH OZARK PLATFORM (Including SOUTH OZARK ARCH, and OZARK DOME)

The South Ozark Platform is a broad depositional platform south of the Ozark Arch and Ozark Dome. It extends eastward from the Ardmore Basin to the Reelfoot Trough in Arkansas. The Simpson in

Figure 10. Reference induction log for Simpson Group in Anadarko Basin. Apache Field, Section 3, T5N-R12W, Caddo County in western Oklahoma. This well is productive in the McLish, Joins (referred to as "Arbuckle" on scout ticket), and Arbuckle.

this area exhibits thicknesses and lithofacies of a tectonically stable, marine "flat-topped" platform (Plate 2). Shale is mostly absent throughout this province, or, limited to a few thin beds that increase in number toward the Ouachita Trough where, unfortunately, well control is sparse. The closest well to the ancestral Ouachita Trough is the Reserve No. 1 Hazen in Prairie County, Arkansas (Suhm, 1978); thick Simpson and Viola lithologies are interpreted to be restricted deep marine deposits. Similar facies are present in northern Mississippi in the Black Warrior Basin (Henderson, 1991; Mellen, 1982). The Simpson thickens from a feather edge in northern sectors on the platform to nearly 1,600 ft to the south near the junction with the Ouachita Trough, Fort Worth Basin, and Ardmore Basin at the Ardmore Basin/South Ozark Platform Hinge. Vast areas of northern parts of the South Ozark Platform consist of shallow-water, restricted marine to supratidal carbonates, and barrier to peritidal sand complexes and sabkha-like tidal flats. Overall, subsidence appears to have been slightly less than sedimentation, which, in a shallow water setting resulted in diminished thicknesses due to sediment reworking. Additionally, sediments deposited in this province were periodically exposed to subaerial elements as seen from solution breccias and cave-fill deposits that were observed in Everton (Joins/Oil Creek) outcrops in Arkansas at measured geologic sections 3, 14, 15, 18 located on the map in Figure 3B (Suhm, 1970). These deposits are interpreted to have formed during Everton time. Everton and post-Everton karst is described by Turner, et al (2007). Similar features are described by Craig et al (1988) in the Joachim Dolomite (McLish) exposed in the Ozark region of Arkansas. Both occurrences suggest short term exposure concurrent with underlying karst collapse perhaps reaching into the Arbuckle. Furthermore, Simpson sand appears to have filled sinkholes developed in Arbuckle carbonates on the Ozark Dome in Missouri and eastern Kansas (Lee, et al 1948; Thompson, 1991; Gore, 1952). Fluvial braided Simpson sand complexes originating from the Canadian Shield may have at times covered the Ozark region.

Due to truncation after deposition the distribution of Simpson can only be inferred in the core areas of the Ozark region, such as the Ozark Dome and South Ozark Arch. From reconstructed isopach maps included here, the Ozark Dome had an effect on dispersal routes of quartz sand originating from the Canadian Shield. Isopach maps show that Oil Creek and McLish sands of the Simpson Group were carried to locations southeast of the Ozark Dome, and from there were laterally transported across the South Ozark Platform by westerly-moving currents. Sands accumulated in coalescing barriers, strandlines, and sand banks. However, southwest transport of these sands ceased where the South Ozark Platform adjoins the deeper water of the Ardmore Basin. Some sand spilled over into the Ardmore Basin, but most of it was redirected toward the Oklahoma Shelf by northwest moving currents. The lack of Bromide sand on the South Ozark Platform is interesting, and perhaps the result of uplift of the Ozark Dome at the beginning of Bromide time, coincident with a change in marine currents. For example, the dome acted as a barrier that caused southward-moving sand to shift westward bypassing the South Ozark Platform with the consequence of entering Oklahoma from the Oklahoma Shelf farther west.

The base of the Simpson Group on the South Ozark Platform is commonly marked by sharp well log contacts - a function of identifiable lithologic change with the underlying Arbuckle (Powell and Cotter of Arkansas). Upper parts of the Arbuckle contain siltstone, chert, and thin streaks of shale, including K-bentonites (Figures 12-14). Previous studies by Suhm (1970, 1974, and 1997) and this one conclude that the South Ozark Platform and Ozark Dome were uplifted and eroded at the end of Ibexian (Canadian) time coincident with a sea level lowstand at the Sauk-Tippecanoe interface. Consequently, exposed silty and cherty limestones of the Arbuckle were selectively karstified over much of the South Ozark Platform creating reservoir quality rocks such as at Wilburton Gas Field, Latimer County, Oklahoma (Carpenter and Evans, 1991; Mescher, et al 1993). The hiatus at the Arbuckle-Simpson unconformity increases in magnitude, or, "time-lost", at locations toward the Ozark Dome where progressively older Arbuckle strata were eroded and overstepped by the Simpson as sea level rose.

Wireline contacts are sharp and unconformable with the overlying Viola, or in the absence of the Viola, the Woodford. Original thickness of the Simpson cannot be determined in northeastern areas due to erosional contacts at the top of the Simpson, but it does appear that Simpson truncation becomes more pronounced north of the 200-ft isopach line shown on the "Middle and Upper Simpson" isopach map of Plate 2. This includes a large part of the Oklahoma Shelf discussed below. The Simpson is assumed, however, to have covered large parts of the Ozark Dome before truncation, albeit in reduced thickness. The unconformity at the base of the Viola is impressive; the Viola truncates progressively older Simpson beds toward the axis of the Ozark Uplift, where it is unconformable on strata as old as the Oil Creek and Everton Formations. This overstep has resulted in the development of stratigraphic truncation traps in several Simpson formations (Plates 4-9). Truncation was the result of post-Simpson uplift of an arch in an area related to, but south of, the Ozark Dome, here termed the "South Ozark Arch". In this context, the South Ozark Arch is more viewed as a tectonic feature of Viola age rather than a depositional province, although it shows nearly identical sedimentologic similarities with the South Ozark Platform. The northern boundary of the South Ozark Arch with the Ozark Dome is at a position marked by a basement fault that corresponds to the Southwest City Fault, an extension of the Southwest Ozark Lineament discussed below. Further, this interpretation suggests that the Southwest City Fault also represents a growth fault separating the South Ozark Platform and South Ozark Arch from the Oklahoma Shelf. Thicker Simpson accumulations are found on the less stable downthrown side of the Oklahoma Shelf to the north, relative to the more stable South Ozark Platform.

OKLAHOMA SHELF AND SOUTHWEST OZARK LINEAMENT

The Oklahoma Shelf is the most geographically extensive Simpson sedimentologic province in Oklahoma. It includes all of the Cherokee Platform and Anadarko Shelf structural provinces, and the north segment of the Anadarko Basin (Plates 1 and 2). The Simpson shows little change across these tectonic provinces other than a southward increase in thickness. The boundary of the Oklahoma Shelf with the Anadarko Basin is gradational and arbitrarily placed at the 1,000-foot isopach contour line as seen on the "Upper and Middle Simpson" isopach map (Plate 2). This value reflects an interpreted transition from Simpson shallow water deposition to deep water resulting in gradual increases in the amount of shale. Further, in consideration of southward thickening and pa-

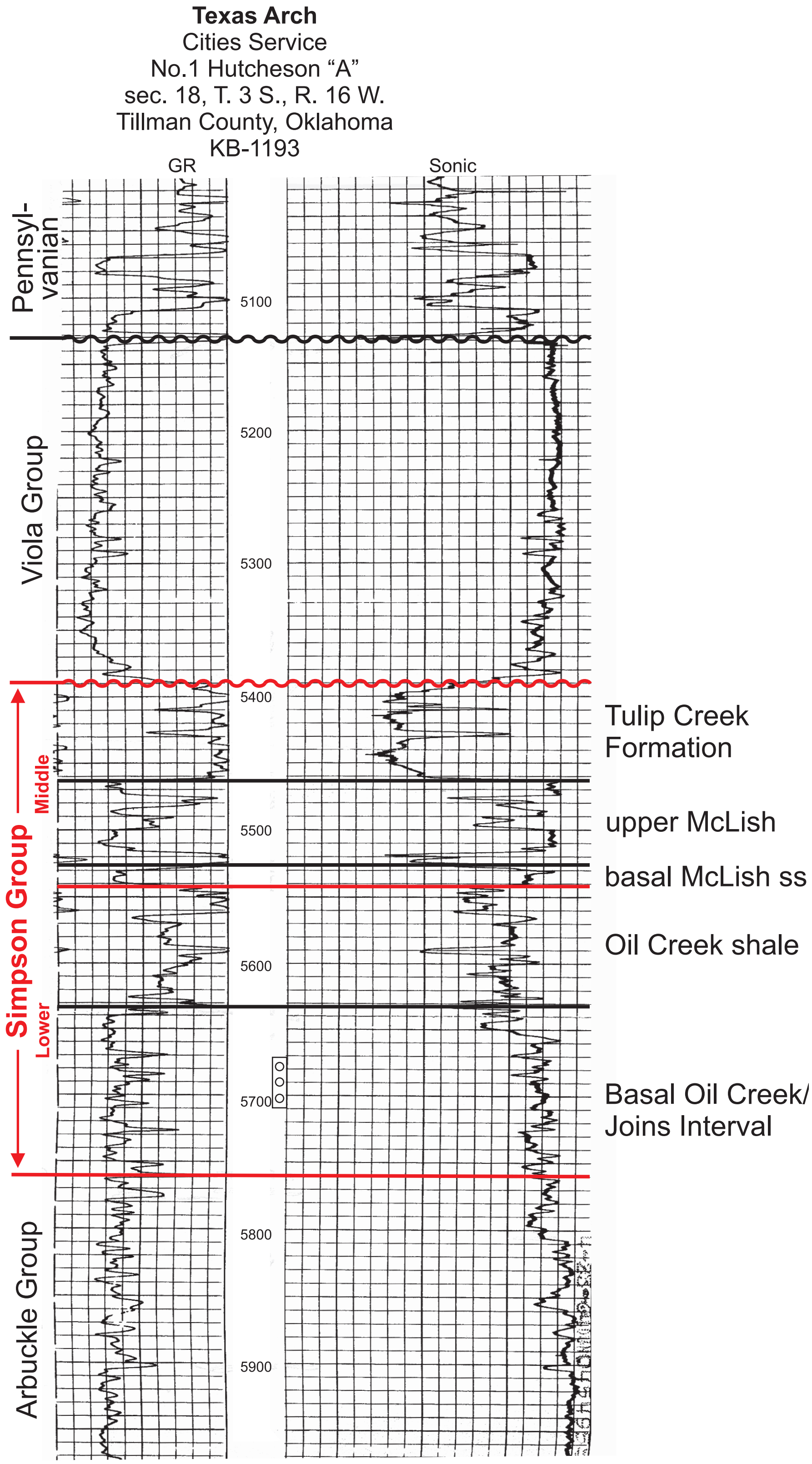


Figure 11. Reference gamma-ray/sonic well log for Simpson Group on the Texas Arch. Cities Service, No.1 Hutcheson "A," Section 18, T3S-R16W, Tillman County in southwestern Oklahoma. The Bromide and part of the Tulip Creek are truncated and overstepped by the Viola.

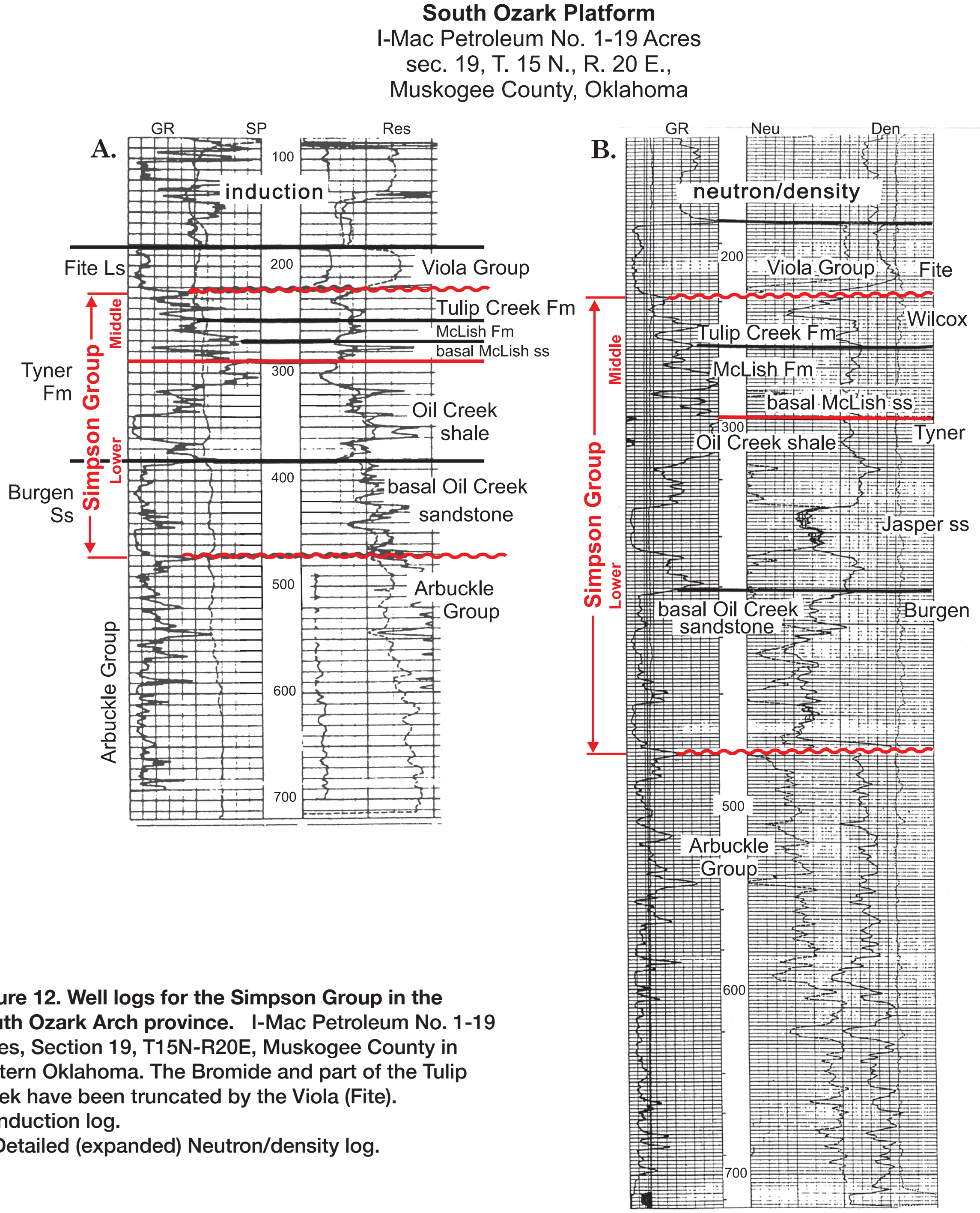


Figure 12. Well logs for the Simpson Group in the South Ozark Arch province. I-Mac Petroleum No. 1-19 Acres, Section 19, T15N-R20E, Muskogee County in eastern Oklahoma. The Bromide and part of the Tulip Creek have been truncated by the Viola (Fite).
A. Induction log.
B. Detailed (expanded) Neutron/density log.

leohydrologic deepening, the depositional slope of the Oklahoma Shelf is interpreted to be steeper than that of the South Ozark Platform. Because of this the Oklahoma Shelf is perhaps better described as a seaward dipping depositional ramp rather than a platform. Northward on the Oklahoma Shelf at locations close to Kansas, Simpson formations are thin with minimal depositional (accommodation) rates. Moreover, the McLish and Tulip Creek Formations are so thin that it is difficult to separate them from one another; the two could easily be lumped together, as is done in Kansas. Interestingly, in Major County during early Whiterockian time following Oil Creek deposition, the Oklahoma Shelf was under very shallow water when a meteoroid struck to create an impact crater about 10 miles in diameter (Carpenter and Carlson, 2000). Logs for wells drilled in the "Ames Crater" in the area of T20N-R9W show that parts of the Oil Creek Formation were removed by the impact resulting in a crater that was later filled with McLish shales (Repetski, 1997). This feature is seen on Cross Section E-E' (Plate 14). The crater may also be recognized on various plates included in this report as a circular pattern of Arbuckle production.

The present-day Nemaha Fault and the more westerly Midcontinent Rift (if present this far to the south) are located in the central part of the Oklahoma Shelf (personal communication, Kevin Crain). In context of structural provinces of Northcutt and Campbell (1995) to be discussed later, the Nemaha Fault forms the western edge of the Cherokee Platform. Lower members of the Simpson show little sedimentological influence of the Nemaha Fault that might suggest tectonic activity. However, in late Simpson time, vast quantities of Bromide sand accumulated on the Oklahoma Shelf (Figure 9A), with maximum thicknesses of over 250 ft near the incipient Nemaha Fault on its west side in what is interpreted to be a sediment-loaded tectonic basin in Canadian County, referred to in this report as the "Canadian County Sub-basin." Bromide sandstone on the east side of the Nemaha Fault is thinner. Apparently, the western side of the Nemaha Fault was affected by crustal instability or weakness resulting in a thicker depositional column than on the eastern side of the fault. Since Simpson formations older than the Bromide do not show thickening, or facies abnormalities, perhaps the earliest tectonic movement of the Nemaha Fault began in Late Whiterockian time.

The Oklahoma Shelf is separated from the South Ozark Platform on the east by what is interpreted to be a southwest-northeast basement flexure, called the "Southwest Ozark Lineament" (Plate 2). This feature was introduced by Suhm (1997) to separate thicker shale-rich Simpson lithologic associations of the Oklahoma Shelf from shale-free Simpson facies of the South Ozark Platform. Contour deflection at this lineament observed on isopach maps visible on Figure 9 (Suhm, 1997) and in Wagoner and Muskogee Counties on Plate 2 suggests that the Oklahoma Shelf subsided at greater rates than the adjoining South Ozark Platform, likely due to crustal weakness. Lithologic differences, as well as differences in thickness, are readily seen in well cuttings and subsurface logs. For example, in comparison with high-energy deposits of the stable South Ozark Platform, the Oklahoma Shelf provided slightly more accommodation space and was, in consideration of paleogeography, protected by barrier sandstones that covered the South Ozark Platform at various times. Consequently, clay, and less quartz sand (except the northerly derived Bromide sand) is more prevalent on the Oklahoma Shelf. The existence of the Southwest Ozark Lineament is also supported by having a position relative to, and possible connection with, well-known faults such as the McClain County Fault located southwest of the lineament (shown on the Viola structure map), and the Seneca Fault located northeast of the lineament, described by Siebenthal (1908) and shown on the geologic map of Oklahoma (Miser, 1954). Although the Seneca Fault has variable, seemingly insignificant vertical displacement, outcrops near Pryor in Mayes County (GPS: 36°18'24.40"N; 95°17'50.32"W) show mineralized breccia and fault gauge material suggestive of a deep fault and crustal weakness. Further, it is reasonable to think that the McClain County Fault, Southwest Ozark Lineament, and Seneca Fault bordering the Oklahoma Shelf were connected. If so, they might represent a near continuous and connected trend of basement weakness that may have served as a plumbing system for deep-seated conduits or pathways for basinally-derived mineralizing fluids of the Tri State lead/zinc district of Missouri, Oklahoma, and Kansas (Coveney, et al 2000; Garven, et al 1993). This feature, to be discussed later, may also have played a role in hydrocarbon emplacement in the Simpson. A branch of the Seneca Fault trends eastward from Mayes and Delaware Counties in Oklahoma into Missouri where it is termed the Southwest City Fault. McCracken (1964) named this fault and illustrated it in a north-south stratigraphic cross section that shows an Arbuckle section that is thicker on the north side (that of the Ozark Dome) relative to a thinner section on the south side (South Ozark Arch). These thickness variations are suggestive of a syndepositional fault that was active in Cambrian and Ordovician time. Moreover, from evaluating trends seen on the geologic map by the Missouri Geological Survey (1939), the Southwest City Fault may have extended in the subsurface 100 miles farther to the northeast near the northwest corner of Douglas County, Missouri. The position of this fault is illustrated in Figures 20-22 where it is interpreted to be part of a fault system that separates the South Ozark Platform and South Ozark Arch from the unstable Ozark Dome.

OUACHITA TROUGH AND FORT WORTH BASIN

Southern reaches of the Ardmore Basin were connected to deeper open marine waters of the Fort Worth Basin. Eastward from the Fort Worth Basin, however, another seaway, or, more correctly, a narrow arm, branched into Arkansas where it is known as the "Ouachita Trough" in which Simpson equivalents were deposited. Today, those equivalents are found within the Ouachita Mountains where they are among the oldest strata comprising the thick sedimentary package known as "Ouachita facies." Simpson equivalents include, in ascending order, the Crystal Mountain Sandstone, Mazarn Shale, the Blakely Sandstone, and the Womble Shale. The Womble and Mazarn are exposed along the frontal thrusts of the Ouachita Mountains, such as near Atoka in Atoka County, Oklahoma at Black Knob Ridge. Black Knob Ridge is the type section called "Global Stratotype Section (GSS)" for the base of Katian stage at the Simpson/Viola contact as discussed by Goldman, et al (2007) and Carlucci, et al (2015). Ordovician Ouachita facies are also exposed much farther to the east in the Potato Hills, and Broken Bow and Benton Uplifts (Plate 1). The Womble Shale and the Blakely Sandstone were encountered in only a few wells in the Ouachita allochthon; even fewer wells penetrated the older and deeper Mazarn Shale and Crystal Mountain Sandstone. Simpson equivalents make up a relatively small part of the 30,000-foot thick Paleozoic age rocks composing the Ouachita Mountains in Oklahoma and Arkansas. Strata within the Ouachita Mountains are, for the most part flat-lying, with complex configurations adjacent to faults and fault blocks. The abundance of flat-lying strata in the Ouachita Mountains is remarkable given that the thrust complex was transported northward a distance as much as 100 miles from its original depositional site in the Ouachita Trough, mostly in Texas. Perhaps, the entire Ouachita package was trans-

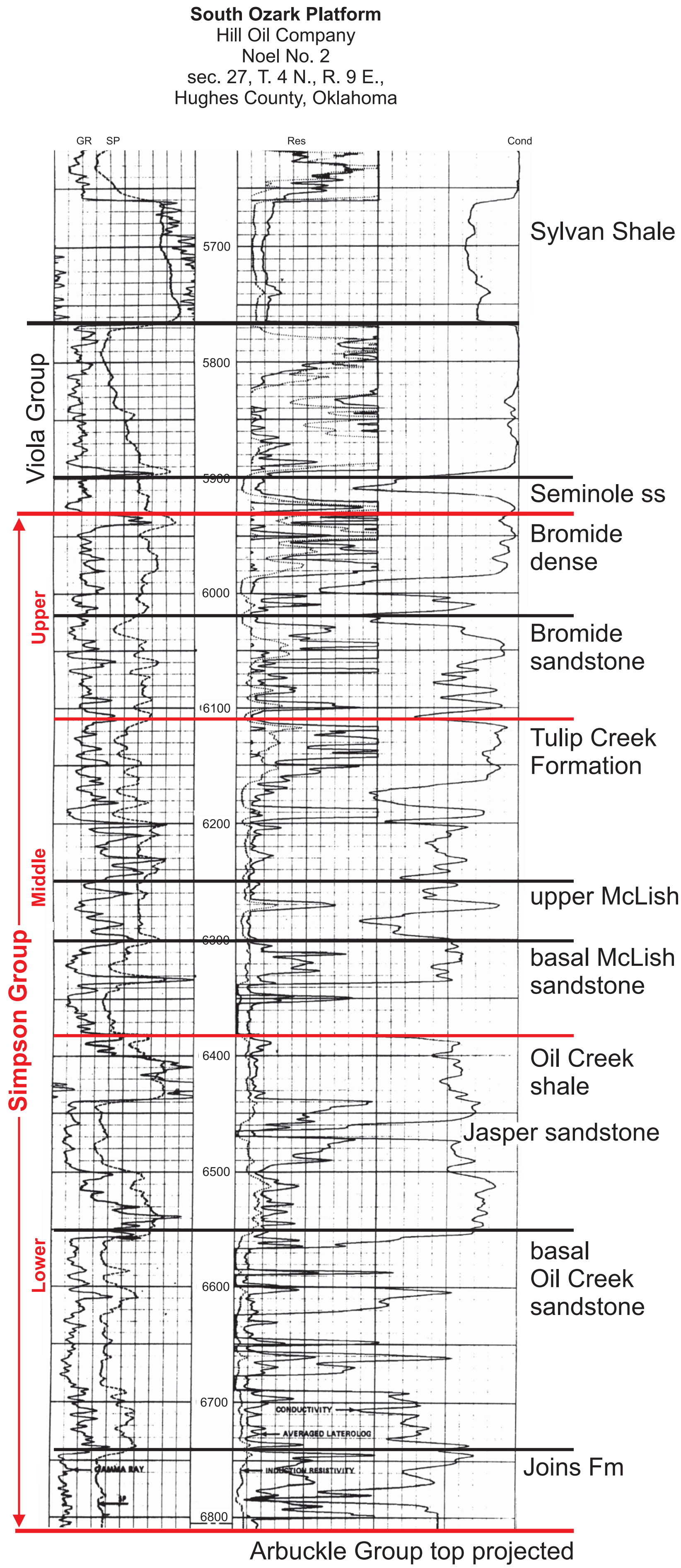


Figure 13. Induction log for the South Ozark Platform province. Hill #2 Noel, Section 27, T4N-R9E, Hughes County, Oklahoma.

ported *en masse*. The distance of 100 miles is similar to what earlier investigators reported (Hendricks, 1959; Miser, 1929), and explained more fully in the "Exploration" section of this paper.

No wells have penetrated the original in-place (autochthonous) Ouachita facies of the Simpson in Oklahoma and Arkansas. However, it is likely that some sections of Ouachita strata are preserved at their original depositional location in northern parts of Ouachita Trough just south of the South Ozark Platform at a position that can only be inferred from seismic and gravity/magnetic interpretations. The junction between the South Ozark Platform and Ouachita Trough, here called "South Ozark Platform/Ouachita Trough Hinge," does appear to extend farther south than the Sohio No. 1 Weyerhaeuser, McCurtain County, Oklahoma, and the Hunt No. 1 Neely, Lamar County, Texas (Figures 3, 23). Both wells have platform-deposited sections of limestone, sandstone, and shale buried beneath thousands of feet of thrusted Ouachita rocks. The lithology and remnant textures of these subthrust sections seem to indicate similarity to strata deposited in shallow water such as found on the South Ozark Platform. Wireline-log signatures are similar also (Milliken, 1988; Leander and Legg, 1988). In the area of the Potato Hills in Latimer County, the Chesapeake #2-34 Mary penetrated a complete section of "platform" Simpson beneath 25,000 ft of thrusted strata (Plate 13, Cross Section D-D'). Bromide platform carbonates in this well are interbedded with thin shales denoted by numerous gamma-ray spikes, a characteristic that suggests some degree of proximity to their Womble Shale counterparts in the Ouachita Trough. Increases in clay are also seen in older Simpson formations in this well.

The Simpson thickens southward on the South Ozark Platform toward the Ouachita Trough and Reelfoot Rift with a corresponding increase in shale and detrital admixtures. Moreover, all Simpson equivalents in the Ouachita Trough, in the interval Crystal Mountain Sandstone, Mazarn Shale, Blakely Sandstone, and Womble Shale, including the older Arbuckle equivalent known as the Collier Shale (oldest formation of the Ouachita facies), have variable amounts of high-quartz sandstone, limestone, and argillaceous sandstone and limestone. The primary source of detritus for these formations was from the erosion of the Texarkana Platform located south of the Ouachita Trough. The nature of pre-Simpson rocks constituting this source area may be similar

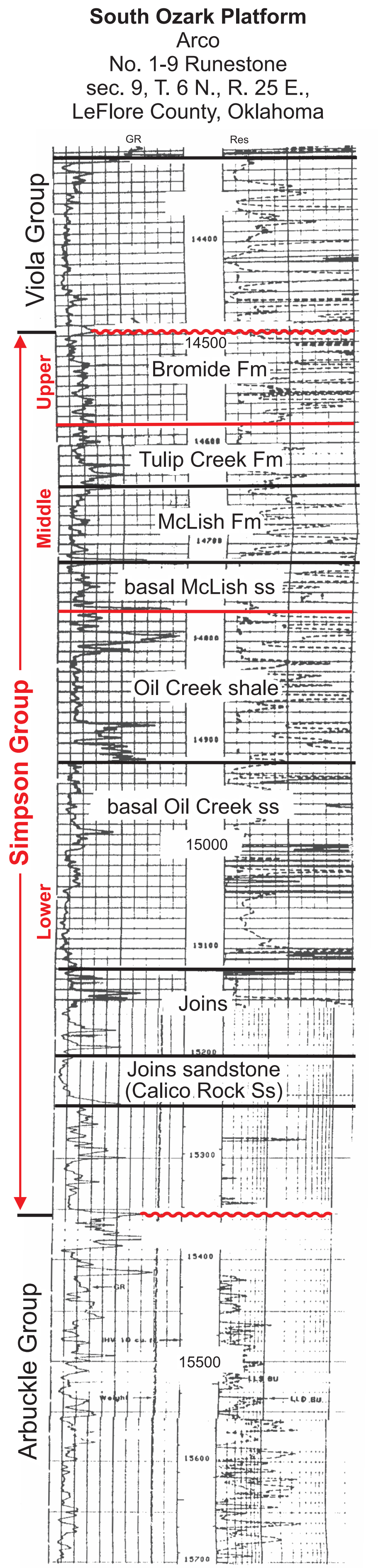


Figure 14. Reference induction log for the Simpson Group on the South Ozark Platform. Arco No. 1-9 Runestone, Section 9, T6N-R25E, Le Flore County in eastern Oklahoma.

to that reported by Howe and Thompson (1984) in their studies of the Pascola Arch in northeast Arkansas. They document the presence of thousands of feet of detrital Cambrian sedimentary rocks in the subsurface. Rocks such as these, at one time, may have been exposed on the Texarkana Platform, and through erosion contributed detritus to Ouachita formations mentioned above. Furthermore, not only would the Pascola Arch be the closest "look-alike" source area to the Texarkana platform, but a connection between the two is seen from gravity maps published by the USGS and Braile, et al (1986).

As shown in Figures 3 and 23, the Ouachita Trough was connected on the west with the deeper marine open waters of the Fort Worth Basin (Ardmore Basin). From that junction, the narrow arm of the Ouachita Trough extended eastward to the embayment area of Arkansas to join the less turbid waters of the Reelfoot Trough. As discussed by Lowe (1989) the Ouachita Trough appears to be the product of a failed rift system positioned between the continental interior block of the South Ozark Platform on the north, and on the south by a block of continental crust called Texarkana Platform. From the standpoint of Simpson deposition, the Texarkana Platform is invoked as a source area for clay that was carried into basins in Oklahoma. The existence of this provenance is supported by Dix, et al (1994) and Gleason, et al (1995). Later in the Paleozoic the Texarkana Platform served as a source area for various clasts in Stanley and Jackfork flysch (Mississippian) described by Walthall (1967). It was from this work that Paine and Meyerhoff (1970) interpreted the clasts as indirect evidence of the existence of a large block of exposed continental crust that they termed the Texarkana Platform. Shideler (1970) also speculates that a shallow marine Simpson depositional system may have existed on the northern shelf edge of the Texarkana Platform adjacent to the Ouachita Trough; the presence of this carbonate platform is inferred from the variety of pebbles and other detrital components found in the Johns Valley Shale (Morrowan).

Eastern segments of the Ouachita Trough terminate at the Reelfoot Trough. Ordovician rocks typical of "Ouachita facies" have not yet been found in western Mississippi, in contradiction with an open ocean connection shown by Lowe (fig. 8, 1989). This information supports the contention that the Ouachita Trough was a barred Black Sea-like basin during Simpson time and likely marked by oxygen-

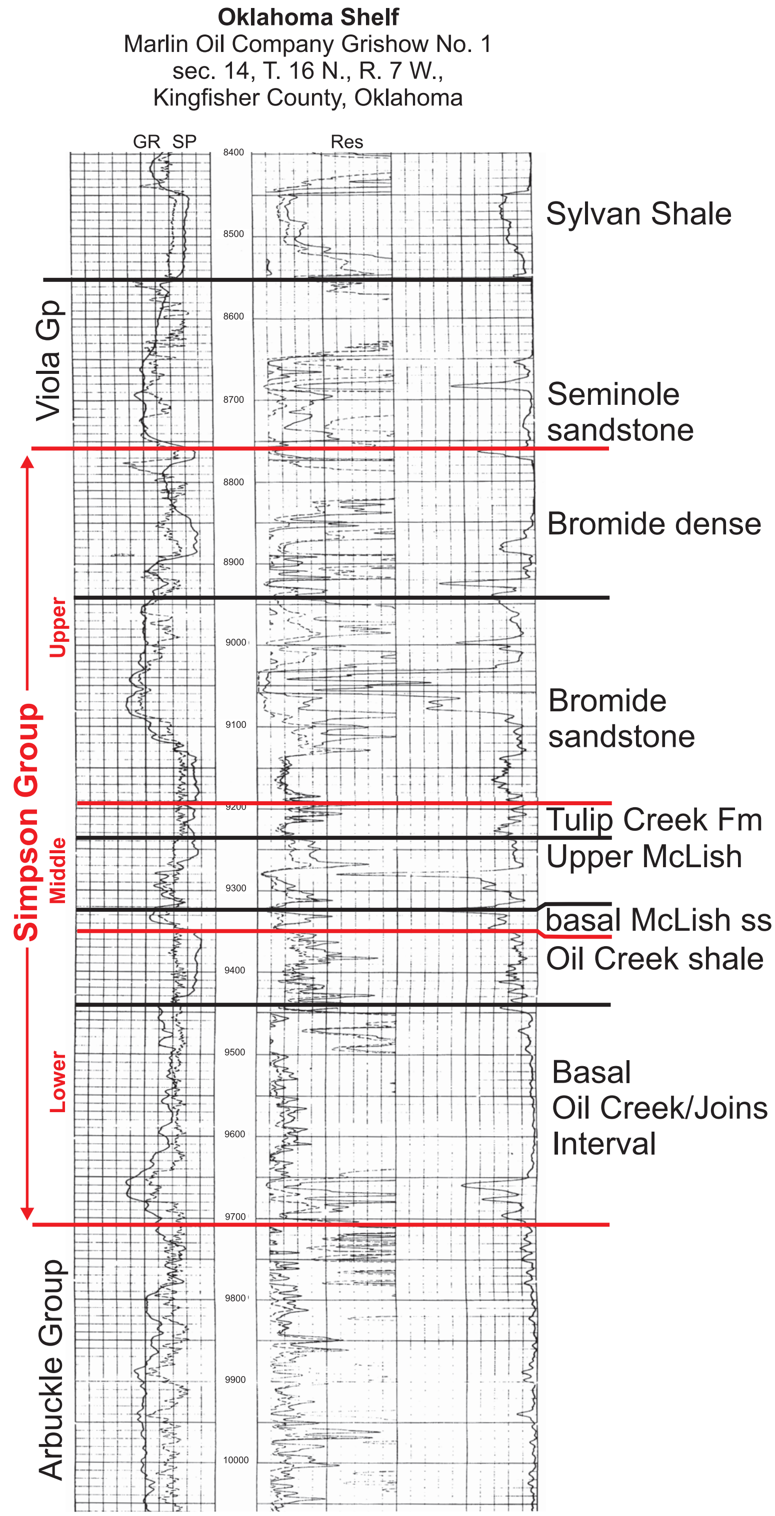
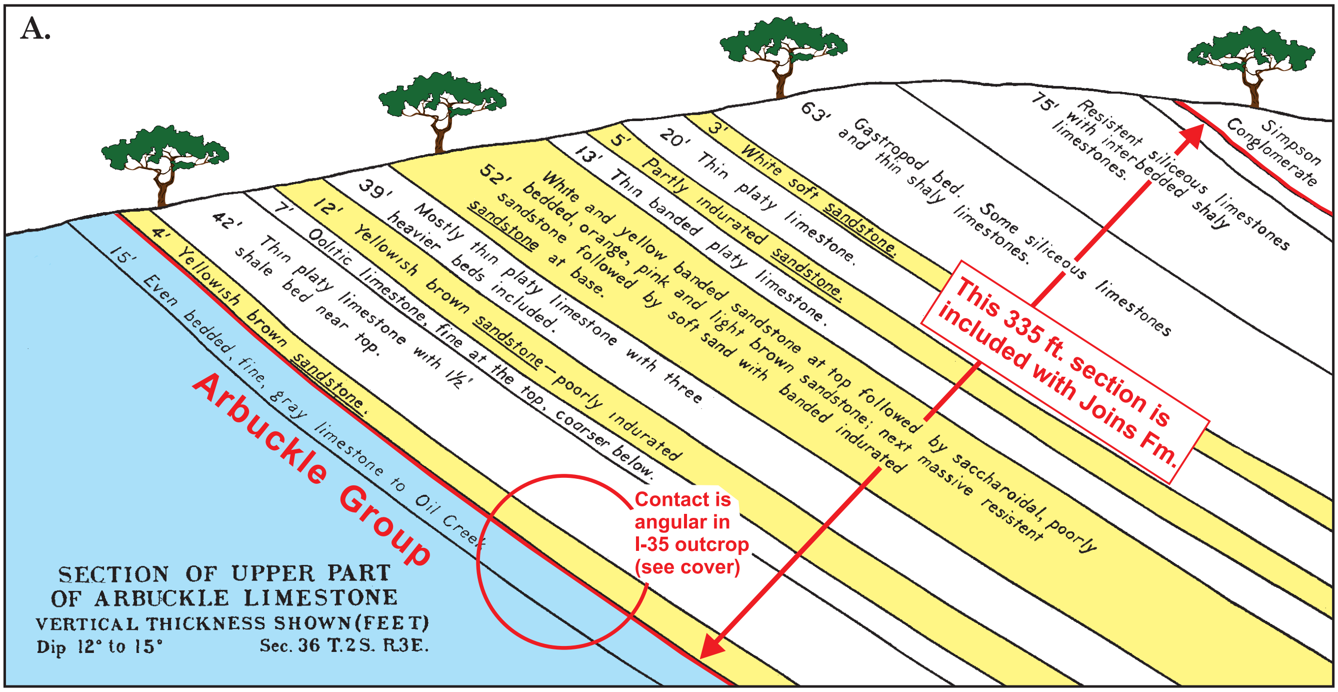
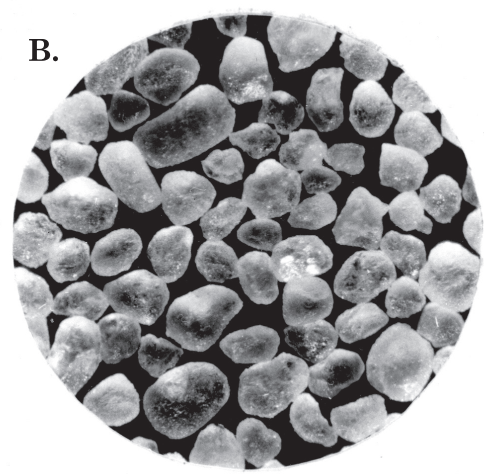


Figure 15. Reference induction log for the Oklahoma Shelf province. Marlin No. 1 Grishow, Section 14, T16N-R7W, Kingfisher County in northern Oklahoma.

depleted bottom conditions (anaerobic) as suggested by relatively thick beds of organic-rich black shale and dark-colored carbonates. Apparently, nutrients





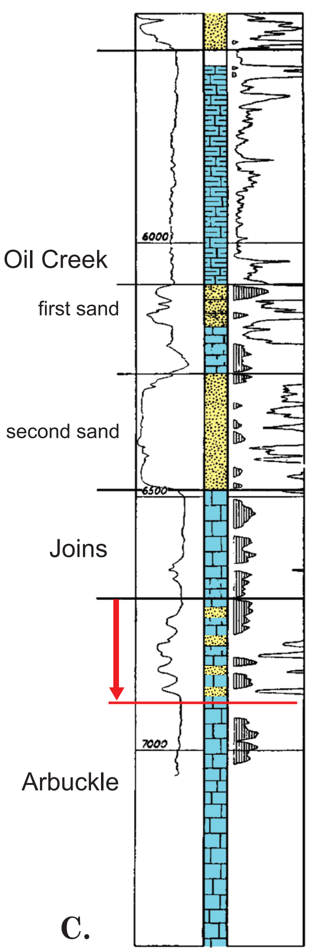


Figure 16. Surface and subsurface examples of Simpson/Arbuckle contact.
A. Several hundred feet of sandstones and sandy carbonates above Arbuckle Group carbonates and below the "Simpson conglomerate" (Joins) were classed as "upper part of Arbuckle" by Decker (1929). However, in this paper this sandy interval is included with the lower part of the Joins. It is similar to the section along Interstate 35 illustrated on the cover photo. Sandstones (yellow) are easily recognized and mapped in the surface and subsurface, in contrast to fossils.
B. Quartz sand was identified by Ham (1950, plate 13a) as upper Arbuckle in a section he termed "upper West Spring Creek." However, in this paper St. Peter-like sandstones such as this one are classified with the Joins Formation.
C. Lithologic and electric-log section of Simpson/Arbuckle contact in Cumberland Oil Field 25 miles southeast from the outcrop in 16A (modified from Cram, 1948, Fig.2). Red arrow shows 300 ft of dolomitic sandstone that Cram classed with Arbuckle. In this paper, this interval (red) is included with Joins Formation of the Simpson Group; its stratigraphic position is similar to that of the Calico Rock Sandstone in Arkansas (Figures 14, 17).

from the open ocean in the Fort Worth Basin were transported into the Ouachita Trough to be consumed by plankton living in its oxygenated upper layers of water. The lack of oxygen in bottom water helps to explain the absence of shelly fossils in substrates. It also appears, evident from thick chert deposits, that Early Paleozoic waters were rich in biologically-derived silica, perhaps in addition to silica derived from underwater volcanic vents. In sum, the paleogeographic interpretation expressed above is that the southern continental margin of North America (Laurentia) in Ordovician time was not at the edge of the Ouachita Trough, but at the southern edge of the Texarkana Platform. The open ocean at the southern extremity of the Texarkana Platform is known as the Iapetus Sea and identified from a sedimentary succession of Simpson equivalents in the subsurface Suwannee Basin of Florida. The tectonic setting of Ordovician time is further discussed by van Staal and Hatcher (2010).

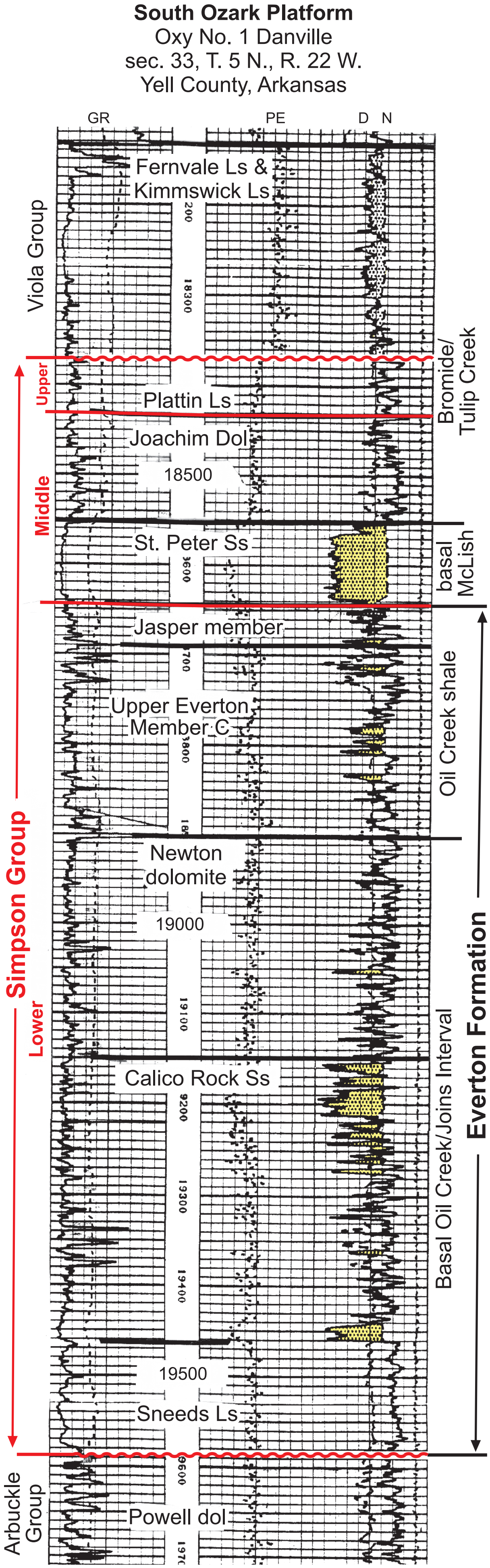
SIMPSON GROUP STRATIGRAPHY

INTRODUCTION

Basal Simpson Outcrops in Ozark Mountains in comparison with those in Arbuckle Mountains

Unraveling Simpson Group stratigraphy in Oklahoma began with studies by Suhm (1965) in the Ozark region of eastern Arkansas by mapping and measuring outcrop sections of Arbuckle, Simpson, and Viola equivalents exposed in the Batesville Manganese District. This project was followed by a more specific study in northern Arkansas of the Everton Formation along the Buffalo and White Rivers (Suhm, 1970), which resulted in correlation of the Everton with the Joins and Oil Creek Formations of Oklahoma (Suhm, 1974, 1997). The Everton Formation was named by Ulrich (in Purdue, 1907, p. 251-252), for exposures near the town of Everton, Boone County, Arkansas, where it is disconformable on the Powell Dolomite (Arbuckle) and disconformable under the well-known St. Peter Sandstone (McLish and Tulip Creek Formations). Correlation of near complete sections of the Everton and St. Peter Formations (Simpson) along the Buffalo and White Rivers allowed various members of the Everton to be placed in their proper vertical and lateral stratigraphic positions (Suhm, 1970). The stratigraphic relationships of the Everton Formation and its members were previously unknown. Moreover, the methodology of this field study was similar to that used by Decker and Merritt (1931) in their study of Simpson exposures in the Arbuckle Mountain area. The Everton was found to be more than 650 ft thick in northeastern Arkansas, thinning to 350 ft in northwestern Arkansas, somewhat analogous to Simpson thinning in the Arbuckle Mountain area. Both the Joins in Oklahoma and lower Everton in Arkansas are better developed in basinal positions where they are thicker and where deposition was more continuous and less likely to be affected by potential removal by erosion and facies changes across short distances. The oldest Everton member is the Sneeds Dolomite (a Joins equivalent) which is below, but in facies with, the overlying Newton Sandstone Member (Figure 3B). Suhm (1974) identified the Newton Sandstone as correlative to the Burgen Sandstone of northeastern Oklahoma, which, in turn, was found to be equivalent with the basal Oil Creek sandstone (Suhm, 1997). Furthermore, lateral facies that exist between the Sneeds and the Newton Sandstone in Arkansas (Suhm, 1974, Fig. 20) are similar to the relationships between the Joins Formation and basal Oil Creek sandstone in Oklahoma, in the context of this report. This is, in part, the reason for introducing an informal stratigraphic unit termed "Basal Oil Creek/Joins Interval" for the lower Simpson Group in Oklahoma. This name enables detailed classification of Simpson formations from subsurface logs, such as those that appear on cross sections in Plates 11-14. The name is not intended to be formalized.

At surface and subsurface locations where the basal Simpson sandstones are absent, carbonates of the Sneeds in Arkansas and the Joins in Oklahoma rest on carbonates of the Arbuckle. And, although the Simpson and Arbuckle are both carbonates they are distinguished from one another by lithology. For example, in the Ozark and Arbuckle Mountains, Arbuckle dolomites are light gray, dull, silty, partly cherty, and very finely crystalline. Those in the Joins and Sneeds are not dull and cherty but with varying degrees of crystallinity and often with sand-sized quartz grains. Moreover, throughout much of the outcrop belt in northern Arkansas, the Sneeds Member of the basal Everton consists of a ubiquitous basal sandstone conglomerate less than ten feet thick containing angular to subrounded granules and pebbles of terrigenous chert and dolomite in a sandy to very sandy dolomite matrix. The chert and dolomite pebbles were derived from the erosion of the underlying cherty carbonates of the Powell, Cotter, and Arbuckle — formations that comprise the extensive "Great American Carbonate Bank" that was exposed on the Ozark Dome at the beginning of Whiterockian (Tippecanoe) time. Correlation has shown that Everton sandstone, or basal conglomerate, is thin but also widespread, and not always equivalent with localized intraformational conglomerates of the Joins in the Arbuckle Mountains mentioned by Decker and Merritt (1931). Rather, Decker and Merritt (1931) mention the commonality of limestone conglomerates interspersed throughout the Joins and Arbuckle, and state on page 15, "Locally, also, a similar con-



glomerate occurs within the Joins a considerable distance above the base …" and "A similar conglomerate occurs at a number of locations a short distance below the Hormotoma gastropod bed and the algal bed near the top of the Arbuckle." The lowest Joins conglomerate in stratigraphic proximity to the gastropod bed more likely represents a position correlative with the Sneeds in Arkansas. An important development of this present study shows that in parts of southeastern Oklahoma the Joins is coupled with basal sandstone, informally called "basal Joins sandstone," which likely equates with the Calico Rock Sandstone Member of the Everton Formation in Arkansas (Figure 4). Unfortunately, it appears that the "Joins sandstone" was erroneously classified with the upper part of the West Spring Creek Formation of the Arbuckle Group (Decker, 1929). It is proposed in this report that these questionable "upper Arbuckle" sandstones and sandy carbonates should be included with the Joins Formation of the Simpson Group thereby positioning the Simpson/Arbuckle contact at the base of this sandstone. This position equates to the sandstone above the redbed complex of the West Spring Creek Formation of the Arbuckle Group described by Musselman (1995), and Fay (1989, 1995), and which is shown on the cover of this report. This contact also represents a suitable sequence boundary between the Sauk and Tippecanoe Sequences, and, from information in this report can be recognized by geologists throughout Oklahoma. Sandstone is not only more readily mapped and more geographically extensive than erratic limestone conglomerate used to define the base of Simpson by Decker and Merritt (1931), but in the subsurface, quartz sandstones are recognized both on well logs and in drill cuttings. Even in areas where discrete sandstone beds are seemingly absent, modern logs are sensitive enough to detect slightly siliceous intervals within the carbonates that allow separation from the Arbuckle. Using modern logs in this manner is analogous to insoluble residue studies 50 years ago; for example, dissolving rock and sample specimens to determine quantity and mineralogy of insoluble substances within carbonates for classification and correlation purposes (Ireland, 1944). Irrespective, subsurface geologists currently use the presence or absence of quartz sandstone to distinguish the Simp-

Figure 17. Neutron/density reference well log for Simpson Group equivalents of South Ozark Platform in Arkansas. Oxy No. 1 Danville, Section 33, T5N-R22W, Yell County, Arkansas. Note the "Joins-equivalent" Calico Rock Sandstone below carbonates of the Newton and above the Powell (Arbuckle).

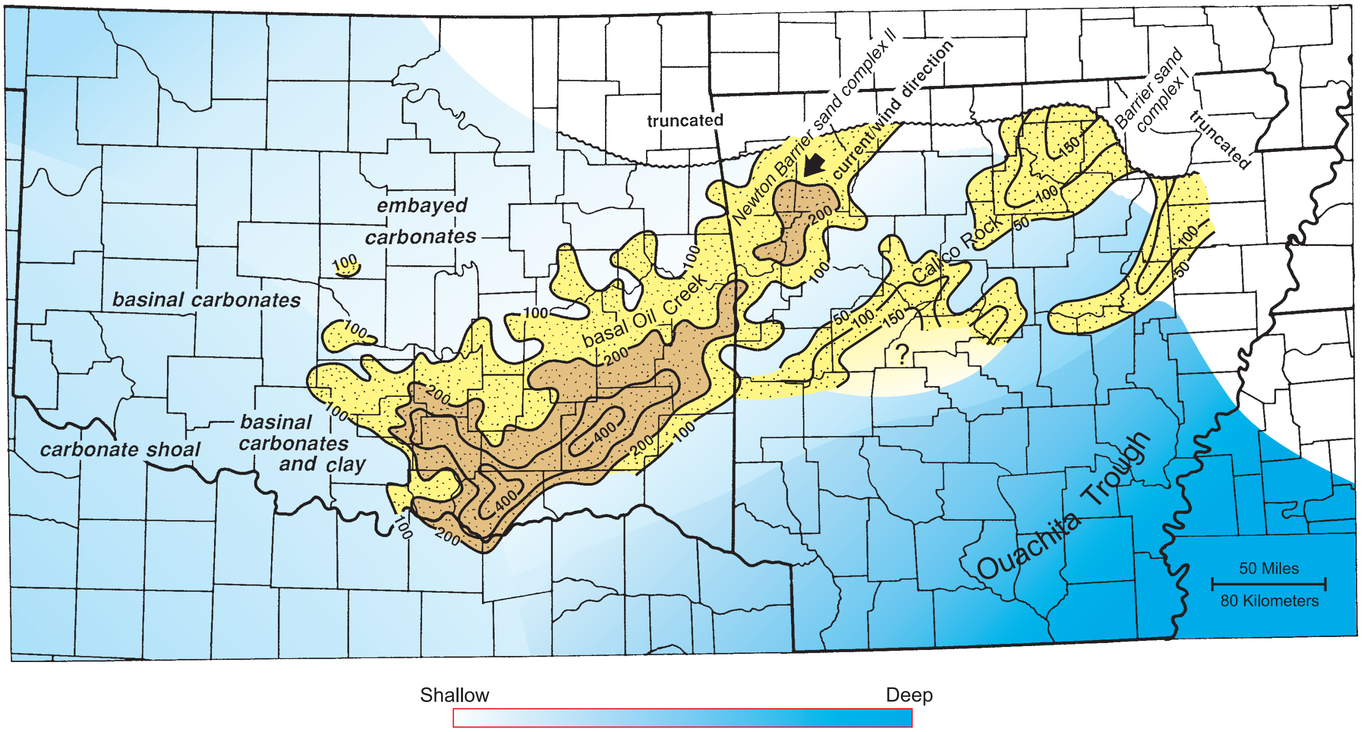


Figure 18. Basal Simpson sandstones of Tippecanoe Sequence. Platform-edge sandstones of Calico Rock Sandstone in Arkansas are combined with younger and overstepped shoreline sands of Newton and basal Oil Creek. Southwestward movement of the barrier-like Calico Rock and Newton sands from Arkansas into central Oklahoma is estimated to have taken thousands of years. Sandstones thicker than 200 ft are shown in brown. Limited well control in southeastern Oklahoma allow for the possibility of a genetic link between sandstones of the Calico Rock and those in the Joins Formation of the Simpson Group. Modified from Suhm, 1997, figs 11 and 12.

son from the Arbuckle. Additional support for defining the Joins (and other formations) in this manner is derived from enclosed isopach maps that show local and regional trends of thickening. The expectation of the amount of thickening or thinning of the Simpson for any well being drilled in Oklahoma can be predicted from these maps.

Revised Basal Simpson contact in Arbuckle Mountain Area

At the turn of the nineteenth century, the United States Geological Survey (USGS) initiated geologic mapping programs across the country. In the Arkansas Ozark region Purdue (1907), Ulrich (1911), and Purdue and Miser (1916) studied and mapped formations of the Powell, Everton, St. Peter, Joachim, Plattin, and Kimmswick. In the Arbuckle Mountain area Taff (1902, 1904), studied, named, and mapped lithologic characteristics of the Arbuckle, Simpson, and Viola Groups. Ulrich and Girty identified fossils listed in his reports. However, on that map, Taff (1904) mistakenly included thick limestone, known today as Bromide, with the Viola. Since presence of sandstone was an important mapping criterion for Taff (1904) its absence in the upper Bromide likely prompted him to include it with the Viola. Alternating sandstone, limestone, and shale of the terrigenous-rich section that Taff (1904) called Simpson "formation" perhaps best fits a group of rocks we today call a sequence, and furthermore, Taff (1904) introduces the "Simpson" on page 23 saying, "After the Arbuckle limestone was deposited there was a general change in the nature of the sediments. The top of the limestone seems to have been slightly eroded locally and upon the surface were deposited beds of pure sand. At other places the Arbuckle limestone• is overlain by shaly and impure lime-the basal beds of the Simpson formation. On these local sandy beds at the base there were deposited greenish shales and thin crystalline and shelly limestones interstratified with a number of beds of sandstone, making a total thickness ranging from about 1,200 to 2,000 feet."

The geologic map of the Arbuckle Mountains that Taff (1904) prepared is one of Oklahoma's earliest geologic maps, and impressive by today's standards. More important, however, and relevant to the contact between the Arbuckle and Simpson, a comparison of Taff's map with the one by Ham (1955) reveals that the upper part of what we call Arbuckle today was

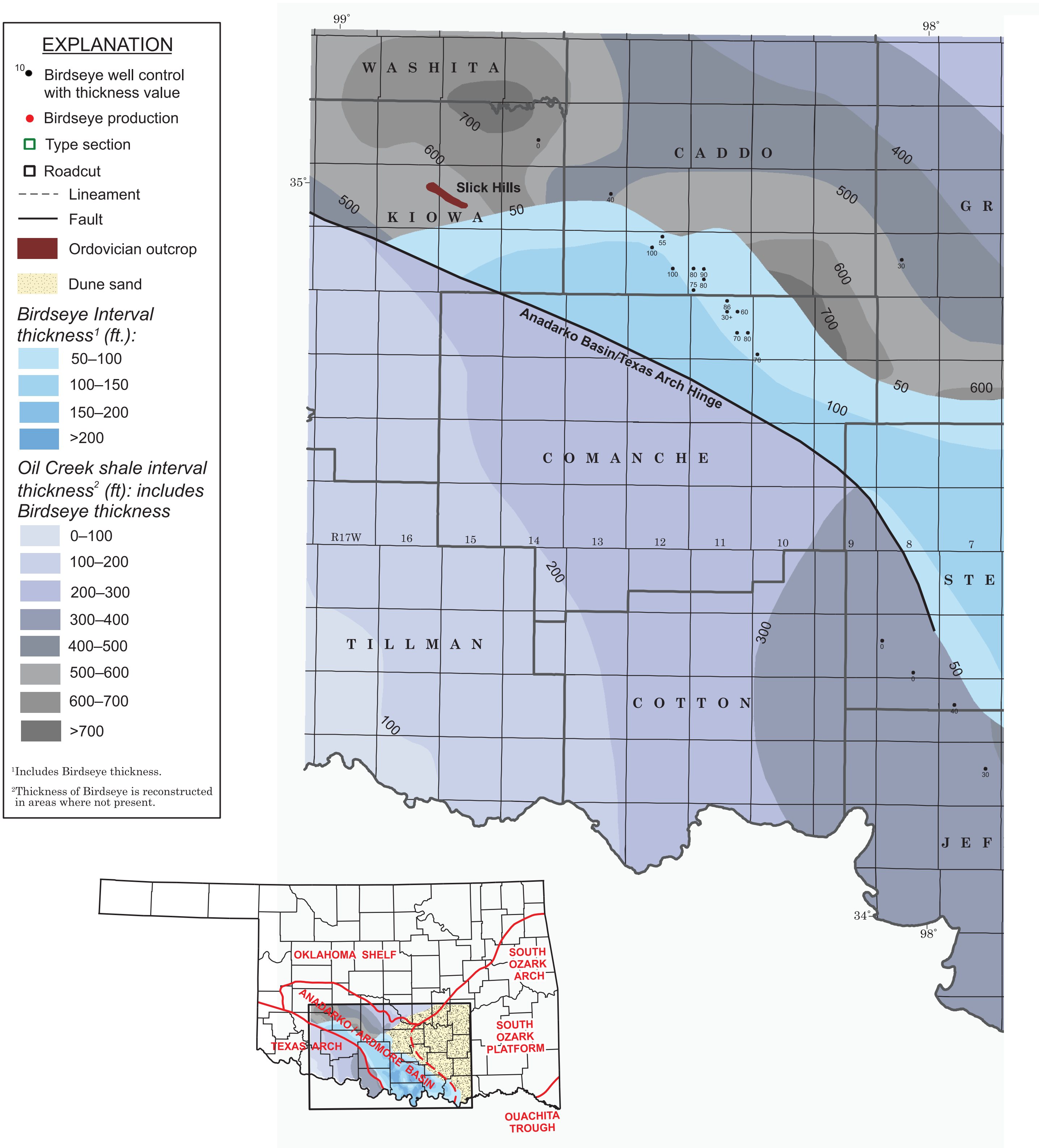
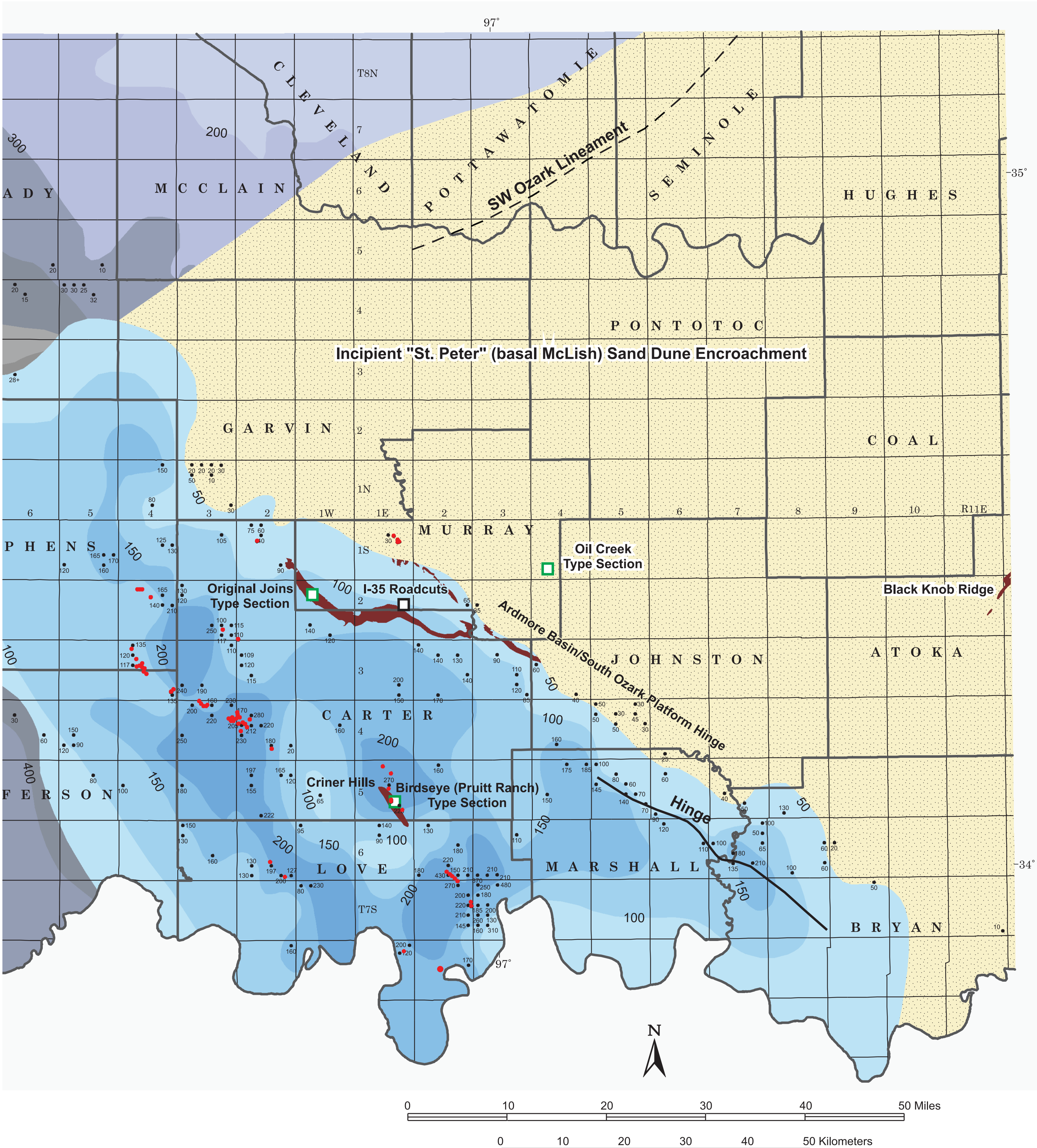


Figure 19. Birdseye limestone isopach map superimposed on the Oil Creek shale with well control points, outcrops, and type sections. The Birdseye in blue is the uppermost member of the Oil Creek shale (gray or blue-gray). Map shows thicknesses greater than 50 ft; at thicknesses less than 50 ft the Birdseye is difficult to distinguish from other limestones in the Oil Creek shale. It is unconformable under the basal McLish sandstone. Yellow shows the distribution of sandy terrain of the incipient St. Peter sand sheet following deposition of the Oil Creek shale. Wells productive from the Birdseye are in red.



Incipient "St. Peter" (basal McLish) Sand Dune Encroachment
SW Ozark Lineament
Oil Creek Type Section
Original Joins Type Section
I-35 Roadcuts
Black Knob Ridge
Ardmore Basin/South Ozark Platform Hinge
Criner Hills
Birdseye (Pruitt Ranch) Type Section
Hinge
CLEVELAND
POTTAWATOMIE
SEMINOLE
MCCLAIN
HUGHES
PONTOTOC
GARVIN
COAL
MURRAY
JOHNSTON
ATOKA
CARTER
LOVE
MARSHALL
BRYAN
N
0 10 20 30 40 50 Miles
0 10 20 30 40 50 Kilometers

mapped as Simpson by Taff (1904), including at the type section Camp Simpson (Section 12, T1S-R6E). Apparently, Taff (1904) mapped thin sandstones as Simpson, not Arbuckle. Gould (1925) agrees and on page 14 states, "At or near the base, near the top, and in the central portion (of the Simpson) there are members of massive sandstone, usually pure white, ranging up to 100 feet thick, which are used for glass sand." Further, the correlation table prepared by the USGS included with Gould (1925) shows the system boundary between the Cambrian and Ordovician to be at the base of the Simpson Group, similar to what is proposed in this report.

Fossils played a secondary, often minor role in physical aspects of early field mapping. Formation differentiation within the Simpson and more detailed age designation took place twenty years after mapping by Taff (1904). Ulrich (1911, 1929) not only identified many of the fossils collected by early investigators, but he assigned relative ages to the rocks containing them and named all formations of the Simpson — Joins, Oil Creek, McLish, Tulip Creek and Bromide. Published works by paleontologists Charles Decker (1929, 1930) and E.O. Ulrich (1929), paved the way for Decker and Merritt (1931, p.6), " … to divide the Simpson into formations which would represent the natural physical and faunal subdivisions." They placed the previously named Joins, Oil Creek, McLish, Tulip Creek and Bromide Formations in proper stratigraphic order. Contacts of each formation were established and, to their way of thinking, each formation represented a sedimentary cycle, each with basal sandstone, or, in the case of the Joins, an ill-defined basal conglomerate. However, new research on the Joins from this study alleges that Decker and Merritt (1931) relied more on paleontologic content than stratigraphic evidence in selecting a base for the Joins, and, that the intraformational conglomerate that they selected to be the base of the Joins, was stratigraphically too high, and only one of many localized conglomerates in the Joins. Perhaps, other conglomerates, especially those interbedded with sandstones lower in the section should have been used. At the time, however, Decker (1933) chose to classify these sandstones with his newly-formed West Spring Creek Formation of the Arbuckle Group using *Ceratopean* gastropods. Paleontologic discrepancies, using the presence or absence of *Ceratopean* gastropods in the Powell, Black Rock, and Smithville Formations in northeastern Arkansas, resulted in similar classification problems (Ulrich, 1911; Hedden, 1976).

Other examples of sandstones mistaken to be Arbuckle that perhaps should have been included with Joins are described below:

1. Decker (1929) measured an interval of 75 feet of Simpson-like quartz sandstones in Section 36, T2S-R3E several hundred feet below what was, at the time, described as the base of the Simpson (Figure 16a). A few years later Decker (1933) included these sands with the upper part of his newly named West Spring Creek Formation rather than the Joins which contradicts the stated purpose of Decker and Merritt (1931, p. 6) for classifying the Simpson, "to divide the Simpson into formations which would represent the natural physical and faunal subdivisions." In other areas several years later, Decker (1939, p, 27), states, "Several sandstones occur in the upper part of the formation (West Spring Creek). Northeast of Woodford (sec. 24, T. 2 S., R. 1 W.) there are five sandstones ranging from about 8 to 12 feet in thickness. Southeast of Sulphur (sec. 1, T. 3 S., R. 3 E.) a number of sandstones, one 50 feet thick, are exposed. In the eastern part of the Arbuckle Mountain area this formation also contains much sandstone, as at Mill Creek. The bed being mined for glass sand at Mill Creek, (sec. 6, T. 2 S., R. 4 E.), is thought by the writer to belong to the West Spring Creek formation." Perhaps the sandstones at the above locations should have been included with the Joins, not Arbuckle, since they were mapped by Taff (1904, http://pubs.usgs.gov/pp/0031/report.pdf) to be within the lowest parts of the Simpson Group.

2. Ham (1950) described widespread sandstones within the upper West Spring Creek, about 285 feet below a Joins conglomerate. Sandstone photomicrographs of what Ham (1950) called "young Arbuckle" sand shown in Figure 16B share striking similarities with sandstones of the Simpson Group; Ham (1950) described these sandstones as being more mature, being better sorted and rounded, than the Simpson – a description that would aptly fit any Simpson sandstone. Given the spirit of Taff (1902, 1904) in creating the Simpson as "beds of sandstone at the base, middle, and top," the sandstones described by Ham (1950) are interpreted to be lower Joins or basal Simpson rather than Arbuckle.

The above contradictions of sandstone affinity — whether part of the Simpson or Arbuckle — may not only have been due to poor choice of selecting an ill-defined intraformational conglomerate at its base by Decker and Merritt (1931), rather than sandstone by Taff (1902, 1904), but may also have been due to the relocation of the Joins type section a few years after it was named by Ulrich (1929). According to Harris (1957), it was moved to a new informal type section that was established 11 miles east of its original location on Joins Ranch (GPS: 34°24'31.42"N; 97°19'13.46"W) to State Highway 77 next to Interstate 35 (GPS: 34°21'52.29"N; 97° 8'36.00"W). The Joins is thinner at its original type section than along the relocated section (Decker and Merritt, 1931, Table 2) in contradiction to isopach maps in this report that show the Simpson to thicken westward across the Arbuckle Mountains, not *eastward*. Apparent discrepancies in these thicknesses were not discussed by Decker and Merritt (1931) or Decker (1941), nor were they mentioned by geologists that followed. The faunal content of the Joins was studied by Derby (1969) along the relocated type section and found that part of the upper part of the West Spring Creek Formation was Whiterockian in age and not Canadian, supporting the contention of this paper that the sandstones be included with the Joins Formation.

Therefore, new information about the Joins included here requires re-interpretation. The Joins Formation along Interstate 35 consists of sandstone, dolomite, and limestone with an apparent terrigenous component that is above, and contrasts with, thick and monotonous red and light gray carbonates of the Arbuckle. The contact between the Simpson and Arbuckle is shown on the cover of this publication, and shown to be a contact with slight angularity. Further, as just mentioned, paleontological support for revision of the boundary along Interstate 35 is supported by the discovery of Simpson-like shelly fossils in rocks that had previously been defined as Arbuckle (Derby, 1969, 1973). Although Derby (1973) did not refer to the beds in question as Simpson he did determine their age to be Whiterockian (see correlation chart on Figure 1), and not Canadian as originally thought by Ulrich (in Decker, 1930). The Whiterockian age assignment by Derby (1973) is significant, in that it implies a paleontologic (time) affinity closer to the Simpson than Arbuckle. Additional support for realignment for the base of the Simpson (Joins) is derived from the discovery of subsurface occurrences of K-bentonites discussed in the next section.

In sum, in an attempt to clarify subsurface Simpson lithostratigraphy, this study recommends that the base of Simpson (Joins) be extended downward to include sandstones presently assigned with the West Spring Creek Formation of the Arbuckle Group. According to the North American Commission on Stratigraphic Nomenclature (2005) "revision of a boundary is justifiable if a minor change in the boundary will make a unit more natural and useful. The original name may be retained." It will be shown in this paper that the Joins is not without basal sandstones, and that those basal sandstones represent the lowest and oldest occurrence of significant basal Simpson detritus above the "Great American Carbonate Bank." This may include sandstones originally classified as upper West Spring Creek or Upper Arbuckle, but regardless, the sandstones represent deposition along shorelines at maximum lowstand positions of the Tippecanoe Sequence, at a time of sedimentologic "change" – a change that unites the five formations of the Simpson with a common tectonic and depositional history, i.e., sequence. Consequently, in the context of this report, the Simpson began with an initial influx of quartz sand that gradually spread across a widely exposed, partly karsted, terra rossa weathered Arbuckle land surface. The contact with the Arbuckle represents the Sauk/Tippecanoe sequence boundary, one that is expressed as widespread unconformity in cratonic settings. The Simpson ended with regional uplift and erosion followed by the beginning of another sequence with a boundary below Katian-aged Viola. At this juncture in geologic time, major environmental change produced new ecosystems and life forms that are represented by those composing the "Great Ordovician Biodiversification Event" (Webby, 2004).

JOINS FORMATION

Joins as part of "Basal Oil Creek/Joins Interval"

The original intent of Taff (1902, 1904) and Gould (1925), it is believed, was to include sandstones near the Simpson/Arbuckle contact with the Joins, namely for ease of mapping. Limestones below the sandy carbonates were classed with the Arbuckle Group. Similarly, this report follows that understanding, although some investigators may question this assignment. It is common for the Joins to contain thin beds of very dolomitic to very calcareous sandstone, or beds of sandy carbonates, moreover, beds of quartz sandstone in the Joins may resemble the basal Oil Creek sandstone. The upper contact of the Joins, however, is placed below thicker sandstones of the overlying basal Oil Creek sandstone. However, in many parts of subsurface Oklahoma, the basal Oil Creek sandstone may be absent, in which case the top of the Joins is selected at a position below the ubiquitous Oil Creek shale. Absence of the basal Oil

Creek sandstone is attributable to pinch out through lateral facies change from sandstone to carbonate – a change that can take place across distances as short as a few miles (e.g., well #2 on Plate 3). In the past, carbonate facies of the basal Oil Creek sandstone have been recognized not as a facies, but rather as the Joins limestone, mainly because of its position below the Oil Creek shale and above the Arbuckle. Due to this understanding, and for ease of mapping, the designation "Basal Oil Creek/Joins Interval" is introduced to include all lithologies of the Joins and basal Oil Creek sandstone below the Oil Creek shale and above the Arbuckle. The name appears on cross sections and isopach maps included in this report, and on the Excel spreadsheet as "OCKB Group Thickness." The basal Oil Creek sandstone is retained as an informal member of the Oil Creek Formation and mapped separately, and shown on the Excel spreadsheet as "OCKB Net Sd." A partial view of the thickness of the "Basal Oil Creek/Joins Interval" is shown on Plate 4 as background under the basal Oil Creek sandstone isopach.

The Joins in lower parts of the "Basal Oil Creek/ Joins Interval" in southern Oklahoma contains thin to thick beds of sandstone at its base (Figure 16C). These sandstones are interpreted to be stratigraphically equivalent to the Calico Rock Sandstone in Arkansas (Figures 1, 2, 14, 16C, and 17; Plate 4). The Calico Rock Sandstone is the oldest of the St. Peter-like sandstones in Arkansas (Figure 18). It represents an amalgamated barrier-sand complex that migrated by southwesterly moving currents westward across a platform of Arkansas and southeastern Oklahoma (Suhm, 1975, 1997). Sand migration took place at sea level lowstand at most basinward positions such as is expressed by the presence of Calico Rock Sandstone in the Oxy #I Danville in Yell County in western Arkansas (Figure 17). Sixty miles west from this well in Leflore County, Oklahoma the Calico Rock Sandstone is present as thin beds of sandstone below the basal Oil Creek sandstone (Figure 14). Limited well control precludes construction of a Calico Rock Sandstone (or basal Joins sandstone) isopach map. Farther west into various parts of Oklahoma, this sandstone interfingers with limestone and dolomite of the Joins Formation. Not only were the sands transported westward but they also appear to have thickened to the south. For example, sandstone at the base of the Joins in a few wells in the area of T6S-R6E in Marshall and Bryan Counties (discussed in the next section) lend support for this interpretation. The southern limit of the basal Joins sand (and Calico Rock) is unknown due to a lack of well control; in fact, some sand could have spilled into the Ouachita Trough where it is known as the Crystal Mountain Sandstone, although "faunal" time equivalency with the Simpson may be in question.

In sum, variable lithologies and thicknesses of the Joins are attributable to facies relationships with the basal Oil Creek sandstone. In addition to consisting of varying amounts of sandstone, the Joins Formation contains sandy ostracodal, pelletal, and oolitic limestone, lime mudstone, and dolomite of various crystallinity. Gastropods and ostracods are locally abundant, but species diversity is low, suggesting deposition in restricted or harsh environments. This seems reasonable since over a large area of Oklahoma, the Joins was embayed by the time equivalent portions of the more seaward basal Oil Creek and Calico Rock 'barrier' sand complex (Figures 16, 18, and Plate 4). Joins carbonates at locations south of the "barrier" represent a time-equivalent offshore marine facies. Absence of shale in the Joins is notable. Shale is rare in the Joins across all depositional provinces perhaps with the exception of locally developed subordinate thin layers in basinal settings. Equally ubiquitous is the overall lack of chert — in contrast to a relative abundance of chert in the underlying Arbuckle. Chert, however, may be present in the Joins in the form of detrital chert pebbles that are part of locally-developed intraformational conglomerates. The base of the Joins in the subsurface, as discussed next, is recognized not so much by rock sample or cuttings but from wireline logs.

Subsurface Simpson/Arbuckle Recognition and Provincial Distribution

The frustration of identifying the Joins/Arbuckle contact from well logs is mentioned by Dietrich (1955), who states, "It is believed that many of the subsurface problems occurring from the surface separation of the lithologically similar Joins and Arbuckle lithologies may be resolved by the inclusion of the Joins within the Arbuckle group." This controversial opinion, however, was not the consensus of contemporary geologists. Moreover, Allison and Allen (1997, p. 179) responded to his comment, "As the Arbuckle become more and more important as a potential oil and gas reservoir, ignoring the presence of the Joins, or including it in the Arbuckle, is scientifically and economically reckless, particular when the two units can be separated successfully and confidently through standard lithologic- and paleontologic-identification techniques." During the course of this study, thousands of logs on file at the log library of the Oklahoma City Geological Society were marked by previous geologists who identified the Joins/Arbuckle contact at positions consistent with those selected in this report (i.e. based on the presence of sandstone in the Joins, and its absence in the Arbuckle). This provided empirical support of the ideas in this report. Admittedly, the boundary was difficult to interpret from well logs located in areas where the basal Joins sandstone is absent, or where the detrital fraction in the Joins was unnoticeable. Analysis of well cuttings, where available in those areas, helped to define the boundary. However, in spite of obstacles, electric-logs can be used to select an approximate depth for the contact. Even older logs can be useful in boundary recognition where they were "run" deep enough to span an interval several hundred feet into the Arbuckle in order to view broad changes in SP patterns. For example, the SP curve changes from "clean" and positive in the Simpson to a slightly suppressed SP ("dirty" intervals) in the boundary area, and then back to better developed "clean" SP in the Arbuckle. The interval of suppressed SP responses, or dirty intervals, at or near the supposed Arbuckle contact is indicating the presence of silt and shaly carbonates that represent the transition from carbonate domain of the Arbuckle into the detrital or clastic realm of the Simpson. Resistivity within this "dirty" interval may express itself as slightly lower resistivity or "wetter" intervals brought about by larger quantities of disseminated clay minerals.

The Simpson can be separated from the Arbuckle perhaps more easily, by using logs with gamma-ray and neutron-density curves. For example, individual beds of sandstone within the Joins are recognized by a density porosity curve that is higher than the curve for neutron porosity. This creates a cross-over pattern, sometimes called "gas effect" (Figure 6A). In the absence of definitive sandstone beds, however, differentiation is based on presence or absence of silt-to-sand size quartz detritus that is characteristically interspersed within lower Simpson carbonates, but absent in the Arbuckle. Terrigenous detritus is recognized on modern logs from density curves that shift slightly to the left, in the direction of higher porosity; detrital-free carbonates of the Arbuckle generally do not shift left. Prior to the advent of neutron and density logs, insoluble residue logs were used to separate the Simpson from the Arbuckle (McCracken, 1955). Gamma-ray curves are useful in determining contacts of strata; they measure radioactivity of rocks. Radioactive elements are concentrated in organic matter dispersed within and between clay minerals of shale. Thin shales less than 10 feet thick are often overlooked in well cuttings, however, they are readily seen on modern gamma-ray logs and are commonly present in the upper parts of the Arbuckle. High, often offscale, values of gamma-ray, therefore, are suggestive of organic-rich shales. Shales, along with organic-rich carbonates, are dispersed throughout the Simpson Group but they appear in greater frequency near the boundary with the Arbuckle, often recognized by clusters of individual gamma-ray spikes. Within these "clusters" a few spikes are unique, and important markers for the top of the Arbuckle. These are thin shales that display not only high values of gamma-ray radioactivity but which are marked by excessively high porosity neutron/density values such as shown on Figure 8. These beds are known as K-bentonites, named from their potassium (K) content, and likely representing volcanic ash. They have been documented to be stratigraphically useful in time correlation; they are similar to the Diecke and Millbrig K-bentonites at the base of the Viola, and bentonites in the upper Knox Dolomite in eastern North America (Kolata, et al 1996, p. 51). Their occurences at sequence boundaries are interesting and suggestive that volcaniclastic clay within the bentonites was related to ash falls from large eruptions (Huff, et al 2010; Keller and Lehnert, 2010). Perhaps, therfore, they may serve as a proxy for widespread tectonic activity that took place at the beginning of Whiterockian time, marking the onset of the Tippecanoe sequence. Another consequence of tectonic activity was climate change resulting in increased rainfall and corresponding high discharge of detritus from source areas (Harper, et al 2015).

In many areas of Oklahoma subsurface identification of the Simpson/Arbuckle interface may also be resolved from cuttings and cores by the presence of redbed horizons. For example, Arbuckle (Sauk) deposition ceased in response to a major sea-level fall with the effect that Arbuckle carbonates were exposed and subjected to prolonged subaerial exposure, weathering, and erosion. Landscapes of that time were likely beveled to peneplain, taking on a reddish-orange tinge from oxidized clay that was left over from the weathering processes, producing a terra rossa landscape. Arbuckle redbeds exposed in the Arbuckle Mountains are shown on the cover of this report. Redbeds are mentioned by Decker and Merritt (1931), but without discussing the significance of the color. In the subsurface, well cuttings stained reddish brown enable Arbuckle identification. Additionally, presence of vugs, caverns, intact and collapsed caves, and solution-enlarged fractures and joints in the limestone may be indicators of weathered Arbuckle. However, such features are difficult to recognize from well cuttings; modern logs may be more helpful in interpretation of solutional features, as shown by Carpenter and Evans (1991). Seismic depiction of paleokarst may be in the form of "no-data" zones due to scattering effect of sound waves bouncing off solutional irregularities and breccias. The presence of karst might also show as seismic dip anomalies in underlying and overlying strata.

In the following paragraphs the Simpson/Arbuckle contact is discussed for each Simpson depositional province. The name of the corresponding structural province is within parentheses. As will be seen, the distinction between the Arbuckle and Simpson is readily discernible in areas where the Simpson is thin and where the Arbuckle was karstified, such as the South Ozark Platform, Texas Arch, and parts of the Oklahoma Shelf. However, the contact is less well defined in the Ardmore/Anadarko Basins where deposition was continuous and thicker.

South Ozark Platform (Arkoma Basin). The Joins consists of sandy carbonates usually below the well-defined ubiquitous basal Oil Creek sandstone. However, in many areas of the South Ozark Platform quartz-sand content of the Joins is so great that it may be difficult to separate from the overlying basal Oil Creek sandstone. At locations north of the South Ozark Platform in the area of the South Ozark Arch, the Joins and equivalents in Arkansas appear to be absent, either by virtue of facies change with the overlying Burgen and Newton Sandstones, or, through overstep by younger beds (Figure 12). The Joins is readily identified and separated from the underlying Arbuckle in most areas by higher sand content (Figure 13 and 14). This contact is seen on well logs as a change from "spiky" high gamma-ray curves ("dirty") reflecting thin beds of silt and clay of the Arbuckle (Powell Formation in Arkansas) to relatively "cleaner" and lower gamma-ray signatures for the Joins, also known as Lower Everton in Arkansas (Figure 17). In the absence of gamma-ray logs the Simpson/Arbuckle contact can be roughly located by utilizing the SP curve. For example, extending over a vertical interval of several hundred feet, the upper part of the Arbuckle has a positive SP curve (deflection to left) that gradually decreases to the right toward its top (indicative of higher shale and silt content) and which becomes positive again into the Simpson. The contact between the Simpson (Joins) and Arbuckle is arbitrarily placed a hundred feet or so above the point of maximum concavity. Resistivity may be little changed across this interval, unlike other provinces where larger amounts of quartz sand detritus in the Joins produces a lower resistivity relative to that in the Arbuckle. Detritus in the Joins is also expressed by higher density porosity than that seen in the Arbuckle. In Wagoner County, Oklahoma, however, the Arbuckle may contain silty dolomites (Powell Formation), which may also produce the effect of high density porosity. Gamma-ray curves help to separate the two; commonly the Arbuckle has characteristically higher gamma-ray signatures. In the Wilburton Gas Field in Latimer County, Oklahoma, the contact is readily seen on neutron/density logs, especially where karsted pay zones of the uppermost Arbuckle Group are filled with thin beds of Joins and basal Oil Creek sandstone (Carpenter and Evans, 1991).

Oklahoma Shelf (Cherokee Platform). The Joins Formation consists of dolomite or limestone below the basal Oil Creek sandstone or, where the sandstone is absent, below the Oil Creek shale. It is part of the proposed "Basal Oil Creek/Joins Interval" that consists of the carbonate facies of the basal Oil Creek sandstone *and* Joins. The Joins limestone signature in this province is classic, in the sense that reported descriptions and illustrations in the literature show the Joins to have concave (or low) SP coincident with high resistivity. In deeper more basinal parts of the Oklahoma Shelf, however, the Joins may contain thin organic shales that may be confused with similar looking shales in the upper Arbuckle. Additionally, but unfortunately, it is all too common for the Joins to lack quartz sandstone or detrital admixtures. This renders them similar in appearance to the Arbuckle thereby making the contact difficult to locate, especially where stratigraphic markers of organic-rich shales and K-bentonites within the upper Arbuckle are absent. Notwithstanding, the contact is arbitrarily drawn at the base of dominantly sandy Joins - as best that can be determined from well cutting samples and wireline logs. From petrologic data and their experience with well cutting studies and correlations in central and southern Oklahoma, Allison and Allen (1997) identified the top of the Arbuckle in northwest Oklahoma County at a stratigraphic position similar to that reported in this paper. In the same area, Dietrich (1955) placed the contact at a similar stratigraphic position from fossils. Dietrick (1955) reports that in a core at 7,568 ft in the Midcontinent Petroleum Corporation No. 2 Young (Section 31, T14N-R3W) Decker (1952) identified the graptolite, *Didymograptus bifidus*, common to the Joins Formation. It was found in beds above the Arbuckle at a depth 245 ft below the base of the Oil Creek shale. The thickness of the "Basal Oil Creek/Joins Interval," therefore, is 245 ft at this location. Figure 15 is a reference log in Kingfisher County for the

Oklahoma Shelf.

In eastern segments of the Oklahoma Shelf in Pottawatomie County in central Oklahoma, cuttings in the Stewart No. 1 Newhouse (Section 18, T6N-R5E) consist of a hundred feet of redbeds in the uppermost Arbuckle that appear to be time equivalents with the redbed interval in the Arbuckle Mountains 40 miles south (see cover). Beds above the redbeds were classed with the Joins (Informal Oil Field Communication, 2015). Limestone stained red below the Joins is Arbuckle and represents oxidized clay left behind during weathering. It is envisaged that in the closing years of Arbuckle deposition, the landscape may have been one of widespread subaerially exposed karsted carbonates that were subjected to oxidation, and possibly sabkha-like supratidal flooded surfaces that produced red-stained solution-collapse breccias similar to those described by Friedman (1980).

Texas Arch (Hollis Basin). In southwestern Oklahoma, both the Arbuckle and Joins consist of a variety of similar carbonate types, ranging from dolomite to limestone. All of these rock types display crystallinity of various sizes and textures that contain a variety of obscure to well preserved grains and clasts. However, the main difference between the similar-appearing carbonates is that the Joins is slightly sandy, the Arbuckle is not. Chert can also be used to differentiate Joins from Arbuckle; it is scarce to absent in the Joins but common in the Arbuckle. The neutron/density log is useful in defining the base of sandy carbonates of the Simpson because of its sensitivity to the presence of quartz. Resistivity curves are also helpful; the Joins is commonly characterized by lower resistivity, compared with more resistive Arbuckle carbonates. From an interpretation of a core and well log from the Texas Arch in Texas that was provided by Whiteside and McCommons (see their fig. 2, 1991), the base of the Joins is placed at the top of non-sandy Arbuckle carbonates approximately 100 ft below sandy oolitic carbonates that they assign with Ellenburger "A" or upper Ellenburger. The upper Ellenburger "A" of Whiteside and McCommons (1991), therefore, is classed with the Joins in this paper. Sandy dolomites of the Joins are productive in southern Love County, Oklahoma (T8S-R2E), and, according to McCommons (personal communication, 1992) their equivalents produce oil in various parts of the Fort Worth Basin in Texas.

Anadarko and Ardmore Basins. The contact of the Joins with the Arbuckle may be difficult to determine in basinal areas, especially where deposition was uninterrupted. From density logs, the base of Joins is placed beneath the lowest quartz sandstone resting on thick monotonous often cherty Arbuckle carbonates. On a cautionary note, chert may express itself on neutron/density logs as thin intervals seen as "crossover", where the density curve plots farther to the left than the neutron curve. This pattern is similar to sandstone, but without noticeable porosity. The contact is also arbitrarily placed at a change, or deflection, on the density log from carbonate-dominated density values of the Arbuckle to silica-rich (sandy) density of the Joins. "Density deflection" is found on density logs in the area of the Apache Field, Caddo County, Oklahoma. When the Joins contact is defined in this manner, its base invariably extends downward to include what some may assign with the upper part of the West Spring Creek Formation of the Arbuckle Group. In Healdton Field in Carter County in southern Oklahoma this interval would correspond with, what is known as the "Wade Zone" of the West Spring Creek and part of the "Bray Zone," subsurface terms proposed by Latham (1968). The Wade and part of the Bray are included with the Joins in this paper. The Wade and Bray, are occasionally productive from low permeability crystalline dolomites above the more productive porous and crystalline "Brown Zone" dolomite of the Arbuckle Group. With a color that represents the presence of oil (or perhaps weathering), the Arbuckle "Brown Zone" is the most prolific reservoir at Healdton and Cottonwood Creek Fields (Waddell, et al 1993; Read and Richmond, 1993). The Wade and Bray are truncated and absent in the nearby Cottonwood Creek Field. A few townships to the south, in the Marietta basin, the Simpson/Arbuckle contact is difficult to define from electric-logs due to a scarcity of quartz detritus in the Joins. However, from information included in this report, such as isopach maps and interval thickness values, the top of the Arbuckle can be projected from any Simpson or Viola horizon. Should questions still persist about the position of the contact, another good rule of thumb (in consideration of thickening toward the basin at rather uniform rates) is that the thickness of "Basal Oil Creek/Joins Interval" (which includes the carbonate facies of the basal Oil Creek sandstone and Joins) is about the same thickness as the overlying Oil Creek shale. This amount will allow the stratigraphic position of the Simpson/Arbuckle contact to be approximately determined. Sandy dolomites of the Joins are productive in southern Love County, Oklahoma (T8S-R2E), and being drilled horizontally. In southeast Oklahoma in the Cumberland Field (T6S-R7E) in Marshall County, Cram (1948, p. 348) makes the following observation regarding the Arbuckle from a log illustrated in Figure 16c: "In the upper 300 feet of the section (referring to upper Arbuckle) several thin dolomitic sandstone beds occur. Small amounts of gas were found in this sandy section." This study interprets the 300 feet of so-called "upper Arbuckle" sandstones on this electric-log to be representative of the Joins rather than the Arbuckle.

OIL CREEK FORMATION

Basal Oil Creek sandstone and Burgen Sandstone

In keeping with formation designations put forth by Decker and Merritt (1931), the basal Oil Creek sandstone is the lowest sandstone of the Oil Creek Formation above the Joins Formation. It is the lowest informal member of the Oil Creek Formation. The Oil Creek shale, also referred to here as an informal member, is in the upper part of the Oil Creek Formation. The Oil Creek shale maintains subsurface identity across all provinces and acts as a marker with which to facilitate identification and correlation of the basal Oil Creek sandstone. The basal Oil Creek sandstone is not only more limited in distribution than the Oil Creek shale, but it in facies with the Joins Formation. Lateral carbonate facies of the basal Oil Creek sandstone may be combined with the Joins to comprise the stratigraphic unit introduced in this report as the "Basal Oil Creek/Joins Interval." The "Basal Oil Creek/Joins Interval" together with the Oil Creek shale comprises the interval known as the "lower part of the Simpson Group." Put another way, the Joins Formation, and informal members basal Oil Creek sandstone and Oil Creek shale are within the lower Simpson. The lower Simpson is correlative with the Everton Formation of Arkansas studied by Suhm (1970). In northeastern Oklahoma in the vicinity of Wagoner and Tulsa Counties the basal Oil Creek sandstone is called the Burgen Sandstone. It was named by Taff (1905) for exposures at Burgen Hollow along the Illinois River in Cherokee County where this sandstone rests on Arbuckle (Cotter) carbonates (Figure 3B). The Burgen was one of the first Simpson formations to be exploited for oil in the early 1900's – primarily because of drilling depths less than 1,500 ft combined with high recoveries. In older literature the Burgen was given the oil-field name "Hominy sandstone" (White, 1926), or "Turkey Mountain sandstone." Aurin, et al (1921) described the Turkey Mountain as consisting of coarsely crystalline porous dolomite. Today, the Burgen and basal Oil Creek sandstones are primary exploration targets because of their high oil and gas recoveries, such as seen in the Oklahoma City Field, Golden Trend and Eola-Robberson Fields in central and southern Oklahoma, and Broken Arrow and Stonebluff Fields of Tulsa County.

Plate 4 shows the distribution of the basal Oil Creek sandstone and Burgen Sandstone in areas where it is 25 ft and thicker. Had the thickness been contoured at values less than 25 ft their areal extent would be larger. Interestingly, using a 10-foot sand limit the isopach would reveal a sand body similar in shape to the present-day spit at Cape Cod, Massachusetts — but similar in size to the Florida Peninsula (see Figure 20) — lending support for similar environments for the basal Oil Creek sandstone in Oklahoma, and one consisting of embayments, bay mouth bars, spits, and barrier islands. The basal Oil Creek sandstone is the thickest of the Simpson sandstones, attaining thicknesses greater than 400 ft in the eastern part of the Arbuckle Mountains in Bryan County. In areal extent, it is the second largest sand body after the Bromide sandstone. The basal Oil Creek and Burgen sandstones correlate with the Newton Sandstone (Everton) in Arkansas (Suhm, 1974), and when combined with the Calico Rock Sandstone (the lowest Everton sandstone) the sand body complex extends for a distance of 300 miles from northeastern Arkansas to south-central Oklahoma (Figure 18). The sand body is 50 miles wide and up to 200 ft thick in northwestern Arkansas but expands to twice that width on the South Ozark Platform of Oklahoma, where, in places, it is over 350 ft thick. It is linear and parallel to, yet transgressive with respect to older basal sandstones of the Joins Formation in Bryan and Marshall Counties, Oklahoma, and the Calico Rock Sandstone in northeastern Arkansas. It appears to have originated as a braided-stream system located in eastern Missouri, similar to that of the Calico Rock Sandstone. From Missouri, sand was added to, and mixed with, coeval clear-water marine carbonates on the South Ozark Platform of Oklahoma and Arkansas. Sand accumulated in a composite of barrier, back-barrier, and peritidal complexes. From isopach maps, the geometry of the sand body suggests rapid westward progradation by longshore and tidal currents on a low gradient in poorly defined, shallow channels. Lesser rates of subsidence on the South Ozark Platform enabled the quartz grains to remain in this "littoral" environment long enough to be transported laterally for significant distances along the shoreline. Also, as seen from subsurface logs, variations in thickness of the sand may take place across short distances. In the northern part of the South Ozark Platform, five circular "thins" shown as "blue circles" on the basal Oil Creek sandstone isopach map (Plate 4) may have been areas hydrologically scoured by activities associated with extreme weather. Sand also filtered into sinkholes on the karsted carbonate floor of Arbuckle (or older Simpson carbonates) to account for some of the abnormal increases in sand thickness. North-south trends of channel-like thickening are present in parts of northeastern Oklahoma. The southern limit of the sand sheet in Oklahoma is not known due to lack of well control.

Southwest transport of the sand across the South Ozark Platform terminated in deeper water near the Ardmore Basin/South Ozark Platform Hinge. As seen in Figure 9B sand was stacked up at the hinge line. It was then contemporaneously redistributed and carried to the northwest by platform-edge currents similar to those that form the "hook" of Cape Cod. Some fine-grained sand spilled into the Ardmore Basin. Farther basinward, quartz sands grade to limestone and argillaceous carbonates of the "Basal Oil Creek/Joins Interval." Lewis (1982) and McPherson, et al (1988) report a diverse normal marine fauna. The basal Oil Creek sand complex apparently shifted en masse, or transgressed with time to the northwest in response to rising sea levels. During the transgression, sand within the barrier complex continued to be reworked by marine processes.

The basal Oil Creek sandstone is mature quartz sandstone lithologically similar to the St. Peter Sandstone and other Simpson sandstones. It is commonly medium-grained but can range from fine to coarse; it contains well-rounded to rounded, frosted quartz grains cemented by variable amounts of silica or carbonate. Porosity in siliceous sandstones is dependent upon the extent of diagenetic overgrowths. It appears that porosity is higher where films of clay surrounded individual grains, which, according to Bosco and Mazzullo (2000) has the effect of inhibiting diagenetic precipitation of quartz overgrowths. Elevated sandstone porosity in the Ardmore and Anadarko Basins may have been enhanced due to the availability of clay from nearby sources. Similar porosity preservation is also recognized in basal McLish, Tulip Creek and Bromide sandstones. By way of contrast, however, low-porosity quartz sands on the South Ozark Arch and South Ozark Platform in the area of the Arkoma Basin were geographically removed from sources of clay. Further, south of high displacement faults in deeper parts of the Arkoma Basin in the older Antlers Graben under the Ouachita Mountains, thermal activity may have facilitated the dissolution of quartz grains releasing silica to be redistributed as overgrowths that occlude porosity in a manner discussed by Bjorlykke and Edgberg (1993).

Oil Creek shale and Tyner Formation

The Oil Creek shale member consists of mostly dark-colored shales and limestones, however, limestones are abundant to such an extent that use of the word "shale" in "Oil Creek shale" may be somewhat misleading. The rock succession of this interval is classed as an informal member of the Oil Creek Formation, because of its entrenchment in subsurface literature. Notwithstanding, its lithology is characteristically displayed on electric logs as high and "spiky" gamma-ray (GR) with low SP and resistivity. The features are readily identified on well logs across all depositional provinces. Plus, the Oil Creek shale occupies an interval between two of the most widespread and recognizable sandstones in Oklahoma, the basal Oil Creek sandstone and the overlying basal McLish sandstone. Contact with the basal Oil Creek sandstone (or, in its absence, sandy dolomite of the Joins) is conformable, but contact with the overlying basal McLish sandstone is unconformable over a large part of Oklahoma. The contact with the McLish represents a significant faunal hiatus (Derby, et al 1991; Ethington, et al 2012). However, in basinal settings where basal McLish sandstone is absent, such as in the Ardmore Basin, the contact between the Oil Creek shale and McLish Formation appears to be conformable and difficult to separate on subsurface logs.

Overall, the Oil Creek shale consists of thinly interbedded fossiliferous limestone, dolomite, varicolored shale, and sandstone, and in the Arbuckle Mountains the Oil Creek shale contains a marine offshore fauna (Lewis, 1982). Interestingly, shale beds are commonly thinner and less numerous than limestone beds. Over most areas of Oklahoma the sequence of thinly interbedded limestones and limy shales of the Oil Creek shale is commonly dark in color, likely indicative of large amounts of organic carbon that accumulated in poorly oxygenated clay-rich substrates. Nutrient availability is presumed to have been important in leading to increased faunal diversity contributing to the "Great Ordovician Biodiversification Event." The Oil Creek shale is also recognized as a source rock for hydrocarbons to be discussed later. But what is notable is that this shale is the first source rock following deposition of the Arbuckle Group. It is one that contains the earliest incursion of significant quantities of clay into Oklahoma attributable to climate change of increased humidity and rainfall that initiated chemical weathering of source areas. Weathering on the Texarkana

Platform yielded clay that was washed into the Fort Worth Basin and transported in suspension northwestward into the Anadarko and Ardmore Basins. Clay contributions also originated from the weathering and erosion of rocks on the Transcontinental Arch located west and north of the Anadarko Basin. Clay in the Anadarko Basin and Oklahoma Shelf was mixed with carbonates, and some clay even reached the Texas Arch contributing to the deposition of argillaceous dolomite and shale. These argillaceous zones are expressed on logs by low or poor SP, high and "spiky" gamma ray, and low resistivity. This characteristic "Oil Creek" log response enabled correlation into the Tobosa Basin of Texas (Wright, 1965).

The Oil Creek shale is thickest in the Anadarko and Ardmore Basins where it attains thicknesses greater than 800 ft (Plate 4). Electric-log thicknesses exceeding 800 ft, however, are suspicious and may be attributed to steep dips or repetition by faulting. The middle part of the Oil Creek shale is the most argillaceous with resistivities lower than its upper and lower parts. This regional characteristic results in confident correlations. Further, the middle portion of this interval may reflect a sea level highstand, which together with large amounts of clay influx helped to suppress carbonate deposition. A widespread limestone named Pruitt Ranch Member by Harris and Harris (1965) is present within the upper part of the Oil Creek shale. The name "Birdseye" (rather than Pruitt Ranch) is used throughout this paper. It is exposed in the Criner Hills of southern Oklahoma where outcrops consist of sublithographic to lithographic limestone with stromatolites and beds of ooids, intraclasts, pellets, and scattered fossil fragments (Harris and Harris, 1965). Intergranular pores between, and/or within the grains were later filled with secondary calcite giving the appearance of "eyes of birds," hence the subsurface designation "Birdseye Limestone" where it is a petroleum reservoir. Electric-logs display uniform "high-resistivity" limestone, similar to that seen in the Viola limestone. High resistivity typically represents a lack of porosity. However, cores and cuttings from the Birdseye limestone may display oil-saturated voids such as one might associate with moldic or vuggy porosity; but the voids are not interconnected. This contrasts with "low-resistivity" limestone in other formations that has interconnected pores (Verwer, et al 2011). The position of the Birdseye limestone above and below low-velocity shale enables it to be readily seen as a reflector on seismic records. In some areas of southern Oklahoma, McLish limestones with properties similar to the Birdseye are separated by 50 to 100 ft of argillaceous limestone and shale, prompting some subsurface geologists to include the Birdseye with the McLish rather than Oil Creek shale. Admittedly, the Birdseye is difficult to separate from the limestone facies of the lower parts of the McLish. Birdseye production is located in structurally complex areas such as Healdton Field where the reservoir is fractured and subcropped by Pennsylvanian strata. Additionally, the Birdseye occupies a favorable stratigraphic position above black organic (sourcing) shales of the Oil Creek Formation suggesting that production recoveries might increase with horizontal drilling.

The Birdseye limestone is commonly less than 250 ft thick and present in the subsurface over a broad area in the Anadarko and Ardmore Basins in southern Oklahoma (Figure 19). The absence of terrigenous clay and silt within the Birdseye is notable. Deposition likely took place in shallow subtidal to intertidal and shoal environments in "clear-water" marine embayments within the Anadarko and Ardmore Basins. The apparent contradiction of shallow water origin within a basinal setting such as seen on Figure 19 is explained by carbonate deposition that kept up with, or exceeded the rate of subsidence. Perhaps also, at this time in geologic history, there may have been diminished terrigenous influx at a time when sea level was lowered. It is not inconceivable that the Ardmore Basin may have become land locked at various times in its past, in a fashion not unlike the Mediterranean Sea, but more likely, that this facies may be expressive of a major climatic change toward aridity that affected the east half of Oklahoma and the larger region of the northern Midcontinent occupied by the precursor "desert" for St. Peter sand sheets. The distribution of the Birdseye limestone in Texas has not been studied. The Birdseye becomes less recognizable as a distinct stratigraphic unit in western segments of the Anadarko Basin, mainly because it grades to shale and fine-grained limestone, likely reflecting higher clay content due to the presence of positive areas of the more humid Transcontinental Arch. Near the junction with the South Ozark Platform to the east, the upper part of the Birdseye appears to grade into, or even merge with the basal McLish sandstone, implying the potential for a complementary facies relationship that shares similar lowstand marine depositional environments. Both lithologies may represent an important change in the climatic history to one of aridity. Furthermore, windswept dust may have facilitated precipitation of carbonates, similar to the process discussed by Swart, et al (2014).

In northeastern parts of the Oklahoma Shelf in northeastern Oklahoma, the Oil Creek shale correlates with parts of the Tyner Formation. Outcrops along the Illinois River show the Tyner to consist of green to dark-gray, partly sandy shale and thin beds of quiet water (lagoonal) sandy to very sandy and finely crystalline dolomite with gastropods and ostracods (Huffman, 1965; Bauer, 1989). A large part of the Tyner was deposited in "barrier-protected" lagoonal and estuarine environments landward of coeval Oil Creek and McLish barrier island sands. Also, as might be expected in an estuarine setting, fine-grained lithologies of the Tyner often display offscale gamma-ray values implying large amounts organic matter. In Wagoner and Osage Counties, west of the Illinois River, thin oil- and gas-bearing Oil Creek sandstones (along with younger Simpson sandstones) are assigned with the Tyner. Ireland (1944) illustrated the truncated geometry of the Tyner Formation in northeastern Oklahoma from insoluble residue studies. Some Simpson sandstone reservoirs termed 'Tyner' may also be stratigraphically equivalent to the slightly younger McLish and Tulip Creek Formations. Moreover, from scout tickets and other production data, Tyner production has been designated as Simpson, Hominy, or Burgen. Regardless, reservoirs and traps for hydrocarbons in thin Tyner and Simpson sandstones are the result of pinch out trends brought about by their truncation by the overlying Viola or Woodford and younger formations such as illustrated by Ireland (1944), Huffman (1958), and Shannon (1962). Recent studies in northeastern Oklahoma, suggest that recoveries are higher where the Simpson is overstepped and sealed by the Woodford, rather than Viola. Part of this may be explained by close proximity of Simpson reservoirs to prolific source beds within the Woodford Shale.

It should be emphasized that log signatures of not only the Oil Creek Formation but other Simpson formations, including the Burgen and Tyner, maintain their characteristic geometries across large areas of northeastern Oklahoma. Because of this, Simpson formations named in the Arbuckle Mountains will likely replace the names, Burgen and Tyner, in northeastern Oklahoma (Figure 4A). Regional features such as these are an indication of persistence of similar lithologies. Low SP, 'spiky' gamma-ray, and low-resistivity curves that allow identification of the Oil Creek shale across most areas of Oklahoma, however, are absent in wells on the South Ozark Platform, with the exception of parts of Coal County where remnant shales with elevated gamma-ray radioactivity are positioned at the base and top. Rather, shale and argillaceous lithologies of "typical" Oil Creek are replaced by high energy intraclastic carbonates and sandstones. In Arkansas, the Oil Creek shale is correlative with dolomitic sandstone Member "C" of the Everton Formation where, in outcrop, it consists of dark, stromatolitic dolomite of supratidal origin and dolomitic to slightly dolomitic sandstone interpreted to be cheniers (Suhm, 1974). The Oil Creek shale is also correlative with the Jasper Member of the Everton Formation. The Jasper consists of calcareous to siliceous sandstone and limestone below the unconformity at the base of the St. Peter Sandstone (Figure 3B). The sandstone is shown on the western side of a cross section prepared by Suhm (1970, fig. 3; 1974, fig. 4). In Oklahoma, the basal sandstone of the Jasper Member is shown as a northeast trending sandy body on the Oil Creek shale isopach map (Figures 12, 13, Plate 5). It is as much as 80 ft thick with a linear, very narrow geometry that is parallel to the isopach trend and, presumably, the paleoslope. The sand body is interpreted to be barrier sand modified by southwest moving longshore currents. It is likely that the sandy dolomitic shale and thin beds of sandy finely crystalline dolomite of the lower Tyner discussed in previous paragraphs formed in protected lagoonal environments behind the Jasper barrier. Specific information about faunal and lithological characteristics of the Tyner can be found in Bauer (1989).

MCLISH FORMATION

The McLish Formation was named by Ulrich (1929) and more thoroughly defined by Decker and Merritt (1931) who mapped it across the Arbuckle Mountains. The McLish has one of the more well-defined and persistent basal sandstones of formations that comprise the Simpson Group. Not only is it one of the thickest and best-developed sandstones across the entire area of the Arbuckle Mountains (Plate 6), but it is widely distributed across large parts of the state at thicknesses less than 25 ft. Since the basal sandstone can be mapped as a distinct rock unit across wide areas of Oklahoma, the basal sandstone is proposed for consideration as a formal member of the McLish Formation. In this report, it is called the "basal McLish sandstone". The basal sandstone is in facies relations with other parts of the McLish Formation. In relation to formations overlying and underlying the McLish Formation, Decker and Merritt (1931) noticed conformable relationships between the Tulip Creek and Oil Creek Formations in western parts of the outcrop belt. However, they reported unconformable contacts in outcrops about 50 miles to the east. They had not attempted correlation into the subsurface at the time of their study. Derby (1991) and Ethington, et al (2012) have identified faunal differences between the McLish and Oil Creek Formations in outcrops in the Arbuckle Mountains, and elsewhere. In fact, they interpret the unconformable contact at the base of the McLish (St. Peter Sandstone in Arkansas) as representing a major sequence boundary between the Tippecanoe and Sauk sequences, rather than at the base of the Joins and Oil Creek Formations frequently discussed in this report. An explanation for this difference of opinion can be better understood by examining regional Simpson relationships shown on Figure 2. Figure 2 is a regional cross section that shows the St. Peter Sandstone contact (unconformable) with "Arbuckle" carbonates at locations on the continental interior. When traced southward, however, the St. Peter and Everton thicken and the unconformity at the base of the St. Peter merges with the more extensive unconformity at the base of the Everton Formation in Arkansas. Thus, it appears that the unconformity representing the greater lowstand (hence sequence boundary) is not the one at the base of the McLish or St. Peter, but the unconformity at the base of Joins and Oil Creek (Everton). Moreover, from isopach maps included in this study, the geographic locations of various sandstones at lowstand positions may be compared. For example, the McLish lowstand is farther to the north (or landward) than the more basinal lowstand sandstones of the Joins and Oil Creek.

Basal McLish Sandstone

Although not the thickest, the basal McLish sandstone is one of the most widely distributed quartz sandstones of the Simpson Group in Oklahoma. It is the offshore marine equivalent of the more widespread St. Peter Sandstone to the north. It is productive in the Fitts Field in Pontotoc County, Eola-Robberson and Golden Trend Fields in Garvin County, and fields aligned along the Nemaha Fault (Plate 15). Plate 6 shows the distribution of the basal McLish sandstone at thicknesses greater than 25 ft up to thicknesses exceeding 125 ft. However, the areal extent of the sand sheet would be considerably larger if constructed at a minimum value of 10 feet. Productive McLish wells located outside the sand sheet of Plate 6 are productive from sandstones thinner than 25 ft.

McLish sandstone is composed of fine- to medium-sized, spherical, well-sorted, rounded, frosted quartz grains cemented by variable amounts of silica or carbonate. These characteristics are shared with other supermature Simpson and St. Peter-like sandstones. Heavy minerals are scarce, but where present they consist of zircon and tourmaline grains. Frosted and pitted quartz grains and their bimodality suggest an eolian influence perhaps one that was generated under conditions of aridity, such as was prevalent during the deposition of the Birdseye limestone of the Oil Creek shale and the St. Peter Sandstone. The purity and textural maturity of Simpson sandstones also suggest that they were derived from earlier generation quartz sands (Dake, 1921; Bunker, et al 1988). The sandstone is commonly white but some specimens have a light greenish tinge due to green clay that coats many of the quartz grains and because of thin green shale partings within the formation. The sandstone is locally cross-bedded and ripple marked. The basal McLish sandstone has a ubiquitous log signature across most parts of the state; for example, upward from the Oil Creek shale it has gradually increasing (better developed or, "positive") SP with decreasing gamma-ray that is coincident with decreasing resistivity (Figure 5). This pattern reflects a change from calcareous shale of Oil Creek upward to noncalcareous more porous sandstone of the basal McLish. This log pattern shares similarities with a coarsening-upward profile.

The basal McLish sandstone grades to limestone and shale in western and southern parts of the Anadarko and Ardmore Basins where it transitions to the McLish Formation. The limestone may be similar in log character to the underlying Pruitt Ranch Limestone (Birdseye), and where beds of McLish limestone are thicker than 30 ft it may be difficult to separate them from one another. At locations farther west, but still in basinward positions, the interval occupied by the basal McLish sandstone is shaly and marked by diminished SP. It is not uncommon for low-resistivity shale to be present and in facies relationships with the sandstone.

The basal McLish sandstone is not recognized as a distinct stratigraphic unit on the Texas Arch. However, its lateral equivalent, classed with the lower part of the McLish Formation, is predominantly carbonate consisting of 10 to 20 ft of porous, slightly sandy dolomite that displays well-developed SP and low-resistivity (Figure 11). On the northern part of the Oklahoma Shelf the basal McLish sand body thins and interfingers with sandy limestone. At locations even farther north, this interval is thinner and indistinguishable from carbonates of the overlying McLish.

Similarly, in northeastern Oklahoma near the South Ozark Arch the basal McLish sandstone is unrecognizable as distinct sandstone; rather, it grades to very dolomitic sandstone and finely crystalline dolomite to become inseparable from other lithologies of the McLish. This interval is known in the subsurface as part of the often productive Tyner, or Hominy formations. Carbonate enrichment of this St. Peter equivalent may have been due to embayment by a sand barrier to the south. In Illinois River exposures the McLish is absent to very thin, but according to Bauer (1989) strata containing "conodont assemblage II" might represent the presence of at least part of the McLish (Figure 1). A dashed line on the McLish isopach map (Plate 6) shows areas where the McLish has been removed by pre-Viola erosion. It is likely that McLish in diminished thicknesses once extended farther northeast of the dashed line. In Arkansas, the basal McLish sandstone is correlated with the St. Peter Sandstone. St. Peter outcrops in the Ozark Mountains of Arkansas show tens of feet of erosional relief on underlying Everton/Oil Creek carbonates (Suhm, 1970, 1974). The stratigraphic importance of this contact is further discussed by Ethington, et al (2012). Where outcrops are not available for study, unconformities can be inferred where stratigraphic intervals abruptly thicken, or thin, between wells. This is seen from electric-logs in east-central Oklahoma where the basal McLish sandstone thickens, coincident with a corresponding thinning of the underlying eroded Oil Creek shale. A comparison of maps on Plates 5 and 6 show a band of five or six narrow north/south linear configurations. A channel cut pattern is especially noticeable on the Oil Creek shale isopach (Plate 5) as light blue. Perhaps during basal McLish lowstand, channels such as these may have provided a means to transfer McLish sand to the main basal McLish sand body to the south. In the eastern part of the state on the eastern part of the South Ozark Platform, the top of the basal McLish sandstone is below a thin, "hot" gamma-ray deflection caused by what is probably an organic shale or ash deposit (Figure 7). Basal McLish sandstone is overlain by, and a facies of higher-resistivity carbonates or calcareous to very calcareous and dolomitic sandstones of the upper McLish Formation discussed in the next section.

South and west transport of McLish sand across the South Ozark Platform toward the Ardmore Basin ceased at the hinge line. Here, sand banks accumulated in shallow water. At about the same time sand migrated northwest, parallel to the hinge, by strong northward-moving currents. Westward termination of basal McLish sand near the Ardmore Basin/South Ozark Platform Hinge is interesting, and may be suggestive of syndepositional faults. Some of the sand build-ups on the upthrown side, however, spilled over into the Ardmore Basin to laterally grade to McLish carbonates. In the southeastern corner of the state, where the South Ozark Platform meets the Ouachita Trough, the South Ozark Platform/Ouachita Trough Hinge, the southern limit of the basal McLish sand sheet has not been determined due to lack of subsurface control. It is likely that some sand was carried past the platform edge into the Ouachita Trough to comprise sandstones of the Blakely (St. Peter equivalent) in a fashion similar to that of the older sandstones of the Crystal Mountain (basal Oil Creek/Joins). Should these autochthonous (in place) sandstones be present at favorable depths in this corner of Oklahoma, they may be attractive exploration targets.

McLish Formation

The McLish Formation is above the Oil Creek shale of the Oil Creek Formation and above the basal McLish sandstone, where it is present as discussed previously. The McLish consists of limestone, dolomite, sandstone, and minor beds of green to gray shale. Calcareous or dolomitic sandstone, sometimes as much as 75 ft thick, is common near the base in close contact with the thicker basal McLish sandstone (Plate 6). Limestone, which dominates over dolomite, is common in the upper parts of the McLish; it is commonly fossiliferous and contains interbeds of lithographic limestone and thin beds of slightly green glauconitic limestone. The McLish Formation represents a continuation of transgressive, clear-water, shallow-marine sedimentation in arid to semi-arid environments that began with deposition of the basal McLish sandstone. The detrital clay fraction, although minor, probably originated from surrounding source areas of both the Transcontinental Arch and Texarkana Platform.

Subsurface identification of the McLish is facilitated by its conformable position above the widespread basal McLish sandstone. The contact with the overlying Tulip Creek is more difficult to recognize. It appears to be conformable and is arbitrarily placed at a change from principally high-energy calcarenite and fossiliferous limestone of the McLish to the detrital-rich Tulip Creek Formation consisting of shale, shaly sandstone, and/or argillaceous carbonates. On well logs the upper contact ranges from abrupt to gradual, but in most instances it is at a position above relatively high-resistivity responses of the McLish and below Tulip Creek shales that have poor SP and lower resistivity. Additionally, across most of the Oklahoma Shelf (Cherokee Platform) the top of the McLish may be seen by gamma-ray curve deflection from clean, low gamma-ray of the McLish to higher gamma-ray (almost offscale) of the Tulip Creek. This pattern is coincident with poor SP, commonly across a thicker interval of SP concavity, similar to concavity observed at the Simpson/Arbuckle boundary. The contact is more difficult to recognize in the absence of shale such as in the Arkoma Basin and parts of the Cherokee Platform where both the Tulip Creek and McLish consist of similar-appearing sections of clay-free carbonates and sandy carbonates. At the opposite extreme in the Ardmore and Anadarko Basins, where the Tulip Creek sandstone has changed facies to shale, the top of the McLish Formation is placed at the top of either a sequence dominated by high-resistivity limestone or very calcareous resistive shale that is described in the next section.

On the Oklahoma Shelf, the McLish Formation is composed of limestone, dolomite, and some shale. However, from T7N-T10N and R1W-R7E, the McLish above the basal McLish sandstone, if present, can be divided into three, widespread fining-upward calcareous sandstones or sandy limestone beds, each separated by shaly intervals (Figure 5). In townships farther northeast, such as in the area of T13-14N and R14-15E, the tripartite stacked sandstones are thinner and not well defined. Also, on northern parts of the Oklahoma Shelf near the Kansas state line, the McLish becomes thin and nearly unrecognizable as a separate stratigraphic unit and appears to merge with both the Oil Creek below and with the Tulip Creek above (see Plate 7 and Cross sections D-D' & E-E' on Plates 13 & 14). In the middle part of the ancestral Oklahoma Shelf, corresponding in position to the present-day Nemaha Fault, the upper part of the McLish consists of near-continuous sandstone at least 50 ft thick with a north-south trend interpreted to represent northward migrating offshore sand bars. Some of the sand comprising this unit may have originated from reworking the underlying basal McLish sandstone and subsequent northward transport from the edge of the Ardmore Basin. Basinward, or west, from this sand accumulation McLish sandstone becomes calcareous and less porous, a characteristic that allows its separation from the more detrital or "shaly" overlying Tulip Creek Formation. McLish limestone persists southeastward in southern Garvin County along the Ardmore Basin/South Ozark Platform Hinge and adjacent areas. Here, the top of the McLish is defined by low SP and an offscale "resistive" limestone. Elsewhere, however, McLish limestone may share lithologic similarities with that of the Tulip Creek and be difficult to separate.

On the South Ozark Platform combined sandstone thicknesses for the upper McLish seldom exceed 50 ft (Plate 7). Apparently, the sand was somewhat evenly distributed by strong currents that flowed westward across the South Ozark Platform similar to older Simpson sandstones. McLish sandstone is thicker at its western edge near the Ardmore Basin (Plate 7). North-moving currents in the Ardmore Basin dispersed McLish sand into elongated north south configurations similar to that seen in the basal McLish and basal Oil Creek sandstones.

Even though the McLish is truncated in northeastern regions of the South Ozark Platform and Oklahoma Shelf, the upper McLish probably covered the entirety of northeastern Oklahoma at one time. Moreover, the McLish is productive on the Cherokee Platform near its present-day truncation limit where petroleum geologists might refer to it as "Wilcox" or Tyner. As indicated from well logs used in this study, the McLish does not appear to be stratigraphically represented in the Illinois River outcrop belt due to truncation and overstep by Viola (Fite) carbonates. This interpretation is paleontologically confirmed, in part, by Bauer (1989). When the upper McLish is traced eastward into Arkansas, McLish sands and carbonates change facies to upper parts of the St. Peter Sandstone (see fig. 19 in Suhm, 1997) and perhaps lower strata of the Joachim Dolomite.

TULIP CREEK FORMATION

Tulip Creek is a name used by Ulrich in 1928 (in Harris, 1957) and applied by Decker and Merritt (1931) as a Simpson formation in the Arbuckle Mountain area at a stratigraphic position between the McLish and overlying Bromide Formations. However, according to Decker and Merritt (1931), the Tulip Creek was thought to be localized and unsuitable for subsurface correlation. So, before subsurface mapping and correlation could be initiated for this study the Tulip Creek Formation had to be redefined. As defined in this report, the top of the Tulip Creek is placed at the top of the "basal" sandstone of the Tulip Creek (or its lateral equivalent) rather than shale as defined by Decker and Merritt (1931). It is considered to be a formation consisting principally of sandstone and associated facies. In the absence of sandstone the upper contact of the Tulip Creek facies is arbitrarily recognized as a sandy limestone marker (or similar facies) at an equivalent stratigraphic position of the sandstone. Also, because of these stratigraphic changes the designation "Tulip Creek sandstone" will be used in place of the name Tulip Creek Formation. However, with an extensive occurrence across half the state, the Tulip Creek sandstone might be appropriately referred to as an informal member of the Tulip Creek Formation. The Tulip Creek Formation would, therefore, consist of the Tulip Creek sandstone and its facies. A type log was established in central Oklahoma (Figure 5) and it was from this location that the Tulip Creek sandstone, along with several other Simpson subdivisions, was correlated in all directions across the state. Correlation of the "type log" to the Arbuckle Mountain area resulted in a successful tie with Tulip Creek outcrops at the type section.

Correlation of the Tulip Creek sandstone in this manner revealed that it has an extent comparable to other large Simpson sandstones (Plate 8) and that, in northeastern Oklahoma, is correlative with parts of the productive Tyner Formation (often called "Wilcox"). Thicknesses may exceed 200 ft. In south central Oklahoma it may be referred to as the "3rd Bromide sandstone." The widespread distribution of the Tulip Creek sandstone as mapped in this report is in contrast to statements made by Decker and Merritt (1931) who originally thought that the Tulip Creek had ill-defined contacts and was locally restricted to southern Oklahoma (see Fig. 2 on page 16, Decker and Merritt, 1931). However, in spite of their statement of "restricted distribution", they concluded that faunal differences were sufficient enough for segregating the Tulip Creek from the McLish and Bromide; they also thought that the Tulip Creek shared slightly more similarities with the overlying Bromide than the McLish. They defined the top of the Tulip Creek to be at the top of a shale sequence below the basal Bromide sandstone. However, a short distance north and east of the type section, this shale interval wedges out, with the effect that the top of the Tulip Creek at the type section coincides with the top of the Tulip Creek sandstone (as used in this report) below the Bromide sandstone. Results from this subsurface study shows that the Tulip Creek sandstone is different from the Bromide, and that the Tulip Creek should not be thought of as a locally-developed basinal phase of the Bromide as put forth by Decker and Merritt (1931) but a distinctive sandstone formation. When correlated in the subsurface the Bromide sandstones may look similar to the Tulip Creek on wireline logs, but it is more common for the Tulip Creek to have lower resistivity than the Bromide sandstone. Furthermore, during correlation it was found that the Bromide possessed more erratic sandstone distribution than the Tulip Creek. Therefore, Bromide sandstone was found to be more of an unreliable correlative entity than the Tulip Creek sandstone (see Plate A). It was perhaps because of these complex facies changes that Statler (1965) combined the Tulip Creek with the Bromide.

The most distinctive well log characteristic of the Tulip Creek sandstone over most areas of its occurrence is upward coarsening geometry that typically expresses itself as a funnel-shaped gamma-ray and SP curves. From the base upward, the SP becomes better developed coincident with a gamma-ray decrease shift to the left. Resistivity shown on the right half of the log also tends to slightly increase upward, in concert with a decrease in shale rendering a funnel configuration but then sharply decreases with porous, often "wet", sandstone (Figure 5). From a depositional perspective this log geometry indicates that low-energy marine conditions changed to higher energy shallow-water beach-like environments, likely brought about by either a fall in sea level (or a decrease in subsidence) or increased terrigenous input or both. In basinal settings south of the Arbuckle Mountains this coarsening-up appearance shares similarities with a turbidite log signature.

In the southern part of the Oklahoma Shelf the Tulip Creek is bounded by upper and lower marker beds consisting of shale with low resistivity. Shale markers facilitate correlation and serve to separate sandstones of overlying and underlying formations, such as between the Tulip Creek and Bromide. Where these markers are absent such as in localized sand build ups in the southern parts of the Oklahoma Shelf, the conformable contact between Tulip Creek sandstone and Bromide sandstone was difficult to establish. Sandstones were separated on the basis of porosity, however, with Tulip Creek sandstone having porosity higher than that found in Bromide sandstone. High porosity sandstones, such as the Tulip Creek, are also commonly accompanied by better-developed SP, and lower resistivity. Unfortunately, in the area of T4N-R5W, log characteristics of the sandstones were too similar and difficult to separate; therefore, out of convenience, the upper boundary of the Tulip Creek was expanded upward to include what actually may have been lower Bromide sandstone. At some locations a thin limestone interval separates the Tulip Creek from Bromide sandstones, such as seen at the 8,115 ft depth on Well No. 1 on Cross Section B (Plate 11).

Tulip Creek sandstone consists of fine- to medium-sized grains that are rounded, frosted, and well-sorted. The sandstone is siliceous to dolomitic and locally cross-bedded. Smith (1993) reported poorly-cemented green chloritic sand in the Tulip Creek, and Cronenwett (1956) noted black-shale fragments in the sandstone and thin interbeds of dark shales. These have the effect of imparting low resistivity to the sandstone. They noted marine fossils within interbedded shales. In southeastern Grady County the Tulip Creek sandstone consists of several 10- to 30-ft sandstone beds amounting to about 150 ft (Flores and Keighin, 1986). Many of these beds fine upward from medium-grained sand near the base to fine-grained sand at the top. Some beds even have basal conglomerates with granules and pebbles of limestone. The sandstones also show scour features and high- to low-angle cross-laminations. Flores and Keighin (1986) interpret the sand to have accumulated in subtidal channels influenced by bottom currents with the locus of sand transport from the northeast; this is confirmed from maps in this study.

The areal geometry of the Tulip Creek sand body is strikingly fan shaped with a deltaic configuration, and, interestingly, with a size and geometry similar to that of the present-day Mississippi River delta (Plate 8). In terms of source areas, sand transport patterns, and geographic location, Tulip Creek sandstones share similarities with the McLish and Oil Creek sandstones rather than Bromide sandstone. The abrupt northeastern termination of the Tulip Creek sand body in northeast Oklahoma toward the South Ozark Arch and along the Illinois River (shown on Plate 8) is not its depositional limit but rather the result of post-Simpson/pre-Viola erosion. It is likely that sands of the Tulip Creek once extended farther northeast of the present "truncation limit" shown on Plate 8. Interestingly, the trend of productive "Tyner" wells that are parallel with this truncation limit gives the impression of stratigraphic entrapment of oil, likely from long distance hydrocarbon migration pathways. If so, it opens the possibility of discovery of other Simpson reservoirs at or near their respective truncation limits.

From a paleogeographic perspective, the geometry of the sand body suggests that the point source for quartz sand into northeastern Oklahoma was perhaps northwest Arkansas in what may have been a braided stream system, one that accreted westward. At this time the Ozark Dome is interpreted to have been slightly positive, and positioned north of Tulip Creek sand dispersal systems – as it was throughout most of Whiterockian (Oil Creek and McLish) time. The similarity of the quartz grains in the Tulip Creek with older Simpson sands also lends support to the idea that quartz originated from the Canadian Shield. However, it is also likely that part of the detrital component of the Tulip Creek may have originated from re-working of older Newton (Oil Creek) and St. Peter (McLish) sandstones that may have once covered the Ozark Dome. Sand progradation westward into Oklahoma was rapid, aided by low accommodation rates. It is envisioned that sand entered the sea in Oklahoma under the influence of strong longshore currents. Sand fanned out in deeper water to form a delta-like system, interpreted to be a subaqueous fan deposit. The frontal part of the Tulip Creek sand body terminates at the Anadarko and Ardmore Basins with the effect that these delta front sands become thicker with a geometry that suggests the sands were reworked and redistributed by currents, flowing not only to the northwest, but also, for the first time, to the southeast, a direction similar to Bromide sands. Interestingly, the sand pattern at the terminus is unlike the abrupt termination seen in older Oil Creek and McLish sands. The supply of sand was so great, moreover, that some sand spilled across the Ardmore Basin/South Ozark Platform Hinge into the Anadarko and Ardmore Basins where it was distributed farther to the west by currents. Farther west, in deeper parts of the Anadarko and Ardmore Basins, the Tulip Creek consists of thick sections of shale. Unfortunately, lower parts of the overlying Bromide are also shale making the contact with the Tulip Creek difficult to recognize. Similarly, the contact with the underlying McLish is difficult to recognize at locations north and west of Canadian County where the Tulip Creek interfingers with shale and thin carbonates of the underlying McLish. In north-central Oklahoma, geographically removed from thicker parts of the sand body, the Tulip Creek consists of predominantly shales, argillaceous carbonates and sandy dolomites which are interpreted to be tidal-flat deposits. Farther north in northwestern parts of the Oklahoma Shelf, the Tulip Creek is thin. That, coupled with log characteristics that lack distinction from the Bromide, makes it difficult to separate the two formations. A stratigraphic case could be made for including the Tulip Creek with the Bromide and labeling it "upper Simpson," as is done in Kansas. The McLish could also be included with the "upper Simpson" since it too is difficult to separate from the Tulip Creek. On parts of the Oklahoma Shelf (Cherokee Platform) in T14N-T21N and R2E-R14E thinning of the Tulip Creek sandstone may be due to scouring by the overlying Bromide sand (Plate 8). This area also roughly corresponds to thickening in the Bromide. Intraformational unconformities (diastems) are fairly common in shallow marine sandstone. In southwestern Oklahoma on the Texas Arch the Tulip Creek consists of shales and shaly limestone that are unconformable under the Viola; the Bromide is thin to absent.

Across broad parts of the southern part of the South Ozark Platform, the east-west trending Tulip Creek sand body interfingers with sandy carbonates at the fringes. In Coal County, for example, organic-rich shales marked by offscale gamma-ray curves are present at the base of the Tulip Creek and allow differentiation from the McLish. The upper contact with the Bromide, however, is without such shales and, unfortunately, the Bromide sandstones also grade to carbonates in approximately the same area as the Tulip Creek "fringe" with the result that the contact between the two formations can't be readily distinguished. Commonly, however, relative to the Bromide, the Tulip Creek is characterized by better developed SP and lower (cleaner) gamma-ray curves in addition to lower resistivity (an indication of higher porosity). Elsewhere on the South Ozark Platform, such as in the broad area of T5N to T10N and from about R12E to R27E, a thin gamma-ray streak that "kicks" offscale is present at the top of the Tulip Creek (Figure 7). The origin of radioactive shale-streaks with high API gamma-ray values is questionable, but may represent a short-lived, environmentally-caused biokill anomaly.

Subsurface well logs included here allow the Tulip Creek sandstone to be correlated with sandstones that are called Wilcox or Tyner in northeastern Oklahoma. Lithostratigraphic correlation to Arkansas shows sandstone of the Tulip Creek to be equivalent to the upper part of the St. Peter Sandstone and to silty and sandy dolomites of the Joachim Formation discussed by Suhm (1965). This correlation is biostratigraphically confirmed from conodonts collected in the Arbuckle Mountains of Oklahoma and the Ozark area of Arkansas and Missouri (Craig, et al 1986; Bauer, 1990).

BROMIDE FORMATION

The Bromide Formation contains the thickest and most widespread sandstones of the Simpson Group; it is the most productive of all the Simpson formations. Ulrich (1911) first named Bromide from carbonate exposures he deemed older than Viola at a "type" locality near the town of Bromide in Johnston County, Oklahoma (Section 19, T1S -R8E). Earlier, those exposures were mapped by Taff (1902, 1904) as lower Viola limestone, likely due to an absence of characteristic Simpson-like sandstones within those carbonates. Decker and Merritt (1931) retained the name Bromide that Ulrich proposed and mapped and measured several outcrop sections spanning the Arbuckle Mountain area including two sections near the town of Bromide. The type section at Bromide town site in Coal County, Oklahoma (Section 32, T1S-R8E) has the distinction of being located farthest to the east than any other Simpson formation; in fact, this type section is more representative of rocks deposited on the South Ozark Platform than in basinal settings as in western parts of the Arbuckle Mountains. Perhaps because of this, according to Harris (1957, p. 87), the Bromide type section was informally moved to the vicinity of Highway 77 (Interstate 35) where the section is better exposed and "more typical" of other formations of the Simpson Group. Here, the Bromide is divisible into a lower or basal 60-foot sandstone that is overlain by about 370 ft of limestone and shale. This may seemingly have been a convenient division, but in areas outside the Arbuckle Mountains, the basal sandstone is not a widely correlative and distinctive unit. Successful correlation of the Bromide Formation across Oklahoma in this report was due, in part, to recognizing it, not as described from exposures in the Arbuckle Mountain area by early investigators, but as a complex stratigraphic unit occupying a position between the more easily recognized overlying formations of the Viola and underlying Tulip Creek and McLish Formations. But more important, a centrally located well log (Figure 5) enabled the Bromide to be correlated and mapped across the state including a tie with type sections in the Arbuckle Mountain area. Upper Bromide carbonates of the Upper Mountain Lake Member and the Pooleville Member named from outcrops in the Arbuckle Mountain area are not recognized in this report because of their inability to be recognized, and correlated in the subsurface.

Decker and Merritt (1931) did not extend their outcrop studies of the Bromide into the subsurface to establish ties with the well-known Wilcox sand in the subsurface of northeastern Oklahoma. The name "Wilcox"originated from Wilcox Oil and Gas who discovered oil from this sandstone in 1914 in Tulsa County (Jordan, 1987). It was recognized by Powers (1928) to be the same sand on which Simpson oil was first produced in 1908 at nearby Glenn Pool. Use of the name is entrenched with explorationists and occasionally still being used, especially in oil-rich counties in the eastern part of the Cherokee Platform, as discussed by various authors in Oklahoma Geological Survey Bulletin 40 published between 1926 and 1930. However, it is hoped that the name "Wilcox" will be replaced with the name Bromide or Tulip Creek using maps, type logs and cross sections included in this report. Confusion between the "Wilcox" and Bromide became apparent when the name 1st Wilcox was applied to Viola-age sandstone in Seminole County. White (1926) and Levorsen (1928) discussed the problem of the "Wilcox" (Bromide) and a younger post-Wilcox Simpson (Seminole sandstone). Harris (1957), also, mentions that the "Wilcox" has, at one time or another, been equated with the Burgen (Oil Creek) McLish, Tyner, Tulip Creek, and, of course, the Bromide. The 1st Wilcox-Seminole problem will be discussed in the "Viola" section

The distribution of Bromide sandstone and associated facies is derived from well-control points and outcrops (Plate 9). Over most areas of Oklahoma the Bromide Formation consists of varying amounts of sandstone, limestone, dolomite, and shale, the proportion and order of which are dependent on depositional province. Sandstone and shale are common in the lower Bromide at or near the base, but not restricted to the base (Figure 15). A common characteristic that seems to extend across several provinces, however, is that the upper part of the Bromide is composed of dense limestone known as "Bromide Dense." It is classified as an informal member of the Bromide Formation in this report due to its ability to be mapped and ease of recognition. The word "dense" aptly describes a very finely crystalline to sublithographic upper limestone facies of the Bromide Formation consisting of high resistivities, PE values of 5, and close tracking of the neutron and density curves with little separation (Figure 15). It resembles the Plattin Limestone of Arkansas. Siliceous intervals in the Bromide Dense member, as might be found in southern Oklahoma, are shown on logs by slight crossover of the neutron-density curves, but without porosity.

Limestones of the Bromide Formation and Viola Group are often lithologically similar in well cuttings and may be difficult to separate from one another. Commonly shale beds separate the two. The Viola and Bromide limestones appear to be more easily separated on well logs by characteristic deflections of gamma-ray, SP, and density curves. For example, Bromide limestones tend to display poor or flat SP associated with slightly higher gamma-ray signatures that contrast with better developed SP and a lower gamma-ray of the Viola. In older logs, the boundary of the Bromide with the Viola may be recognized by a change in SP curve; for example, the silty and shaly limestone ("dirty interval") in the uppermost Bromide is recognized by slightly suppressed SP. "Clean" limestones of the Viola are above the interval of reduced SP.

In the basinal positions where larger amounts of shale are present at the top of the Bromide, 'off-scale' gamma-ray curves show as spikes on well logs. Thin shale, and occasionally bentonites, are present in upper Bromide and lower Viola, similar to those observed at the top of the Arbuckle Group. The well-known Millbrig and Deicke K-bentonites (volcanic ash) that are present in the lower Viola in eastern North America are discussed by Kolata, et al (1996). Bentonites, however, are few in number in Oklahoma at a similar stratigraphic position, and, therefore are not as useful in boundary recognition (Leslie, et al 2008; Huff, et al 2010).

The contact between the Viola and Bromide is easy to recognize where Bromide carbonates are overlain by the Viola-aged Seminole sandstone, but where upper Bromide carbonates change facies to quartz sandstones, the sand-on-sand contact with the Viola Seminole sandstone may be difficult to place. In fact, similarities of lithologies and log signatures may be so great, such as in eastern parts of the Oklahoma Shelf, that the sandstones are confused with one another, however, careful stratigraphic correlation, guided by maps and cross sections included in this report, should assist in differentiation between the two.

Compared with older limestone in the Simpson Group, especially in the Arbuckle Mountain area, the Bromide is distinguished by having a greater variety and number of fossils. Brachiopods, sponges, trilobites, crinoids, bryozoans, and gastropods are abundant. Apparently, favorable marine conditions encouraged diversity. However, perhaps in concert with the evolution of land plants (Vecoli, et al 2011), diversity was also brought about by environmental hardship associated with falling sea levels that took place at the end of Bromide time. This stress may have provided the "spark" leading to even more diverse faunal regimes of the Katian-aged "Great Ordovician Biodiversification Event" (Webby, 2004).

Bromide sandstones consist of fine-to coarse-sized, rounded, and frosted quartz grains bound by calcareous or siliceous cement. High-porosity sandstones have very little cement. Ripples, cross-laminations, and burrows are noted in outcrops and the subsurface (Flores and Keighin, 1986). Bromide sandstones vary greatly in thickness and number within the formation. For example sandstone may occupy the entire interval from the Tulip Creek to the base of the Viola, as in parts of central and north-central Oklahoma, or, near the fringe of the sand body there may be as many as 30 individual sandstones interbedded with limestone. The Bromide sand body has the geometry and sedimentary characteristics of a shallow-water subaqueous fan or marine-modified delta with a northern source area (Plate 9). Within the larger Midcontinent, Bromide sandstone is interpreted to be the basinward equivalent of the Starved Rock Sandstone, the youngest member of the St. Peter Sandstone. This is seen on cross section of Figure 2 and described by Nunn (1986), Templeton and Willman (1963), and Fraser (1976). Apparently, the Starved Rock quartz sand body migrated south-

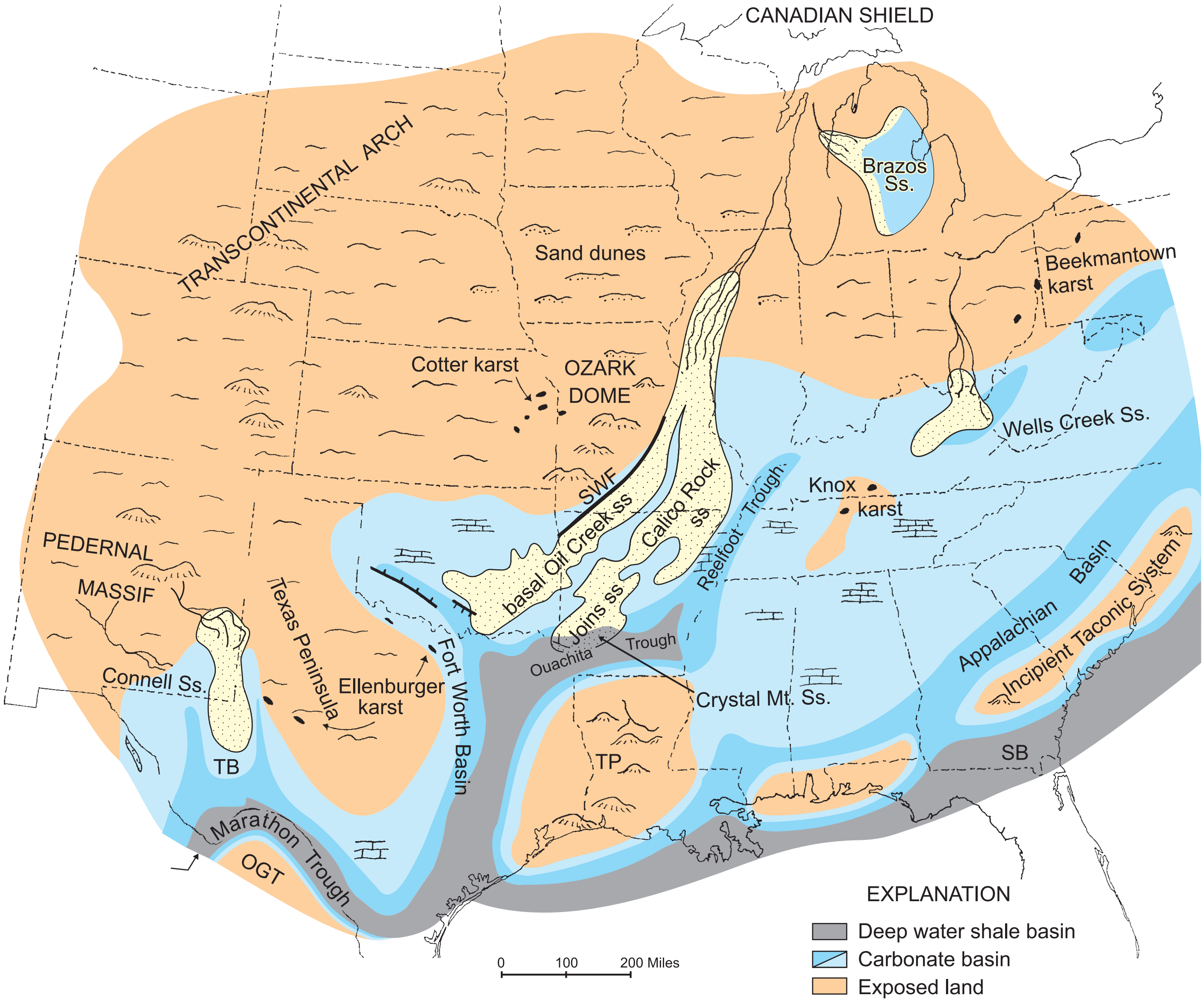


Figure 20. Early Whiterockian (lower Simpson Joins, Oil Creek, and Everton) paleogeography. **The first "sands" to be deposited on an extensive Ibexian tropical karstified platform during the Whiterockian lowstand include the Joins/Calico Rock Sandstone in Arkansas followed by the Newton/Burgen/basal Oil Creek sandstones. Deep marine Iapetus deposits are shown in gray, as are starved basins of the Ouachita and Marathon Troughs hosting "Ouachita facies." The geometry of Texarkana Platform (TP) is interpreted from Paine and Meyerhoff (1970) and Lowe (1989). Other features shown on map are considered from Droste and Shaver (1983), Edson (1935), Freeman (1953), Galley (1958), Smith, et al (1993), Thomas (1985), Dutton, et.al (2005), and Wright (1965). SB= Suwannee Basin (Andress, et al 1969); OGT=Oaxaquian Grenville Terrane (Ortega-Gutierrez, et al 1995; Dickinson and Gehrels, 2008); TB=Tobosa Basin; MT=Marathon Trough; SWF=Southwest City Fault. The Appalachian Basin may be synonymous with segments of the Taconic Foreland Basin but it is landward from the "Incipient Taconic System" consisting of older linear horsts and grabens with variable amounts of sediments and volcanics (Whitehead, et al 1996; Washington and Chisick, 1994).**

westward from the Canadian Shield across parts of Illinois, Iowa, Missouri, and on or across the western side of the Ozark Dome in eastern Kansas. In eastern Kansas, the St. Peter (probably Starved Rock) is mostly less than 50 ft thick, but some wells have drilled through 200-400 ft of sand that appear to have accumulated in stream and karst depressions developed on the underlying Arbuckle (Cole, 1975; Lee, et al 1948). With further southward transport, sand entered relatively deeper water in Oklahoma where dissipation of transport energy caused the sand to spread out, filling much of the Anadarko Basin. Sand termination is abrupt at the south end of the Anadarko Basin at a syndepositional fault with the Texas Arch giving the appearance that the Texas Arch "dam" stopped southward migration of sand.

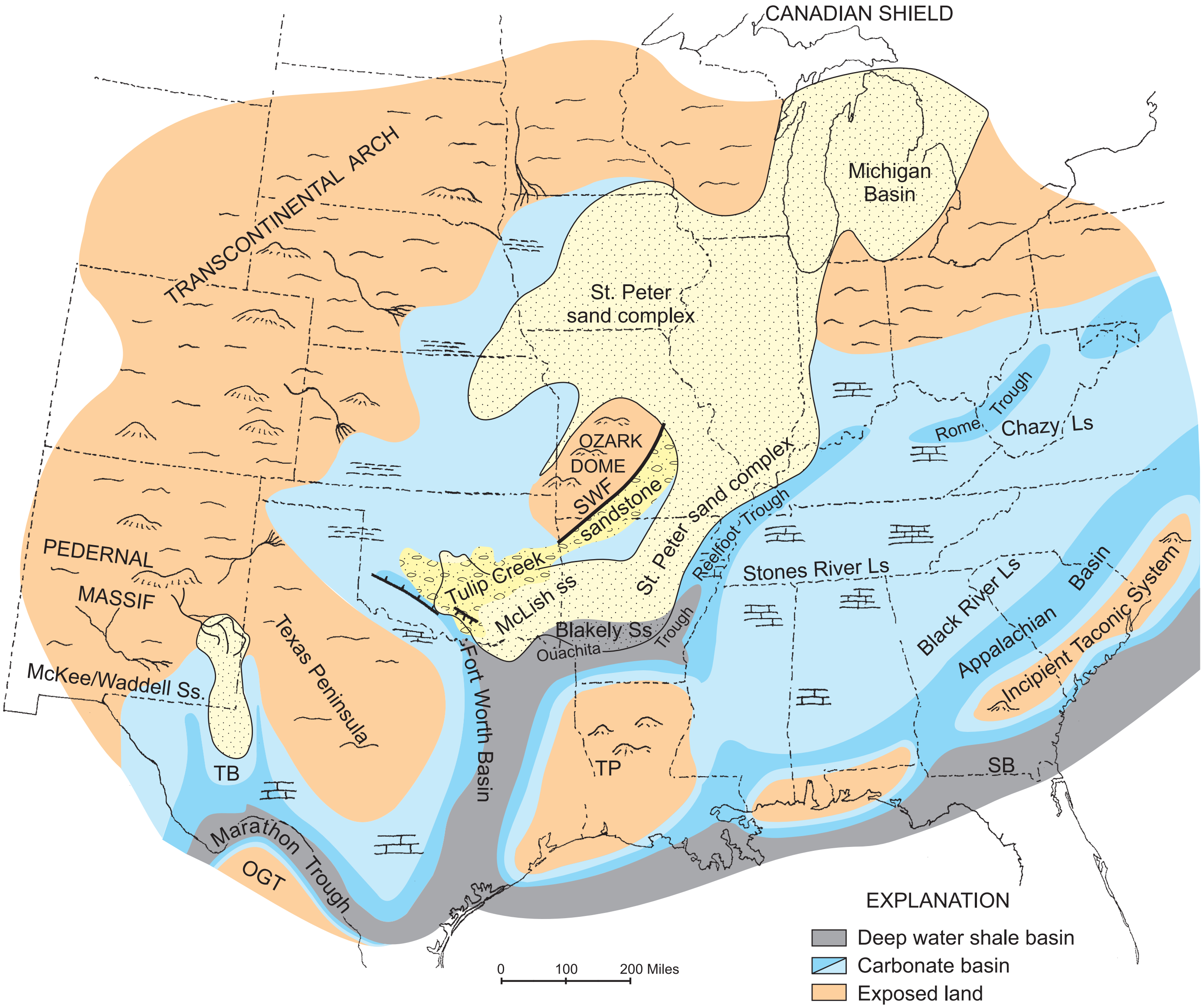


Figure 21. Middle Whiterockian (middle Simpson McLish, Tulip Creek, St. Peter, and Joachim) reconstructed paleogeography. St. Peter and McLish sandstones are located on the east side of the Ozark Dome (Dapples, 1955). The younger Tulip Creek sand body in Oklahoma may partly consist of reworked Newton and basal Oil Creek sandstones exposed on the Ozark Dome (circles) in addition to contributions from north. This interpretation is considered from work of Cole (1975), Droste and Shaver (1983), Galley (1958), Sloss (1988), Sweet (1992), Thompson (1991), Witzke (1980), and Wright (1965). Shale-rich "starved" Ouachita and Marathon Troughs hosted "Ouachita facies" consisting of black shales, limestone, and chert shown in gray. Gray also represents open-ocean deposits of the Iapetus Sea. Rome Trough from Gao, et al (2000). SB= Suwannee Basin (Andress, et al 1969); OGT=Oaxaquian Grenville Terrane (Ortega-Gutierrez, et al 1995; Dickinson and Gehrels, 2008); TP=Texarkana Platform, TB=Tobosa Basin; SWF=Southwest City Fault. The Appalachian Basin (also called Taconic Foreland Basin) is landward from the "Incipient Taconic System", which consists of older linear horsts and grabens that were filled with variable thicknesses of sediments and volcanics (Whitehead, et al 1996; Washington and Chisick, 1994).

Southward-moving currents are not only inferred from areal sandstone distribution patterns but appear to be confirmed by Bromide fossils. Many Bromide fauna share similarities with those in Bromide-equivalent strata in the northern Midcontinent and, also, appear to be younger in Oklahoma suggesting an area of origin to the north and subsequent transport to the south (Ulrich, 1929, p. 77).

Bromide sandstone thickening across the Oklahoma Shelf is due to a regional increase of accommodation space and one that significantly increases toward the Anadarko Basin (see inset map for Plate 9). Bromide production in deeper parts of these provinces is limited, partly due to diminished porosity. Occluded porosity is likely the result of diagenetic changes related to elevated burial temperatures

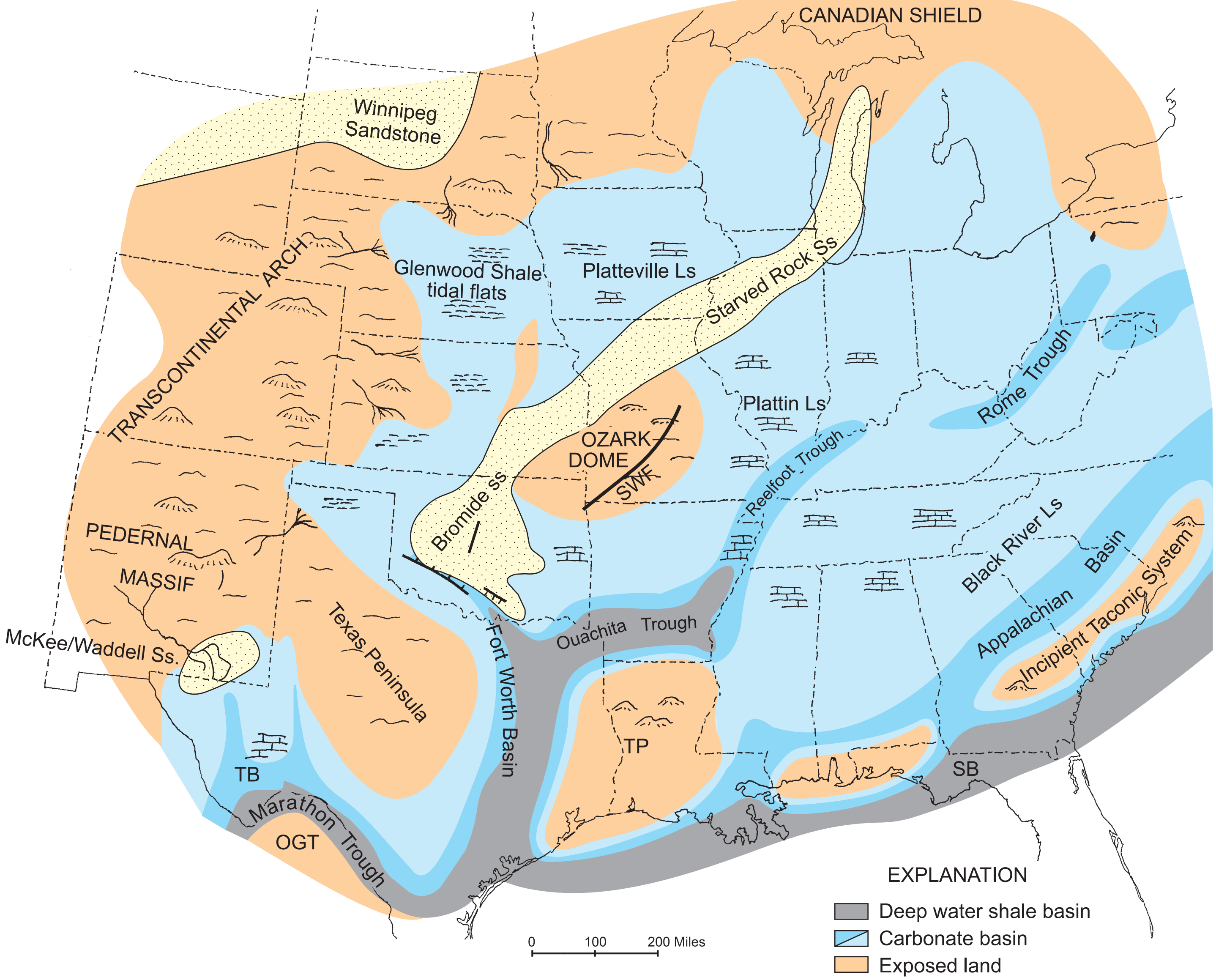


Figure 22. Late Whiterockian (upper Simpson Bromide and Plattin) paleogeography. The distribution of Bromide sand is shown, along with the Starved Rock Sandstone to the north. Not only was the Bromide sand derived from a northerly source but it is likely that minor amounts originated from the erosion of previously deposited St. Peter-like sandstones exposed on the Ozark Dome. Paleogeography is considered from Droste and Shaver (1983), Nunn (1986), Sloss (1988), Sweet (1992), Templeton and Willman (1963), Fraser (1976), and Thompson (1991). The thin vertical line in Oklahoma is the trace of what may be a trace of the ancestral Nemaha deep fault, a south extension of the ancestral Nemaha Uplift (NU) described by Berendsen and Doveton (1997). Deep marine Iapetus deposits are shown in gray, as are starved basins of the Ouachita and Marathon Troughs. SB= Suwannee Basin (Andress, et al 1969); OGT=Oaxaquian Grenville Terrane (Ortega-Gutierrez, et al 1995; Dickinson and Gehrels, 2008); TP=Texarkana Platform, TB=Tobosa Basin; SWF=Southwest City Fault. Rome Trough from Gao, et al (2000). The Appalachian Basin may be synonymous with segments of the Taconic Foreland Basin but it is landward from the "Incipient Taconic System" consisting of older linear horsts and grabens with variable amounts of sediments and volcanics (Whitehead, et al 1996; Washington and Chisick, 1994).

at depths greater than 10,000 ft. In Canadian County and central Grady County, Oklahoma west of the Nemaha Fault Bromide sandstones thicken to a maximum of over 300 ft. Overlying Bromide limestones also show anomalous thickening in this area. Thickening is local, however, and seems to have affected only the youngest Simpson strata. This relationship suggests that thickening is due to the presence of a sub-basin within the Oklahoma Shelf that formed in Late Whiterockian time. This feature is introduced in this report as the "Canadian County Sub-basin." It is an area of suspected crustal weakness that resulted in increased thicknesses, probably due to earliest movements associated with the Nemaha Fault, a fault that was likely a "deep fault" and syndepositional.

Bromide sandstone appears to be blanket-like across large areas of Oklahoma, with the exception of the Arbuckle Mountains area where it is thickest along the northwest-southeast Ardmore Basin/South Ozark Platform Hinge. The area in and around the hinge also appears to be at the confluence of southeast-moving currents of the Oklahoma Shelf with west-moving sand-free currents of the South Ozark Platform. Another area of thickening is north of the McClain County Fault and west of the Nemaha Fault. The Bromide sandstone is erratic in thickness east of Nemaha Fault in parts of McClain, Cleveland, and Pottawatomie Counties. Greater variation in thickness may not only be due to depositional vagaries, but be the result of pre-Viola lowstand erosion. Intense runoff created incised valleys and river channels that might have been filled, not with sand, but with lime debris and carbonates of the Viola during subsequent sea level rise. However, even in areas not affected by pre-Viola subaerial erosion, explorationists have long held the view that Bromide sandstones shale out across short distances, especially at the hinge line margins as shown on the isopach map (Plate 8). In areas where sandstone is absent, Bromide shales rest with apparent conformity on sandstones of the Tulip Creek which also exhibits erratic thickness variation, such as seen on Cross Section A-A' (Plate 3). Because of variability of facies, the lower contact of the Bromide with the Tulip Creek may be difficult to determine. The basal contact is perhaps least difficult to recognize in those areas where the Tulip Creek sandstone is present, such as shown on Plate 8. However, where sandstone of the Bromide is in contact with sandstone of the underlying Tulip Creek the problem becomes being able to distinguish the two sandstones. Bromide sands generally tend to be more calcareous and marked by higher resistivities than those in the Tulip Creek. In the Anadarko and Ardmore Basins and deeper parts of the Oklahoma Shelf, green to black basinal Bromide shales (classed with the Tulip Creek by some investigators) occupy the interval between the top of the Tulip Creek sandstone and Bromide sandstones. Bromide sandstones are thin and change facies to dolomite in the western parts of the Anadarko Basin. In this area, upper Bromide limestone is shaly and poorly defined. So here, and on the Texas Arch (where the Tulip Creek is also predominantly shale), the lower contact of the Bromide with the Tulip Creek cannot be easily defined from well logs; it simply lacks distinguishing lithologic and log characteristics. Additionally, on the Texas Arch, the Bromide is thin, similar to that in northern parts of the Oklahoma Shelf near Kansas. The Bromide is absent closer to the core area of the Texas Arch due to truncation by the overlying Viola, or, possibly because the Simpson was never deposited there (Figure 11). Suspected sources of terrigenous clay within the Bromide Formation were from the Transcontinental Arch and Texarkana Platform, not the carbonate-dominated Texas Arch.

On the South Ozark Platform appreciable amounts of sandstone and shale are scarce to absent in the Bromide. An explanation for their absence is shown from sand distribution patterns (Figures 20-22). Interpretation of those maps suggests that terrigenous material from the Canadian Shield shifted to the west from positions that sourced the Oil Creek and McLish sands. Bromide equivalent sands bypassed the South Ozark Platform in Arkansas and eastern Oklahoma and were carried west through Kansas to enter Oklahoma from the north. In the absence of sand, the South Ozark Platform was a depositional site for high energy shallow marine and peritidal Bromide carbonates. On the southern parts of the South Ozark Platform, Bromide limestone and shale in the Chesapeake No. 2-34 Mary (Cross Section D-D' on Plate 13), display a spiky gamma-ray profile reflecting increased amounts of clay and organic material. It is assumed that this terrigenous clay reflects input, or spillover, from the Womble Sea that covered the Ouachita Trough to the south. In areas north of the No. 2-34 Mary with better well control, sandy limestone and dolomite of the Bromide rests on similar-appearing carbonates of the Tulip Creek, making the contact with the Bromide difficult to discern; Bromide carbonates, however, generally exhibit poorly developed SP and a higher resistivity than those of the Tulip Creek. In Latimer County, Wahlman (2010) found the Bromide to be predominantly nearshore and intertidal limestone and dolomite with sandy streaks a few inches thick consisting of fine to medium-sized well sorted quartz grains. The quartz grains were probably transported by winds and aberrant currents that occasionally came from the northwest, in the direction of the Bromide sand sheet. Porous zones in Bromide secondary dolomite, along with Tulip Creek dolomite, are productive in the vicinity of Wilburton Field. Wahlman (2010) found dolomite in basinward positions to be better reservoirs because of their coarser crystallinity, rather than more finely crystalline penecontemporaneous dolomite deposited in peritidal lagoonal environments to the north. Interestingly, north of this area and in the vicinity of the Southwest Ozark Lineament in Lincoln and Okfuskee Counties where Bromide sandstone is present, there appear to be

Bromide channel-filled sandbodies incised into the underlying Tulip Creek (Plate 9). Farther eastward from this area, the Bromide formation thins depositionally toward the South Ozark Arch. The Bromide may have covered the Ozark Dome, but this cannot be confirmed because the Bromide has been removed by pre-Viola and Woodford erosion. The Viola truncation belt is shown on the Bromide isopach map (Plate 9) and illustrated in a regional cross section prepared by O'Brien and Derby (1997). The Bromide Formation was correlated with the Plattin Limestone in Arkansas where stratigraphic complications are briefly discussed by Suhm (1997).

VIOLA GROUP

INTRODUCTION

From exposures in the Arbuckle Mountain area, Taff (1904) applied the name Viola to 500-700 ft of limestone between darker colored argillaceous rocks of the upper Simpson, and green shales of the Sylvan. Its "type" locality is located at the eastern edge of the Arbuckle Mountain area near Viola town site in Johnston County. The contact of the Viola with the Simpson Group is a major unconformity (O'Brien and Derby, 1997) and sequence boundary (Carlucci, et al 2015). This unconformity is seen in northern Arkansas at the base of the Viola (Kimmswick and Fernvale Limestones) where it rests on the Bromide-equivalent Plattin Limestone (Freeman, 1972; Suhm, 1965). However, at basinward positions in western parts of the Arbuckle Mountains, data included here and in Dennison (1997) suggest that the contact is more representative of non-deposition than one produced by erosion.

The Viola Group consists of limestone of the Viola Springs and Welling Formations. These formations can not be recognized in the subsurface from electric logs. However, in many parts of the subsurface the lower part of the Viola commonly consists of sandstone and or dolomite that can be separated from overlying limestone. This distinctive lower unit is called the Seminole sandstone (Plate 10). It is oil-bearing and shares striking lithologic and stratigraphic similarities with Simpson sandstones. Its lateral geometry, however, is different from those of Simpson sandstones. The areal distribution of the Seminole sandstone suggests that the Ozark area was uplifted and eroded after Simpson deposition. Reworked sand was incorporated into the basal Viola. This structural shift might be related to the onset of the Taconic Orogeny that affected the eastern part of North America at the end of Whiterockian time. Structural and volcanic activity in this area appears to be partially confirmed by thin bentonitic shales in the upper part of the Simpson and lower Viola in Oklahoma (Leslie, et al 2008). The widespread Millbrig and Deicke K-bentonites in the eastern parts of the United States are discussed by Kolata, et al (1996), and Huff, et al (2010).

In consideration of the entirety of the Midcontinent region, Katian-age Viola carbonates record one of the greatest eustatic sea-level rises in geologic history. Sea level highstand was at levels comparable to that of the older "Great American Carbonate Bank."

SEMINOLE SANDSTONE

The lower part of the Viola Group consists of limestone across most of the state, but in the subsurface in central Oklahoma the lowest portions of the Viola consists of a relatively thick and extensive sandstone (and associated dolomite) called the Seminole sandstone, a name taken from oil-rich Seminole County. The sandstone is as much as 70 ft thick, and, across a broader area it laterally grades to dolomite which in turn grades to limestone. The sandstone is unconformable on the Simpson. Its vertical proximity and lithologic similarity with sandstone of the Simpson Group make it difficult to separate on logs. However, maps provided here show regional facies relationships of both sandstones that may enable separation of the Seminole from the Bromide. The Seminole sandstone, including its associated dolomites, has oil productivity similar to sandstones of the Simpson Group.

Because most explorationists did not realize that the Viola had an associated basal sandstone and because it is the first Simpson-like sandstone under the Viola, the sandstone was (and still is) erroneously termed the "First Wilcox," the name of which implies a relationship with the thicker "Second Wilcox" (Bromide sandstone) of the Simpson Group. However, several years after the discovery in the Greater Seminole Oil Field, geologists realized that the principal productive sandstone below the Viola limestone was actually younger than the "Wilcox" (Bromide) — apparently it was correlated to a position above the productive sandstone on Wilcox farm in the Glenn Pool Field. White (1926) recognized it as post-"Wilcox" and Levorsen (1928) gave it the formal name, "Seminole sandstone member" of the Simpson "Formation". On page 308, Levoren (1928) says, "The Seminole sandstone member is generally known in the Seminole County fields as the "Wilcox" or "First Wilcox" sand. It has been recognized, however, by all of the geologists working in the field as a younger and different sand than the true or original Wilcox sand of Oklahoma. The writer is indebted to Luther White for his suggestion of the need for a separate name for this sand, and, for the name Seminole sand member. The Seminole sand member is a definite stratigraphic unit in the upper part of the Simpson formation." Years later, well log correlations by Cronenwett (1956) confirmed that the sandstone in this interval was a facies of the Viola rather than Simpson. In her discussion of subsurface names of Oklahoma, Jordan (1957, p. 174) states that in the discovery well where it was named, the Seminole, "Consists of up to 55 feet of sandstone in the Viola. Equal to 'Seminole Wilcox' or 'First Wilcox' of Seminole area, not 'First Wilcox' of Bromide fm." ... "the term (Seminole) is preferable to "First Wilcox.'" And in her discussion of the "Wilcox" sand, Jordan (1957, p. 207) writes, "'First Wilcox' sand of the Seminole area should be called Seminole sand."

It was later realized that this Viola/Simpson contact represented an unconformity, and that the Seminole was above the unconformity. Furthermore, the unconformity between the Seminole (1st Wilcox) and Bromide ("2nd Wilcox") was found to be angular (O'Brien and Derby, 1997, and Suhm, 1997), and shown in Cross Section B-B' on Plate 11 and Figure 2. The name, "Seminole sandstone member" of Levorsen (1928) and White (1926) is retained in this report, with the recommendation that it and its associated dolomite facies become the "Seminole Formation" of the Viola Group.

The name "Wilcox," as a productive Simpson sandstone, is entrenched with explorationists and occasionally still being used, especially in oil-rich counties in the eastern part of the Cherokee Platform. However, it is hoped that this name will be replaced with formation names used in central Oklahoma and the Arbuckle Mountain area. Maps, type logs and cross sections included in this report can be used to enable "standardization" of Simpson terminology in future subsurface studies. However, it is recommended in this report that the name "First Wilcox" (1st Wilcox) be abandoned completely and replaced by "Seminole," or Bromide, where appropriate. Similar recommendations were made by Disney and Cronenwett (1955), Cronenwett (1956), Schramm (1965), Statler (1965), and more recently by O'Brien and Derby (1997) and Suhm (1997). Under geologic protocol, or what is known as "the stratigraphic code," the name "Seminole" can be applied to this "younger" sandstone as a formation or member of the Viola Group. For example, according to the North American Commission on Stratigraphic Nomenclature (2005, p. 1565) under Article 20. — Abandonment: "An improperly defined or obsolete stratigraphic, lithodemic, or temporal unit (such as the Wilcox) may be formally abandoned, provided that (a) sufficient justification is presented to demonstrate a concern for nomenclatural stability, and, (b) recommendations are made for the classification and nomenclature to be used in its place."

The Seminole sandstone is present in central and north-central Oklahoma with an extent less than other Simpson sandstone bodies. Interestingly, it has a northwest-to-southeast orientation that is opposite to trends in the Simpson (Plate 10). That, in itself, testifies to differences in depositional history, paleogeography, and age. Moreover, the geometry represents an agglomeration of shoreline sands that encircle the southwest flank of the Ozark Dome, also unique. The Seminole sandstone consists of from one to several beds of sandstone, attaining a maximum aggregate thickness of 70 ft. Lithologically, the Seminole sandstone is fine- to medium-grained, with frosted, rounded quartz grains remarkably similar to older Simpson "St. Peter-like" sandstones. Lithologic likeness is attributed to its origin; the Seminole sandstone was derived from the erosion of preexisting Bromide, Tulip Creek, and older Simpson sandstones exposed on the Ozark Dome following post-Simpson/pre-Viola uplift. Plate 10 shows an area labeled "coastal sand plain" band that represents the extent of that part of the Bromide sand that was removed by erosion and incorporated into the Seminole. It also consists of sand derived from the erosion of Tulip Creek and older sandstones that were exposed farther to the northeast. Seminole shoreline sands are overstepped by Viola carbonates, or equivalents called upper Tyner, and Fite, as part of the "Great Viola Transgression." Similarly, the Harding Sandstone in Colorado is the basal sandstone for the Fremont (Viola) Limestone and part of this Ordovician transgression. The Harding is a time-stratigraphic equivalent of the Seminole sandstone; it appears to have been deposited in environments similar to the Seminole sandstone but in the area of the Transcontinental Arch (Maher, 1950; Allulee and Holland, 2005).

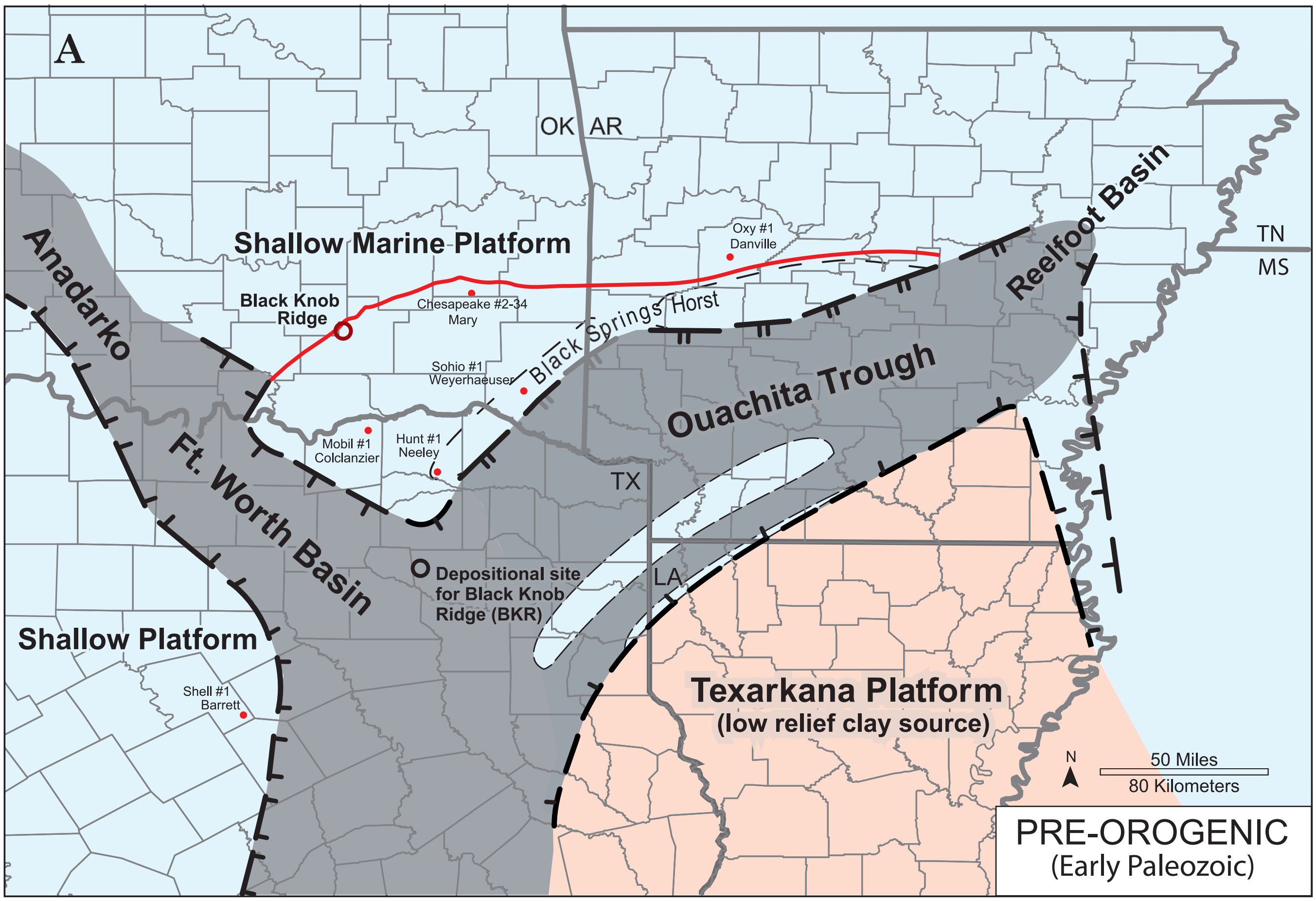
The Seminole sandstone interfingers basinward (down dip to the west) to crystalline, sucrosic, sandy dolomite referred to here as the "dolomite fringe." Parallel to the Seminole sandstone, this dolomite is informally called "Seminole dolomite" (Plate 10). In the area of Pottawatomie, Cleveland, and McClain Counties the dolomite is fine to coarsely crystalline with varying amounts of quartz grains. The environment of deposition is likely peritidal, principally shallow subtidal and offshore from the sandstone. The dolomite contains scattered grains of quartz, likely windblown. Additionally, quartz is present as thin beds of very dolomitic sandstone. The quartz has a source similar to that of the Seminole sandstone; having been derived from the erosion and reworking of the underlying and laterally-adjacent Bromide sandstone. It appears that at the end of Bromide time, intense runoff created incised valley and river channels. These channels were later filled with Viola sandy lime debris and carbonates. Evidence for this lies with pronounced variations of Viola thicknesses seen on detailed isopach maps, especially for a broad area north and northeast of the Golden Trend. This "paleodrainage system" may have also created secondary stratigraphic traps within the underlying Bromide sandstone. Thicknesses variations of Viola carbonates are further discussed by Smith (see Fig. 16, 1997). The position of the dolomite facies relative to that of Seminole sandstone suggests that the source of some of the dolomite may have been from the erosion of older Simpson dolomites exposed on the Ozark Dome (Plate 10). These "detrital dolomite" dust-source particles may have served as "precipitation seeds" for the dolomitization process taking place within lime muds accumulating in subtidal magnesium-rich environments (Lindholm, 1969). Porosity is fair to excellent within dolomite-rich parts of the lower Viola, and, in production value, dolomite may be as prolific as the Seminole sandstone.

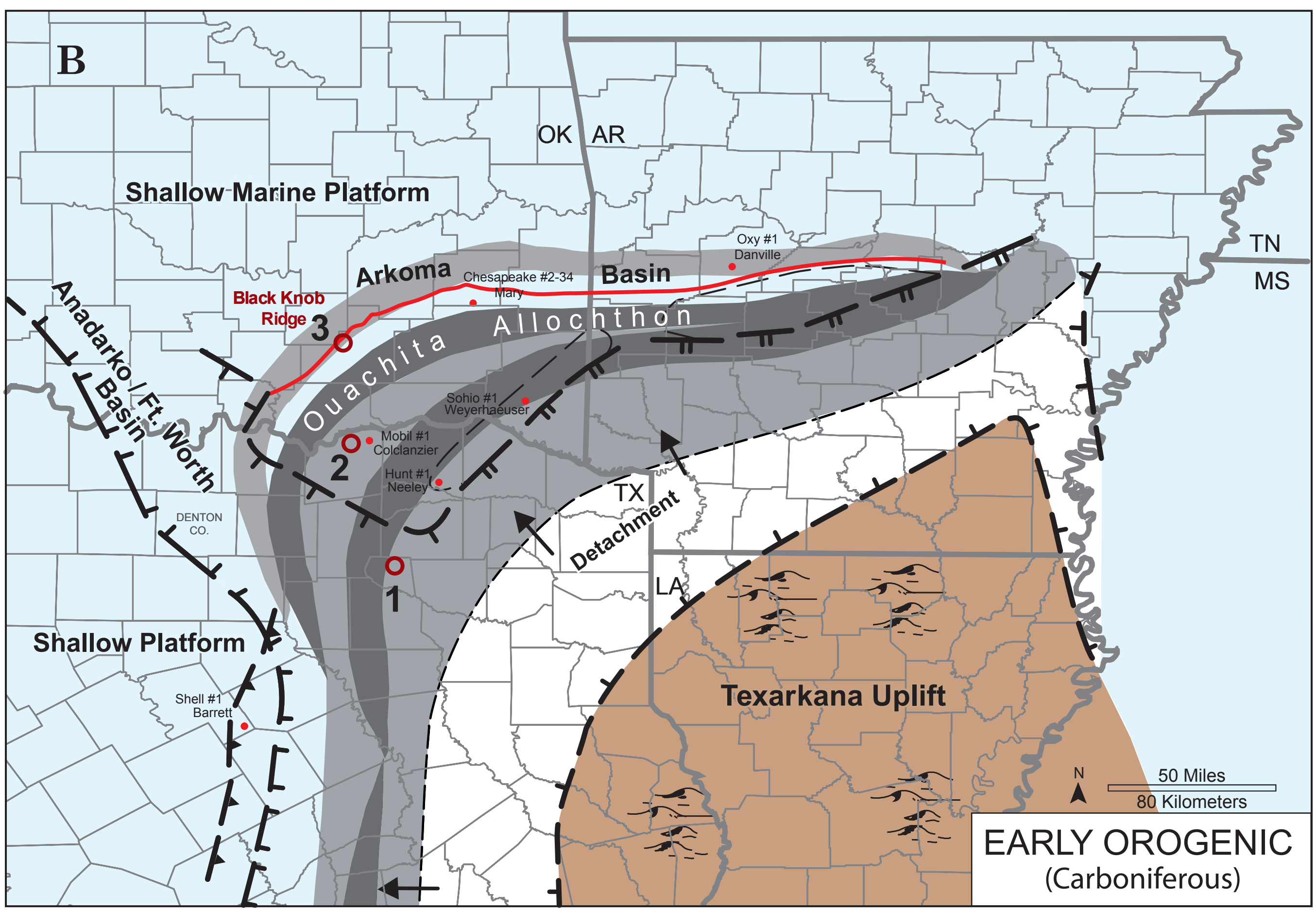
In deeper marine and more basinward positions the dolomite facies of the Seminole sandstone grades to limestone of the lower Viola. In Love and Jefferson Counties in southern Oklahoma in the area of the Marietta basin, productive lower Viola limestone is known as the "Chocolate Brown Zone" (see Plate 15). The "Chocolate Brown Zone" consists of medium to dark brown cherty lime mudstone with a fetid odor, especially when broken. The color and fetid odor are characteristics that suggest the presence of hydrocarbons, opening the possibility that such limestones may serve as self-sourcing reservoirs. The "Chocolate Brown Zone" is silicified in variable amounts rendering it brittle, and in areas that were structurally stressed by local tectonics, the lower Viola is productive from fractures, and it is even considered to be a horizontal drilling target (Candelaria and Roux, 1997).

OUACHITA FACIES OF THE SIMPSON

Simpson equivalents are present in the lower part of the thick "Ouachita facies" composing the thrust complex of the Ouachita Mountains in southeast Oklahoma. Its northern edge is marked by the Choctaw and Ti Valley Faults represented by a dashed line on most of the enclosed plates. Simpson equivalents were deposited in a linear "Ouachita" seaway about 130 miles wide; the reconstructed northern edge of the Ouachita Trough is estimated to be located about 100 miles south of the Choctaw and Ti Valley Faults, in what is north Texas and southern Arkansas. It is termed "South Ozark Platform/Ouachita Trough Hinge." Late Mississippian and Early Pennsylvanian tectonic activity created conditions for lateral sliding that caused the Simpson and younger beds in the Ouachita facies to slowly move en masse northward out of the trough to various positions over cratonic strata of the South Ozark Platform. Thick shale sequences within the Mazarn and Womble (Simpson equivalents), acted as glide planes in this displacement process. Imbricate thrust sheets, repeated sections, tight folds and overturned strata, are the product of this movement, especially in the vicinity of features that might impede horizontal sliding. In consideration of stratal contortions and the lithologic similarity of shales and sandstones composing the "Ouachita" Simpson, stratigraphic differentiation of Simpson strata was, and still is, difficult, resulting in correlation and mapping errors (Miser and Purdue, 1929; Tomlinson and Pitt, 1955; Pitt, et al 1961; and Lowe, 1989). Furthermore, it is virtually impossible to produce a composite strati-graphic section (a standard reference section) for the Simpson Ouachita facies with which to correlate, especially in light of facies differences from one end of the Ouachita Mountain to another (Jusczuk 2002). Simpson equivalents are exposed in the Oklahoma portion of the Ouachita Mountains in three widely spaced areas — Potato Hills, Broken Bow Uplift, and Black Knob Ridge near the town of Atoka. Between these exposures, the Simpson is buried to depths that exceed 10,000 ft beneath thick sections of Mississippian and Pennsylvanian strata. Consequently, very few wells drilled in the Ouachita Mountains have penetrated complete sections of Simpson equivalents. In spite of these problems, it can be agreed, however, that in Oklahoma and Arkansas the traditional Simpson stratigraphic succession is, from bottom to top, Crystal Mountain Sandstone, Mazarn Shale, Blakely Sandstone, and Womble Shale. The Bigfork Chert, a Viola equivalent, is above the Womble, and the Collier Shale, an Arbuckle equivalent, is below the Crystal Mountain Sandstone.

From conodonts evaluated by Repetski, et al (1994), Ethington, et al (2012), and Ethington (1984) several of the above listed "Simpson" formations appear to be Whiterockian. The ages of the Mazarn Shale and the underlying Crystal Mountain Sandstone, however, are questionable. The Crystal Mountain Sandstone is included with Simpson because of similarity in lithology and thickness with the Calico Rock Sandstone in Arkansas, and, according to Pitt (1955), similar to the McLish Sandstone. The Crystal Mountain ranges in thickness from 100 to 800 ft (Stone and Bush, 1984; Pitt, 1955); the younger Blakely Sandstone is about 500 ft thick. The Mazarn Shale separates the two sandstones. The Mazarn consists of thin layers of siliceous and calcareous sandstones, siltstones, and shales; the sandstones may be slightly arkosic with volcanic debris (Jusczuk, 2002). The Crystal Mountain and Blakely Formations are texturally and mineralogically similar to St. Peter-like sandstones of the Simpson Group (Pitt, 1955), but contain minor amounts of feldspar and carbonate grains (Craig, et al 1993). These sandstones are predominantly medium-grained with well-sorted, rounded-quartz grains, some of which exhibit secondary quartz overgrowths. The sandstones are calcareous to siliceous and of reservoir quality. In Arkansas, Branner (1937) reported Crystal Mountain porosity of 17 percent. Other investigators report the Blakely Sandstone to be fine-grained quartz sandstone with interbeds of limestone and varicolored silts and shale (Jusczuk, 2002). The Crystal Mountain and Blakely Sandstones are commonly massively bedded with obscure cross laminations (Bierschenk, 1989; Davies and Williamson, 1977). The Crystal Mountain and Blakely represent deposition in either shallow water with strong bottom-traction transport currents (Davies and Williamson, 1977), or in deeper water by submarine gravity flows (Lowe, 1989). From unpublished field studies the Crystal

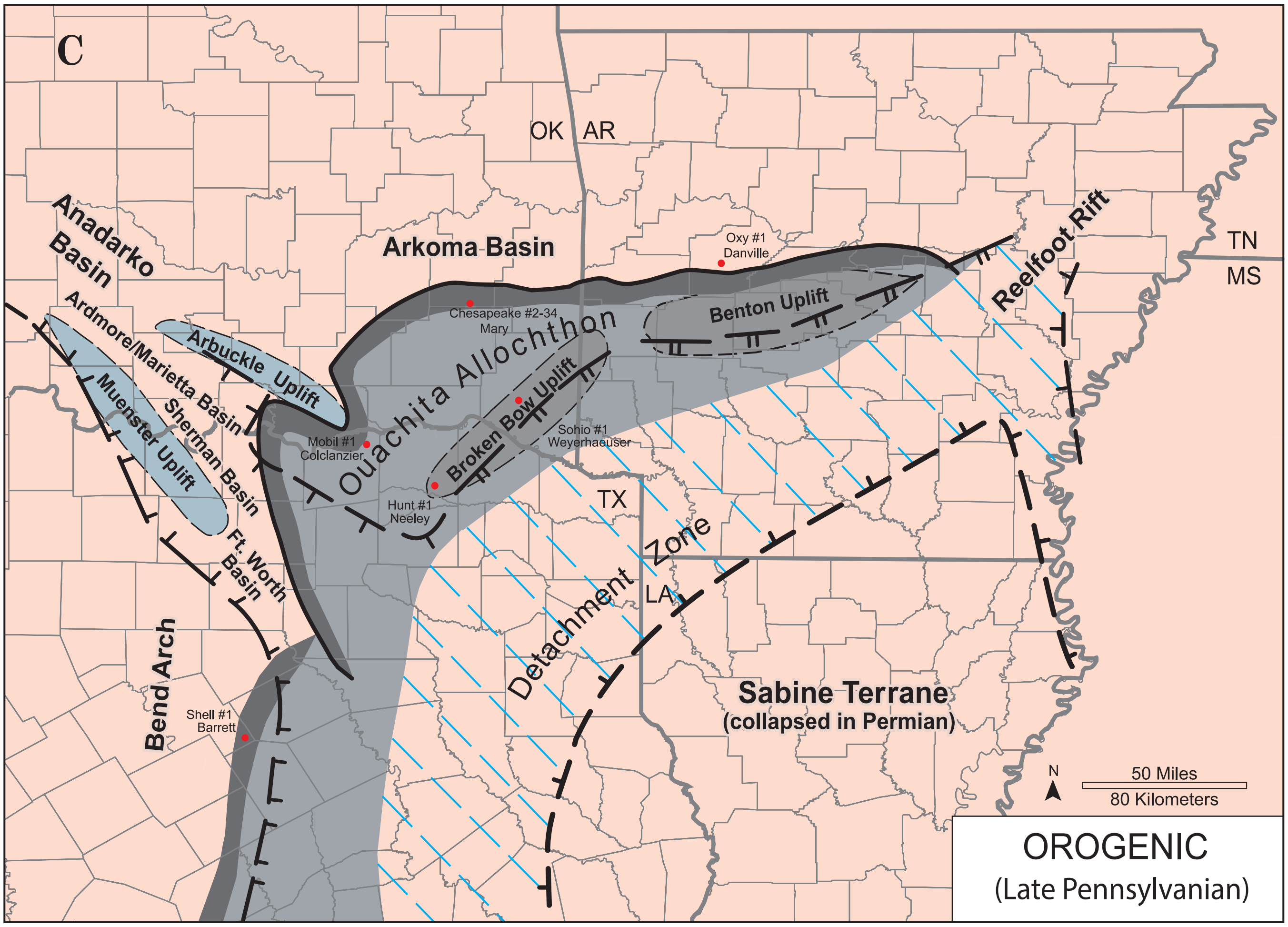

A
OK
AR
TN
MS
Shallow Marine Platform
Oxy #1
Danville
Black Knob
Ridge
Chesapeake #2-34
Mary
Black Springs Horst
Reelfoot Basin
Anadarko
Sohio #1
Weyerhaeuser
Ouachita Trough
Mobil #1
Colclanzier
Hunt #1
Neeley
TX
Ft. Worth Basin
Depositional site
for Black Knob
Ridge (BKR)
LA
Shallow Platform
Shell #1
Barrett
Texarkana Platform
(low relief clay source)
N
50 Miles
80 Kilometers
PRE-OROGENIC
(Early Paleozoic)


B
OK
AR
TN
MS
Shallow Marine Platform
Oxy #1
Danville
Arkoma
Chesapeake #2-34
Mary
Basin
Black Knob
Ridge
3
Ouachita Allochthon
Anadarko / Ft. Worth
Basin
Sohio #1
Weyerhaeuser
2
Mobil #1
Colclanzier
Hunt #1
Neeley
TX
Detachment
DENTON
CO.
1
LA
Shallow Platform
Shell #1
Barrett
Texarkana Uplift
N
50 Miles
80 Kilometers
EARLY OROGENIC
(Carboniferous)

Mountain Sandstone contains a basal chert and limestone conglomerate, much like that of the basal Everton in Arkansas. Field studies also show that in the Hot Springs area of Arkansas, the Crystal Mountain contains boulders of granite and Arbuckle-like limestone; their origin is questionable but they may have been derived from adjacent submarine fault scarps (Lowe, 1989) or from the erosion of paleotopographic highs such as the Black Springs Horst introduced in this study and shown on the Viola structure map (Plate 15). Similarly, in Arkansas, the Blakely Sandstone contains beds of large, rounded, metaarkosic boulders (Morris, 1974). Quartz grains composing the Crystal Mountain and Blakely Sandstones were derived from the craton to the north (Reid, et al 1994; Lowe, 1989), probably the Canadian Shield, and carried southward across the South Ozark Platform, perhaps on the western margin of the Reelfoot Trough at a lowstand position comparable to that of the Calico Rock Sandstone. But also, in light of new paleogeographic considerations published in this report there is the possibility that cratonic Cambrian sandstone may have been exposed and eroded on the Texarkana Platform and carried into the Ouachita Trough to mix with northerly-derived sands. From consideration of sandstone cross beds, Lowe (1989) and Craig, et al (1993) suggest that these Ordovician sands, once in the Ouachita Trough, were transported westward toward Oklahoma to interfinger with equivalent shale facies. The Crystal Mountain and Blakely Sandstones are not developed in western parts of the Ouachita Mountains. The Crystal Mountain Sandstone is not present in the Sohio No. 1-22 Weyerhaeuser, a deep well in Section 22, T5S-R24E.

The Womble Shale is the thickest organic-rich black shale comprising Simpson equivalents in the Ouachita facies. The Womble is easily identified on well logs; it has an uninterrupted log signature of thick shale, and is at a stratigraphic position below the Big Fork Chert (Viola). It is as much as 1,600 ft thick (Stone and Bush, 1984) and consists of dark, organic-rich fissile shales with some dark-gray, fine-grained limestone. It appears to have been deposited in deep water environments with reduced amounts of oxygen, perhaps the result of restricted circulation.

Figure 23. Geologic history of the Ouachita System (with an explanation of removal from Viola structure map).
A. Depositional Setting for Early to Middle Paleozoic. Prior to uplift of Muenster and Arbuckle blocks, basinal muds and carbonates were deposited in the Anadarko (Ardmore) and Fort Worth Basins. The Ouachita Trough was a "starved" basin in which craton-sourced quartz sandstones of the Crystal Mountain and Blakely were deposited along with dark-colored carbonates and clay of the Mazarn and Womble Shales and chert of the Big Fork. It was bordered on the north by an intermittently high source area called Black Springs Horst. Erosion of the horst provided detritus for Johns Valley Shale. The Texarkana Platform (Paine and Meyerhoff, 1970) was a larger source for much of the fine-grained detritus, including that in the Simpson Group, but in Mississippian time the Texarkana Platform became structurally active and topographically elevated, contributing voluminous amounts of Stanley, Jackfork, and Johns Valley detritus to the Ouachita Trough and adjacent basins. An elongated intermittently-exposed horst-like depositional platform (blue) system may have been a northern segment of the Texarkana system. The current Ouachita thrust front (Choctaw Fault seen as red line on map) represents the approximate north margin of the Morrowan/Atokan deep fault zone discussed below in Figure B. Significant outpost wells are labeled.
B. Orogenic activity during Morrowan Basement fault positions remain unchanged from Figure 23A. In Late Morrowan-Early Atokan time tensional forces in the southern part of the South Ozark Platform resulted in crustal subsidence with a downthrown component estimated to be 10,000 ft. Several downthrown blocks proximal to red line will comprise the precursor "Arkoma Basin." Concurrent with this "collapse," vertical uplift took place on the Texarkana Platform. The combined effect of this vertical activity, estimated to be 10,000 ft of downward collapse and 10,000 ft of upward movement, was to allow mostly plastic rocks of the Ouachita Trough to be moved northward toward available accommodation space. The vacated area of the Ouachita Trough is labeled "Detachment." Later in Morrowan and Early Pennsylvanian extensional grabens of the Arkoma Basin along the red line were filled with Atokan detritus, most of which was originated from the north, but which, on occasion, mixed with south-derived terrigenous material eroded from advancing Ouachita thrust sheets (Newman, 2012). From estimated restorations, the Ouachita thrust front occupied three successive positions (1, 2, and 3) during northward advance. At some period in Early Pennsylvanian northward movement of the "gravity slide" was interrupted, or paused, at position 2 just south of the present trace of the Ti Valley Fault, south of the Choctaw Fault shown as red line on Figure 23. In this area, from seismic lines used in this study and in cross sections prepared by Buchanan and Johnson (1968), Atokan strata reached maximum fill; Atokan strata appear to be absent a short distance farther south from the depocenter. The fill and younger beds were overridden by a final northward "push" of the thrust complex later in Pennsylvanian time with an interpreted extent north of the Choctaw Fault shown as light gray shading and marked as position 3 (now absent by erosion). Perhaps some of the deep faults served as impediments for the northward movement of Ouachita thrusts. The dark red circles show the interpreted movement of the Black Knob Ridge section from original depositional site (position 1) to various thrusted positions in Atoka County, Oklahoma (position 3).
***FIGURE 23C IS ON NEXT PAGE**



C. Late Paleozoic Orogenic Features. Tectonic activity spanning millions of years was responsible for uplift of the Arbuckle/Tishomingo block and Muenster Arch. After its uplift, the Muenster Arch separates the Ardmore Basin from the Fort Worth Basin, creating the Marietta/Sherman Basin. Uplift of the Black Springs Ridge under the allochthon at the end of Atokan time imparted anticlinorium geometry to the core of the Broken Bow and Benton Uplifts.

Dix, et al (1994) and Lowe (1989) report a southerly source for clay and greywacke in the Womble of the Ouachita Trough, perhaps from the "disjoined craton" called the "Texarkana Platform" (Lowe, 1989; Paine and Meyerhoff, 1970) or "Llanoria" (Miser, 1921, 1929), or "southern Laurentia" (Shaulis, et al 2012). The southern landmass is reported to have consisted of a mixture of Cambrian and older sedimentary, metasedimentary, and mafic igneous rocks (Dix, et al 1994). Black shales within the Womble and older Mazarn may prove to be excellent source rocks for hydrocarbons since they tend to have TOC (total organic carbon) in amounts as much as 2.38%, well above what is required for source rock material (Informal Oil Field Communication).

Simpson sandstone reservoirs in the "Ouachita facies" are better developed in eastern parts of Oklahoma — closer to sources of quartz sand. The combination of potentially porous and permeable matrix reservoirs with black shale suggests that Simpson equivalents in the Ouachita Mountains may have future economic importance. Not only would clay have been available to coat quartz grains (with the effect of preserving porosity in sandstones) but black organic-rich shales would provide hydrocarbons. Further, burial history may have been more favorable to Simpson reservoirs within Simpson Ouachita facies than in platform facies of the South Ozark Platform. This will be discussed further in "Petroleum Potential."

PALEOGEOGRAPHY AND GEOLOGIC HISTORY

SETTING THE STAGE

Evidence for Climate and Structural Change: New Paleogeography and Tippecanoe Sequence

A new chapter in geologic history began with the culmination of the Cambrian transgression. Twenty million years of Arbuckle carbonate deposition on the "Great American Limestone Bank" ended. A reorganization of the structural fabric and climate of North America took place. Terrigenous-rich sediments of the Simpson replaced carbonates, but during the transition from one sedimentologic system to another, a large expanse of "Arbuckle" carbonate terrain was subaerially weathered to karst landscapes. The name given to the eroded landscape on which the Simpson rests is the sub-Tippecanoe unconformity. Karst is documented in eastern Kansas (Lee, et al 1948), Missouri and Arkansas (Purdue and Miser, 1916; McKnight, 1935), Kentucky and Tennessee (Anderson, 1991; Kyle, 1976), and Texas (Adams, 1965; Wright, 1965). In Oklahoma the effects of solution are recognized in the subsurface in the Arkoma Basin (Antlers Graben) on the South Ozark Platform in the Wilburton Field, Latimer County (Carpenter and Evans, 1991), Cherokee Platform on the Oklahoma Shelf in the Oklahoma City Field (Gatewood, 1970), Ardmore Basin in southern Oklahoma (Waddell, et al 1993), and Texas Arch (Whiteside and McCommons, 1991). In deep parts of basins, Arbuckle deposition appears to have been transitional with the Simpson.

Terrigenous components of Simpson strata were the product of paleogeographic change. The emergence of the Texas Peninsula (Texas Arch) and the Texarkana Platform in northeast Texas and Louisiana produced rifts at their edges that accentuated the young Anadarko/Ardmore Basins and Ouachita Trough. The oldest stratigraphic units of the core areas of the Ouachita Uplift consist of plastic shale and sandstone with interbeds of limestone of Ordovician age. Strata older than these do not exist, probably because they were not plastic and couldn't move under compressional conditions. A conclusion can be made, therefore, that prior to Ordovician time, the Ouachita Trough may not have existed as a trough, but rather as a carbonate platform, part of the "Great American Carbonate Bank." These carbonates may have provided the brittle floor from which the Ouachita rift was to form — a rift to accommodate the well-known "Ouachita facies." The rift likely formed during the Ordovician, at which time it began to be filled with Simpson-equivalent detritus, from sources in the south. For example, traditional Simpson paleogeographic reconstructions for Oklahoma and Texas show the southern edge of the North American craton to be occupied by open ocean (Iapetus Sea). Some geologists equate the edge of the craton to be the South Ozark Platform, and the ocean to be the Ouachita Trough. Studies in this report, however, require not the construction of a southern ocean at this juncture, but a large "sourcing" landmass such as shown in Figures 20-22, north of which was located the Ouachita Trough.

The Ouachita Trough is therefore envisioned as a narrow, restricted and rift-like trough bordered by land to the north (South Ozark Platform) and a craton to the south. Lowe (1989) shares a similar conclusion and places the Ouachita Trough south of the "Great American Carbonate Bank" of the South Ozark Platform and north of an inferred "disjoined" craton. The name given to the craton south of the Ouachita Trough is "Texarkana Platform," a name originally proposed by Paine and Meyerhoff (1970). The Texarkana Platform was principally a source area, or landmass, that was exposed at various geomorphic configurations and elevations throughout most of Paleozoic time. During the Simpson, for example, it was a low-lying cratonic landmass similar to that of the Texas Arch and Ozark Dome. Another craton-like land area is present in Mexico bordering the Marathon Trough and Tobosa Basin of Texas where it is given the name Oaxaquian Grenville Terrane (OGT). The Ouachita Trough extends northeast to Arkansas where it merges with the Reelfoot Trough. From interpretations of subsurface data in Prairie County, Arkansas, (Suhm, 1978, 1997) Ordovician carbonates precipitated in the shallow and warm-water marine system at the junction of the

Ouachita Trough with the Reelfoot Trough. This portion of the Reelfoot Trough had somewhat limited circulation and, in consideration of thickening, deposition was continuous from Arbuckle to Simpson time.

From studies of boulders and pebbles in the Johns Valley Formation, a Ouachita facies, Shideler (1970) states that a shallow marine Simpson depositional system, similar to that of the South Ozark Platform, may have been positioned on the northern shelf edge of the Texarkana landmass — mainly to account for numerous Ordovician-like possibly ice-carried limestone fragments in the Johns Valley shale. A similar shallow marine system may have been present east of the disjoined craton at the present-day location of Mississippi, at least during Ordovician time, rather than a deep Ouachita-like rift as illustrated by Lowe (1989). Additionally, Suhm's studies and those of Hale-Erlich and Coleman (1993) suggest that western Mississippi was the depositional site for Ordovician cratonic carbonates rather than lithologies characteristic of "Ouachita facies" (referred to as "western Mississippi slate belt"). Rift development in western Mississippi, however, may have taken place after Ordovician time to account for the presence of younger Ouachita-like rocks in this area. East and south from Mississippi, sialic and mafic source areas (here labeled Incipient Taconic System), provided terrigenous material to the Appalachian Basin. Perhaps K-bentonites in the Arbuckle and Simpson Groups in Oklahoma owe their origin to volcanism in this area, as do the bentonites in the Knox dolomite (Kolata, et al 1996).

Other significant paleogeographic features interpreted from isopach maps included in this publication show that the topography in the area of the Ozark Dome affected the location of sand transport corridors originating from the Canadian Shield. It is envisioned that the Ozark Dome consisted of low carbonate hills in northwest segments, now central Missouri, whereas in southeast and southern sectors it was partly submerged and termed South Ozark Arch and South Ozark Platform. The Ozark Dome may have been separated from the South Ozark Arch/Platform by a southwest-northeast trending basement fault termed Southwest City Fault by McCracken (1964) shown as a black line on Figures 20-22.

EARLY SIMPSON

As shown in Figure 20, lowest levels of the sea existed in earliest Whiterockian time. Quartz sand was derived from a braided stream complex east of the Ozark Dome, and carried by longshore and tidal currents southward into Arkansas to form the Calico Rock barrier sand complex. The absence of appreciable quantities of clay, in not only early Simpson sandstones such as the Calico Rock but all Simpson sandstones and strata on the South Ozark Platform in Oklahoma, is explained by invoking source rocks consisting of Cambrian sandstones relatively free of clay. The characteristic pitted, frosted, and rounded grains found in all high-quartz Simpson sandstones may have been due to uncushioned grain impact during eolian winnowing of clay and silt. It is further interpreted that Calico Rock sand was carried to the southernmost edge of the South Ozark Platform where it adjoins the recently-formed Ouachita Trough. At this location, sand "spilled over" into the Ouachita Trough to comprise the Crystal Mountain Sandstone. Interestingly, the Crystal Mountain Sandstone has locally-developed conglomerates with granitic and Arbuckle boulders that apparently were derived from the erosion of upthrown blocks of the Black Springs Horst at the south edge of the South Ozark Platform. The Ouachita Trough was "starved" and filled with south-derived euxinic muds and thin beds of limestone to comprise younger strata of the Mazarn, Blakely, and Womble that are equivalent to the Oil Creek, McLish, and Bromide, respectively.

The Calico Rock barrier complex of Arkansas extended into eastern Oklahoma where it is informally called the basal Joins sandstone. Lagoons and bays landward from the barrier were sites of deposition for carbonates and thin beds of sands that comprise the Joins and Everton Formations. Low species diversity, consisting mostly of gastropods and ostracods, indicate that the sea was periodically restricted in circulation, likely with high salinities and temperatures that hindered the growth of browsing and burrowing organisms. Intertidal sediments were periodically reworked to generate intraformational conglomerates and scour-and-fill contacts. "Primary" dolomite, lime mudstones, and quartz sandstone were likely deposited in supratidal, sabkha-like tidal-flat environments typical of arid zones (Suhm, 1974). Under higher energy conditions coarse-grained intraclastic, oolitic, and pelletal carbonates accumulated in intertidal to shallow subtidal environments. Carbonates in front of the barriers, and behind, commonly have scattered or '"floating'" quartz grains that were wind transported from nearby sand complexes. Later, but still during early Simpson time, sea levels continued to rise and the Calico Rock Sandstone and basal Joins sandstone were buried by sand and sandy carbonates. A second flood of sand originating from the north resulted in deposition of a sand barrier complex consisting of the Newton and Burgen Sandstones and the basal Oil Creek sandstone. Sand of the Newton and Burgen even filled sinkholes developed in karsted parts of the Sneeds Dolomite (Joins) and Arbuckle at places in the western Ozark region (Purdue, 1907). The basal Oil Creek barrier was 50 mi wide and 200 ft thick in Arkansas but expanded to over 100 miles wide and 400 ft thick in Oklahoma at the junction of the South Ozark Platform with the Anadarko/Ardmore Basin in what is now the Arbuckle Mountain region (Figure 18). As water depths increased toward the basins, southwest transport of sand slowed. Additionally, isopach maps show that the direction of currents changed at the edge of the platform; sand was redirected by longshore currents to the northwest in shallow water parallel to the edge of the deep-water basins. Adjacent coeval limestone, often with windblown "floating" quartz grains, contains a benthic faunal assemblage indicative of normal-marine salinities and circulation.

The Ardmore, Anadarko, and Fort Worth Basins were interconnected and bordered by growth faults at places, and their open seas accommodated thick sections of marine limestone and shale of the Oil Creek shale. Clay in the Oil Creek represents the first incursion of significant amounts of clay into Oklahoma, and from well logs used in this study, it is likely that clay originated from nearby sources, such as from weathered terranes, on the Transcontinental Arch and Texarkana Platform. The Canadian Shield contributed minor amounts of clay. Additionally, the Texas Arch was far removed from terrigenous contamination, with the exception of eolian contributions represented by sandy intertidal to shallow subtidal lime grainstones of the Joins. Farther west from the Texas Arch, in the Tobosa Basin of west Texas, the Connell Sandstone, an Oil Creek equivalent, consists of quartz grains recycled from the Cambrian Bliss Sandstone that was exposed on the Pedernal Massif (Wright, 1965; Suhm and Ethington, 1975).

Near the end of Oil Creek time, the influx of terrigenous clay in the Anadarko and Ardmore Basins diminished. Turbid environments were replaced by clear, shallow-marine waters favoring the development of carbonate banks consisting of oolites, lime mudstone, and stromatolitic limestone. The limestone is referred to as "Birdseye," an informal subsurface name that, in this study, replaces the Pruitt Ranch Member of the Oil Creek Formation. Depositional rates of carbonates in the Ardmore and Anadarko Basins kept up with, and sometimes exceeded, subsidence of the basin, resulting in shallow-water Birdseye limestones over 200 ft thick. Likewise, in northern Arkansas, the sea became shallower and more protected following the Newton/Burgen sand invasion. Sedimentation exceeded subsidence and beds of supratidal dolomitic sandstone of Member C (Everton/Joins) and chenier sandstone of the Jasper Member (Everton) were deposited in what is interpreted as an area that was dominantly arid. Sandstone in the upper Everton consisted of quartz that was probably derived from local sources, such as from the erosion and reworking of exposed older Newton and Calico Rock sands in the area of the Ozark Dome. Strata such as these, in Oklahoma and Arkansas, provide compelling evidence for climate change toward aridity, an aridity that was going to continue in Middle Simpson time during deposition of the McLish and the well-known "desert" sandstones of the St. Peter. Wind-swept dust from desert landscapes may have facilitated widespread precipitation of calcium carbonate through nucleation (Swart, et al (2014).

MIDDLE SIMPSON

Shown in Figure 21, sand dunes were distributed across the Midcontinent at lowstand positions at the beginning of McLish and St. Peter deposition. The lack of an effective soil cover on the continent was conducive to eolian erosion and transport of quartz grains likely derived from the disintegration of Cambrian sandstone and other rocks on the Canadian Shield. In Arkansas, sand from the north entered the sea at a shoreline position similar to that of the older Calico Rock sand. St. Peter sandstone is absent in the Reelfoot Trough due to facies change to carbonates; there was no apparent depositional pause in the transition from Everton to St. Peter. Pre-St. Peter erosion, however, did take place farther west on the South Ozark Arch creating a disconformity with as much as 20 ft of erosional relief on the underlying Jasper Member of the Everton Formation. The St. Peter sand sheets, most of which were reworked by transgressive marine processes, spread westward by longshore drift into Oklahoma where the sandstone is known as the basal McLish sandstone (Figure 20). Sand mixed with the more dominantly marine lime of the McLish at its fringes. The southern limit of the McLish sandstone in Oklahoma and St. Peter in Arkansas is unknown. However, in southeast Oklahoma and south Arkansas it is likely that the sand spilled over into the Ouachita Trough to become known as the Blakely Sandstone.

In Major County, during the Oil Creek-McLish transition, a meteoroid hit the shallow water of the Oklahoma Shelf to create an impact crater 10 miles across. Marine clay of the McLish filled the crater (Repetski, 1997). Cross Section E-E' published here as Plate 14 and log sections published by Coughlon and Denney (1993) are helpful in understanding the origin and timing of the impact feature. The impact did not cause noticeable change in the climate since there was little lithologic change within nearby depositional provinces. The crater can also be identified on several maps included in this publication by the circular distribution of Arbuckle production from the rim of Ames Crater (T. 19-20 N, R. 20-21 W.).

The basal McLish sand accumulated to thicknesses of 150 ft, an amount somewhat thinner than sandstones in the Oil Creek or Bromide Formations. Thickest McLish sand accumulations are found at the southwest edge of the South Ozark Platform near the Ardmore Basin. Some of this westward moving sand spilled into the Ardmore Basin, but most was redistributed to the northwest by a shallow current system paralleling basin margins on trend with a feature which was to become known as the Nemaha Uplift. Following deposition of basal McLish sandstone, younger McLish and Tulip Creek sediments were deposited under rising sea levels. Tulip Creek sands consist of new sand influxes of quartz that came from the north and older reworked Newton sandstones (Everton) that were exposed on the Ozark Dome. From the area of the Ozark Dome, southwest-moving current systems carried Tulip Creek sand into epeiric seas of central and southern Oklahoma, where sand fanned out in a deltaic or subaqueous fan configuration. Sand supply was so great that some of the sand began to fill the Anadarko and Ardmore Basins. The Tulip Creek sandstone is thick in eastern parts of the Anadarko Basin but absent to the west where water was deeper. Tulip Creek sandstone is thin to absent in shallow-water environments of the Texas Arch. In the Tobosa Basin of west Texas, the Waddell Sandstone was deposited as a basal McLish sandstone equivalent. This was followed by deposition of the thicker McKee Sandstone, a Tulip Creek equivalent (Wright, 1965).

LATE SIMPSON

Figure 22 shows that the tectonic fabric of the Midcontinent region changed in Bromide time. The Nemaha Uplift in northeastern Kansas and southeast Nebraska is interpreted to have experienced its first growth in Bromide time (Lee, 1943). The Ozark Dome and the South Ozark Arch were elevated above sea level, as was perhaps flanks of the Texas Arch. The combination of localized uplift, higher sea levels, and regional changes in source areas had the effect of nudging sand transport corridors to the west, and for the first time, west of the Ozark Dome. In contrast to earlier sand invasions, a linear sand body originating from the Canadian Shield, referred to as the Starved Rock barrier complex of the St. Peter, consisted of sand that was carried southward and westward by strong tidal and longshore currents at locations between the ancestral Nemaha Uplift in Kansas and the Ozark Dome of Missouri into central Oklahoma. Minor amounts of sand may have originated from the erosion of earlier St. Peter-like sandstones exposed on the Ozark Dome. St. Peter-like sandstone interpreted to be Starved Rock/Bromide was encountered in thicknesses over 400 ft apparently as a channel sand in Johnson County in northeastern Kansas (McQueen and Greene, 1938, p. 42). In Grady County, Oklahoma, Flores and Keighin (1986) report that Bromide sand filled low-relief subaqueous channels. The Bromide displays fining upward sequences, cut-and-fill structures, and shale-pebble conglomerates, all of which are seemingly reserved for turbidites of deep-water submarine fans. Water depths in this area, however, were probably less than 150-200 ft. Maximum Bromide sand thicknesses are located near the junction of the Oklahoma Shelf with the Anadarko Basin in central Grady and Canadian Counties, Oklahoma. Here, Bromide sandstones thicken to over 300 ft in an area termed the "Canadian County Sub-basin." Overlying Bromide limestones also thicken. Relative to Bromide thicknesses nearby, this amount of thickening is suggestive of the development of not only a syndepositional basin but its position west of the Nemaha Fault suggests that the Nemaha may have been a "deep fault," or basement fault, that facilitated syndepositional movement. Similar structural movement in the vicinity of Garvin County, Oklahoma at about the same time is confirmed through "seismic interpretation" (Figure 26 to be discussed later).

From the illustration in Figure 22, the almost triangular geometry of the Bromide sand has the appearance of filling the Anadarko and Ardmore Basins, as if having been confined to those basins at a syndepositional fault located along the Anadarko Basin/Texas Arch Hinge. A few miles north of the hinge in the area of the Slick Hills in Kiowa County, Bromide sandstone outcrops show cross-bedding, that, according to Donovan, et al (1991), suggest that currents flowed northwest and also southeast, parallel to the strike of the Anadarko Basin, perhaps confirming the interpretation taken in this paper that the Anadarko and Ardmore Basins were connected with a larger seaway in the Fort Worth Basin. Clay in the basins likely originated from the Texarkana Platform. Adjacent to the low-lying land area of the Texarkana Platform, but within the Ouachita Trough, larger amounts of black organic clays are represented by the Womble Shale. In southern and western Oklahoma limestone and shale interfinger with sandstone at the periphery of the main sand body. Sand is scarce in the Ardmore Basin and Bromide shales are stacked above shales of the underlying Tulip Creek. Much of the green shale that commonly marks the top of the Bromide Formation across large parts of Oklahoma indicates a northern source. Clay within green-shale partings seen in shallow marine "Plattin" limestones in the Ozark region of northern Arkansas was similarly sourced from the north.

POST-SIMPSON AND VIOLA

At the end of Whiterockian time seas receded and Simpson deposition ceased. Source areas of the Canadian Shield and Transcontinental Arch had been beveled to a peneplain, effectively cutting off the supply of terrigenous material to basins in the interior of North America. The Ozark Dome was slightly positive with the effect that older Bromide and Tulip Creek sandstones were exposed to erosion thereby providing a local source of sand to comprise the lower Viola Seminole sandstone. The geographic position of the Seminole sand body marks the approximate position of the earliest Viola shoreline at lowstand (Plate 10). The Harding Sandstone in Colorado, a time-stratigraphic equivalent of the Seminole sandstone, appears to have been deposited in similar transitional environments (Maher, 1950; Allulee and Holland, 2005). Interestingly, not only are Harding and Seminole sandstones similar in age, but both were (and perhaps still are) erroneously thought to be Simpson equivalents rather than Viola. Regardless, both of these Viola-age sandstones are overlain and overstepped by shallow marine Viola carbonates. Viola seas invaded vast areas of the Midcontinent, including the Transcontinental Arch, prompting Ross (1976) to call this oceanic encroachment the greatest inundation in North American history, perhaps second to the "Great American Carbonate Bank" of Late Cambrian time.

PART 2

SIMPSON EXPLORATION

VIOLA STRUCTURE MAP

Although younger than the Simpson Group, the Viola Group has been discussed numerous times throughout this report, in the context of both academic geology and exploration. In fact, the Viola is illustrated on all cross sections included in this report. An isopach map of the total Viola group thickness is not shown as a separate map in this report, but it is combined (as background) with the Seminole sandstone isopach map (Plate 10). Viola thicknesses are also included on an Excel spreadsheet as supplemental material within this report.

Early geologists studied and named formations of the Viola Group from outcrops in the Arbuckle and Ozark Mountains. However, it was found that these formations could not be readily traced into the subsurface and correlated. They were less than 100 ft thick and lacked physical characteristics that allow them to be distinguished on electric-logs, therefore, no attempt was made to correlate those formations across Oklahoma. Conversely, however, the Viola as a "Group" along with its overlying companion, the Sylvan Shale, are readily recognizable as a pair and were easily "picked" from "electric" logs across most parts of Oklahoma. Viola limestone has been used as a subsurface datum for Ordovician structure at least since 1920 when the Simpson was found to be oil-bearing (Levorsen, 1928).

The contact of the Viola with the Bromide is unconformable and at a sequence boundary known as the Katian unconformity. In the subsurface, however, this contact is not always clearly defined from well logs and may be questionable in some areas, such as where the basal sandstone of the Viola called the Seminole sandstone (erroneously called "1st Wilcox") is in contact with Bromide sandstones, or where limestones of the Viola and Bromide are lithologically similar. The unconformity is more likely to be seen in a regional sense, such as the Viola's progressive overstep of gently tilted beds of the Simpson in a direction toward the Ozark Arch as shown on cross sections (Plates 12 and 13). A similar overstep relationship is seen from well logs on the Texas Arch in the Hollis Basin, and also in west Texas at the western edges of the ancient Tobosa Basin where the Montoya (Viola) oversteps the Simpson (Suhm and Ethington, 1975) shown on Figure 2 and Plate 12. Overall, however, the contact of the Simpson with the overlying Viola was identified on most well logs without conflict.

The Viola structure map on Plate 15 was compiled from unpublished structure maps provided during exploration endeavors and from structure maps compiled from an interpretation of seismic data. Seismic mapping, even when tied to existing wells, is highly interpretative, therefore, the structures and depths that appear on the Viola structure map may contrast with interpretations of other geologists and geophysicists. The Viola limestone was used as a mapping datum because of its seismic clarity. It is also used as a proxy for Simpson, and even Arbuckle, structure since the geometry of structures, and faults of the Simpson (and Arbuckle) are similar with those of the Viola. Moreover, an Excel spreadsheet shows thicknesses for the Viola, which can be added to the Viola subsea values on Plate 15 to create an approximation of Simpson structure. Similarly, an Arbuckle structure map can be constructed when Viola and Simpson thicknesses are added to Viola subsea values.

The Viola structure map is useful to explorationists because it is a viable reservoir and exploration target. The Viola is a common datum for most of the pre-Pennsylvanian structure maps compiled by explorationists because it is readily recognized on logs and serves as a proxy for Simpson structure. Further, for better well control, hence accuracy, Viola depths can be estimated in wells that did not penetrate the Viola, such as those drilled to the Hunton Group or Sylvan Shale if their respective average thicknesses are known.

Seismic visibility of the Viola reflector is due to the presence of velocity contrasts between overlying and underlying formations. Contrasts from "hard" to "soft" strata produce unique reflector packages that are readily seen and correlated on most 2D data. However, where the Simpson lacks low-velocity shale and porous sandstone (or dolomite) the reflector packages are commonly less noticeable. Reflector packages are commonly absent in carbonate-dominated sections, such as within and between the Simpson, Arbuckle, and Viola in the Arkoma Basin and portions of the Cherokee Platform. Conversely, velocity differences are present in the Simpson in parts of central and southern Oklahoma to allow separation from the Viola and Arbuckle, and even specific formations within the Simpson. Three dimensional (3D) seismic data, with corresponding higher resolution, does allow a degree of confidence in differentiating both structural and stratigraphic features not apparent with 2D data. Also, 3D mapping will more accurately show structural configurations and positions of the crests, relying less on interpretations of geophysicists. In some areas of Oklahoma the locations of crests in formations of the Simpson may shift with depth, thereby affecting the mapped drilling locations. For example, the location of the Oil Creek crest might be different from the crestal location for that of the Bromide, such as shown by Smith (1997). The amount of structural closure, expressed in feet, may also be slightly different for specific Simpson formations. Anomalous relationships such as these might be due to local variations in the timing of structural forces taking place during Simpson time.

Viola structure is combined with subcrop information (Plate 15). Subcrop maps show locations of particular formations (or groups of formations) that are thin or absent beneath unconformities. For example, structural activity such as uplift and faulting might have taken place after deposition of the Viola (or Simpson) resulting in partial to complete subaerial erosion of those groups, shown as gray patterns on the Viola structure map. Eroded landscapes in the gray area were buried by younger Pennsylvanian, Morrowan, and Woodford strata of varying thicknesses. Subcrop patterns are helpful in unraveling the structural history of an area. Subcrop data shown on the Viola structure map was derived from published and unpublished geologic maps and subsurface information, including unpublished seismic data. Subcrop patterns have an exploration value that enables interpretation of structural features such as anticlines, fault blocks, and fault trends that may be potential oil and gas traps. On most isopach maps included in this report, Simpson subcrop patterns follow, and are usually parallel with, contours labeled "truncation limit." Potential drilling sites might be present at or near the updip termination of subcroped reservoirs, especially at structurally high positions, not only in the Simpson, but in younger beds. Additionally, subcrop information included here might enable projected tops of Simpson formations to be more accurately predicted before a well is drilled, or, during the course of drilling the well. Projected formation tops would be less (shallower) where the Viola is thinner due to partial erosion within the subcrop belt or absent altogether. Caution should be exercised, however, during drilling (before electric logs are run) since the contact between the Viola and Simpson may be difficult to pinpoint from drill cuttings — especially if the lower Viola consists of a sandy facies of the Seminole sandstone, which could be easily mistaken for sandstone belonging to the Simpson. Such a miscalculation may render Simpson structural targets to be deeper than anticipated.

Simpson production shown on the Viola structure map is classified by color according to specific formation. Wells productive from the Seminole sandstone/dolomite (lower Viola) are also indicated, as are wells that are productive from the Arbuckle. Overwhelmingly, most Arbuckle production is from uppermost carbonate reservoirs where secondary porosity may have been generated from weathering and erosion taking place at sea level lowstand at the Sauk/Tippecanoe contact. Names of some of the larger oil and gas fields are on Plate 15. All fields mentioned in this report, however, are shown on Figure 28. Additional information about oil and gas fields can be found on maps prepared by Boyd (2002a and 2002b), and Pritchett (2015).

Absence of Ouachita Mountains Explained

The Viola structure map was constructed from a multitude of Viola maps Suhm prepared during the course of exploration activities in Oklahoma. Thousands of miles of seismic data were examined and tied with subsurface information available from nearby wells. It was found that various "reflector packages" seen on seismic lines were characteristic of certain groups of rock formations, especially those that displayed different densities and sonic velocities. Velocity variations generated seismic contrasts which produced readily-seen reflector packages. Noteworthy is the package that consists of low velocity Sylvan Shale sandwiched between high velocity carbonates of the Hunton and Viola, or, the package created by the low velocity Woodford between the Sycamore and Hunton. In the Arkoma Basin, two seismic packages predominate, the Atoka/Wapanucka/Cromwell reflector set and the Woodford/Hunton/Sylvan package (the Viola is below the Sylvan). Both of these two seismic packages were traced across the Arkoma Basin, and from long seismic lines that extend southward into the Ouachita Mountains, the Woodford/Hunton/Sylvan reflector package was found to extend beneath the thrust sheets of the Ouachita Mountains. Similarly, but within the Ouachita thrust complex, their equivalents, Novaculite (Woodford) and Bigfork Chert (Viola), form a seismic couple (reflector set) that exhibits a structural style that vividly contrasts with the more competent subthrust (platform) section. Consequently, the Viola on the South Ozark Platform was mapped under the thrust, and in order to illustrate it, the Ouachita thrust complex was removed from the Viola structure map. The structurally lowest part of the Viola under the thrust is within a broad graben located in the south part of the South Ozark Platform (Atokan strata of the Arkoma Basin overlie the Viola). The name "Antlers Graben," taken from the nearby town of Antlers in Pushmataha County, is applied to this feature to denote the structurally lowest part of the "Morrowan-deformed" South Ozark Platform ("Arkoma Basin"). At depths estimated to be greater than 40,000 ft below sea level, the Antlers Graben represents a complex of grabens and horsts, large and small in both areal extent and vertical displacements. Although well control is limited, the Simpson and Viola do not appear to appreciably thicken into this graben, thus ruling out the presence of any apparent syndepositional activity that might be indicative of a depositional basin. From interpretation of seismic data and stratigraphic analyses, it was determined that the Antlers Graben formed during Morrowan time after Caney deposition, at a time shortly before the advance of the Ouachita thrust sheets; in fact, subsidence or collapse of the Antlers Graben may have facilitated a northward advance of the thrust sheets. The syndepositional Arkoma Basin formed later during Early Pennsylvanian shortly after the cessation of movement of the Ouachita thrust complex. The western edge of the Antlers Graben is located at the junction with the much younger Tishomingo Horst at or near the Sulphur Fault Zone (Plate 15). Southward from the axis of the Antlers Graben, the Viola gains structure (becomes shallower) to a position that marks the southern edge of the South Ozark Platform at a feature named in this report as "Black Spring Horst" (or Ridge), a paleohigh presently under Ouachita strata of the younger Ouachita Broken Bow Uplift (Suhm and Campbell, 2001). The subcrop pattern in this area is one of the largest in Oklahoma, and may be hydrocarbon-bearing in a fashion similar to the "buried hill" trap of Zhao, et al (2015). Wells drilled by Hunt Oil confirm the subcrop interpretation seen on the Viola structure map. Additionally, the presence of granite boulders and arkose in the Blakely Sandstone (McLish equivalent) in outcrops in Arkansas provides evidence that the Black Springs Horst, or its structural counterpart in Arkansas, may have existed as an Ordovician paleohigh (Stone and Haley, 1977; Bowing, 1984; Thomas 2012).

It is not the intent of this paper to discuss the origin of the Ouachita Mountains, but a short discussion is warranted to explain its absence on the Viola structure map (Plate 15). Consensus opinion, mostly derived from subsurface data, is that the "Ouachita facies" had been horizontally transported a distance of about 100 miles from their origin in the Ouachita Trough located in Texas and Arkansas and, from what few reports and seismic information have been published, lateral movements are commonly ascribed to have been the result of plate collision, subduction, or other compressionally-driven force. However, an alternative interpretation is proposed in this paper, principally resulting from field work in the Ouachita Mountains and extensive subsurface studies of stratigraphic and sedimentologic relationships between "Ouachita" facies and underlying "platform" sedimentary successions in conjunction with seismic exploration. The importance of excessive vertical tectonic movements on the South Ozark Platform, in combination with the availability of glide planes within incompetent strata of the Ouachita facies, such as Womble or Mazarn shales, cannot be overstated. Interpretations derived from recent deep wells and seismic lines bring to fore the logical conclusion that gravity may have been the primary force for large-scale horizontal movement of incompetent Ouachita strata. Further, early large-scale vertical movements, as they affected burial depths, provide an explanation to the anomalous, if not enigmatic, distribution of oil and gas within the Arkoma Basin -- such as gas being present at locations downdip, rather than updip. This will be discussed later along with illustrations of deep faults (Figure 33).

Data from the Chesapeake No. 2-34 Mary provide supporting evidence for many ideas that follow. This outpost well, drilled to a depth of 26,100 ft in the Ouachita Mountains, Latimer County, Oklahoma, has a near complete subthrust section consisting of strata deposited on the South Ozark Platform. In the subthrust section, the No. 2-34 Mary penetrated 600 ft of upper Arbuckle carbonates overlain by shallow marine Simpson strata amounting to a thickness of 1,200 ft. Above that are 1,500 ft of platform deposits consisting of shallow marine Viola, Sylvan, Hunton, Woodford, and Caney strata. From a structural standpoint the striking feature about this well is that this relatively thin platform sequence (3,300 ft) is beneath an impressive 22,800 ft of relatively flat lying Stanley and Jackfork (equivalent to the

Caney and Mayes) that was originally deposited 100 miles to the south in the Ouachita Trough. The thrust fault at 22,800 ft at the top of the Caney provides an opportunity to contemplate structural relationships between the Ouachita facies and Arkoma Basin (Antlers Graben) platform facies. For example, in order to enable accommodation of this thick Ouachita succession at this locality, it is apparent that the pre-Atokan platform sequence had to have been lowered 22,000 ft below sea level by a Morrowan structural crustal "collapse," in part accomplished by deep faults. The collapsed area is coincident with an anomalous gravity minimum (Figure 33B). Large-scale uplift exceeding 5,000 to 10,000 ft took place in the area of Texarkana Platform south of the Ouachita Trough. Erosion of this uplift provided detritus for the Stanley, Jackfork, and Johns Valley that was carried to and deposited in the Ouachita Trough. Shortly after Stanley and Jackfork deposition, the Texarkana Platform was further uplifted, along with southern segments of the Ouachita Trough. At the same time, but north of the Ouachita Trough, the South Ozark Platform "collapsed," mainly along deep faults at or south of the red line on Figure 23A and B. These vertical faults, in both the collapsed and uplifted areas, have displacements of thousands of feet and are similar to deep faults described in other parts of the world by Beloussov (1962, p. 628), "These zones of subsidence and uplift next to faults seem to indicate that when forces deep within the earth attempt to draw the crust downward or to uplift it, they make use of primary deep faults as weaker surfaces along which to concentrate the most intensive uplift or subsidence, or both alternately. The origin of these primary deep faults and of the primary divisibility of the earth's crust is completely unknown." The simultaneous occurrence of this exaggerated vertical activity — estimated to be a lowering of 10,000 ft of the South Ozark Platform and 10,000 ft of uplift on Texarkana Platform — allowed the thick and mostly plastic strata within the Ouachita Trough to be uplifted and to "gravity" slide toward the accommodation space within the Antlers Graben of the South Ozark Platform. Combined vertical relief of 20,000 ft provided sufficient enough gravitational imbalance to cause horizontal movement; this en masse 100-mile movement was not severely impeded by obstacles, but rather, facilitated by glide planes in plastic shales of the Womble (Simpson) and similar shales. Movement is envisioned to have been gradual, taking place in pulses over millions of years, the result of gravitational response to changing vertical movements. Horizontal movement in Arkansas was considerably less than that in Oklahoma (compare illustrations in Figure 23). Interestingly, within an exploration context, there is the expectation that autochthonous potential reservoir targets may be present and preserved at the north edge of the ancestral trough adjacent to the South Ozark Platform in the southeastern corner of Oklahoma. Depths to potential objectives, however, would be greater than 20,000 ft.

In sum, extensional processes of exaggerated vertical uplift of the Texarkana Platform coincident with large-scale subsidence of the South Ozark Platform was critical in creating an imbalance great enough for the Ouachita stratal complex to gravity slide northward to its present position in southeastern Oklahoma and Arkansas. Many questions remain unanswered. Assuredly, the structural history of the Ouachita Mountains is going to be difficult to resolve due to the near absence of pre-Pennsylvanian well penetrations, here, and in the area of the Sabine Uplift (Texarkana Platform). Lack of subsurface data enables differing paleotectonic interpretations; therefore, it is in the tradition of Alpine geology that the one proposed above is introduced. For additional discussions of the history of Arkoma Basin and Ouachita Mountains, including several views opposing those presented here, see Buchanan and Johnson (1968), Hardie (1990), Lowe (1989), Suneson (2008), Jusczuk (2002), Milliken (1988), and Golonka, et al (2006). The Oklahoma Geological Survey is actively engaged in Ouachita Mountain research.

SIMPSON PRODUCTIVITY

The Simpson Group is one of the most prolific oil and gas reservoir systems in Oklahoma. Moreover, Simpson reservoirs have out-produced those in the Hunton and Springer groups, and interestingly, in terms of oil volumes rather than gas, the Simpson compares almost equally with the Deese Group (Figure 24). Further, when one compares the number of wells required to extract that much oil, it took fewer wells to produce oil from the Simpson than the Deese. The Simpson Group is an outstanding exploration and development objective. Prolificacy of the Simpson Group in Oklahoma is due to the favorable combination of 1) reservoir quality and thickness, 2) abundance of structural traps, 3) availability of source beds, and, 4) suitable burial depths/temperatures.

Lithology and Porosity

The principal focus of this paper has been with mapped distribution of thickness and porosity of individual Simpson reservoirs (Plates 4-10). Quartz sandstones are emphasized since they are the most

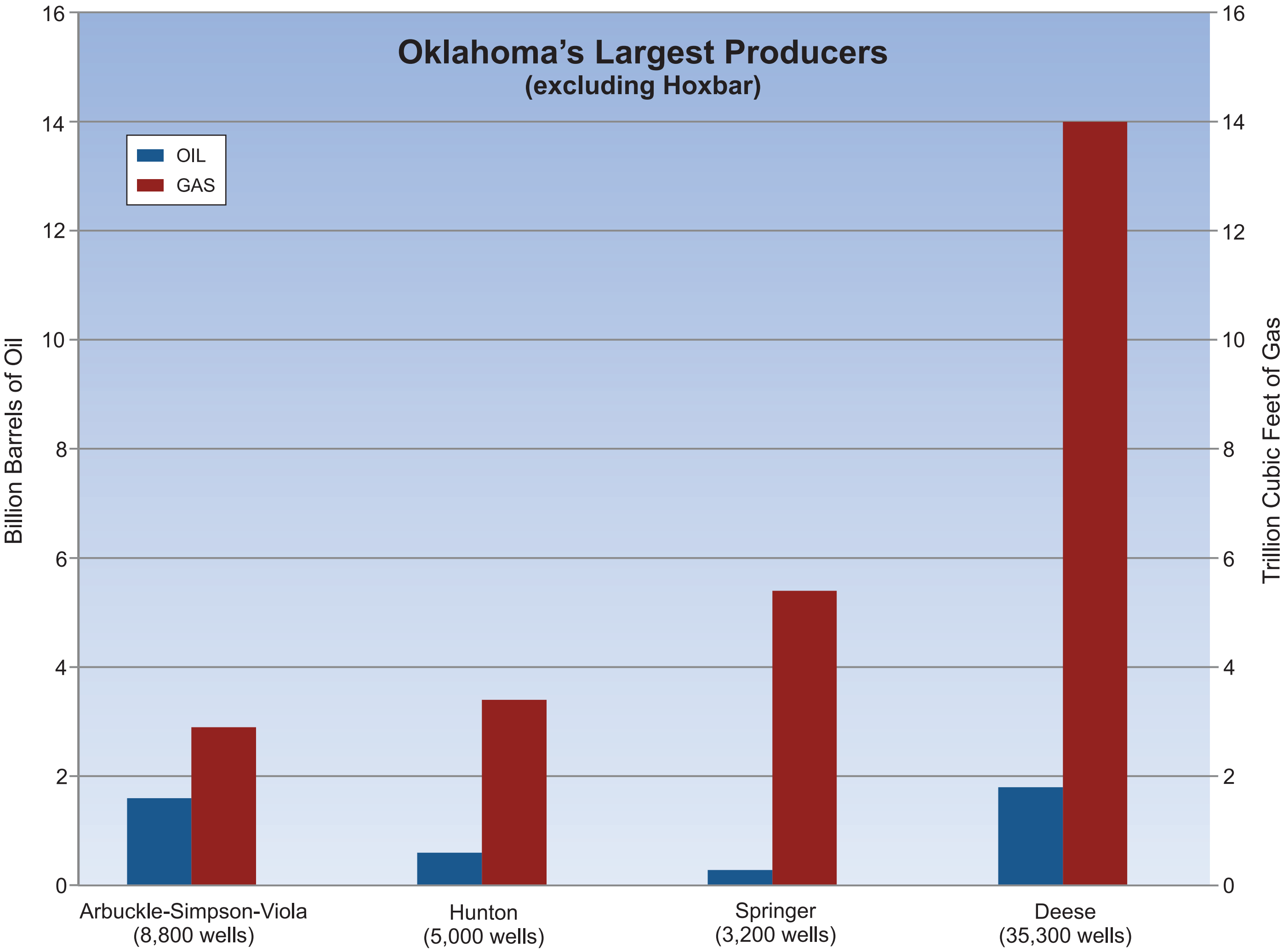


Figure 24. **Histogram of Simpson oil and gas production compared with Hunton, Springer, and Deese. Simpson oil recoveries, when combined with Arbuckle and Viola, have "out-produced" the Hunton and Springer Groups and compare almost equally with oil recovered from the Deese Group.**

prolific conventional reservoirs of the Simpson Group. Sandstone porosities as high as 30 percent, often accompanied by permeability over 1,500 md, are responsible for unusually large per-acre recovery yields from the Simpson. This yield is comparable to that of other groups of rocks in Oklahoma, occasionally exceeding it. It is believed that early migration of hydrocarbons and their emplacement into Simpson traps may have had the effect of preserving porosity by inhibiting secondary mineral cements (Marchand, et al 2002; Bloch, et al 2002). However, other reasons for high porosity such as vagaries of the depositional environments and source areas as they relate to digenetic processes are put forth by Taylor, et al (2010). Specifically, in this regard, empirical data show that most of the productive Simpson reservoirs are located in areas proximal to ancient clay-bearing paleogeographic systems such as those found in the Anadarko and Ardmore Basins. Clay in basin waters would have been available to provide "coats" for quartz grains, much like dust rings. "Coats" may have retarded precipitation of pore-filing mineral cements. Bosco and Mazzullo (2000) report this effect from the presence of clays on quartz grains in Simpson sandstones in west Texas. In central Oklahoma, Abdalla, et al (1997; see fig. 7) provide examples of Simpson clay coats that inhibit mineral precipitation across a wide range of grain sizes. In sand quarries in the Arbuckle Mountains, Oil Creek and McLish sandstones are friable and especially porous due to these thin clay coats and the near absence of mineral cements, making them suitable for hydraulic mining. Similarly, within the Golden Trend, Eola-Robberson, and Cumberland oil fields and several other fields on the ancestral Oklahoma Shelf, porous Simpson sandstones were deposited in marine environments where clay was available for precipitation on detrital grains. Within the Golden Trend, in particular, micropores interspersed within the clay coats are capable of holding irreducible water (water tightly held because of physical attraction of the solid for the liquid). This produces a "wet-looking" resistivity profile on "electric" logs for oil-bearing sandstones rather than traditionally high resistivities for oil. Water saturations in some of these pay sands will invariably calculate high (>50%) which may be an incorrect indicator of the rocks' productivity, resulting in an absence of testing, or perhaps abandonment of the well (Schulze, et al 1985). Such wells might even be considered to be passed-over-production candidates opening up the possibility for recompletion of the wells. That is why it is important to look for other indications of oil to support the decision to "set pipe" and test. Specialists known as "mud loggers" can assist in the evaluation of oil shows in drill cuttings using chemicals and gas detectors, while service companies can perform DST's (drill stem tests) and other oil production tests. On a cautionary note, highly-porous friable pay sandstones in this area may be subject to formation damages during completion, but keeping production rates down with small choke size helps prevent the entrance of damaging and erosive formation water into the borehole. Consulting engineers with local experience are usually available to help with completion efforts.

Sandstone porosity is noticeably reduced in the Arkoma Basin. Apparently, porosity-preserving clay was not available to coat grains, plus, burial history was different. At depths exceeding 4,000 ft Simpson sandstones usually have low porosity and are considered "tight". Mineral cements consisting of calcite, dolomite, or silica, are commonly present in amounts that completely obliterate pore space. Here, and in other areas of Oklahoma, silica cements may have originated from pressure solution of detrital quartz grains with subsequent syntaxial overgrowth of silica (Bjorlykke and Egeberg, 1993). Because of this, deeply buried sandstones of Simpson are commonly "tight" in parts of the South Ozark Platform and the Anadarko and Ardmore Basins. Carbonate cements in Simpson sandstones commonly form later than secondary quartz overgrowths. Dolomite and calcite are common cements across Oklahoma. Higher porosity is to be found in dolomite- cemented sandstone.

Carbonate reservoirs within the Simpson are becoming increasingly important, especially with the advent of horizontal drilling and improved completion techniques. Fractured limestone, such as the upper Oil Creek "Birdseye" limestone is productive in broad areas in the Anadarko and Ardmore Basins of southern Oklahoma where multiple episodes of bending and faulting have produced secondary fracture systems. The Birdseye is as thick as 300 ft thick (Figure 19) and although not yet tested horizontally has characteristics that appear to make it a favorable target for horizontal drilling. Also, this hard and brittle Birdseye high-velocity limestone is positioned between low-velocity source shales, resulting in a readily identifiable reflector with which to correlate and map.

Carbonates, especially porous and permeable dolomite strata, are prolific reservoirs in structural traps. Pore space in dolomite originates through recrystallization of calcite (limestone), where, during replacement, large-sized calcite is replaced by smaller-sized dolomite, thereby creating intercrystalline porosity. Dolomite is identified from the neutron-density log. Dolomite displays a wide gap between the neutron and density curves; limestone has little-to-no gap, or separation. Also, most neutron-density logs are "run" by service companies that use a limestone matrix value of 2.68, rather than 2.87 for dolomite. This value imparts a porosity value for dolomite that is incorrect and different from values specified on log scales (found at the bottom and tops of logs). If the rock is determined to be dolomite (from cuttings), and logs can't be "run" again, subsurface geologists add a few percentage points to the porosity value. This will change calculated water saturations and increase the possibility of setting pipe to complete and test reservoirs in the well.

The best known and most prolific Ordovician carbonate reservoirs are dolomites in structural traps, especially dolomite that is associated with, and laterally proximal to, the Seminole sandstone of the Viola Group (Plate 10). Production has also been established from the "Joins" sandy dolomite facies north of the Oil Creek sand sheet in vicinity of the Nemaha Fault (Plate 4). Joins dolomite is also being exploited horizontally from wells in Love County near the Red River and from horizontal wells in the Oklahoma City Field — in dolomite identified as Joins by Decker (1935). Less well-known dolomite pay zones are present in the Joins and "Basal Oil Creek/Joins Interval" in other areas of the Anadarko and Ardmore Basins. Joins carbonates are productive in the Arkoma Basin where they rest within a few feet above karsted Arbuckle in Wilburton Field, Latimer County. Production that is reported as "Arbuckle" may be Simpson in part, such as within Healdton Field in Carter County, Apache Field in Caddo County, Oklahoma City Field, West Mayfield Field in Beckham County, and "Ames Crater" in

Major County. Correlation has shown that carbonate production in these fields is from both the lowest Simpson (Joins) and upper parts of the Arbuckle. When oil and gas field discoveries are made they are often in remote areas distantly removed from "control wells" or type sections. That, coupled with the stratigraphic complexity of Simpson formations, results in errors in reporting the correct name of the producing reservoir to the Oklahoma Corporation Commission, a state regulatory agency. Proximity of carbonates of the Arbuckle and Simpson with one another also invites confusion about stratigraphic identity, as is the fact that most Arbuckle hydrocarbons are positioned within its uppermost carbonates immediately below the Simpson. Arbuckle production shown on Plates 3, 4, 4b, and 14 may reflect, in a general sense, the distribution of karsted landscapes of the past. Be aware, however, that karst and the effects of karst are not necessarily confined to the Arbuckle. For example, carbonates in the lower parts of the Joins show the effects of karst as well. Perhaps that observation, along with similarity of porosity types testifies to a commonality of origin. Field studies of the Everton Formation (Joins/Oil Creek) in northern Arkansas show several karst related solution breccias about 100 ft above the Powell (Arbuckle) unconformity (Suhm, 1970, p. 116-117) Additional information about these breccias can be found in Turner, et al (2007). Presence of these breccias suggest that sea level was low during Everton deposition and that the carbonates were periodically exposed to subaerial weathering and dissolution. Carbonate porosity in this interval is intercrystalline and vuggy, much of it due to fracturing and brecciation associated with collapse of caverns in strata of basal Simpson or Arbuckle. Empirical data indicate that reservoirs with this type of secondary carbonate porosity can produce slightly off structure, unlike sandstone reservoirs with matrix porosity. Unfortunately, drilling to potentially karsted and brecciated reservoirs in lower parts of the Simpson is expensive because hundreds, if not thousands, of feet of often unproductive Simpson strata have to be penetrated to reach the objective. Add another 200-500 feet of hard and slow drilling through the upper Arbuckle to test potentially cavernous intervals. When one considers the total number of wells drilled in Oklahoma, relatively few wells have been drilled deep enough to test this potentially high-reserve reservoir system. Certainly, future wells should test this interval.

Structural Traps

One of the most important requirements for achieving high production rates from the Simpson Group is to select drill sites located on suitable structural traps. Structural traps such as anticlines, domes, and upthrown fault blocks account for an estimated 90% of Simpson production. For that reason it is important to accurately map subsurface features, but unfortunately, flat-lying Pennsylvanian and Permian strata overlie and obscure most of the deeper Simpson structural traps, often with angular unconformity. However, where the Simpson is at shallow depths, such as in the Arbuckle Mountain area, traditional surface geologic mapping can be employed to locate structures. SW Davis Field in Murray County was discovered from anticlinal outcrop patterns shown on geologic maps. Likewise, in the northern part of the Arkoma Basin, Mississippian strata on geologic maps have a structure that mimics structure of the Simpson; local thickening of the Mississippian, however, may distort the structural picture making the Simpson unattractive. Photogeologic and geomorphic maps that show interpreted subsurface structures from river drainage patterns and other topographic elements may be commercially available to the explorationists; however, based on dry hole information, they appear to offer little help in defining deep structures. On the other hand, positive results from geochemical and radiometric surveys may give some comfort to the operator drilling Simpson targets, but it may be more likely that positive anomalies originated not from a Simpson structural trap, but from one of many shallower stratigraphically stacked pay zones. Gravity and magnetic surveys may be helpful in locating structural traps, but leave unanswered questions about the depth and the magnitude and timing of the structural feature. Seismic data offer the best tool to use to locate drillable Simpson structures in Oklahoma. Previously-shot 2D data are readily available from brokerage firms. Seismic lines reprocessed from 100 percent field data (wiggly trace) are the least expensive, and may be the most difficult to interpret (in some areas) due to resolution problems. CDP (common depth point) seismic lines (2D) show improvements, are easier to interpret, but are more expensive. 3D-seismic data are the most expensive and, in most instances, easiest to interpret and correlate. However, in structurally complex areas, even seemingly sound 3D interpretations may result in a dry hole.

Simpson Group reservoirs are productive in fault-block traps, commonly with associated rollover. Faults are most always vertical and cannot be relied upon to trap and seal migrating oil and gas; for example, in extensional structural settings,

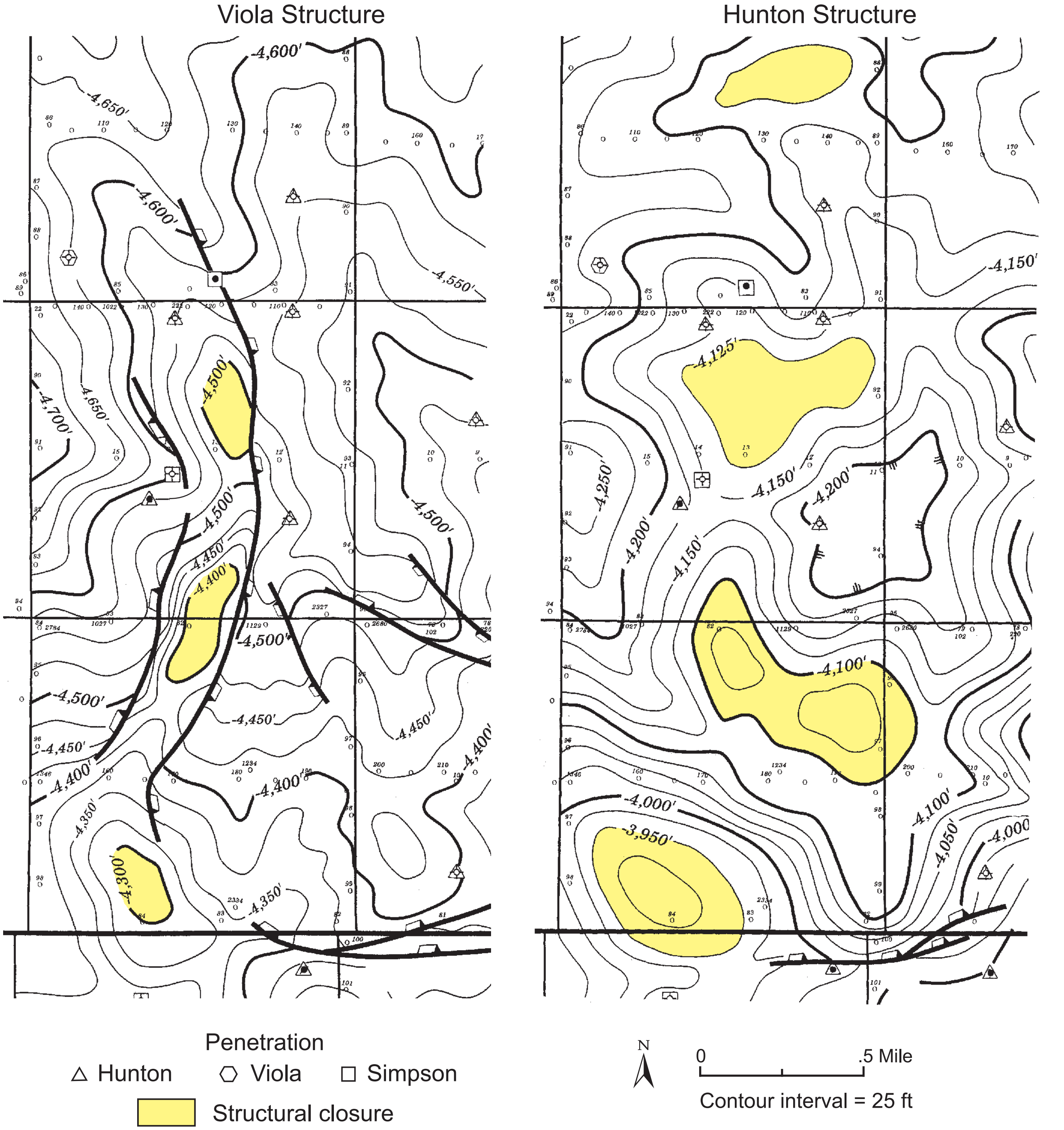


Figure 25. Timing of structural activity from structure maps on the Cherokee Platform. Structure maps for identical areas, but mapped on different horizons, are compared. Fault blocks shown on the Viola map are absent on the Hunton (base of the Woodford) map. This suggests that Viola (and Simpson) structures are "old" and, therefore, were likely to have captured hydrocarbons during early migration. Small dots represent shot points for 2D seismic lines that were used to construct the subsea structure maps.

such as that which prevails over most of Oklahoma, there is the possibility of lateral leakage. Experience has shown that most productive wells are those located on the upthrown sides of faults, rather the downthrown side. Additionally, by being upthrown, Simpson reservoirs would likely be "hydrocarbon-sourced" by favorable juxtaposition with beds on the other side of the fault. Hydrocarbons can originate from source shales of the Oil Creek (discussed below), or from shales of the Woodford, Caney, Springer, or Pennsylvanian, so any Simpson juxtaposition with these strata would be favorable for charging Simpson reservoirs. Brown staining or even slight "oil cuts" in Simpson sands are encouraging signs to explorationists but their presence may represent past episodes of oil migration pathways, and, not entrapment. Short or long updip migration of oil will cease in local traps, or in broad areas in northern and northeastern Oklahoma where Simpson reservoirs thin stratigraphically and approach their updip limit. Fractures and fault systems, related to the Southwest Ozark Lineament at the edge of the Cherokee Platform, may have served as early pathways for hydrocarbons originating in deeper basinal settings. Also, the Southwest Ozark Lineament system may have been a conduit for mineral charged fluids responsible for lead and zinc mineralization in the tri-state area during Morrowan and later time.

Simpson structural targets have a better chance of being oil-bearing if traps were formed early in geologic time. Simply put, older (early) structures and their reservoirs capture more episodes of migrating hydrocarbons than structural traps that develop late. For example, some traps in Golden Trend Field in Garvin County have been determined to have formed as early as shortly after the deposition of Oil Creek Formation. That movement was then followed by another deformational episode after Bromide deposition, but before Viola. Crustal instabilities that produced traps in Oklahoma may have been local, or regional, perhaps related to Ordovician Taconic (Queenston) tectonic activity, or to Acadian movements in Devonian time. Morrowan and late Pennsylvanian tectonic episodes may have drastically modified or even destroyed these earlier formed traps, or, in an optimistic sense, may have created new ones that would be available for fill by late-migrating hydrocarbons. The lack of appreciable hydrocarbons in the Simpson in the Cement Field Anticline in Caddo County in T5N-R9W, can, perhaps, be ascribed to a structure that formed late in geologic time along with an absence of late hydrocarbon migration. It is because of these reasons that it is important to determine the timing of structural features. Timing can be determined from comparison of structure maps drawn on different reservoirs, evaluation of seismic lines, and by evaluating trends seen on isopach maps and well-log cross sections. For example, timing of structural activity may become apparent through comparisons of a Simpson (Viola) structure map with one contoured at the top of the Hunton (base of Woodford in its absence) illustrated in Figure 25. Although the structure map on top of the Hunton represents an eroded surface sculptured by pre-Woodford subaerial erosion, the absence of faults and anticlinal configurations on this map relative to those on the Viola map is notable by showing less structural activity than that for the Viola, thereby dating most traps as having formed after Viola time but before Hunton and Woodford deposition. Seismic lines across this area provide additional visual evidence for the presence, or absence, of fault cuts at specific stratigraphic horizons. Also, seismic lines, in general, provide information about the timing of structural features by noticing what reflector horizons have been deformed relative to others. Examples of ages of various faults based on reflectors are shown on the seismic line for the Golden Trend (Figure 26). The depth of specific formations that were involved in any structural activity can be identified from synthetic seismograms derived from well logs. Velocity information that allows the conversion of time-to-depth can be obtained from neutron-density logs or sonic logs. Moreover, seismic data in some areas may clearly show a Woodford channel or angular unconformity, and, if the depth of that reflector is known from a nearby well, its time-depth relationship can be estimated without a synthetic seismogram. Also, once a group of two or three contiguous formations (of varying density and sonic velocities) are displayed as "reflector packages" and tied with nearby well logs, their characteristic signatures can be used to convert time-to-depth across broad areas of their occurrence. For example, velocity contrasts within the Atoka/Wapanucka/Cromwell Formations produce one of the more obvious reflector packages in the Arkoma Basin. Similar types of reflector sets are used in seismic correlation across the state.

Timing of structural activity can be ascertained from depositional thickening (or thinning) of rock units. This attribute is more readily observed from strata on the Cherokee Platform (Oklahoma Shelf). For example, Simpson production tends to be more prolific on structures that have condensed stratigraphic sections, better known as "thins." Thinning, in a syndepositional sense, reflects the stability of the underlying crust on which sediments were deposited. For example, when an accommodating area subsides

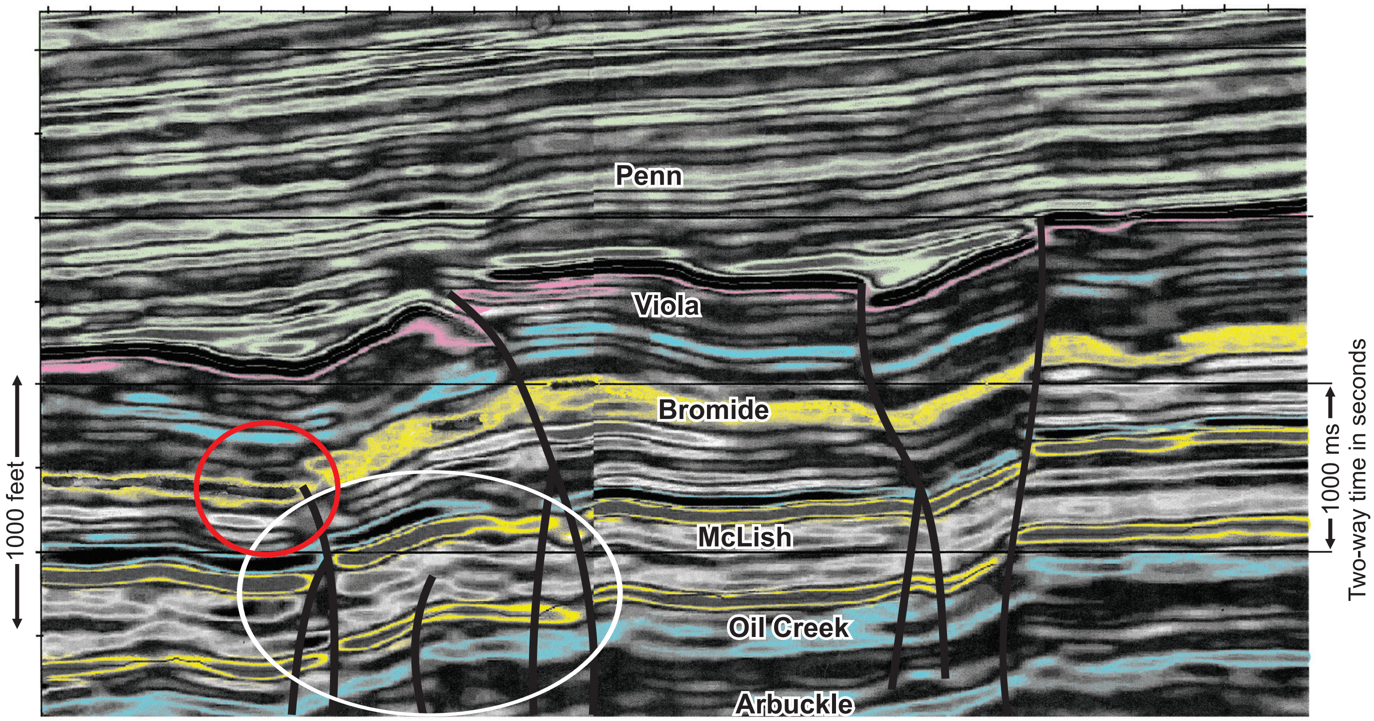


Figure 26. Variations in structural timing from seismic line extracted from a 3D survey. Seismic line is located in the Golden Trend Field at the confluence of Ardmore and Anadarko Basins, and Cherokee Platform (see Figures 30 and 33B). The oldest structural activity observed on this seismic line is within white circle at a fault that does not cut the Bromide; it is dated to be post-Oil Creek/pre-Bromide. Within red circle, the Bromide is faulted but not the Viola, reflecting Post Bromide/pre-Viola structural activity. Not cut by faults, the youngest pre-Pennsylvanian structural activity is uplift and erosion as inferred by the unconformity (pink). Sandstones are yellow. Thickness and porosity variations of the sandstone and facies relationships with other lithologies can be interpreted from interfingering seismic peaks and valleys (seismic courtesy of OK Energy Exchange).

at rates less than surrounding areas — such as one that is attempting to "grow" or become arched upwards in the form of a dome or anticline — deposition is suppressed through sediment by-passing and/or redistribution. This often results in what appears to be a compressed, or thin, vertical section relative to those in nearby wells. Consequently, Simpson thinning can usually be determined by acquiring and comparing thicknesses for arbitrary intervals observed from electric logs. Stratigraphic intervals selected for isopach mapping might be from the top of one formation, or member, to another, such as the top of the Simpson Group to the top of the Tulip Creek sandstone, or, the top of a marker within the Bromide to the base of the Viola Group — or any other markers that show consistencies. Isopach maps of intervals within the Simpson are often compared with isopach maps for Viola or Sylvan. The objective, of course, is to locate emerging structures from "thins" that were present early enough in geologic time to trap migrating hydrocarbons. Seismic data can be used to locate "thins" if electric-logs are not available. Time variations between individual peaks and valleys of seismic reflectors, or groups of reflectors, can be calculated, and values can be contoured in a fashion similar to well logs. Synthetic seismograms are used to convert seismic time values to depths. They are prepared from sonic log velocity information or from velocities interpreted from neutron-density logs. Application of formation names to specific seismic cycles involves some degree of interpretation. Peaks and valleys (formations), when traced laterally, undergo phase changes due to facies change or change in porosity; unconformities, such as at the base of the Woodford, complicate seismic correlations. The seismic marker at the base of the Woodford is readily picked across most areas of Oklahoma and is one that represents the eroded top of the Hunton, Sylvan, or Viola. Isopach maps derived from both electric-logs and seismic data can be integrated with one another and compared to confirm timing of structural growth.

In sum, an early trap is preferable, but it is not a requirement for oil or gas entrapment in Simpson reservoirs. Also, later structural activity (reactivation) such as that which may have taken place in Pennsylvanian time, may have either destroyed the trap or, perhaps, may have compartmentalized it, or even accentuated it. Regardless, untested structures may have to be eventually drilled to determine their productivity.

Stratigraphic Traps

Unlike structural traps discussed above, several Simpson wells in Oklahoma are productive from stratigraphic traps located on structural noses or truncated anticlines. One of the most prolific structural/stratigraphic features in Oklahoma is the truncated anticline of the Oklahoma City Field, where Bromide and other Simpson sands are productive at their point of truncation rather than at crestal positions. This type of subcrop trap is termed "buried hill" and discussed by Zhao, et al (2015). Truncation related to angular unconformities may be visible from seismic data, including older 2D seismic lines. Unfortunately, however, older seismic data offers little help in locating unconformities between strata that are parallel with one another (disconformities) in the Simpson, unlike the more readily-seen disconformity at the base of the Woodford. Angularity at the unconformity may be so minor as to prohibit identification from seismic data or well logs. Truncation traps produced by subtle angularity might have to be determined from regional isopach maps. Truncation bands for specific Simpson reservoirs beneath the Viola and Woodford are illustrated in maps and cross sections included here, and in Ireland (1944), Shannon (1962), and Huffman (1958). For example, regional updip termination of the Tulip Creek sandstone is shown by the trend of productive "Tyner" wells in northeastern Oklahoma (Plate 8). Productive trends are seen from other maps included here. As this study has shown, not all Simpson sandstones are blanket-like in geometry, including the so-called "blanket" sandstones of the Oil Creek and McLish. Rather, most sandstones (and dolomites) of the Simpson exhibit lateral changes in thickness and porosity, and are, therefore, likely to have hydrocarbon potential from pinchout at their fringes. Productive stratigraphic traps such as these are particularly common in sandstones of the Bromide and the Seminole sandstone of the Viola.

Source Beds

Overshadowed by the view that most oil in Oklahoma was sourced by the Woodford, the idea that hydrocarbon source beds are present in the Simpson Group is somewhat new. However, this should come as no surprise since dark-colored (organic) shales and carbonates are scattered throughout the Simpson. These rocks are thought to have provided hydrocarbons to several reservoirs within the Simpson Group. Oil Creek equivalents in Arkansas (Everton Formation) consist of numerous beds of finely crystalline dark-colored dolomite and limestone that release a strong fetid odor when broken (Suhm, 1970, p.108). A brown or black color and cuprous odor implies the presence of decomposed organic matter, such as derived from minute organisms and plankton, and petroleum products. Clay is important in the conversion of organic matter to hydrocarbons. The first time that clay became widely available as a major substrate of ocean bottoms in the Midcontinent area is documented by strata of the Simpson. Moreover, the importance of clay in its role of sourcing hydrocarbons for Simpson reservoirs cannot be overstated. For example, clay substrates facilitated biologic diversity and provided conditions under which algae and other microorganisms would thrive, and that, through their decay would produce hydrocarbons. Clay also suppresses oxidation and its destructive effects on organic matter (Yu, et al 2009). Low-oxygen, clay-rich substrates in Simpson environments were favorable for the preservation of organic matter. Simpson environments hosting organic-rich black shales were within restricted basins and lagoons cut off from circulation, and they were thickest in nutrient-rich areas of the Anadarko and Ardmore Basins during Oil Creek and Bromide time. This idea is supported by Trask and Patnode (1942, p. 265) who show an increase in the organic content of the Simpson toward these basins.

Additional evidence for Ordovician source rocks is attributed to studies of the chemical signatures of oils by Longman and Palmer (1987), Hatch, et al (1987), Wavrek (1992), and Johnson and Cardott (1992) and in west Texas by Katz, et al (1994). They all report the presence of readily identifiable chromatograph signatures unique to the Ordovician. Ordovician oil sources are also identified from the presence of *Gloeocapsamorpha prisca* within the oils and source rocks. This extinct organism (illustrated in Jacobson, et al 1988) was an exclusively Ordovician organic-walled microfossil that was responsible for generating oil and gas found in the Simpson reservoirs. According to Jacobson, et al (1988) the species flourished as either phototrophic planktonic algal blooms or, benthonic bacterial-laminated "oil shale" mats. Simo, et al (2003) appears to prefer a planktonic origin based on the cyclicity of *G. prisca* and associated oxygen isotopes observed within Simpson and Viola platform carbonates in the northern Midcontinent. They state that an increase in numbers of G. prisca is to be interpreted as a rise in sea level coincident with an expansion of the photic zone which would increase growth. However,

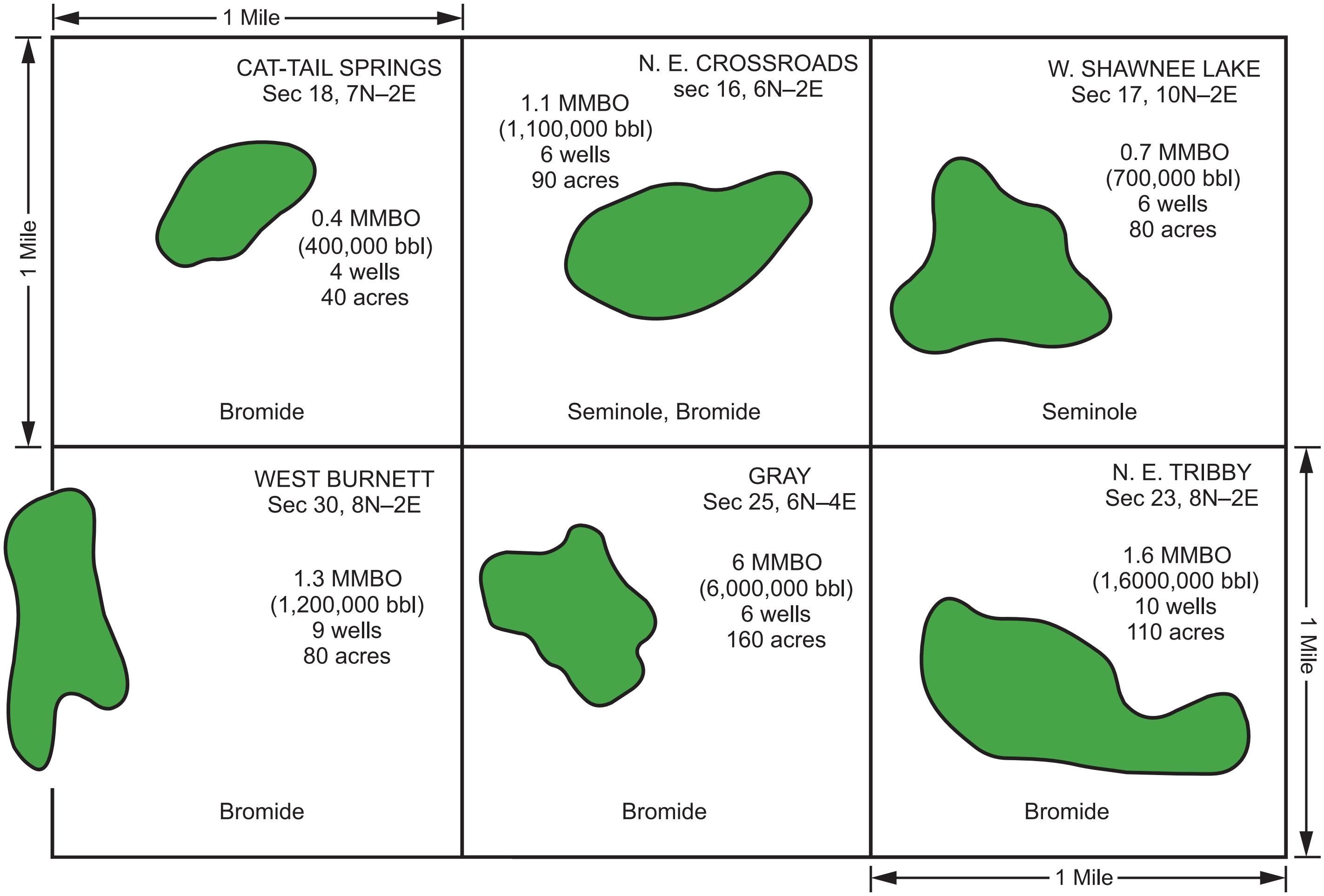


Figure 27. Productivity from small closure within the Cherokee Platform. This tableau illustrates excellent productivity from structures less than 200 acres in extent with vertical structural closure of 10 to 40 ft. The fields were drilled in the mid-20th century and many were developed on 10-acre spacing units. However, in consideration of the strong water drive in the Seminole and Bromide sandstones, similar recovery could have been achieved with 40-acre spacing.

to explain vast quantities of hydrocarbons in Oklahoma, a contrary view is suggested, that endemic *G. prisca*, along with other micro-organisms, lived in shale basins in the photic zone as algal or bacterial mats that favored voluminous production of organic matter and hydrocarbons. A limited number of burrowing and grazing organisms on the sea floor would account for high preservation rates of this organic matter.

In sum, Simpson environments provided ideal habitats that enabled organisms to thrive. Hydrocarbons were generated through their decay and burial. Fetid Simpson carbonates share characteristics with the Devonian in west Texas, the Bakken shale, and in other places where source beds are actively sought after and drilled horizontally. Migration of hydrocarbons from these source beds into Simpson reservoirs resulted in oil and gas accumulations in structural and stratigraphic traps across the state. Thus, in the context of exploration in Oklahoma, source beds within the Simpson provided contemporaneous hydrocarbon sources that were available to fill Simpson reservoirs in early formed traps. The realization that Ordovician source rocks played a major role in contributing oil to Simpson reservoirs should provide new opportunities for explorationists.

Burial Depths and Temperatures

A discussion of burial depths and temperatures in relation to Simpson petroleum occurrences requires the inclusion of a multitude of sciences beyond the scope of this paper. Geologically, and empirically, however, the preponderance of Simpson oil and gas occurrences across parts of all Simpson provinces in Oklahoma implies widespread, favorable, if not optimal, burial depths, temperature, and pressures. Exceptions are discussed here and throughout this report within the context of basin analysis derived from stratigraphy. Favorable Ordovician

EXPLANATION

- *Coalbed Methane*
- Oil Field (GOR <5,000)
- Combination Oil and Gas Field (GOR 5,000-20,000)
- Gas Field (GOR >20,000)
  GOR (Gas to Oil Ratio) based on post-1979 production.
- Simpson Fields discussed in report

SIMPSON FIELD NAMES

1. WEST MAYFIELD
2. AMES
3. APACHE
4. SW BURT
5. OKLAHOMA CITY
6. GOLDEN TREND
7. EOLA
8. SW DAVIS
9. SHO-VEL-TUM
10. HEALDTON
11. COTTONWOOD CREEK
12. SW ENVILLE
13. AYLESWORTH
14. CUMBERLAND
15. FITTS
16. JESSE
17. CENTRAHOMA
18. EAST CENTRAHOMA
19. GREATER SEMINOLE FIELD
20. MAUD
21. ST LOUIS
22. WILBURTON
23. WILCOX FARM (1st Simpson field)
24. GLENN POOL

source beds are also present across all provinces. Hydrocarbons generated in source beds migrated into preserved pore space in conventional Simpson reservoirs, including pores within late-forming dolomites. Widespread water or gas-driven systems, or any combination thereof, on the Cherokee shelf and Ardmore Basin contain mostly oil with a favorable API gravity from 20 to 50 degrees. Heavy and viscous oil with API gravities less than 20 degrees are within Simpson sandstones in shallow breached (or leaking) traps proximal to the Pauls Valley Uplift in the area of Arbuckle Mountains. The distribution of oil versus gas in Oklahoma (Figure 28) shows boundaries that share similarities, not only with Simpson depositional provinces defined in this report, but also with the borders of the tectonic provinces established by Northcutt and Campbell (1995). This coincidence imparts the idea that distribution patterns of oil and gas may be controlled by the basins' tectonic and burial history. For example, Simpson oil is prevalent on the Cherokee Platform and Ardmore Basin (shown in green on Figure 28), but gas (in red) is dominant in the Anadarko and Arkoma Basins. Therefore, an association can be drawn on the basis of burial depths and temperatures of source beds and reservoirs, such that as depth increases, gas predominates over oil, apparently due to higher burial temperatures. Likewise, the occurrence of oil in Ardmore Basin (and Fort Worth Basin) suggests that Simpson reservoirs may have escaped high burial temperatures and pressures. Perhaps thermal maturity is high in the Arkoma Basin because of excessive burial depths caused by high displacement extensional faults related to the "collapse" of the platform (Figure 23). Oil and gas relationships such as these will be discussed in the "Arkoma Basin" section of this paper. Within the Ouachita facies, oil and gas production is essentially nonexistent from Simpson equivalents, other than minor amounts of gas recovered from chert in the uppermost Bromide and Big Fork (Viola) that rest above thick black shales of the Womble. Hydrocarbon potential has yet to be determined from both the Simpson-like Blakely and Crystal Mountain Sandstones found near the southeastern corner of Oklahoma, and from "in-place" Simpson equivalents at greater depths in the Ouachita Mountains.

Trap Size, Productivity, and Outcome

The size and geometry of productive Simpson structures are shown on the enclosed Viola structure map (Plate 15). The contour interval of 500 feet on this map may be too large to properly display the majority of low relief structures of the fields, but it does allow geologists to see structural grain, fault displacements, and subcrops thereby providing a foundation from which to explore for hydrocarbon accumulations or mineral deposits in new areas with new ideas, especially in conjunction with isopach and porosity maps combined with the Viola structure map included in this report.

The discovery and successful completion of an undrilled structure is satisfying to the explorationist. Virgin structures are held in high esteem. Unfortunately however, it is unlikely that many large structures have escaped testing in mature areas that have been seismically explored. On the contrary, in

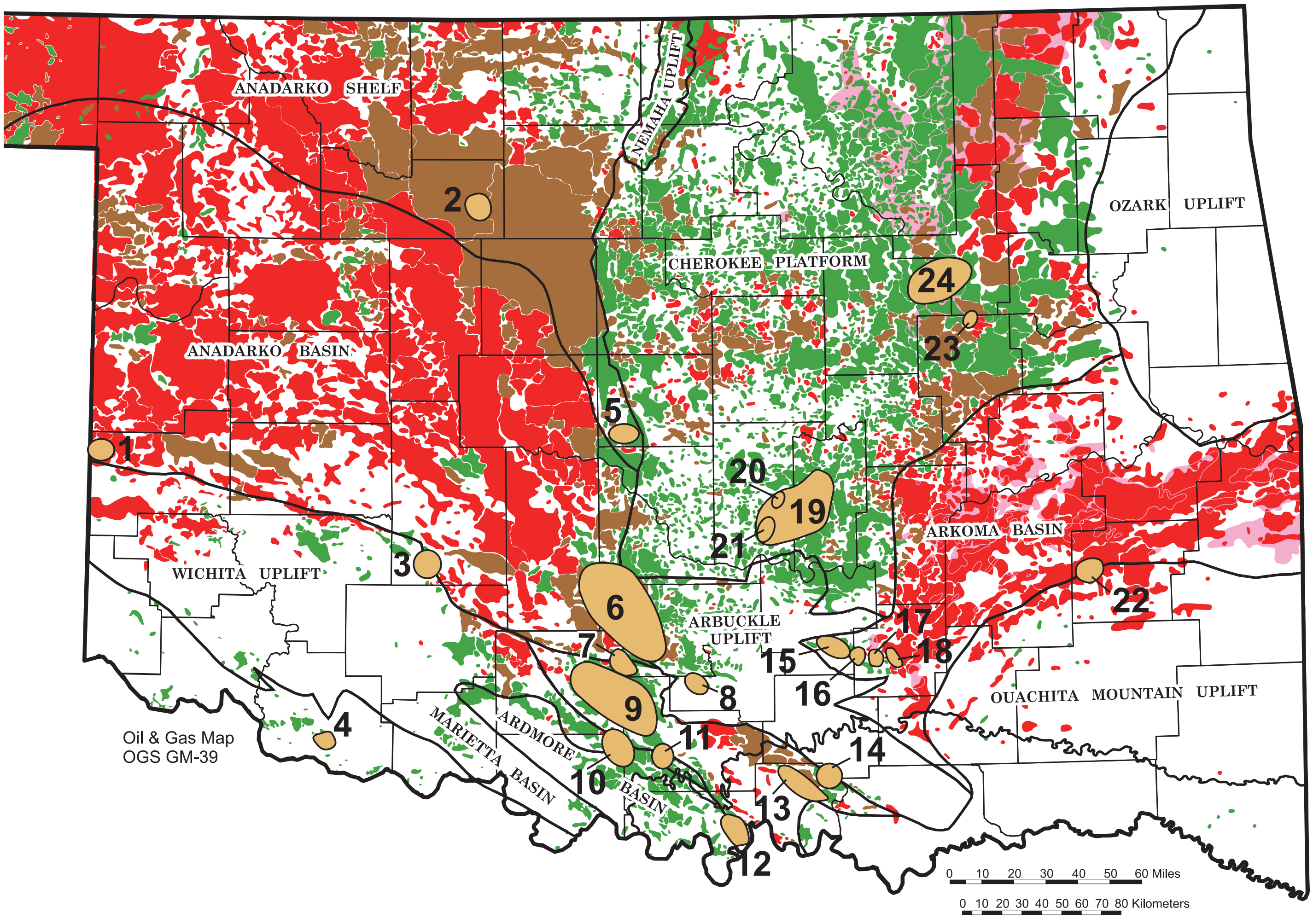


Figure 28. Oil and gas distributions in Simpson in relation to tectonic provinces. Shallow burial depths and low thermal maturity are responsible for oil found on Cherokee Platform and Ardmore Basin, whereas more deeply buried strata coincident with high thermal maturity contain natural gas in Anadarko and Arkoma Basins. The locations of Simpson fields discussed in this report are also shown.

defense of future exploration, many areas in Oklahoma have not been seismically explored. It is also likely that numerous small structurally-closed features have not been properly seismically defined or interpreted, leaving many wells yet to be drilled. Interestingly, the size of the Simpson structure appears to be irrelevant in regard to attaining high recoverable reserves (Figure 27). For example a structure 200 acres in areal extent may yield the same amount of hydrocarbon as a potential wildcat structure that is 20 acres in areal extent, such as some in the Golden Trend Field in Garvin County. Here, the basal Oil Creek sandstone has porosity of from 25 to 35 percent with 2,500-9,000 MD (milidarcy) of permeability with a calculated recovery rate of over 600 bbl/acre-ft. This rate is considerably higher than that for Simpson sandstones in other provinces. In other words, higher recoveries can be expected from small structures when porosity and permeability are high. Recent discoveries of highly productive small structures such as those in the Golden Trend lend merit of shooting 3D in selected areas.

Four outcomes from drilling Simpson targets within the Cherokee Platform shallow oil province include:

1. Both Simpson and Viola are dry. Unfortunately, it is not uncommon to locate and unsuccessfully drill a structure mapped on the top of the Viola. Perhaps closure did not exist because: a) it was mapped improperly; b) the structure formed too late in geologic time with the consequence that oil was not available for migration; c) Simpson reservoirs are not present, or, are deeper than the depth drilled; d) the drill hole deviated and strayed off the projected crest, or perhaps the structural crest of the Simpson is at a differ-

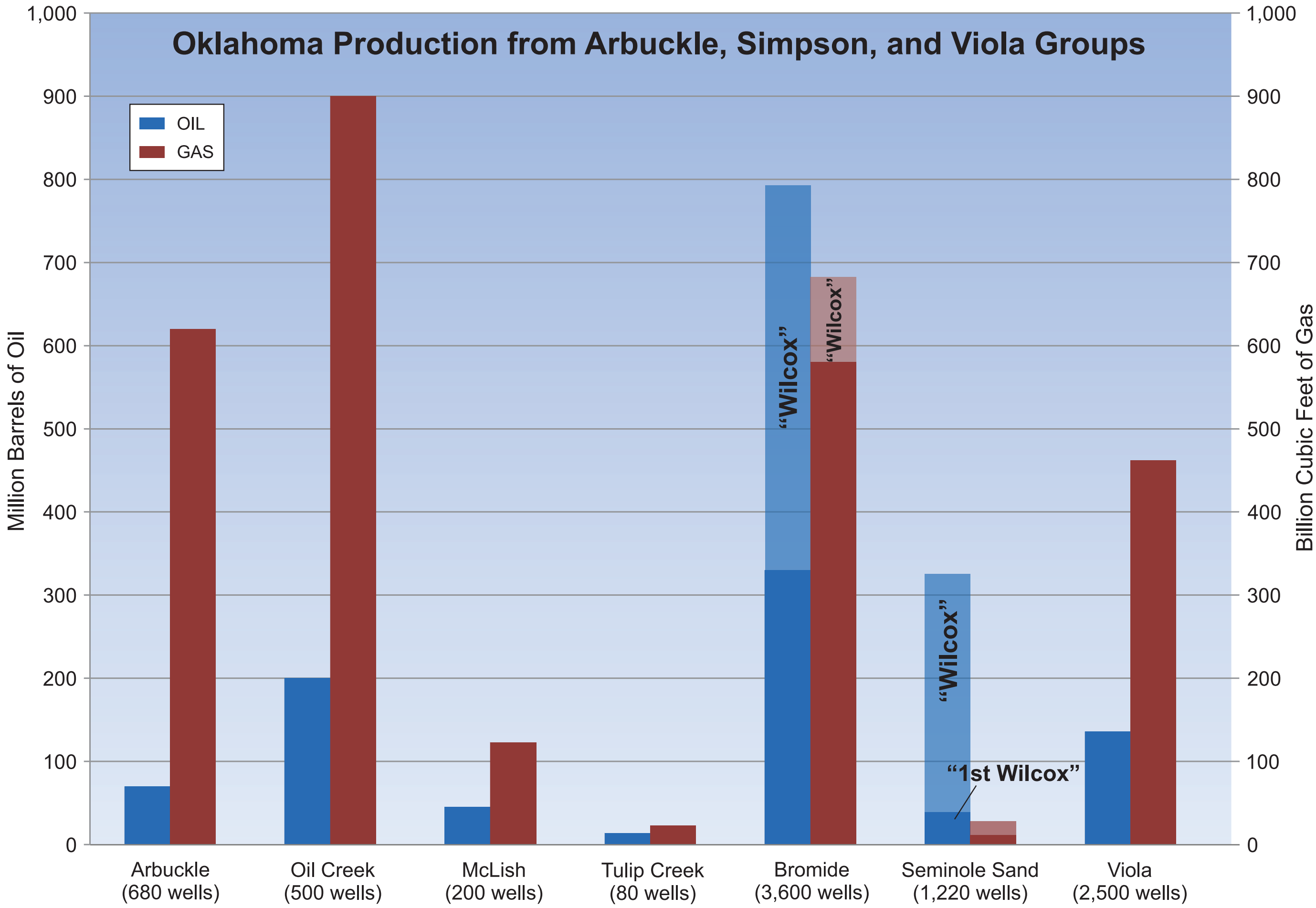


Figure 29. Histogram of productive Simpson formations compared with the Arbuckle and Viola. Comingled production is excluded. Production information using the names Bromide and Wilcox had to be scrutinized. For example, using maps, cross sections, and well data included in this study, "best judgment' is used to place declared Wilcox production with either the Bromide of the Simpson Group or the Seminole sandstone (1st Wilcox) of the Viola Group. It was found that a little more than half of what is called "Wilcox" production in published data is assigned with the Bromide; the other half was interpreted to have come from the Seminole sandstone (1st Wilcox) of the Viola. Application of the name "Wilcox" is discouraged.

ent position different than the Viola crest; or e) drilling or logging problems, such as mud weights were too heavy to record potential shows, lost circulation, etc.

2. Both Simpson and Viola are productive. This is uncommon and unlikely.

3. Viola is productive, but not the Simpson. The simplest explanation is that the well was not drilled deep enough. There is the idea among some explorationists that should the uppermost "Simpson" sand *not* be oil-bearing, drilling should stop, because deeper sandstones will also not be productive. For example, across a large part of the Cherokee Platform this so called "upper sandstone" might be the Seminole sandstone (commonly, yet erroneously called 1st Wilcox) and not the Bromide sandstone of the Simpson Group. Many geologists and operators may not be aware that these two sandstones have vastly different ages, and that an unconformity with slight angularity is present between the Viola sandstone and Simpson reservoirs. Invocation of unconformity, especially an angular unconformity, implies that the Viola and Simpson had different histories of oil generation and migration, and that there was a likely geographic shift in the structural axis rendering a different structural configuration.

4. Simpson is productive, but not the Viola. It is common for the Simpson to be productive and Viola not productive. This may be due to the absence of reservoir quality rocks in the Viola, or, to migration of hydrocarbons taking place before Viola deposition.

PROVINCIAL DISTRIBUTION OF SIMPSON HYDROCARBONS

GENERAL

Before Oklahoma became a state in 1907, local and national agencies undertook geologic mapping programs to evaluate mineral wealth potential of Oklahoma and Indian Territories. Surface mapping was the global mainstay exploration tool at that time. The search for oil in Oklahoma began slightly before 1900 by mapping shallow anticlines in the Ozark and Arbuckle Mountains. Most of the early oil discoveries from the Simpson Group were located in northeastern Oklahoma. Terminology of producing formations within these areas, however, was different. For example, near Tulsa in the foothills of the Ozark Mountains in northeastern Oklahoma, the Simpson pay sands were called the Burgen or "Wilcox." The exceptionally large oil recoveries from the "Wilcox" attracted wildcatters, consequently, it became one of the earliest sought after reservoirs. In discussing early exploration, Sidney Powers (1928, p. 19) says, "The great impetus to subsurface work was the recognition of the Ordovician as a producing horizon, largely because of the work of Fritz Aurin, Frank C. Greene, Luther H. White, G. C. Clark, and E. A. Trager … " and also mentions that "the Wilcox sand was proved in 1921 by fossil evidence in overlying strata to be Ordovician." Powers, and other authors contributing to Oklahoma Geological Survey Bulletin 40 (1926-1930), recognize the Wilcox to be a subsurface stratigraphic unit of the Simpson sandstone below the Viola and above the Tyner Formation in all counties of the Cherokee Platform that are east of Oklahoma City, such as in Lincoln, Creek, Pottawatomie, Seminole, Hughes, Okmulgee, Okfuskee, Payne, Kay, Pawnee, McIntosh, Muskogee, Tulsa, and Wagoner Counties (Figure 4A). The other area of early Simpson exploration, also at shallow depths, was in southern Oklahoma relatively close to the Arbuckle Mountains. Here, however, pay sands were called Simpson, or perhaps Bromide, but not Wilcox. This is perhaps due to the availability of publications and geologic maps of the Arbuckle Mountains prepared by Taff (1902, 1904) and other early geologists.

Knowledge of Simpson reservoirs expanded as more wells were drilled. It was also realized that the character of subsurface rock and the nature of the reservoir were useful in recognizing trends of potential reservoirs for future drill sites. Information about the lithology and fluid content were obtained from cuttings and fluid entry; drilling penetration rates were also recorded since they provided clues about the porosity of the reservoir. Much of this information was recorded and published by state and federal governmental geological surveys and academia, along with articles published by professional organizations such as American Association of Petroleum Geologists (AAPG) Bulletin. While Simpson discoveries were being made in northeast Oklahoma and southern Oklahoma it was natural for exploratory drilling to spread to deeper and richer areas, mainly relying on well control and the expertise of the geologist. With the advent of seismic technology, numerous seismic lines were shot across all parts of the state in the 1940's and 1950's, mostly along section line roads because of easy access. As will be discussed later, one of the first structures to be defined by seismic data was in Maud Field in Seminole County, productive from the Bromide and Seminole sandstones. A few years later, Simpson production was established in the Apache Field in Caddo County, principally through the interpretation of seismic data. At about the same time drilling, completion, and recovery techniques improved. Unfortunately, production volumes from early wells were not required to be published by the state. Eventually, however, in the interest of conservation and protection of the state and those residents who financially benefited from ownership of mineral rights, the state imposed regulations and required the quantities of oil and gas to be measured and recorded. Monthly and yearly cumulative production values were published by state agencies. Complicating this, however, were wells that produced from more than one producing interval or "zone," often with no depth distinction, so there was no accurate accounting of oil produced from specific Simpson reservoirs. Nevertheless, early production figures do convey positive realizations about

EXPLANATION

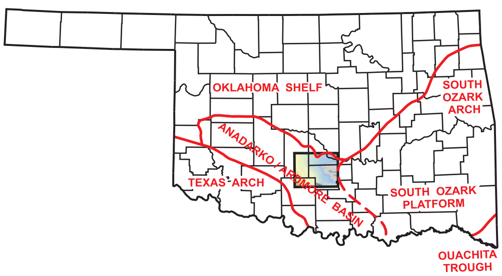
Production:
- Viola
- Bromide
- McLish
- Oil Creek/Joins
- Simpson undiferentiated
- Arbuckle

Fault
-5000 Viola Structure Contour
Golden Trend Area

Subcrops:
- Viola
- Simpson
- Arbuckle

PRODUCTION

FORMATION	OIL (MMbo)	GAS (Bcf)
Viola	15	200
Simpson undiff.	5	35
Bromide	75	300
McLish	6	40
Oil Creek	50	600
Total Simpson	136	975
Arbuckle	1	15
Total "Golden Trend"	600	3000



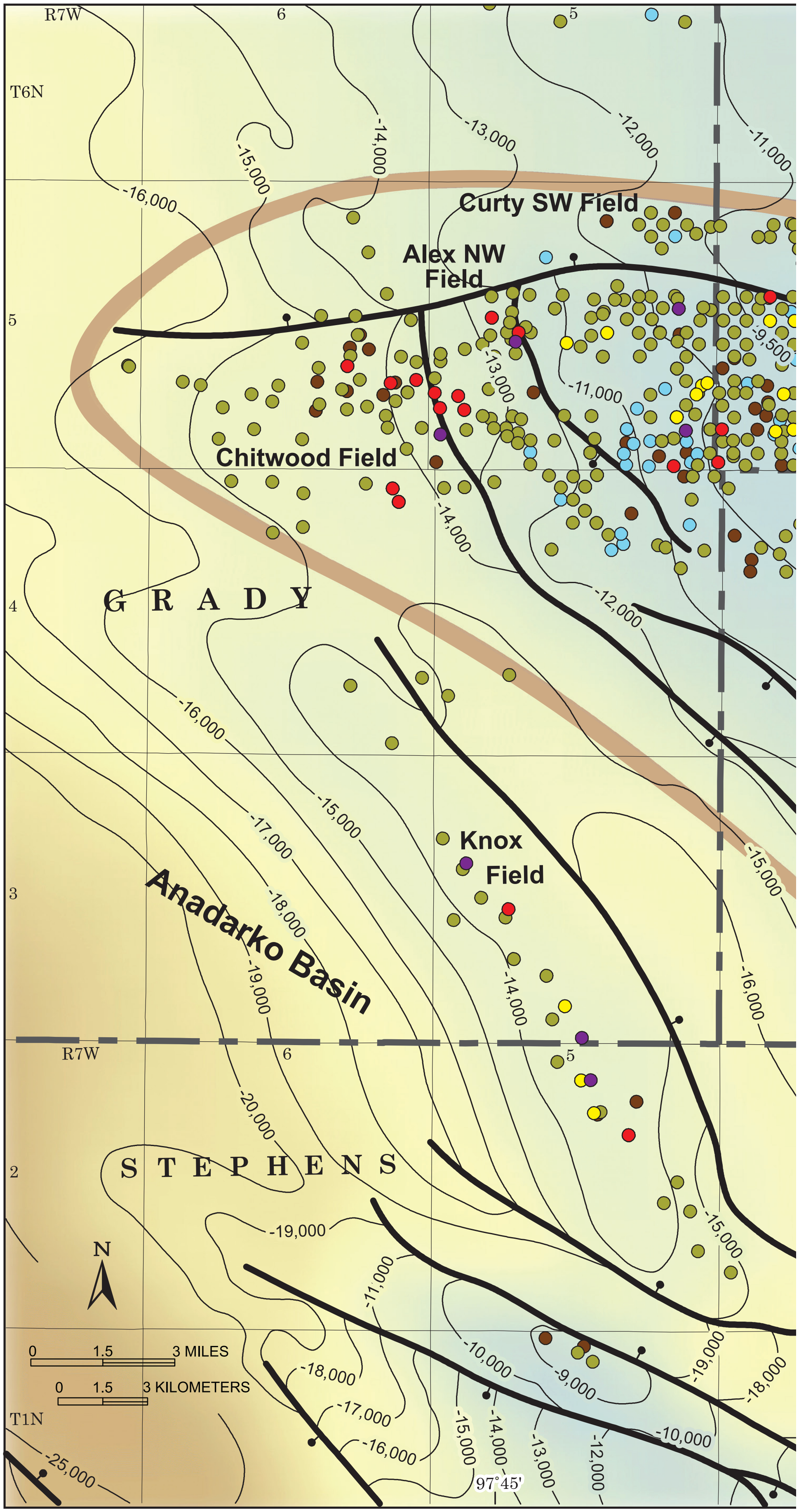
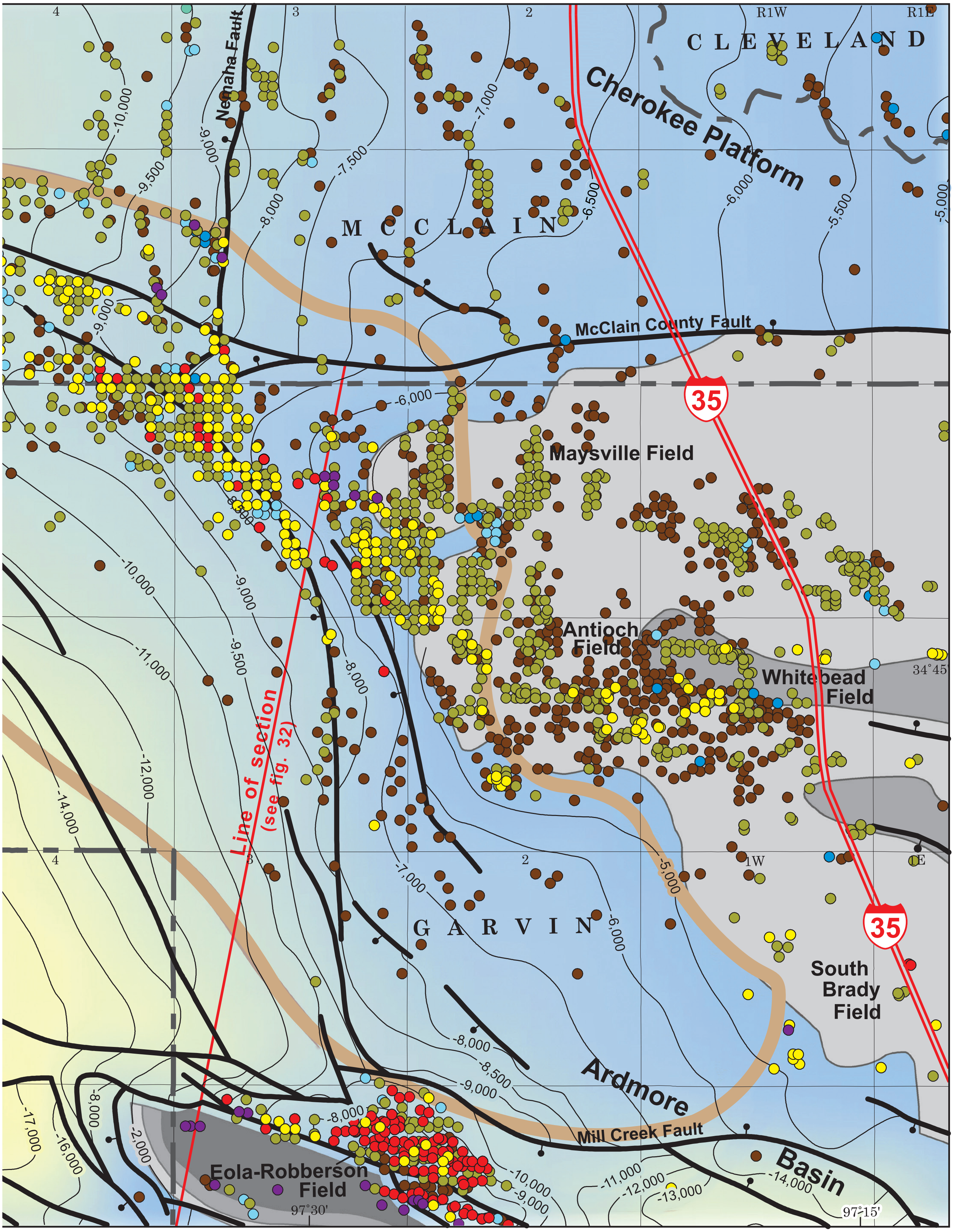


Figure 30. Viola structure map of an expanded Golden Trend Field with pre-Hunton production. Encircled Golden Trend Field (when combined with Alex NW, Chitwood, and Curty SW Fields) is a giant oil field that has produced 136 million barrels of oil from the Simpson as seen from the accompanying table. Nearby Whitebead, Antioch, South Brady, and Maysville Fields are shown east of Golden Trend. Favorable reservoirs combined with an agglomeration of structural traps on a structural nose are responsible for Golden Trend productivity. "Line of Section" is part of a cross section shown in Figure 32. Faults are vertical with variable displacements; strike slip motion is minimal. From a structural standpoint, Golden Trend Field is located at the junction of three faults (Nemaha Fault, McClain County Fault, and Mill Creek Fault). These faults serve as boundaries for the Cherokee Platform, Anadarko Basin, and Ardmore Basin (Plate 1). Separation of the South Ozark Platform Province from the Anadarko Basin is arbitrary and transitional (see (Plate 2).



CLEVELAND
Cherokee Platform
MCCLAIN
Nemaha Fault
McClain County Fault
35
Maysville Field
Antioch Field
Whitebead Field
South Brady Field
Line of section (see fig. 32)
GARVIN
Ardmore Basin
Mill Creek Fault
Eola-Robberson Field
R1W
R1E
34°45'
97°30'
97°15'
-10,000
-9,500
-9,000
-8,000
-7,500
-7,000
-6,500
-6,000
-5,500
-5,000
-11,000
-12,000
-14,000
-16,000
-17,000
-8,500
-2,000
-13,000

the prolific nature of Simpson formations. However, production values derived from commercial services (including present-day services) may be incomplete, especially for older wells, and that names of productive formations may be incorrect since there may have been limited geologic oversight (it was the responsibility of individual operators and companies to provide formation and reservoir names). Notwithstanding, it didn't take long for early explorationists to realize that the average per-acre yield of oil from the Simpson in many areas is greater than that from other groups of rocks. The effect of this is that large volumes can be produced on small structures with minimal acreage holdings. The idea of small cash outlays for acreage and drilling combined with handsome returns invoked a "black gold" romance with investors and early explorationists.

Relative productivity for specific formations of the Simpson Group compared with hydrocarbon recovery from the Arbuckle and Viola Groups is shown as a histogram (Figure 29). The Simpson compares exceedingly well with other groups, but the accuracy of the histogram is limited since production information shown on the histogram includes production from "reservoir-specific" formations, rather than comingled reservoirs. This has the effect of diluting or suppressing actual production volumes. The histogram also gives the illusion that the Tulip Creek and even the McLish are barren of oil and gas, but this may not be so, since it is likely that these intervals were comingled with other reservoirs, or even misnamed, and not included. This is common. Another concern in presenting production data is the reliability of, and even the significance of, the use of the word "Wilcox" on documents submitted to the state by well operators and commercial oil and gas scouting organizations. In an earlier section it was suggested future use of the name "Wilcox" be abandoned because of its tendency to be called Bromide (Simpson) in one area and 1st Wilcox (Viola) in another area. For example, many operators, geologists, engineers, and landmen have a tendency to classify the first productive "sand" under the Viola with the "Wilcox" not knowing that this sandstone has Viola (Seminole sandstone) affinity rather than Simpson. Hopefully, maps and other information included in this report will be used by the petroleum community to alleviate the "Wilcox" problem. The distribution of the Bromide and Seminole sandstones are shown on Plates 9 and 10 so their presence or absence can be predicted in future drilling ventures. For example, when the name "Wilcox" is specifically used on subsurface data in northeastern Oklahoma at well locations far removed from Seminole sandstone limit, "Wilcox" implies the sandstone is Bromide, or perhaps older sandstone such as the Tulip Creek or McLish. There may still be doubts, however, because the enclosed maps may not reflect sand distribution at thicknesses less than 5, 10, or 25 ft. If doubt exists about its classification in this area, the name Tyner might be better suited. Elsewhere, at times when "2nd Wilcox" is used, the name "Bromide" should replace it. In any event, use of the name "Wilcox" by itself without a qualifier should be discouraged. Commercial production-reporting services should also share a responsibility in accurately using the appropriate name of the formation. If the name "Wilcox" has to be used, it should be with a qualifier, such as 1st Wilcox or 2nd Wilcox, never by itself. And, if the name 1st Wilcox is used, it is commonly in the spirit of being the first sand, or a Viola sandstone or Seminole sandstone (see histogram on Figure 29), but regardless, any "Wilcox" designation should be questioned, since it may be either Simpson or Viola. Therefore, in calculating production values for the histogram, the use of the name "Wilcox" had to be interpreted. To derive an answer the location of the well was compared with isopach maps of the Bromide (Plate 9) and Seminole (Plate 10) and those thicknesses that were recorded on the Excel spreadsheet included in this report. The result was that the Bromide constitutes about 60 to 65 percent of the oil that is called "Wilcox" oil, and about 85 percent of the gas. The remaining "Wilcox-designated" production is interpreted to be from the Seminole sandstone. This study also found that the Seminole sandstone is commonly more likely to have oil at updip locations than the more gas-prone Bromide. Given this arbitrary separation, it is clear that Bromide production far surpasses that of the Tulip Creek, McLish, and Oil Creek. Not only is the areal extent of porous Bromide sandstone (Plate 9) the largest, but its extensive reservoir system is laterally connected with basinal Bromide black source shales in the Anadarko and Ardmore Basins. The Bromide is the shallowest Simpson pay sand and the least expensive to drill, and because of that more wells reach total depth in Bromide rather than deeper reservoirs. The unfortunate outcome of this is that deeper Simpson sandstones go untested.

Hydrocarbon distribution in Simpson reservoirs is discussed in the following sections relative to occurrences within tectonic provinces, rather than depositional provinces as discussed in the first part of this paper. Geologic or tectonic provinces defined by Northcutt and Campbell (1995) reflect areas of similar structural styles. Interestingly, they overlap depositional provinces defined here (See Figure 4B and Plate 2 for comparisons). Tectonic and burial histories are of primary importance in controlling the areal distribution of oil or gas (Figure 28). Within the context of tectonic provinces, a few Simpson fields are mentioned below, but more can be found in Northcutt and Johnson (1997), and in articles published by the Shale Shaker (Oklahoma City Geological Society), Oklahoma Geologic Survey, Tulsa Geological Society, and the American Association of Petroleum Geologists.

CHEROKEE PLATFORM

(Eastern part of Oklahoma Shelf depositional province)

Pennsylvanian oil was discovered near Bartlesville, Oklahoma, in 1897, followed a few years later by Simpson oil discoveries. The first Simpson oil was from Bromide sandstones at shallow depths in the Glenn Pool Field in T17N-R12E, near the town of Glenpool in Tulsa County. Powers (1928, p. 10) states: "Few wells in northeastern Oklahoma were carried below the "Mississippi lime" in the early days. The first producing well in what is now called the Wilcox sand (of Ordovician age) was drilled by the Eastern Oil Co., on their J. Berryhill lease in the SW. cor. NE/4 sec. 29, T. 17 N., R. 12 E., near the southwestern edge of Glenn Pool. It was completed Dec. 9, 1908, in sand from 2,331 to 2,369 feet, producing 120 barrels a day." In the general area of the first great oil field of Glenn Pool, forty wells are reported to have produced over two and one half million barrels of oil from the Simpson. In nearby Wagoner County about the same time, the Burgen Sandstone (basal Oil Creek sandstone) produced almost one million barrels of oil from 50 wells. The amount would likely have been larger had production records been complete.

Jordan (1957, p 207) explains the first use of the name "Wilcox." Neumann (1965, p. 214, 215) describes Simpson activity taking place in 1914 a few miles southeast from Glenpool (the name "Wilcox" below refers to the Bromide Sandstone; the Seminole sandstone is not present in this area). "In 1914, Homer F. Wilcox discovered oil in Simpson sandstone at the Gracy Call No. 1 in the SW NE NW of Section 3, Township 16 North, Range 13 East, at a depth of 2,809 feet. This well produced at the rate of 600 barrels per day and opened a prolific pool of high gravity oil. This was probably the first highly profitable pool discovered in a sand of the Simpson Group. This sand was named 'Wilcox' after the discoverer, and the 'Wilcox' sand is still the name of the uppermost sand in the Simpson Group over much of northern and eastern Oklahoma. Later, when a lower sand was discovered in the Simpson, it was called 'Second Wilcox'. With the 'Wilcox' discovery of the Seminole City Pool in 1926 Simpson exploration spread into Seminole, Pottawatomie, and Okfuskee Counties. More than 2,000 wells had been drilled in the six principal pools of the area by the end of 1928, and approximately 300,000,000 barrels of oil had been produced as of that date. … Rotary drilling rigs had been used in other parts of Oklahoma before the discovery at Seminole. It was however in this area that the rotary came into general use. At first, pipe was usually set on top of the Hunton Limestone and cable tools were used for deepening. Later, the rotary was used to drill from surface all the way to the top of the Viola, with cable tools being used for completion of the wells. … Simpson wells flowed by dissolved gas which yielded a good volume of what was then called 'casing head gasoline.' There was, however, insufficient gas-pressure to flow the wells for long periods. A well might be flowing at the rate of 6,000 or 7,000 barrels per day when first completed, and would suddenly stop flowing even though the production for the final hour was at the daily rate. At that point, gas or air-lift was installed and generally production was brought back close to the volume being produced before the flow was interrupted."

Shortly after the name "Wilcox" (Bromide) was used for the Simpson within the oil-rich Glenn Pool Field, these productive sandstones were correlated westward to Seminole County. The Fixico No. 1 well in Seminole County was drilled in 1926 in Section 29, T9N-R6E where it flowed at 6,120 barrels of oil a day from a so-called post- "Wilcox" sand (Seminole sandstone) at 4,065-73 ft Levorsen (1928). It was one of the earliest discovery wells of the Greater Seminole Oil Field, a giant oil field. Levorsen (1928, p. 329) states: "The initial production of most of the wells ranged between 1,000 and 3,500 barrels per day, although wells as high as 9,000 per day were reported." Here, however, without the benefit of an abundance of well logs with which to correlate, the name post-"Wilcox" referred not to the Bromide sandstone as in eastern areas, but a younger sand called the Seminole sand member of the "Simpson Formation" according to Levorsen, (1928). It was later found to be part of the Viola Group rather than the Simpson Group. Although the "Wilcox" was well known as an oil reservoir in the early parts of the 20th century, it was not discussed by Decker and Merritt (1931) and other paleontologists — in part because fossils are difficult to see and recover from samples. Rather, a new group of geologists, known as "subsurface geologists", attempted correlations to and between type sections in the Ozark Mountains and Arbuckle Mountains, such as Aurin, et al (1921). Edson (1935), Levorsen (1928), and White (1926) are but few who published papers on this subject; an excellent summary of the results of these investigators plus many others are found in Harris (1957).

In contrast with other tectonic provinces, Simpson reservoirs on the Cherokee Platform are recognized by their relatively shallow depth (blue on Plate 15) and low structural relief relative to other tectonic provinces. Unfortunately, the 500-foot contour interval on the Viola structure map does not allow recognition of the many small low-relief productive Simpson and Viola oil fields. It is hoped that a map at a structural contour interval of 100 ft will be published in the future. Most faults on the Cherokee Platform are vertical with displacements less than 100 ft, however, a few laterally extensive faults with larger displacement, such as the Wilzetta and Nemaha Faults, may be basement-related. The Nemaha Fault, with the largest displacement, forms the western edge of the Cherokee Platform. The Seneca Fault, a prominent northeast-southwest but low-displacement fault, forms the approximate eastern edge of the Cherokee Platform at its junction with the Ozark Mountains. It is likely basement-related and shares similarities with the Southwest Ozark Lineament and so may be connected with it, as shown on maps in this report. It should also be mentioned that the Southwest Ozark Lineament, is also on trend with the McClain County Fault, an east-west fault that is on the north side of the Pauls Valley Uplift along the county line separating McClain and Garvin Counties. It is illustrated on the Viola structure map, in Figure 30, and tectonic province map of Northcutt and Campbell (1995). Basement-like faults mentioned above, when connected, may have served as a conduit for hydrocarbons originating in the Anadarko and Ardmore Basins. It is also reasonable to hypothesize that this system might have severed as a pathway for Late Carboniferous fluids responsible for lead and zinc deposits in the tri-state area (Garven, et al 1993).

The Simpson thins to extinction in northeastern parts of the Cherokee Platform (gray on the Viola structure map on Plate 15); its formations are truncated and overstepped by the Viola, and farther east, by the Woodford. In spite of thinning, the Simpson tends to retain its characteristic formational log geometries. For example, in and around Wagoner County the Tulip Creek maintains its "coarsening upward" feature (compare Figures 5 and 12). Similarly, a few "Birdseye-type" limestones, albeit very thin, with high resistivity and clean GR are present in the upper part of the Oil Creek shale. Explorationists in this area are likely to encounter different names for Simpson formations, for instance, productive Simpson reservoirs in wells designated as "Tyner" are equivalent to parts of the Oil Creek, McLish, Tulip Creek, and Bromide. The productive Burgen Sandstone (or its oil-field name of Hominy sand) is below the Tyner and was found to be equivalent to the basal Oil Creek sandstone (Suhm, 1974). Joins production in this area is, in part, from porous sandy dolomite and dolomitic sandstone, also referred to as "Hominy sand" or "Turkey Mountain sand" (Aurin, et al 1921; White, 1926). Furthermore, scout tickets and production data may call productive sandstones within the Tyner, "Wilcox" or, "Simpson." It is hoped that this study will add some consistency to what may be confusing terminology. Regardless, recoveries appear to be higher where Simpson reservoirs are overstepped and sealed by the Woodford, rather than younger or older formations. Simpson truncation is illustrated in cross sections by Ireland (1944), Huffman (1958), and Shannon (1962).

In western parts of the Cherokee Platform, the Simpson is deeper and commonly productive from porous Bromide sandstone. Production may be erroneously referred to as "Wilcox," leaving open the question of whether oil is from sandstone assigned with the Bromide or Seminole (Viola). However, this query can be resolved by studying sand distribution patterns and truncated limits on isopach maps for the Bromide and Seminole (Plates 9 and 10). Of course, where the Bromide and Seminole sandstone overlap one another the deeper productive sandstone is the Bromide.

Seismic data on the Cherokee Platform, including early vintage reprocessed 2D seismic data, has sufficient enough resolution to see not only small structures but also, in many instances, the Viola/Simpson contact, and also overlying reflectors of the Woodford and Hunton. Unpublished Viola exploratory maps (seismic) show principal structural traps to be domes and upthrown fault blocks of various shapes and sizes, and orientation. Characteristically, the size of structural traps on the Cherokee Platform is commonly small. However, due to high recovery rates related to high porosity and favorable reservoir energy, traps less than 100 acres in size have yielded over one millions barrels of oil (Figures 27 and 30). The amount of structural closure required for entrapment can be on the order of 25 ft, or, in some instances, 10 or 20 ft higher than adjacent wells with oil shows. Some explorationists use the term "attic oil" for attempts to establish production at positions highest on the structure.

Simpson hydrocarbons on the Cherokee Platform may have been sourced by rocks within the Simpson, such as the Oil Creek shale, or from Woodford and younger source rocks. Empirical data suggest that the Woodford is the primary source rock since it has a vertical stratigraphic separation by as little as 200 ft from Seminole and Bromide sandstones, especially where the Hunton is thin or absent. Additionally, in consideration of the large number of faults with small displacements, such as a hundred feet or less, it is likely that Woodford on the downthrown side would be juxtaposed with Simpson and Viola reservoirs on the upthrown side.

The Seminole sandstone (or its dolomite facies) is the chief producing horizon in Pottawatomie and Seminole Counties in the Maud Field (T8N-R5E), and the giant* St. Louis Field (T7N-R4E, T7N-R5E, and T8N- R4E), along with several other smaller pools within the well-known Greater Seminole area. Interestingly, it was in the Maud Field in 1928 where Amerada Petroleum Company made the first oil discovery on a geological feature using seismic technology (White, 1926; Levorsen, 1928). In regard to the Maud Field, geophysicist Jack Taylor (personal communication, 2000) states in a prospect report: "Wilcox (Seminole sandstone) fields are usually ringed by halos of Seminole dolomite production. ITIO (Indian Territory Illuminating Oil Company) drilled the discovery well for the Greater Seminole Field in Section 16-T8N-R5E in late 1928. Production figures were not easily available in those early years; a well which produced almost 95,000 barrels of oil would never be known if it never blew out or showed high testing rates. Vance Rowe oil report services were not available until a few years later and very few people had access to those reports for decades. This was the cable tool days and drilling was slow. The best well in the Maud Field was 40 acres to the west in 1929, and only three other wells scattered over a two square mile area were drilled that year. Only two more wells were drilled in that two square mile area in the 1930's. After the 1928 discovery time stood still until early 1980's. It was then realized that the dolomite had a productive area of 110 acres with Wilcox productive area of 50 acres inside that. Critical dip closure is 50 feet. Thickening shown from the Viola – Wilcox isopach show thickening outward in all directions outward from the axis. It took relatively few control points to realize this phenomenon."

At the edge of the Cherokee Platform with its junction with the Nemaha Fault zone, Bromide, McLish, and Oil Creek oil and gas fields are aligned in linear north-south fashion along the Nemaha flexure. In spite of some of the fields being small, they have produced large amounts of oil from all Simpson sandstones. This area is currently being explored for horizontal targets. The largest field is the Oklahoma City Field discussed below.

Oklahoma City Field, Oklahoma County. Discovered in 1928, the Oklahoma City Field in the area of T11N-R3W and T12N-R3W, was the first Simpson giant oil field, according to Gatewood (1970). It still holds the record for the largest Simpson oil field in Oklahoma. Much of the following information on the Oklahoma City Field is from Gatewood (1970). The field has produced almost 1 billion barrels of oil and 1.7 trillion cubic feet of gas (1.7 TCFG). Remarkably, only three years after its discovery in 1928, a total of 867 wells had been completed to yield 67 million barrels. Oklahoma City Field is readily recognized in the center of the enclosed Viola structure map (Plate 15) through Viola absence on an anticline (gray subcrop pattern). The breached anticlinal structure is the size of a township (36 square miles) with 1,000 ft of structural closure. It is bordered on the east by the Nemaha Fault with 2,000 ft of displacement. Oil Creek and Bromide pay sands are subcropped by Pennsylvanian shales on the flanks of this large anticline. The Arbuckle is productive on the crest, where recent horizontal drilling activity has resulted in recoveries of additional hydrocarbons from the Arbuckle and Joins.

Arbuckle Production, Oklahoma City Field. The discovery well for the Oklahoma City Field is ITIO No. 1 Oklahoma City (Section 24, T11N-R3W) drilled in 1928. From accounts described by Gatewood (1970, p.229), "It came in as a gusher from the Arbuckle dolomite on December 4, 1928, when the tools were blown from the hole after drilling out cement at 6,042 ft. The maximum rate of flow … was 6,565 bbl./day of oil. The high-gravity, amber-green oil came from the upper zone of banded gray and brown, finely crystalline, slightly porous dolomite containing solution cavities and numerous fractures. The solution cavities are of varied size and commonly the drill bit would drop several feet in the crevices; lost circulation was a problem during drilling." The discovery well yielded 110,000 barrels of oil in its first 27 days and produced more than one million barrels (1 MMBO) of oil after a few years of

*A giant oil field contains more than 500 million barrels of oil recoverable (Halbouty, 2003).

production. A few more wells were drilled to yield an average cumulative production of 160,000 BO per well. Hydrocarbons are present in the Arbuckle 500 ft below the top on the crest of the structure with some "Arbuckle" production originating from what is interpreted to be Joins in this report. In a nearby well, Decker (1935) identified a Joins graptolite at 6,300 ft at an equivalent stratigraphic horizon referred to as Arbuckle. This interval was described by Gatewood (1970, p. 231) to be, "predominantly dolomite, but contains thin streaks 8-10 ft. thick of sandstone with fine to coarse, rounded to subangular grains, some pale-green shale, sandy dolomite." The presence of sandstone is suggestive of the "Basal Oil Creek/Joins Interval" described earlier in this report. Total Arbuckle cumulative production in this field is stated to be 26 MMBO and 68 billion cubic feet of gas (68 BCFG). Curiously, in spite of occupying the structurally highest part of the anticline, the Arbuckle is the least productive reservoir in the field.

Oil Creek Production, Oklahoma City Field. In 1929, the Coline No. 1 Olds (Section 24, T11N-R3W) flowed 4,173 BOPD from the basal Oil Creek sandstone. This reservoir represents the second productive zone in the Oklahoma City Field and the first prolific Simpson producer. The basal Oil Creek sandstone has a porosity of 18 percent and oil recovery factor of 630 BO/acre-ft. Oil Creek average production per well was 280,000 BO with final field production of 114 MMBO oil and 320 BCFG (Gatewood, 1970).

Bromide Production, Oklahoma City Field. By far, the most prolific producer is the Bromide sandstone (referred to as "Wilcox" by Gatewood, 1970). It subcrops the farthest from the crest of the breached Oklahoma City anticline. The discovery well for the Bromide sandstone was the ITIO No. 1 Mary Sudik (Section 31, T11N-R2W) drilled in 1930, and, according to Gatewood (1970, p. 239), "it blew in with a roar, carrying 20 joints of heavy pipe into the derrick. The crew had failed to keep the hole full of mud as they withdrew the drill pipe. The Mary Sudik, was brought under control after 11 days, but in the meantime, carried by a strong north wind, it had sprayed 200 million cu. ft. of gas and 20,000 bbl of oil per day as far south as the university town of Norman, 12 mi away. Later the wind shifted and parts of Oklahoma City received a shower of oil." Initial pressure was 2,686 psi at depths of 6,000 ft. Sandstone porosities of 20-25% and high permeability result in recovery factors of 600 bbls/acre-ft. The Bromide has contributed over 540 MMBO and 800 BCFG to that produced in the Oklahoma City Field. Some of this production is reported as "Wilcox," a term that should be replaced by Bromide to avoid confusion with the Viola-aged Seminole sandstone. The Seminole sandstone is not productive in the Oklahoma City Field.

ANADARKO SHELF & BASIN

(Western part of Oklahoma Shelf depositional province)

This province occupies the northwest quarter of the state. It is west of the Nemaha trend and north of the Anadarko Basin. In map and cross sectional geometries it has the appearance of a monoclinal structural ramp. From the map prepared by Northcutt and Campbell (1995), the Anadarko Shelf gradually becomes deeper southward toward the Anadarko Basin. In this report it is arbitrarily separated from the Anadarko Basin at a Viola subsea of approximately 8,000 ft. Simpson production is sparse on the Anadarko Shelf. It is thought by some to be untested, considering the lack of well penetrations. The notable absence of Simpson production, except for a few small fields in the vicinity of the Nemaha Fault, is not due to an absence of Simpson reservoirs (the Bromide is well developed albeit with low porosity), but scarcity or absence of seismically-defined structural traps. Also, when drilling depths exceed 16,000 ft, such as throughout large areas of this province, there is understandable reluctance and lack of economic justification for operators to drill Simpson targets in the absence of structural traps. The seemingly lack of structural relief, however, may be a favorable trait for horizontal objectives.

ANADARKO BASIN AND ARDMORE BASIN

The Simpson Group is one of the most important oil producing groups within the Southern Oklahoma Fold Belt. Over 600 hundred million barrels of oil have been produced in this area from the five formations of the Simpson Group. The Southern Oklahoma Fold Belt includes the Anadarko Basin, the Ardmore Basin south of the Arbuckle Mountain horst, and, bordered by the Criner and Muenster Uplifts, the Marietta Basin. In Texas, uplift of the Muenster Arch resulted in the segregation of the earlier formed Fort Worth Basin through the creation of a graben-like basin known as the Sherman/Marietta basin to the north (Figure 23c). In a similar fashion, uplift of the Criner horst block resulted in the separation of the Ardmore Basin from the Marietta basin. Contrary to previous investigations that show a "straight line" shared "basement" structural connection from the north edges of the Criner and Muenster Uplifts to the north edge of the Wichita Uplift, this study shows that pulses of tectonic activity were not synchronous nor shared with those uplifts. The Criner and Muenster Uplifts are considerably younger than, and, on different fault trends (fault separated) from the Wichita block (Ham, et al 1964, Plate 15). For example, isopach maps included in this study show little sedimentologic influence by the Criner and Muenster Uplifts during Ordovician time — in contrast with Simpson thicknesses and lithologic associations of the Texas Arch (Wichita block) and associated Anadarko Basin/Texas Arch Hinge. This substantiates differences of origin.

Uplifts in southern Oklahoma are high-displacement pop-up horst blocks that formed during Morrowan time after Springer deposition. Later, flat-lying Pennsylvanian (Deese) strata covered tilted Morrowan structures. But in late Pennsylvanian time, horsts and other structures were reactivated with the effect that earlier formed structures and traps were either accentuated, or obliterated. Regardless, the magnitude of structural relief between the uplifts and basins is immense, measured in thousands of feet as indicated by the Viola structure map (Plate 15). High-relief folds and large-displacement faults provide numerous structural traps for oil accumulation and, in consideration of the relatively few wells that have penetrated appreciable sections within the Simpson (and Arbuckle) many structural traps remain untested in southern Oklahoma. Structural plays include potential discoveries of Simpson reservoirs on untested anticlines and fault blocks and subthrust features. Faults are mostly high-angle vertical or reverse. Low-angle reverse faults illustrated by Huffman, et al (1987) are present at locations where the Ardmore Basin meets the Tishomingo horst (South Ozark Platform) in Marshall County. Similar faults are also present at the junction of the Anadarko Basin with the Mountain View Fault of the Wichita Mountains (Texas Arch) such as shown by Jacobson (1984) and Keller (2012, A Regional Overview of Southern Oklahoma Structures, southern Oklahoma March 7 workshop, or informal communication). Seismic lines south of the Arbuckle Mountains show low-angle, gravity-driven reverse faults within ductile Mississippian and Pennsylvanian shale; they appear to have formed in response to uplift of the Arbuckle Mountains. Structural mapping across Oklahoma shows strike-slip faults to be minimal or nonexistent at the Viola level; vertical displacement always exceeds horizontal movements. Vertical faults of all types provide a variety of favorable juxtapositions of the Simpson with black shale source rocks in not only the Oil Creek, Bromide, and Woodford, but also in shales of the Caney, Springer, and Pennsylvanian. Southern Oklahoma is the most structurally complex of all the provinces, hosting an assortment of uplifts and intervening basins of various sizes and shapes (Figure 32). A similar cross section, but with less vertical exaggeration, can be found in Denison (1982). Both cross sections show that structures were predominantly formed under extensional and compressional tectonics during Morrowan and Pennsylvanian. The result of this deformation is that older Ordovician or Devonian structures are difficult to see from seismic data. Simpson hydrocarbons are found in traps at the southern rim of the Anadarko Basin near contact with the Wichita Mountains (Texas Arch), and parallel with flanks of the Ardmore/Marietta Basins.

A large number of Simpson oil and gas fields in southern Oklahoma were discovered by drilling structural features that were identified from an interpretation of seismic data. Unfortunately, Simpson and Arbuckle targets are difficult to see or differentiate on 2D seismic data, mainly because of great depths to prospective reservoirs and an absence of velocity contrasts. Additionally, not all seismic data are the same; for example, with shallow objectives in mind, older seismic data may have been shot with less dynamite, the energy of which was unable to reach deep objectives. Also, strata with dips over 40 degrees are difficult to image due to physical constraints of the sonic ray path, even with 3D seismic technology. Further, deeper targets may be obscured below high and low angle reverse faults and thrust sheets making them difficult to observe. However, in spite of these seismic limitations, untested structures in southern Oklahoma remain to be discovered. Fortunately, the hard and brittle Birdseye limestone (occupying a position between low velocity shales of the Oil Creek and McLish) provides a suitable reflector with which to correlate and map (Figure 19). A few geologists have included similar "Birdseye-like limestones" with the McLish, or referred to these limestones as the "McLish birdseye". However, data included in this report, especially on cross sections and thicknesses shown on Excel spreadsheets, enable their separation. The Birdseye is productive where multiple episodes of bending and faulting have produced secondary fracture systems. High recoveries from the Birdseye are found on truncated structural features at Healdton and Criner Fields. Birdseye in the Healdton Field has produced about a million barrels of oil from 24 wells, a smaller amount than the 18 MMBO and 6 BCFG produced from 46 wells in the Joins and Arbuckle. Birdseye is considered an attractive target for horizontal drilling due to its position above thick source beds of the Oil Creek shale.

Simpson sandstones are productive in the Enville SW Field (T7S-R3E) in Love County discovered in 1957 where the Oil Creek sandstone produced 11 MMBO and 205 BCFG. The Bromide, McLish, Oil Creek, and Joins are productive in Marshall County, such as in Cumberland Field (T6S-R7E) discovered in 1940 that produced 75 MMBO and 45 BCFG. These reservoirs are also productive along the Madill-Aylesworth Flexure which includes the Aylesworth Field (T6S-R6E) and SE Aylesworth Field (T6S-R7E) discovered in the 1940's, and Madill Field (T5S-R5E) with 16 MMBO and 33 BCFG discovered in 1954 (Huffman, et al 1987) Additional information for these fields and others may be accessed by referring to articles published by the Oklahoma Geological Survey (www.ogs@ou.edu), Shale Shaker (Oklahoma City Geological Society), and other geological societies. A few Simpson fields in the Southern Oklahoma Fold Belt are discussed below.

Apache Field, Caddo County. Apache Field (T5N-R12W) is a shallow oil field in western Oklahoma that is positioned on an upthrown fault block near the Mountain View Fault between the deep Anadarko Basin and the Wichita Mountains (Figure 10). Apache is part of a three-mile long anticline that is less than one-mile wide with over 500 ft of structural closure. Nineteen wells in the Apache Field have yielded 68 MMBO and 11 BCFG, mostly from thick porous Bromide sands. The field was discovered in the 1941 and is one of the earliest fields to be discovered from an interpretation of seismic data (Scott, 1943). The first well was structurally low, but the second was higher and flowed 1,500 BOPD at 3,400 ft; wells drilled at highest structural positions had initial production rates of about 10,000 BOPD (Scott, 1943). Although principal contributions were from the Bromide, minor amounts came from the McLish, Joins, and Arbuckle. The Joins was often classified as Arbuckle in the literature, but in this study the Joins is recognized as a separate unit. Similarly, the Joins was misidentified as Arbuckle farther west in the West Mayfield Gas Field discussed below.

West Mayfield Gas Field, Beckham County. West Mayfield Gas Field (T10N-R26W) was discovered in 1972. It is 80 miles west from the Apache Field, between which there were very few wells with which to correlate. Because of that distance, correlation was difficult, and, what is designated as Simpson and Arbuckle in this report may differ from earlier studies. For example, gas production in West Mayfield was thought to be entirely from carbonates of the Arbuckle Group, including the West Spring Creek, and not from the Simpson Group as stated here. This is understandable given the distance involved and lack of wells with which to correlate, but also, early correlations were made at a time when the stratigraphic contact between the Simpson and Arbuckle was not well understood. In this study, therefore, productive intervals in West Mayfield Field are from carbonates of both the Joins (Simpson) and Arbuckle. There appears to be some agreement with this assessment since a few earlier interpretations refer to this productive interval as the upper part of the West Spring Creek Formation; now included with the Whiterockian (Joins) as discussed by Derby (1969, 1973). Therefore, in this context, the Joins Formation of the Simpson Group is recognized as a major contributor of gas in West Mayfield Gas Field. On electric logs the Joins Formation has concave, or suppressed, SP similar to Joins signatures in other parts of western Oklahoma. The gamma-ray streaks at the top of the Arbuckle suggest the presence of thin beds of organic shale, a characteristic that appears to be ubiquitous to upper parts of the Arbuckle. Reservoirs of West Mayfield Gas Field are 17,000 ft deep on the downthrown side of the Mountain View Fault, but upthrown by about 8,000 ft from a deeper block at 25,000 ft. The field has produced 100 BCFG from six wells in the Cambrian and Ordovician, making the Simpson and Arbuckle the most prolific gas reservoirs in the state. Bromide sandstones are absent. Production from younger formations brings the total field production to 400 BCFG. The West Mayfield structure has about 1,000 ft of vertical anticlinal closure (Gatewood, 1979). In 1972 the discovery well flowed of 32 million cubic feet gas per day (32 MMCFGPD) through 186 ft of perforations from fractured "Joins" and Arbuckle carbonates (Solter, 1980). An offset well had an initial production rate (I.P) of 120 MMCFGPD. Gas is sweet with a low CO2 content. Interestingly, it is believed that no shows of gas were noted in the drilling of the wells, perhaps because the mud system was "overbalanced" (or heavy) due to fear of blowout. The heavy mud, however, served its purpose of pushing gas back into rocks in the borehole to suppress potential blowout. The West Mayfield structural trend extends farther to the west at even greater depths and connects with the Mills Ranch Field in adjoining Texas where gas in the Joins/Arbuckle at 26,518 ft renders it as being one of the deepest productive reservoirs in the world (Gatewood, 1979).

Golden Trend, Grady, McClain, and Garvin Counties. At the far eastern edge of the Anadarko Basin Golden Trend (T2N to T5N and R1W to R6W) is located 30 miles south of the giant Oklahoma City Field. It is a name given to a three-county area in Grady, McClain, and Garvin Counties that consists of an agglomeration of numerous smaller fields (Northcutt, 2000). Production is from reservoirs of the Simpson Group and younger. Like the Oklahoma City Field, Golden Trend can be considered a giant since it produced 570 million barrels of oil and 3 TCFG. The Simpson Group within the Golden Trend has produced over 136 MMBO and almost 1 TCFG of that total, when it is expanded to include nearby Alex NW, Curty SW, and Chitwood fields (Figure 30). Simpson cumulative reserves would increase even more should Maysville, Antioch, Whitebead, and South Brady Fields be included with Golden Trend. These fields are discussed by Springman (2002). Regardless, Golden Trend and surrounding fields consist of an aggregate of several small structures productive from various sandstone reservoirs of the Simpson Group. For example, on one part of Golden Trend both the Bromide and Tulip Creek sandstones may be productive on a small structure in one well, but on a nearby separate structure only the Oil Creek will be productive. All productive structures in the Golden Trend area, however, appear to be part of, and genetically related to, an anticlinal nose on the upthrown side of major faults. One of those faults is shown on the right side of the cross section in Figure 32. Sizes of trapping structures vary, but interestingly from the perspective of an exploration geologist, the size of the Simpson structure may not be an important factor in achieving high recoverable reserves (Figure 27). For example, a structure 20 acres in areal extent in the Golden Trend might yield the same amount of hydrocarbon as a structure 200 acres in areal extent located

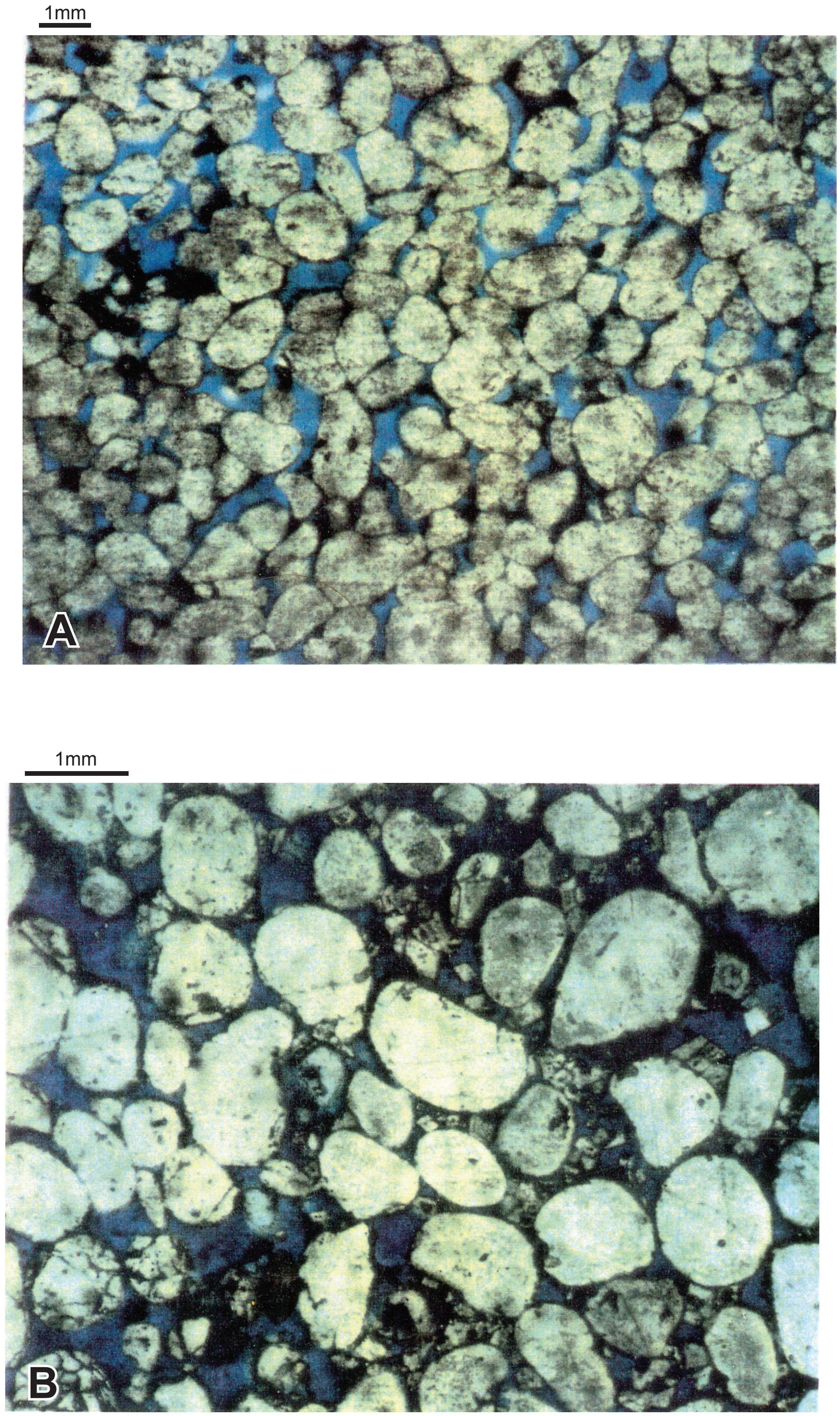
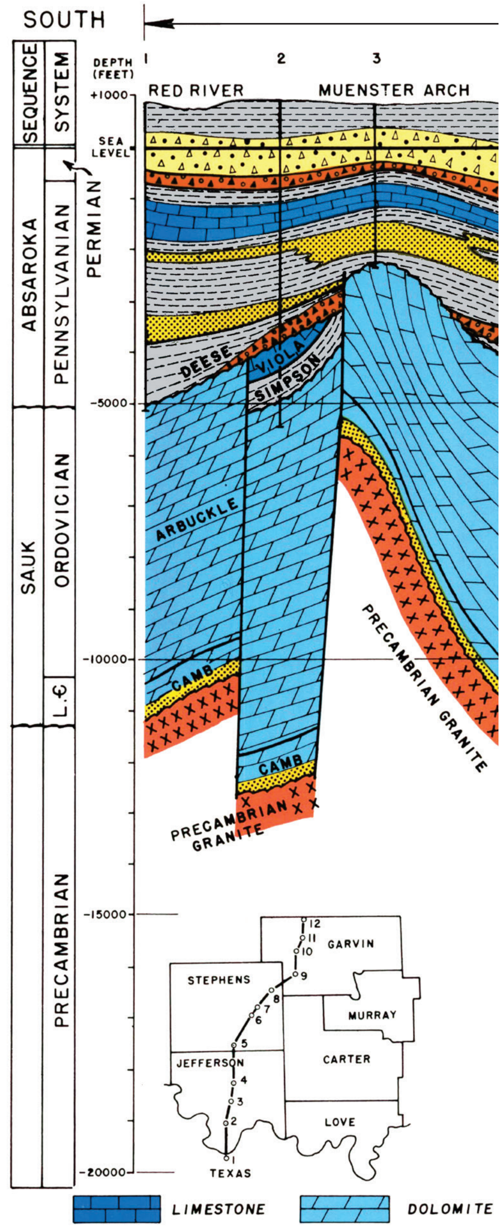


Figure 31. Thin section photographs of Simpson sandstone. Both sandstones are very porous consisting of fine to coarse quartz grains. Blue background represents epoxy-filled pores between the grains. A) Basal Oil Creek sandstone in Christie Stewart #2 Renaker-Gibson core, Whitebead Field, Garvin County (Section 17, T3N-R1W). B). Bromide sandstone from core in Christie-Stewart #1 Moore, Garvin County (Section 23, T3N-R1E).

elsewhere. The explanation of this apparent anomaly is that the basal Oil Creek sandstone in Golden Trend has porosity of 25 to 35 percent and 2,500-9,000 MD of permeability with a calculated recovery rate of 600 bbl/acre-foot. These reservoir characteristics are superior compared to reservoirs outside of Golden Trend. Moreover, Springman (2002) states that Simpson reservoirs located within the area of Golden Trend Field have recoveries that rival those in the Gulf Coast region, saying on p. 55 " … the basal Oil Creek sand is capable of producing (more than) 1,000,000 barrels of oil per well (BOPW), with recovery factors as high as 800 BO per acre-foot (ac-ft.) at depths (less than) 7,000 ft. Shallower Bromide sands are capable of producing (more than) 600,000 BOPW, with recovery factors as high as 400 BO/ac-ft. at depths (less than) 6,000 ft." It appears that high porosity and permeability may be a consequence of thin clay coatings that surround quartz grains thus inhibiting the precipitation of secondary mineral cements. Apparently, clay coats inhibited the precipitation of secondary mineral cements. According to Forgotson, et al (1997), however, high porosities may also be due to dissolution of dolomite cement. Oil Creek and Bromide porosity for wells in T3N-R1W and T3N-R1E are shown on petrographic photos in Figure 31. Porosities of 33% and permeabilities of 8,000 MD have been documented from core analyses of the basal Oil Creek sandstone in Section 24, T1N-R2E (Informal correspondence).

Detailed seismic exploration maps for the Golden Trend, such as those that show fault displacements and orientation relative to structural grain, facilitate an understanding of structural paragenesis. For purposes here, however, insights to structural origins of Golden Trend can be obtained through an examination of the more generalized Viola structure map on Plate 15 and Figure 30. For example, the Golden Trend is located at the southern terminus of the Nemaha Fault zone at a "triple junction" of the Anadarko Basin, Cherokee Platform, and Ardmore Basin. It shares structural characteristics of each. Furthermore, Simpson depositional environments in this oil-friendly area were favorable for the development of porous and permeable reservoirs at ideal burial depths and temperatures. Post-depositional effects adverse to the generation and preservation of hydrocarbons were lacking. Most important, however, was that Simpson reservoirs in the Golden Trend were updip to indigenous and external hydrocarbon sources from the Anadarko and Ardmore Basins. Migrating hydrocarbons from the Woodford, Springer, and Pennsylvanian (in addition to Oil Creek and Bromide shale sources) infiltrated Simpson reservoirs,



and, structural activity, consisting of mainly vertical movements related to extensional forces, took place at several times during the Early Paleozoic. From detailed 3D-seismic data (Figure 26) at least two localized structural pulses affected the Golden Trend area during deposition of the Simpson Group. In late Oil Creek time structural activity manifested itself as small uplifts on a larger anticline contemporaneous with associated faults with displacements of less than 100 ft. Early trapping of hydrocarbons in many of the small anticlines, domes, and horst blocks in the field was probably due to these low-displacement sealing faults. A second structural pulse with similar effects was repeated during Bromide time. This structural movement accentuated closure of earlier-

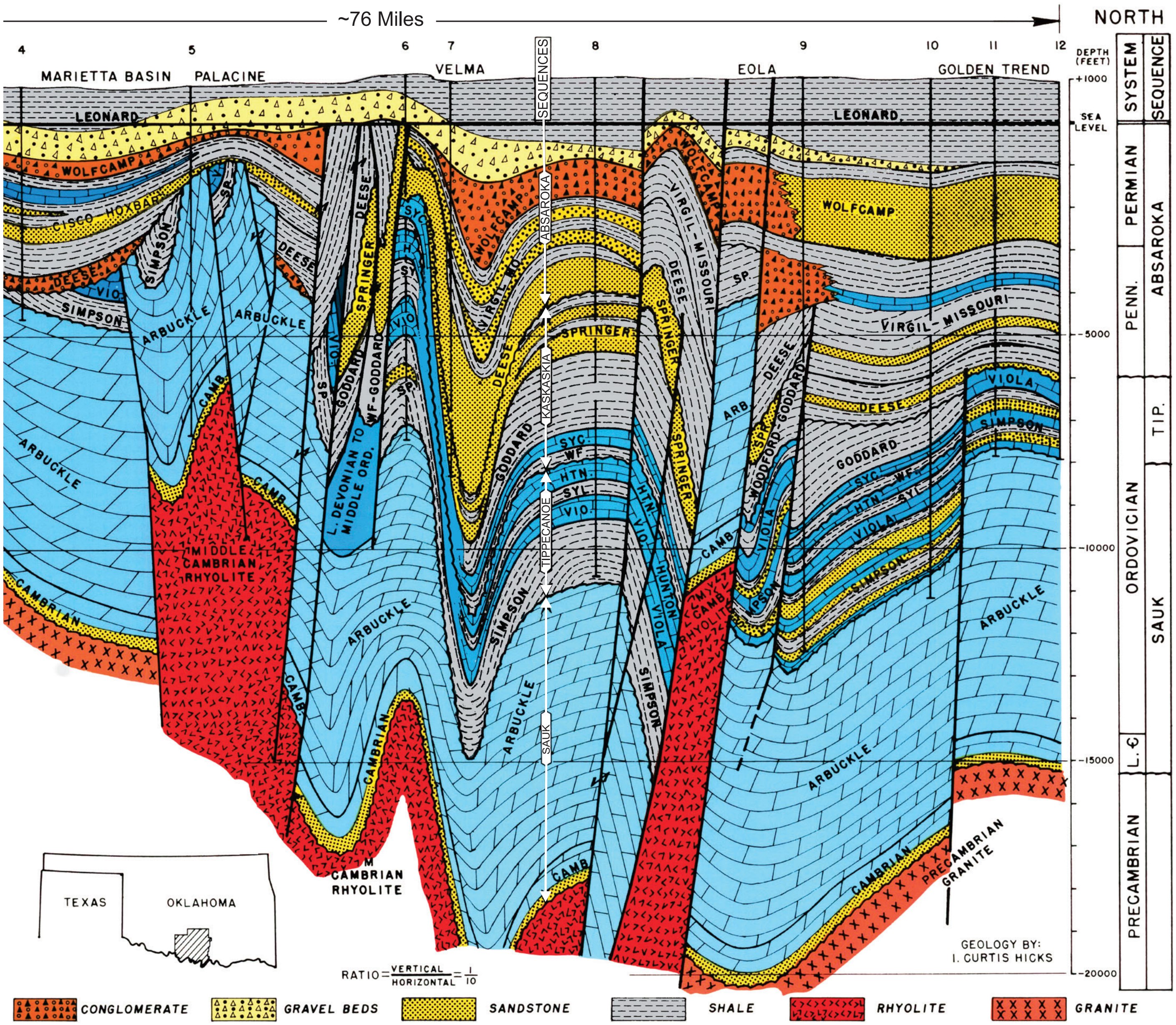


Figure 32. Southern Oklahoma "fold belt" structural cross section from Golden Trend to Red River (from Hicks, 1987). The Ardmore and Anadarko Basins are the most structurally complex areas of the state. Oil and gas are contained within a variety of traps, most of which formed in Morrowan time. Adding to the complexity, many traps were later reactivated during late Pennsylvanian deformation. Sequences are shown at the left and right sides and in the middle in white near Velma Field. The north end of this cross section extends into Golden Trend Field illustrated in Figure 30.

formed structures. Of course tectonic shifts also took place after the Ordovician such as during Devonian, Mississippian, and Pennsylvanian. A seismic line extracted from a 3D survey (Figure 26) shows interfingering effects of lateral phasing of peaks and valleys, likely representing thickness and porosity variations within the sandstone, in addition to facies relationships with other lithologies. Older 2D lines in the general area do not have resolution significant enough to show such seismic intricacies.

HOLLIS BASIN

(Texas Arch depositional province)

Located south of the Wichita Mountains, the Hollis Basin is both a sedimentary basin that formed in Pennsylvanian time; today, it is a low relief structural feature next to the Wichita Mountains. Trap-

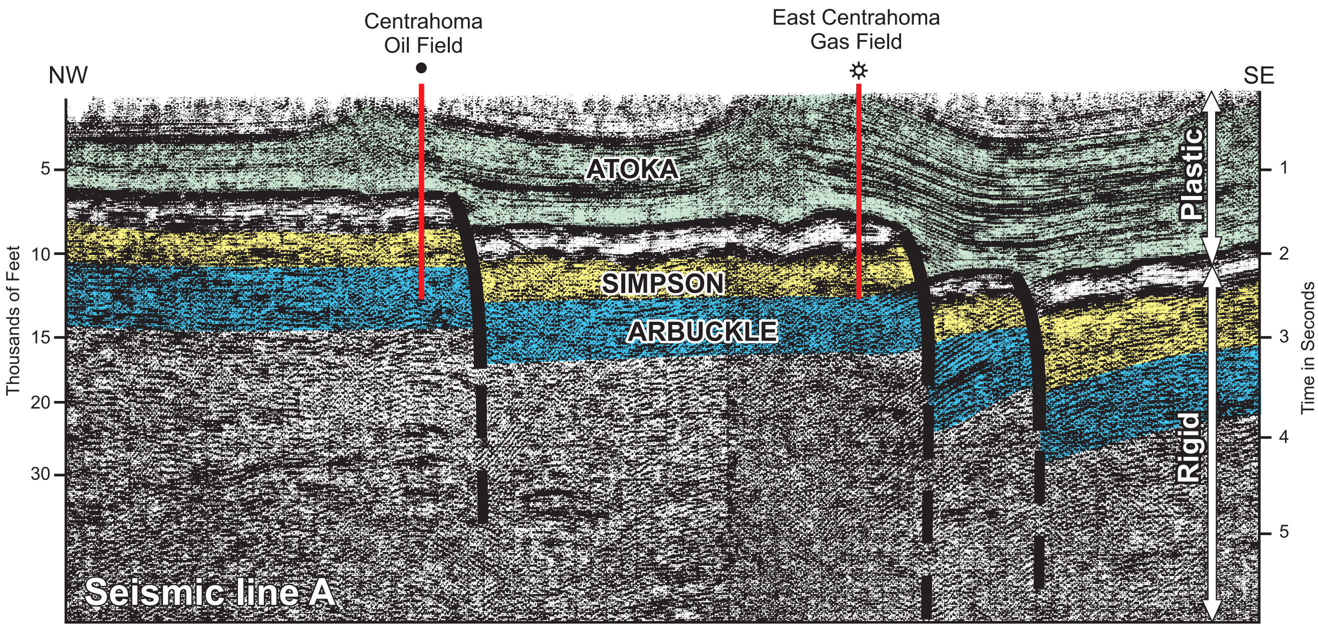


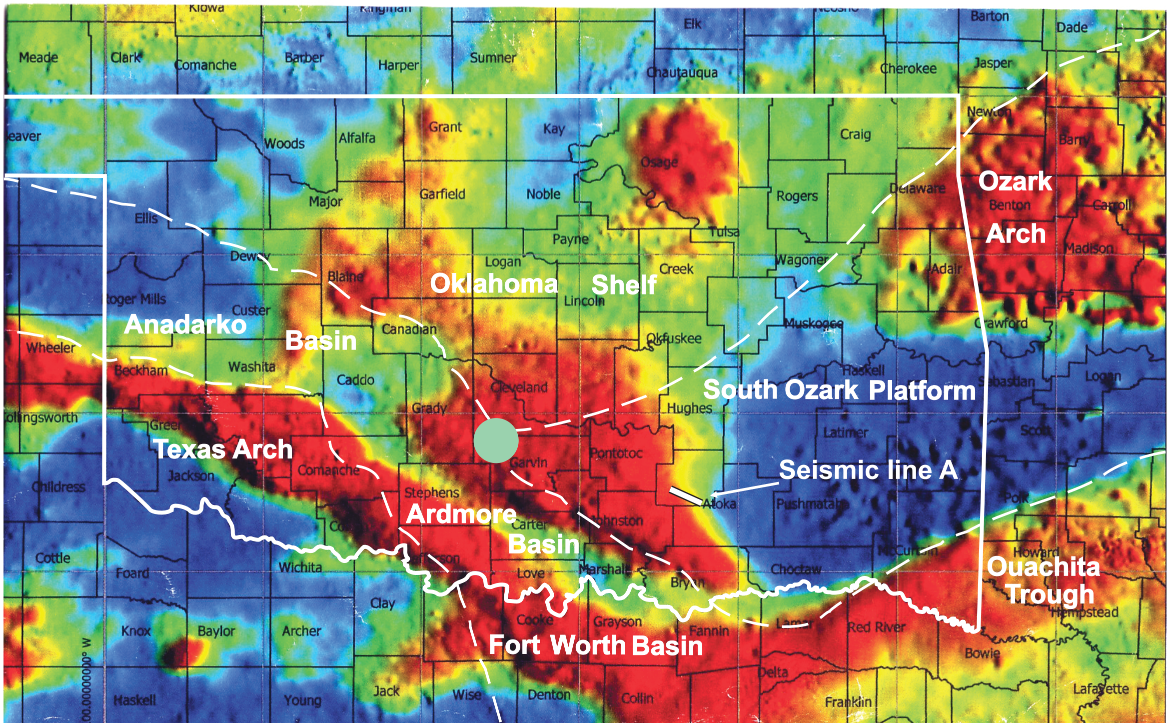
Figure 33. Oil to Gas transition, Coal County, Arkoma Basin.
A. Productive basal Oil Creek and basal McLish sandstones are predominantly oil in the upthrown fault block of Centrahoma Field (5 MMBO) and gas in the downthrown block of East Centrahoma Field (70 BCFG), both in southern Coal County. Location of this seismic line is shown on Figure 33B. Deep faults, caused by excessive subsidence of the South Ozark Platform during Morrowan, suggest that burial depths and temperatures caused oil to convert to gas in the E. Centrahoma Field. Shallower Centrahoma Field was not affected (also see explanation in Figure 23). The Atoka, shown in light green, thickens syndepositionally in the vicinity of "deep" faults. Compressional activity associated with gravity slides (or "collision") distorted the plastic Atokan with little effect on underlying rigid strata. The Choctaw and Ti Valley thrust faults are located about 10 miles from the southeast edge of this seismic line and seen in blue on map Figure 33B. Wapanucka, Woodford, and Hunton are shown in white. (Modified from Cohen, 1982).

ping structures are subtle and of various ages. Prior to basin development in Pennsylvanian, the Simpson in this area was deposited in a non-basinal setting on the ancestral platform of the Texas Arch. The Simpson Group is less than a few hundred feet in thickness, in contrast to thousands of feet thick in the Anadarko Basin a short distance to the north. Quartz sandstones are thin to absent; rather, Simpson formations consist of predominantly platform carbonates. The Simpson contact with the underlying Arbuckle is difficult to identify because of likeness of carbonates, however, chert is relatively scarce in the Simpson. This quality enables distinction from underlying Arbuckle. From the Viola structure map (Plate 15) Simpson is absent in the Wichita Mountains and in most parts of the Hollis Basin, but present in Tillman County, albeit with low well density. There is questionable Simpson production in western Tillman County. One well in the Southwest Burt Field drilled in 1946 pumped 127 barrels a day from what was referred to as basal Simpson Joins dolomite at 4,573 ft (Sears, 1955). Cities Service, No.1 Hutcheson "A," Section 18, T3S, R16W, Tillman County (Figure 11) had a show of oil in a core of thin basal Oil Creek sandstone from 5,673 to 5,692 ft.

ARKOMA BASIN

(South Ozark Platform depositional province)

In addition to being a structural province, the Arkoma Basin is a depositional basin consisting of southward thickening Atokan strata that formed in response to extensional tectonics in Pennsylvanian time. Buchanan and Johnson (1968) suggest that the abrupt appearance of thousands of feet of mid-Atokan strata is evidence for basin formation through growth faulting in Morrowan time. Thickening is seen from seismic data. It also shows that the Arkoma Basin does not terminate at the Ouachita thrust sheet but extends under it for a distance of about 20 miles south from the thrust front. Farther south than that distance the Atoka is less thick and composed mostly of marine platform strata older than Atoka. These strata were deposited on the South Ozark Platform at a time when the Arkoma Basin did not exist. Partly because of this interpretation, the southern depositional limit of the Arkoma Basin was at a position in front of (north of) advancing Ouachita thrust



B. Gravity map with superimposed depositional provinces showing the position of the seismic line in Figure 33 A. Hot colors (gravity maxima) show "mountain roots" that exert strong gravitational pull. Cool colors (gravity minima) reflect thick sections of less dense sedimentary rocks, such as strata over five-miles thick within the Ouachita Mountains in southeastern Oklahoma. This minimum is interpreted to represent the collapsed and deeply buried portion of the South Ozark Platform beneath the Ouachita Allochthon (perhaps including thousands of feet of detrital Cambrian sedimentary rock). Golden Trend Field (green dot) is located at junction of three depositional provinces, the Anadarko/Ardmore Basin, South Ozark Platform, and Oklahoma Shelf (Plate 2). This junction also coincides in position with a "triple junction" of structural provinces, the Cherokee Platform, Anadarko Basin and Ardmore Basin (Figure 30 and Plate 1). (Courtesy of Kevin Crain, 2011).

sheet (see Figure 23B). The position of the present-day Ouachita thrust front is marked by a red line on the Viola structure map and other maps in this report. The structurally lowest part of subthrust Viola is located beneath the Ouachita Mountains in a large graben complex named here as the "Antlers Graben" (Plate 15). Well control is sparse-to-nearly-absent in this area due to Viola depths that exceed 20,000 ft. Documentation of the subcrop pattern is based on an interpretation of strata in a few deep wells in the Broken Bow Uplift in southeastern Oklahoma.

The Simpson and other pre-Atokan formations were deposited in a platform setting and show minor thickening to the south, in contrast to basinal Atokan strata. Additionally, the northern part of the South Ozark Platform was far removed from the clay-rich fairways of the Ardmore and Fort Worth Basins and the Ouachita Trough. Strong currents on the platform kept clay in suspension, never to mix with bottom sediments, as attested by overall absence of shale in the Simpson. Therefore, clay was not readily available to coat quartz grains. Dust rings that coat the quartz grains, such as shown in Suhm (1974, fig. 6c, p. 691), were not thick enough to retard overgrowths of secondary silica, with the result that porosity was occluded. Other digenetic or thermal activity, however, may have also been responsible for low porosity. Partly because of poor porosity of Oil Creek and McLish sandstones, Simpson production is not widespread in the Arkoma Basin. The ubiquitous occurrence of gas, rather than oil, in most reservoirs in the Arkoma Basin was likely due to a conversion caused by high temperatures related to deep burial. Simpson production, mostly oil, is found in western parts of the Arkoma Basin where burial depths were less.

Wilburton Arbuckle Gas Field, Latimer County. Discovered in 1987, the Wilburton Arbuckle Gas Field (T5N-R18E) is productive from karsted Arbuckle carbonates on a large horst block at a depth of from 13,000 to 15,000 ft. The field is expected to recover one half TCFG from 16 wells. Almost all production from Arbuckle limestone is from the upper 500 ft of that group. The discovery well, Arco #2-15 Yorman, had initial production rates of 150 MMCFGPD with 5,300 lbs. of shut-in tubing pressure; the reservoir was karsted, tectonically-fractured vuggy dolomite of the West Spring Creek Formation of the uppermost Arbuckle Group. The karsted nature of this interval is discussed by Carpenter and Evans (1991). The overlying nonproductive basal Oil Creek sandstone is thick and lacks porosity, but carbonates in the underlying Joins have produced minor amounts of gas in a few wells, probably in an area where gas accumulated in locally developed collapse breccias that rest above the eroded Arbuckle surface (Cross section D-D' Plate 13). Similar solution breccias were noted in the Simpson (Oil Creek) in Arkansas in the Everton Formation (Purdue, 1907; McKnight, 1935; Suhm, 1970). Following the discovery of the Wilburton Field in 1987 several companies undertook seismic searches for structural look-alikes. A few wells were drilled on similar structures but were abandoned because the Arbuckle lacked an interconnected karsted reservoir system like that at Wilburton. Consequently, Arbuckle exploration activity slowed a few years after Wilburton discovery.

Upper parts of the Simpson have produced gas from dolomite in the area of Wilburton. Gas has been recovered from Bromide carbonates in a few wells in other parts of Latimer County, such as the first horizontal Simpson well drilled by BP in Section 35, T7N-R22E. From a horizontal length of 12,506-15,050 ft, it yielded almost 3 MMCFGPD (Boyd, 2007). Unlike the importance of structural entrapment in other hydrocarbon provinces, gas accumulations in the Bromide and other Simpson carbonates in the Arkoma Basin appear to be influenced by complex stratigraphic conditions. For example, from petrologic data, Wahlman (2010) reports Bromide gas production is concentrated in secondary dolomite deposited in intertidal, lagoonal, possibly restricted marine environments, rather than early diagenetic dolomite that may have been initially porous, but which was later filled by porosity-destructive calcite. Medium crystalline (secondary) porous dolomite in basinward positions appears to be a more preferable reservoir than finely crystalline penecontemporaneous dolomite. Twenty miles south of Wilburton Field, electric logs of the Chesapeake No. 2-34 Mary in southern Latimer County show the Bromide to be marked by numerous gamma-ray kicks from thin shales. The appearance of shale in #2-34 Mary may represent clay invasion from the Ouachita Trough. Only a dozen wells or so have been drilled into the Simpson under the Ouachita thrust complex and most of these were at locations near the frontal thrusts of the Choctaw and Ti Valley Faults. Farther south from those thrusts, Simpson productivity has not been adequately tested. Exploration is suppressed in the southern part of the South Ozark Platform near its junction with the Ouachita Trough due to unfavorable drilling depths, lack of documented porosity in Simpson sandstones, structural complexity, scarcity of seismic lines available for purchase, and lack of roads and pipelines (infrastructure). However, research has shown that there is the expectation that Simpson sandstones may have more favorable porosity at locales proximal to the shale basin of the Ouachita Trough, where clay may have been available to coat quartz grains to enable porosity development. Additionally, in consideration of great depths, there is the expectation that pore space may have been generated through dissolution of feldspar grains within the sandstones. Organic-rich basinal shales of the Ouachita Trough may have also provided hydrocarbon sources. The location of the platform-trough break has other important implications for the petroleum potential of the subthrust Simpson, such as possible presence of thick reservoir-quality sands that could have piled up at the shelf edge, or perhaps spilled over into the Ouachita Trough, such as the spillover of basal Oil Creek sands and other Simpson sands that took place at the margin of the South Ozark Platform at its contact with adjacent basins. Empirically, it has been demonstrated that basin margins are favorable sites to explore for trapping structures and fractured carbonate reservoirs.

Oil is found in western parts of the Arkoma Basin in Coal County, and, it is in this area that Simpson Group oil production compares favorably with that in southern Oklahoma and Cherokee Platform. High-porosity Simpson reservoirs in these fields provide empirical testimony to the importance of geographic proximity to clay basins such as the Ardmore Basin where clay would have been available for clay coats. The prolific Fitts and Jessie Fields, and the Centrahoma and E. Centrahoma Fields are discussed below. All these fields are a short distance east of the Arbuckle Mountains where high porosity sands of the Simpson Group are exposed in outcrops and quarries (Plates 1 and 15).

Fitts Pool, Pontotoc County. Located on the north flank of the Arbuckle Mountains, Fitts Pool (T2N-R7E) is the largest producer of Simpson oil in the western part of the Arkoma Basin. The Viola is 4,000 ft deep on the faulted Fitts anticline. The anticline is seven miles long, one- to-two miles wide, and has about 700 ft of structural closure. Fitts was discovered in June, 1934 and has produced 225 MMBO and 55 BCFG from over 400 wells. Most production is from high-porosity basal McLish sandstone. Production from the dolomite facies of the Seminole Sandstone is discussed by Puckette, et al (2000).

Jessie Pool, Pontotoc and Coal Counties. Located a few miles southeast of Fitts, Jessie Field (T1N and R7-8E) is an upthrown anticline that is seven miles long, one mile wide. Simpson production confined to structurally highest positions across a length of two miles. Most of the oil in the Jessie Pool is from the basal McLish sandstone. Jessie was discovered in 1935; the first well had an initial production rate of 2,831 BO in 5 hours at 4,621 ft. That interval was deepened 60 ft further into the McLish to a virgin zone that flowed 1,612 BO in 1 hour and 35 minutes (Boyd, 1938). Jessie has produced 4 MMBO. Reservoirs of the Bromide, Tulip Creek, and dolomite facies of the Seminole sandstone also contributed oil.

E. Oconee Field, Coal County. Production in Oconee Field (T1N-R9E) is from basal McLish and basal Oil Creek sandstone reservoirs with 15 to 19 percent porosity at 7,000 ft. With a gas cap and water drive, initial pressure was 3,600 psi; production rates were two MMCFGPD and a flow of 37 gravity oil at a rate greater than 200 BOPD (Morris, 1968). The field is on an anticline on the upthrown side of a fault that encompasses two sections. Eighteen wells on 40-acre spacing have produced over 7 MMBO and 11 BCFG.

Centrahoma Oil Field and East Centrahoma Gas Field, Coal County. Centrahoma Oil Field (T2N-R9E) and the deeper East Centrahoma Gas Field (T1N-R10E) produce gas, condensate, and oil from the basal Oil Creek and basal McLish sandstones. Oil at 7,000 ft is found in the Centrahoma Field on the north, whereas gas at 8,500 ft is produced in the East Centrahoma Field (Anderson (1974). The oil-rich Centrahoma Field is a dome one mile across with 200 ft of closure. Typical initial production rates from basal Oil Creek sandstone were 199 BOPD. The basal McLish was less productive with a few barrels of oil a day and 1.5 MMCFGPD. The total amount of oil produced from 1937 to 1973 is not known, but is estimated to be over 5 MMBO from 15 wells. Centrahoma is fault-separated from East Centrahoma. East Centrahoma is a two-mile-long faulted anticline with over 100 feet of structural closure. In 1960, the basal Oil Creek sandstone had initial production rates of 32 MMCFGPD and trace of distillate; basal McLish sandstone yielded 19.5 MMCFGPD and eight barrels of condensate per million cubic feet of gas. East Centrahoma eventually produced over 70 BCFG.

It is significant that oil, rather than gas, is the dominant hydrocarbon in the Centrahoma Field, and that oil is replaced by gas at greater depths a short distance southeast in the adjacent East Centrahoma Field. Similarly, oil in the Jessie, Fitts, and E. Oconee fields is replaced by gas toward deeper parts of the Arkoma Basin. Apparently, hydrocarbon outcome, whether oil or gas, was not dependent on gas-cap separation during migration, such as oil occupying structurally lower traps than gas (gas is lighter and updip). Since reservoirs of the Simpson shared similar environments of deposition and similar organic sources across this area, the cause of "hydrocarbon outcome" must be related to other factors. Perhaps burial depth and other post depositional effects were at play to account for "downdip gas and updip oil." For example, in view of the paleotectonic history of the Arkoma Basin and the Ouachita overthrust, the preponderance of gas in these areas was likely the result of high thermal maturity due to deep burial depths temperatures and pressures, perhaps related to Morrowan tectonics. Relatively sharp increases in depths in the Arkoma Basin takes place along deep fault "zones," illustrated and discussed in Figures 23 and 33. For example, the seismic line on Figure 33 transects both the Centrahoma Oil Field and the deeper East Centrahoma Gas Field near and along one of these deep fault zones. It appears that proximity to this deep fault produced thermal extremes resulting in Simpson sandstones in East Centrahoma to be gas filled whereas those in Centrahoma contain oil.

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