Chapter 5

Geologic Assessment of Undiscovered Oil and Gas Resources in the Cambrian-Devonian Stratigraphy of the Anadarko Basin, Oklahoma, Kansas, Texas, and Colorado

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By Stephanie B. Gaswirth and Debra K. Higley

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Petroleum Systems and Assessment of Undiscovered Oil and Gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58

Compiled by Debra K. Higley

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Geologic Assessment of Undiscovered Oil and Gas Resources in the Cambrian-Devonian Stratigraphy of the Anadarko Basin, Oklahoma, Kansas, Texas, and Colorado

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Abstract

The Woodford Composite Total Petroleum System contains four Cambrian through Devonian conventional assessment units (AU) in the Anadarko Basin: (1) the Arbuckle-Ellenburger Assessment Unit; (2) the Simpson Group Assessment Unit; (3) the Viola Group Assessment Unit; (4) the Hunton Group Assessment Unit. These assessment units have collectively produced more than 900 million barrels of oil (MMBO) and 7 trillion cubic feet of gas (TCFG) from the Anadarko Basin, which covers central and western Oklahoma, south-central Kansas, southeast Colorado, and the Texas Panhandle. Based on available geologic and production data, the undiscovered oil resources for these conventional assessment units are estimated at a mean of 25 million barrels of oil and 646 billion cubic feet of gas (BCFG).

Introduction

The U.S. Geological Survey (USGS) completed a geologic-based assessment of the undiscovered oil and gas resources of the Anadarko Basin Province in western Oklahoma and Kansas, northern Texas, and southeastern Colorado in 2010 (Higley and others, 2011; fig. 1). The assessment was based on geologic elements and processes within a total petroleum system (TPS) that include: (1) source-rock distribution, thickness, organic richness, and history of generation, maturation and migration; (2) reservoir-rock type (conventional or continuous), distribution and quality; and (3) character of traps and timing of formation with respect to petroleum generation, accumulation and migration. Each TPS contains multiple assessment units (AU), the basic geologic unit of the oil and gas assessment, and undiscovered oil and gas resources were quantitatively estimated within each AU.

Detailed stratigraphic and structural framework studies and petroleum system modeling, combined with historical exploration records and production analyses, were used to estimate the undiscovered, technically recoverable resources. Using this geologic framework, the USGS defined two TPSs (the Woodford Composite and Pennsylvanian Composite) in the Anadarko Basin that contain nine conventional AUs and two continuous (unconventional) AUs. The Woodford Composite TPS includes the AUs that are the focus of this chapter: the Arbuckle-Ellenburger AU, the Simpson Group AU, the Viola Group AU, and the Hunton Group AU (fig. 1). These AUs comprise the strata in the Anadarko Basin from the Cambrian Reagan Sandstone through the Ordovician-Devonian Hunton Group (fig. 2). The conventional Mississippian AU and the continuous Woodford Shale Oil AU and Woodford Shale Gas AU (included in table 1) are also part of the Woodford Composite TPS, but documented in another chapter of this report. The Pennsylvanian Composite TPS includes the conventional Morrowan-Atokan AU, the Desmoinesian AU, the Missourian-Permian AU, the Greater Granite Wash Composite AU, and the continuous Thirteen Finger Limestone–Atoka Shale Gas AU, which are also included in chapter 7 of the DDS.

Geologic Setting

The Anadarko Basin is an asymmetrical, south-dipping sedimentary basin that began during the Precambrian as the southern Oklahoma aulacogen (Rascoe and Adler, 1983; fig. 3). The northwest-trending southern Oklahoma aulacogen is the deepest sedimentary trough in North America and was formed by rift-related igneous intrusive and extrusive occurrences in the late Early Cambrian though the Middle Cambrian (Lindsay and Koskelin, 1991). Following emplacement of Early and Middle Cambrian basement rocks during an episode of igneous activity, a basal transgressive sandstone, the Reagan Sandstone (fig. 4), was deposited across a moderately mature erosion surface of low relief (Johnson, 1989). The sandstone grades upward into a succession of shallow-water marine limestones and dolomites of the Arbuckle Group, which were deposited almost continuously until the Middle Ordovician.

The overlying Simpson Group sandstones and limestones were derived from northeastern and eastern sources. They are overlain by limestones of the Viola Group, followed by the gray and green-gray shales of the Sylvan Shale,

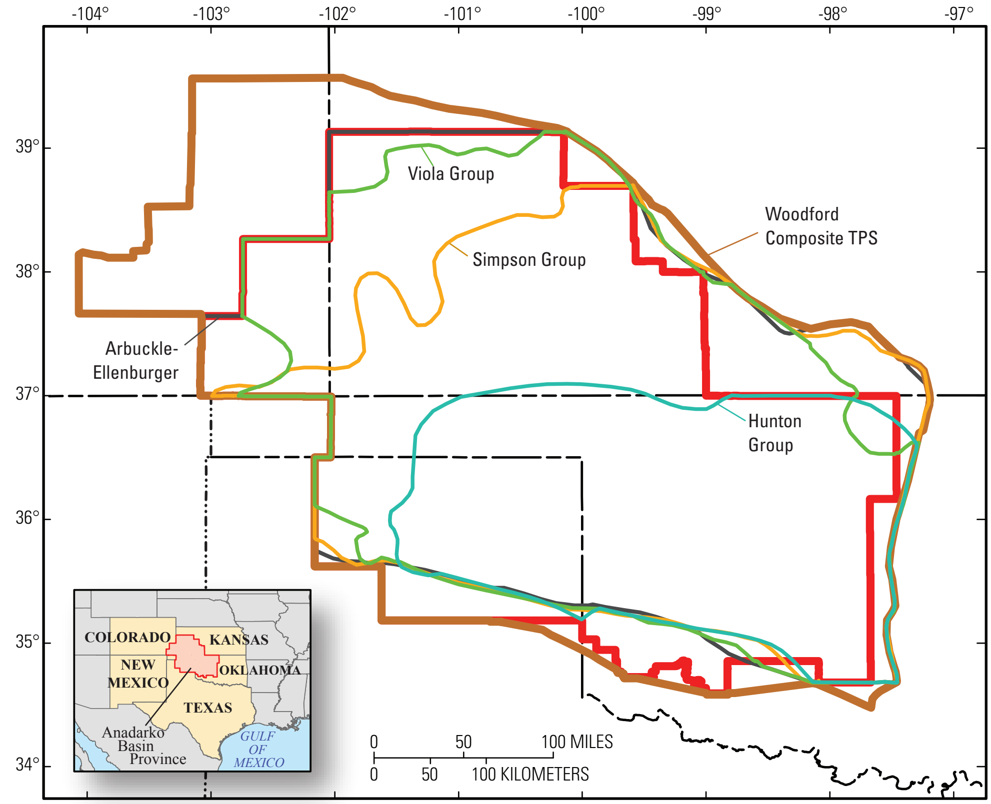

Figure 1. Anadarko Basin Province (red line) and boundary of the Woodford Composite Total Petroleum Systems (TPS; brown line) and assessment units (AU) discussed in this chapter.

and finally the Upper Ordovician to Devonian carbonates of the Hunton Group (fig. 4). The Devonian-Mississippian Woodford Shale unconformably overlies the Hunton Group. The Arbuckle through Viola strata are still present in most parts of the Anadarko Basin, though there is a pre-Woodford unconformity that is widespread in the Midcontinent (Johnson, 1989). The Sylvan Shale, Hunton Group and Woodford Shale are only present in Oklahoma, Texas, and southernmost Kansas.

The present-day basin configuration is largely controlled by movement of the late Paleozoic Wichita fault zone and Ouachita thrust plate (Amsden, 1989). The southern margin of the basin is defined by the Amarillo-Wichita Mountains. The eastern basin boundary is defined by the Nemaha uplift, the north by the Central Kansas uplift, and the west by the Sierra Grande uplift (figs. 5 and 6). The deepest part of the basin is parallel to the southern margin, where petroleum production extends below 20,000 feet (ft).

Basinward dip of strata results in a wide range of production depths for many of the Ordovician through Devonian units in the basin (Smith and Woods, 2000). As much as 15,000 ft of Upper Cambrian through Mississippian shallow marine carbonates and clastics were deposited across the vast Oklahoma basin during an early epeirogenic phase of the Anadarko Basin (Johnson, 1989). Increase in formation thickness towards the basin depocenter was because of an increased rate of subsidence during the Paleozoic.

The majority of hydrocarbons produced in the Anadarko Basin are from Permian-Carboniferous reservoirs (Rascoe and Adler, 1983). However, the pre-Mississippian carbonates and clastics of the Arbuckle, Simpson, Viola and Hunton Groups contribute a substantial volume of gas and oil production in the basin. The Hunton Group (including production from the overlying informal Misener sandstone of the Woodford Shale) has produced approximately 290 million barrels of oil (MMBO) and 5 trillion cubic feet as gas (TCFG) (IHS Energy, 2010). The Arbuckle Group has produced 52 MMBO and 285 BCFG, the Simpson Group 471 MMBO and 1.2 TCFG, and the Viola Group 112 MMBO and 505 BCFG (IHS Energy Group, 2010).

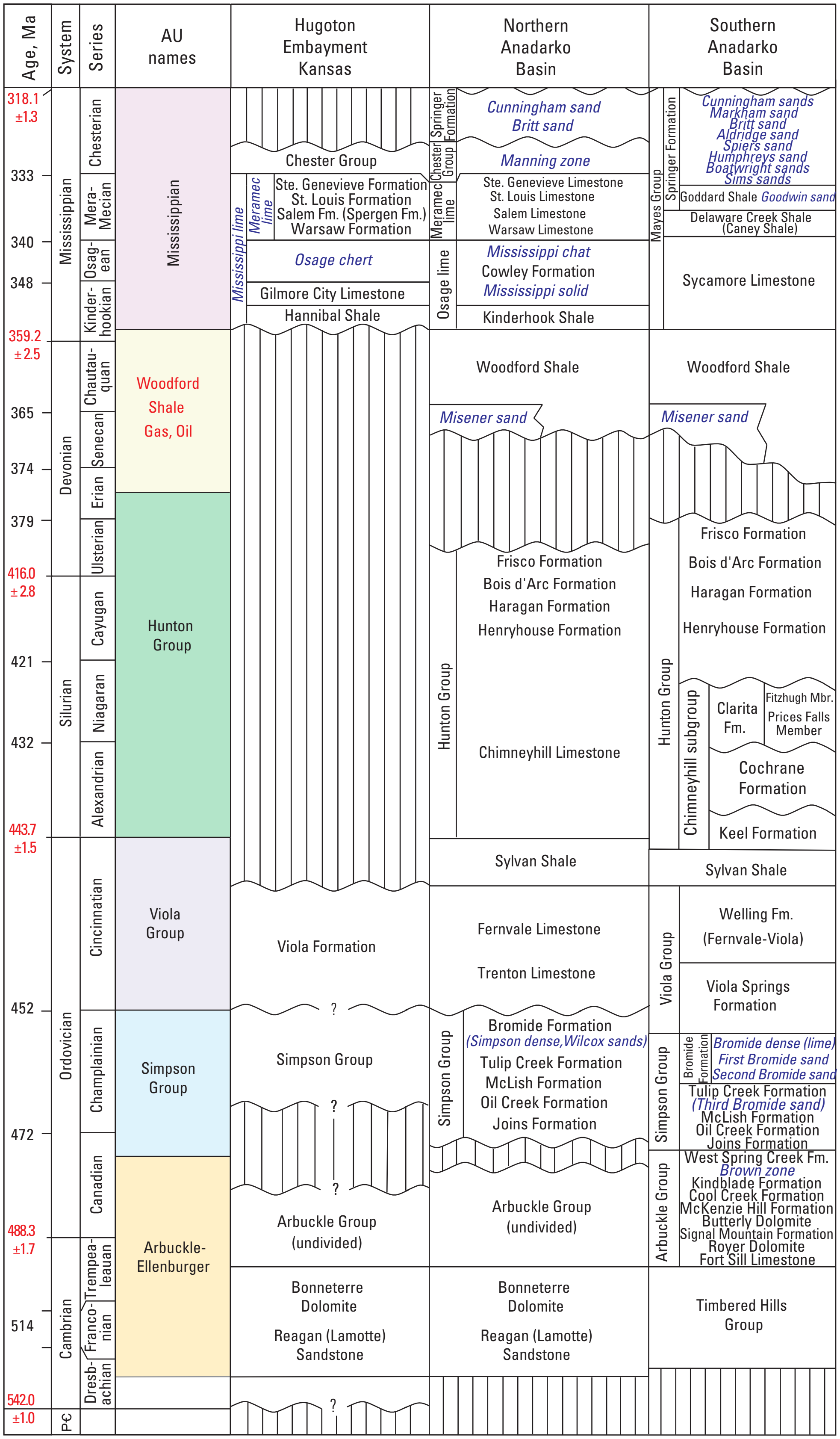

Figure 2. Generalized surface and subsurface stratigraphic columns for the Anadarko Basin and the Southern Oklahoma Fold Belt Provinces for the Precambrian to Mississippian. Assessment units (AU) are included in the Woodford Composite Total Petroleum System. Italics (blue text) indicate informal names. Formal formation- and member-rank units are not necessarily differentiated (as used by Bebout and others, 1993). Modified from Bebout and others (1993) and Henry and Hester (1996). Ages in millions of years (Ma) from Haq and Van Eysinga (1998), and Gradstein and others, (2004) (red text). Fm., Formation; Mbr., Member.

Table 1. Anadarko Basin assessment results for all of the Woodford Composite total petroleum system.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas accumulations, all liquids are included as NGL (natural gas liquids). F95 represents a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. TPS, Total Petroleum System; AU, Assessment Unit. Gray shading indicates not applicable]

Total Petroleum Systems (TPS) and Assessment Units (AU)	Field Type	Total Undiscovered Resources											
		Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Woodford Composite TPS													
Arbuckle-Ellenburger AU	Oil	2	5	12	6	7	24	61	28	0	1	2	1
	Gas					43	164	371	181	0	1	2	1
Simpson Group AU	Oil	2	4	9	5	6	17	39	19	0	0	1	1
	Gas					33	114	252	125	2	9	21	10
Viola Group AU	Oil	2	5	10	5	3	9	20	10	0	1	2	1
	Gas					10	27	58	30	0	0	0	0
Hunton Group AU	Oil	2	8	21	9	8	32	87	38	0	1	3	1
	Gas					71	281	641	310	0	2	4	2
Mississippian AU	Oil	5	16	31	17	15	46	99	50	0	2	4	2
	Gas					125	350	663	367	3	8	17	9
Pennsylvanian Composite TPS													
Morrowan-Atokan AU	Oil	6	14	29	15	21	55	121	61	1	2	5	2
	Gas					101	261	469	271	2	5	10	5
Desmoinesian AU	Oil	2	6	12	6	8	23	52	26	0	1	2	1
	Gas					29	87	167	92	1	3	5	3
Missourian-Permian AU	Oil	10	22	38	23	49	114	223	122	2	4	8	4
	Gas					61	130	231	136	2	4	7	4
Greater Granite Wash Composite AU	Oil	4	14	34	16	22	78	198	90	1	2	7	3
	Gas					192	646	1,496	719	7	24	60	27
Total Conventional Resources		35	94	196	102	804	2,458	5,248	2,675	21	70	160	77
Woodford Composite TPS													
Woodford Shale Oil AU	Oil	175	357	730	393	795	1,750	3,851	1,963	22	51	121	59
Woodford Shale Gas AU	Gas					8,806	15,131	25,998	15,973	94	178	336	192
Pennsylvanian Composite TPS													
Thirteen Finger Limestone-Atoka Shale Gas AU	Oil												
	Gas					3,040	6,229	12,763	6,850	33	73	161	82
Total Continuous Resources		175	357	730	393	12,641	23,110	42,612	24,786	149	302	618	333
Total Resources		210	451	926	495	13,445	25,568	47,860	27,461	170	372	778	410

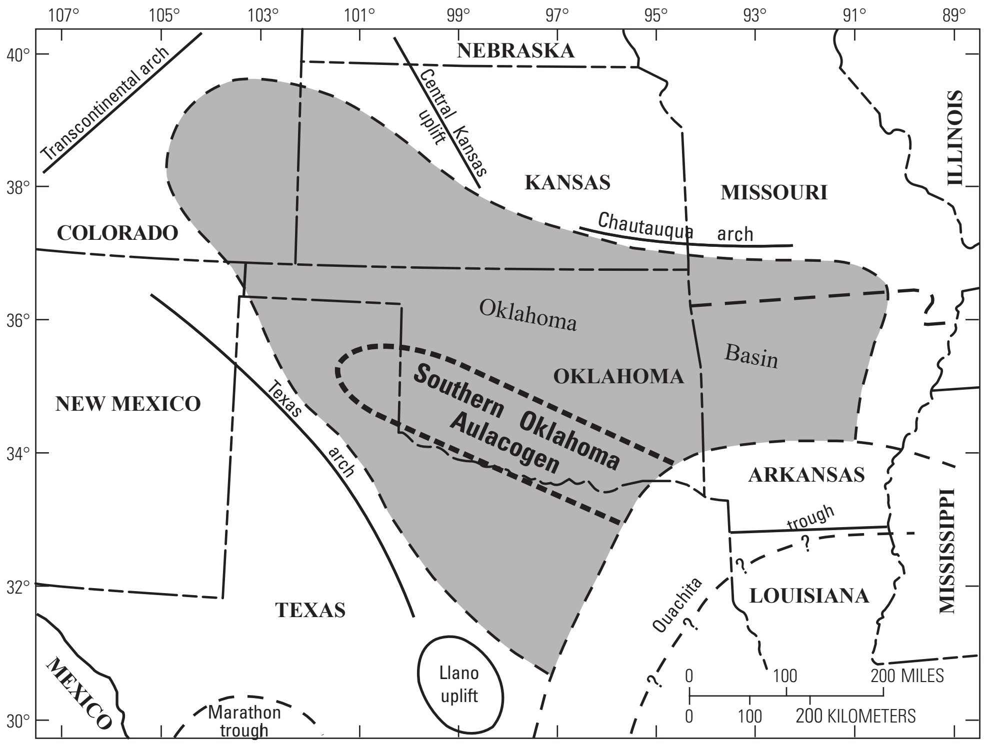

Figure 3. Map of the midcontinent of the United States, showing the approximate outline of the Oklahoma basin, southern Oklahoma aulacogen and other major features that existed in early and middle Paleozoic time. Modified from Johnson (1991).

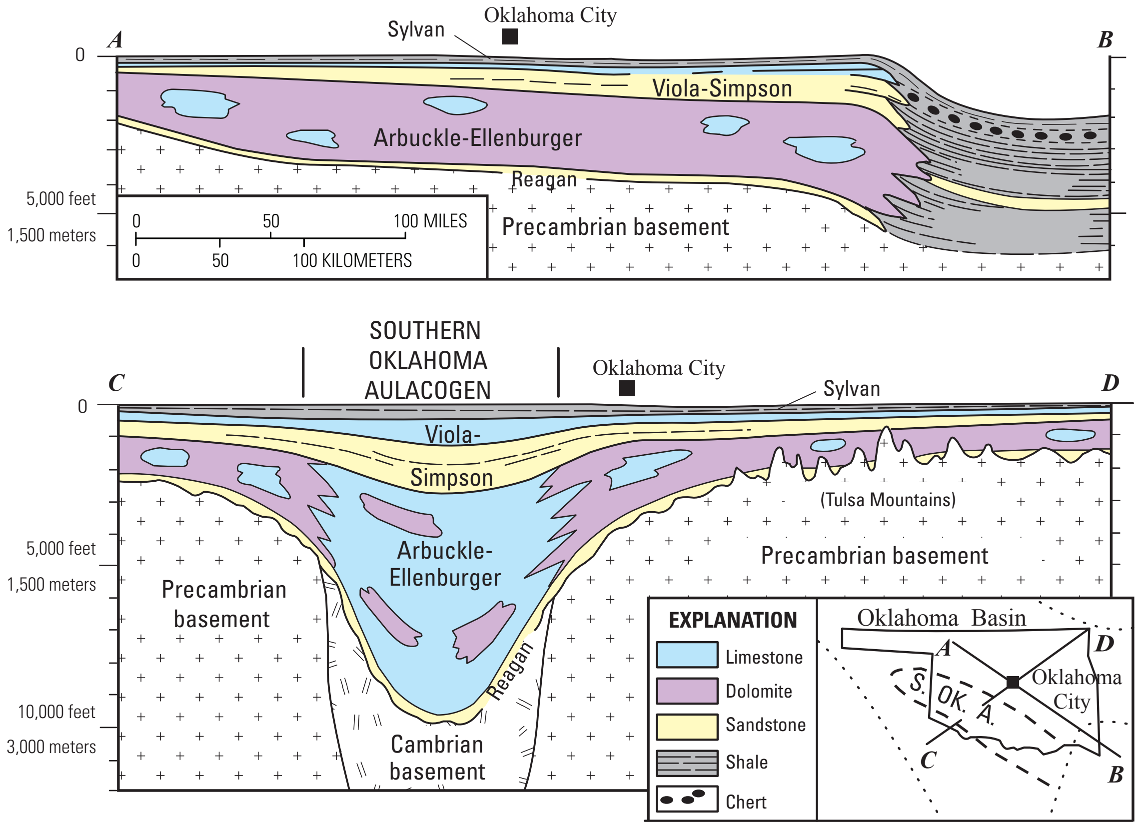

Figure 4. Schematic cross sections showing restored thickness of Upper Cambrian and Ordovician strata in Oklahoma (modified from Johnson, 1991). S. OK. A., Southern Oklahoma Aulacogen. Scale is the same for both cross sections.

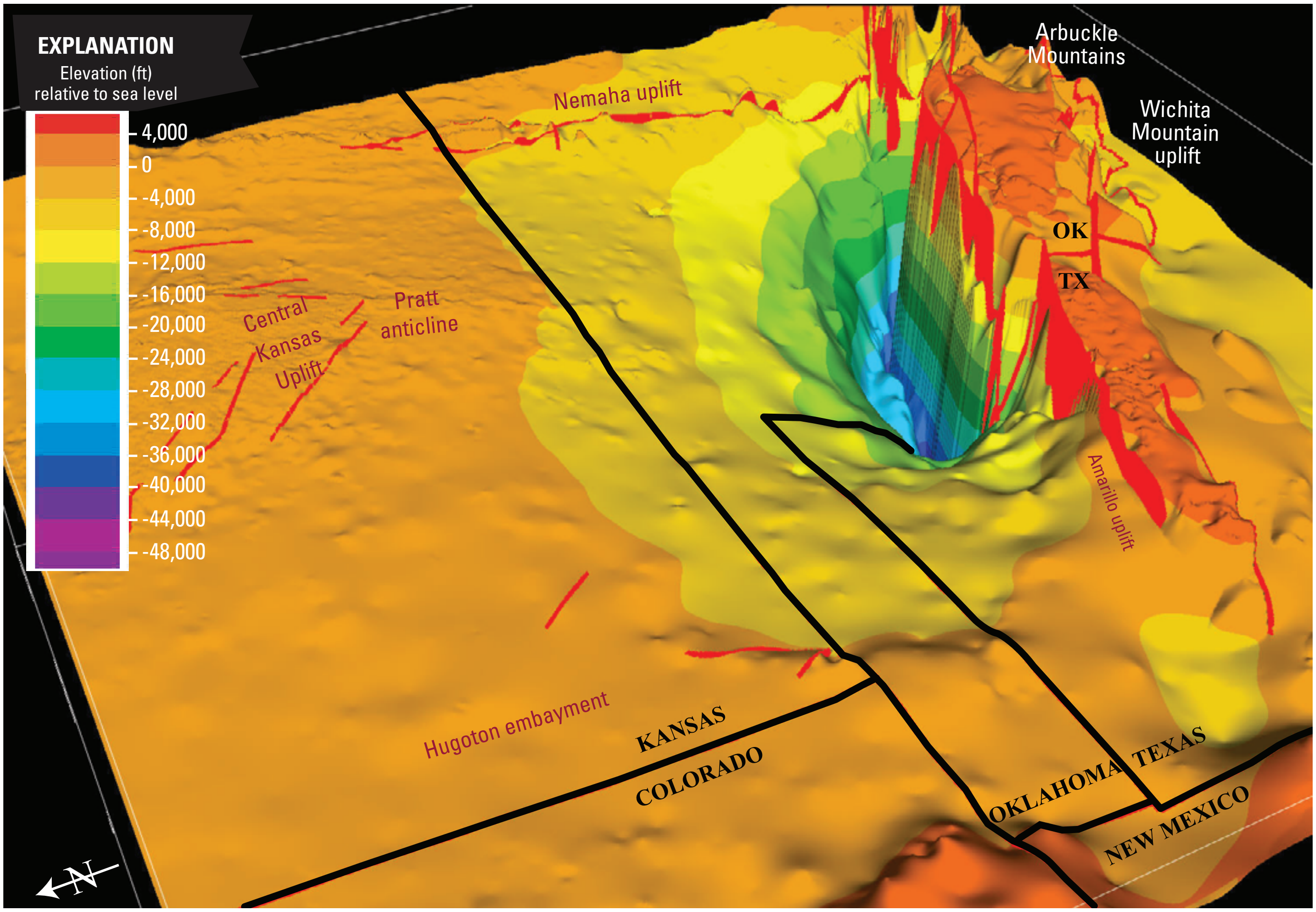

Figure 5. View to the southeast of elevation on the top of the Arbuckle Group. Major structures are labeled. Precambrian faults (red) are from Adler and others (1971). Wichita Mountain uplift faults are vertical for four-dimensional model purposes only, and surface in this area is unknown because of insufficient data. Data sources for this surface include Arbuckle picks from well logs, Rottmann (2000a, 2000b), and edited IHS Energy Group (2009) formation tops.

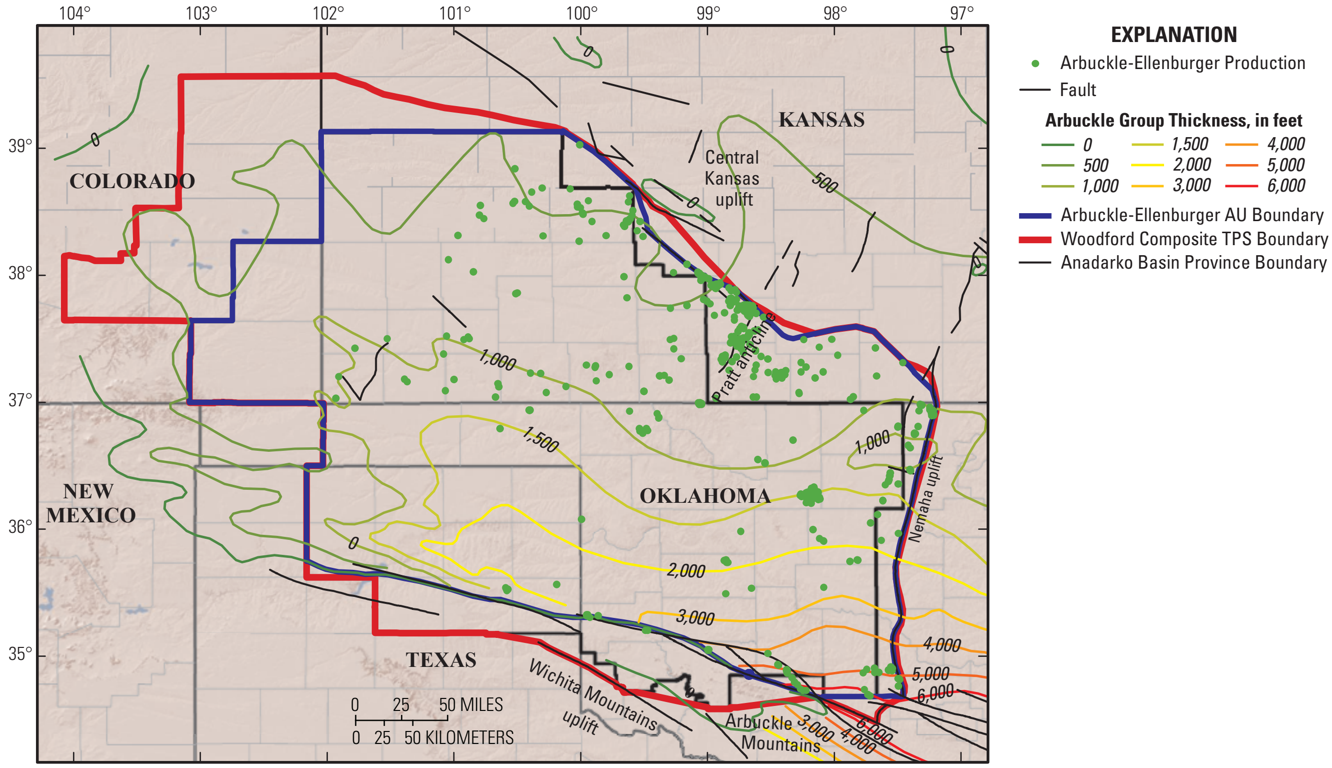

Figure 6. Map showing production from the Arbuckle and Ellenburger Groups and Arbuckle Group thickness; contour interval is 500 feet.

Woodford Composite Total Petroleum System

The Woodford Composite TPS boundary is defined where hydrocarbons generated from the Upper Devonian–Lower Mississippian Woodford Shale and other potential Ordovician source rocks (Arbuckle, Simpson and Viola Groups) have accumulated in Cambrian through Mississippian-age reservoirs (fig. 6). The Woodford Composite TPS is defined by the Nemaha uplift to the east, the border with the Central Kansas uplift to the northeast, the extent of maximum fluid distribution in the Mississippian AU to the north and northwest, the Anadarko Basin province boundary to the west, and the generalized province boundary to the south, mainly because of absence of data in the Wichita-Amarillo uplift areas (fig. 6).

The Woodford Shale was deposited under anoxic conditions in a shallow epicontinental sea over a regional unconformable erosional surface of the Silurian-Devonian Hunton Group (von Almen, 1970; Walper, 1977; Sullivan, 1985). The thickness ranges up to 375 ft across the province, and the Woodford Shale is absent or thin in some areas because of erosion or non-deposition. It is thickest in the southern basin of Oklahoma and where it fills erosional channels of the Hunton Group. The Woodford Shale averages 40-ft thick based on Rottmann (2000b), well-log picks from about 100 wells across the basin, and edited formation tops from IHS Energy Group (2009).

The Woodford Shale in the Anadarko Basin is a dark gray to black carbonaceous, siliceous, pyritic shale (Cardott, 1989). It is considered one of the most prolific hydrocarbon source rocks in the Anadarko Basin (fig. 7), with predominantly Type II kerogen and total organic content (TOC) ranging from 1 to 14 percent (Burruss and Hatch, 1989). Vitrinite reflectance (Ro) data from the Woodford Shale (Cardot, 1989; Price, 1997) is contoured in figure 8. Values range from 4.9 (% R_o) in the deepest basin to 0.5 % R_o on the shelf, and indicate that the Woodford Shale is overmature for gas generation to marginally mature for oil generation in the deep basin and on the shelf, respectively. Vitrinite reflectance values increase along the Nemaha uplift on the eastern edge of the Anadarko Basin (fig. 8). Onset of petroleum generation from Woodford source rocks in the deep basin was at 335 Ma based on one-dimensional burial history modeling from the Bertha Rogers 1 well using variable heat flow through time, and a transformation ratio at 0.1 % R_o and 0.55 % R_o (fig. 9). The same parameters for the West Edmond SWD 1-24 well indicate that the onset of generation occurred at 225 Ma for the Woodford Shale. Completion of generation for the Bertha Rogers 1 well occurred at about 310 Ma; the West Edmond SWD 1-24 well remains in the main oil generation window.

System	Series	Lithostratigraphic Unit (HC Source Rocks in Red)		Relative HC Source Rock Potential (1-5)	Expected Hydrocarbons
Permian (part)	Leonardian	Sumner Gp; Enid Gp.; Hennessey Gp.			
Permian (part)	Wolfcampian	Chase Group Council Grove Group Admire Group	Pontotoc Group		
Pennsylvanian	Virgilian	Wabaunsee Group Shawnee Group	Ada Group		
Pennsylvanian	Virgilian	Douglas Group			
Pennsylvanian	Missourian	Lansing Group Kansas City Group	Hoxbar Group	1-2	Gas Oil
Pennsylvanian	Desmoinesian	Marmaton Group Cherokee Group	Deese Group	1-2	Gas Oil
Pennsylvanian	Atokan	Atoka Gp.; Thirteen Finger limestone		1-2	Gas Oil
Pennsylvanian	Morrowan	Morrow Gp./Fm.; lower Dornick Hills Gp.		2-3	Gas Oil
Mississippian	Chesterian	Springer Formation Chester Group	Mayes Group	1-2	Gas Oil
Mississippian	Meramecian	Meramec lime	Mayes Group		
Mississippian	Osagean	Osage lime	Mayes Group	2	Gas Oil
Mississippian	Kinderhookian	Kinderhook Shale	Mayes Group		
Devonian	Chautauquan	Woodford Shale, Chattanooga Shale		5 +	Gas Oil
Devonian	Senecan Erian Ulsterian	Misener sand			
Silurian	Cayugan Niagaran Alexandrian	Hunton Group			
Ordovician	Cincinnatian	Sylvan Shale; Maquoketa Shale			
Ordovician	Cincinnatian	Viola Group/Formation		2	Gas Oil
Ordovician	Champlainian	Simpson Group		1-2	Gas Oil
Ordovician	Canadian	Arbuckle Group		?	??
Cambrian (part)	Trempealeauan	Arbuckle Group		?	??
Cambrian (part)	Franconian	Reagan Sandstone			

Figure 7. Generalized stratigraphic column for the Anadarko Basin province with oil and gas source rocks (red text). Increases in source rock potential are indicated by larger numbers. Modified from Hatch and others (1986). Hatched vertical lines represent an unconformity (Bebout and others, 1993). Gp., Group; Fm., Formation; HC, Hydrocarbon.

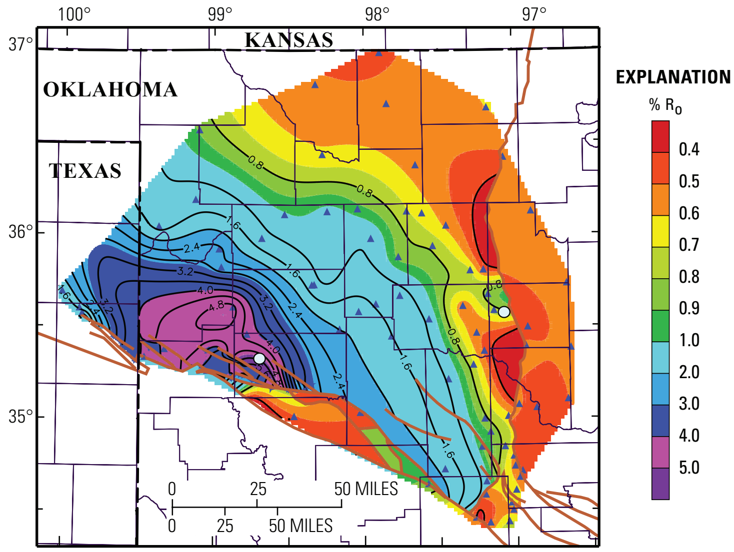

Figure 8. Map showing vitrinite reflectance (%R_o) data for the Woodford Shale. Contour interval is 0.4 % R_o. Blue triangles and white dots indicate locations of %R_o data from Cardott (1989), Price (1997), and Chesapeake Energy Corporation (2009, written commun.). White dot well locations are, from left to right, Bertha Rogers 1 and West Edmond SWD 1-24. Brown lines are faults in the underlying Hunton Group (Rottmann, 2000a).

Arbuckle and Ellenburger Groups

The Arbuckle Group strata were deposited as a vast blanket of carbonate rock on a broad, nearly flat-lying carbonate ramp (commonly referred to as the "Great American Bank") that formed the southern margin of the North American craton during the Late Cambrian and Early Ordovician (Lindsay and Koskelin, 1991). The Arbuckle Group is age equivalent to the Ellenburger Group in Texas, and is the thickest sequence of lower Paleozoic strata in Oklahoma (Johnson and others, 2000). It overlies the Reagan Sandstone, and ranges from 400 to 8,000 ft thick in the basin (fig. 6). It is thickest in the southern Oklahoma aulacogen (fig. 3), where it is limestone, thinning to approximately 4,000 ft of dolomite in the eastern Arbuckle Mountains, and 1,000 to 4,000 ft of dolomite on the shelf. The limestone to dolomite transition occurs near the boundary of the aulacogen (Johnson and others, 2000; fig. 4). Dolomitization was the result of water depth differences and restrictions in water circulation during deposition.

The base of the Arbuckle Group is lithologically defined by the abundance of lime mud that marked the beginning of platform deposition, associated with a rise in sea level (Donovan, 2000). The carbonates were deposited as a transgressive sequence on a shallow platform that was uplifted during the Paleozoic (Gao and others, 1992; Ayan and others, 2000). Dolomite beds in these formations change laterally into limestone along the same stratigraphic interval. Lithologies include algal boundstones and stromatolites, mudstones, packstones, and grainstones, deposited in shallow marine, near-shore to shoreline, and tidal-flat settings (fig. 10). The Arbuckle Group is divided in the southern Anadarko Basin into six formations, and in ascending order are the Fort Sill Limestone, and Signal Mountain, McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek Formations (fig. 2). The Royer Dolomite and Butterly Dolomite are also included in the Arbuckle stratigraphy in the Arbuckle Mountains, and to the north.

The Upper Cambrian Reagan Sandstone, which is part of the Timbered Hills Group in the Midcontinent, is included in the Arbuckle-Ellenburger AU (fig. 2). The Reagan Sandstone was deposited across a moderately mature erosional surface of low relief as the southern Oklahoma aulacogen began to subside during the Late Cambrian; it is a nonmarine, transgressive sandstone (Johnson, 1989; fig. 4). The Timbered Hills Group covers the province, with a thickness of approximately 35 to 120 ft. There is minimal hydrocarbon production from the Reagan Sandstone, with no accumulations reported in the Nehring database (Nehring Associates, Inc., 2009). Oil production from three wells in Kansas and Oklahoma totals approximately 130,000 barrels of oil from the Reagan Sandstone (IHS Energy, 2010).

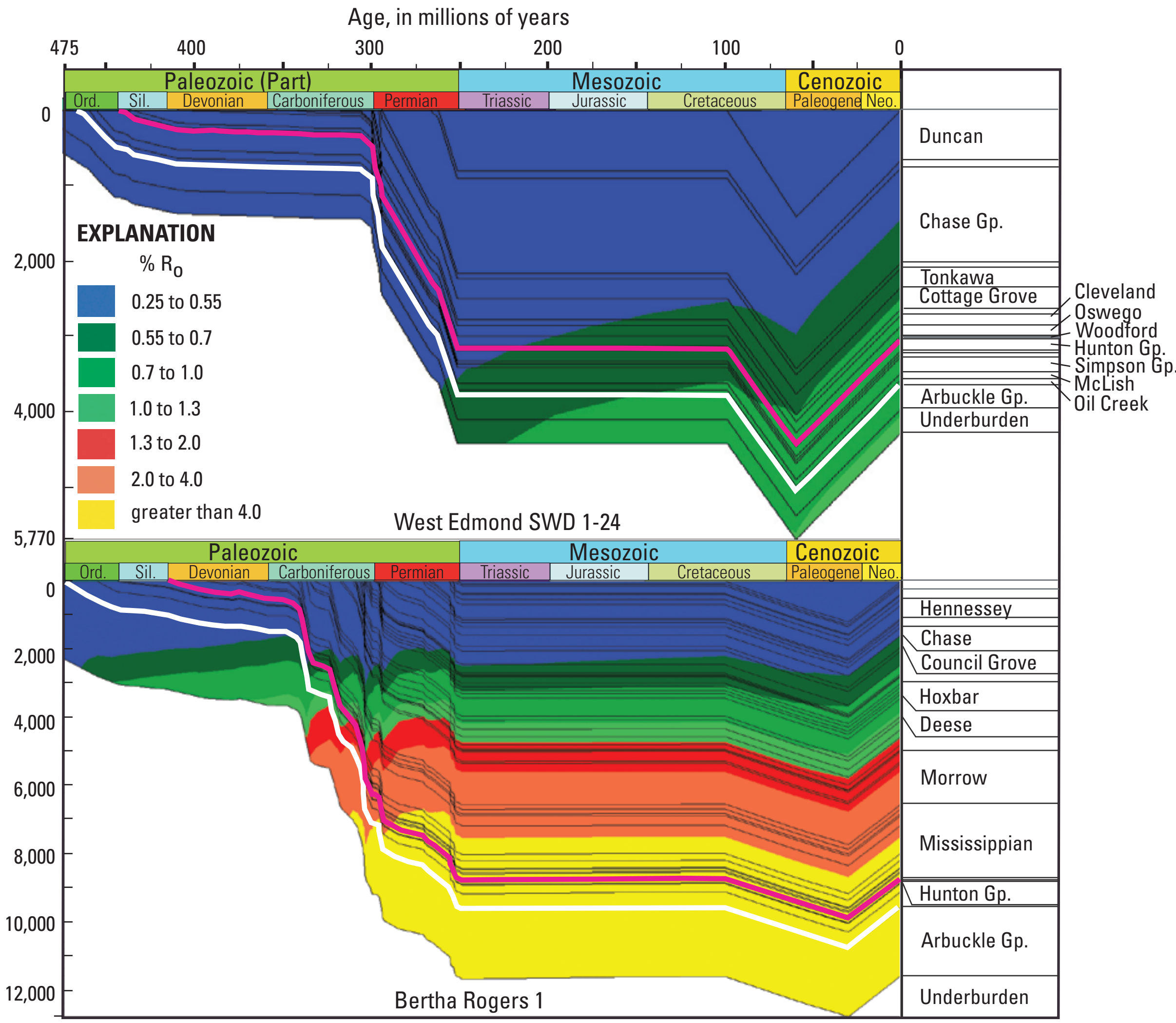

Figure 9. Burial history curves for the Bertha Rogers 1 and West Edmond SWD 1-24 wells. Modeled vitrinite reflectance through time includes heat flow of 70 milliwatts per square meter (mW/m^2) to 260 million years ago (Ma), followed by 40 mW/m^2 for Bertha Rogers 1 and 50 mW/m^2 for West Edmond SWD 1-24. White and pink lines follow the upper part of the Arbuckle Group and Woodford Shale, respectively. Ord., Ordovician; Sil., Silurian; Neo., Neogene; Gp., Group; % R$_o$, percent vitrinite reflectance.

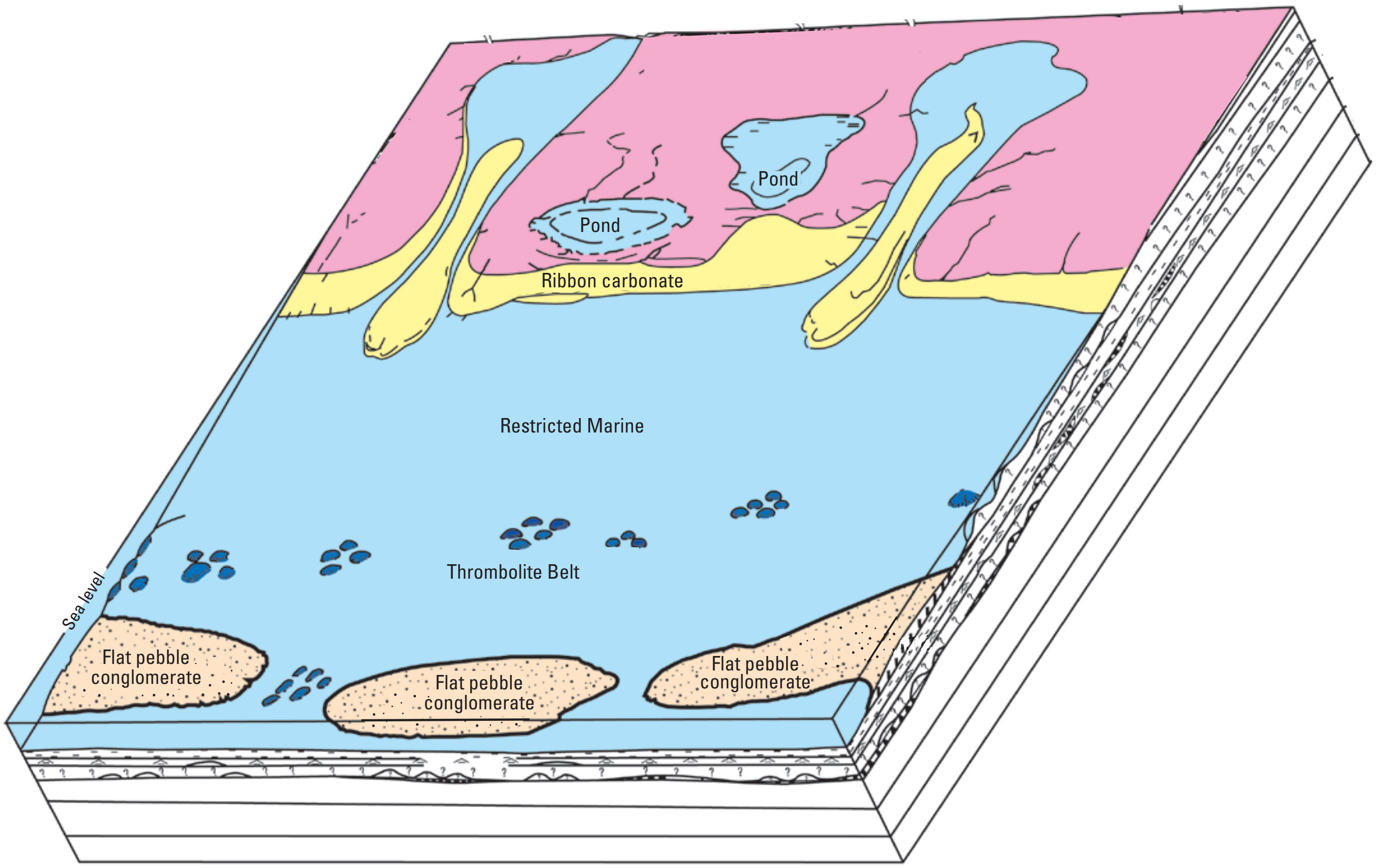

Figure 10. Depositional model of the Arbuckle Group in southern Oklahoma, showing a shallow-marine setting passing landward into a near-shore to shoreline setting, and finally into a tidal-flat setting. Sea-level transgressions and regressions resulted in the deposition of thin carbonate sequences (modified from Lindsay and Koskelin, 1991).

Source Rocks of the Arbuckle Group

Organic-rich rocks of the Woodford Shale and Simpson Group, and possibly the Viola Group, are considered the most likely sources of hydrocarbon for Arbuckle reservoirs (Burruss and Hatch, 1989; figs. 7 and 11). The Woodford Shale is likely the dominant source for the Arbuckle reservoirs, especially where faults juxtapose Woodford Shale source rock and Arbuckle carbonate reservoirs in the basin, or where migration occurred from the deep basin into Arbuckle reservoirs on the shelf.

The source rock potential of the Arbuckle Group has been long debated, as definitive source rocks have not yet been identified (Cardwell, 1977; Brown and Swetland, 1992; Williams, 1992; fig. 7). Bartram and others (1950) and Webb (1976) considered the Arbuckle hydrocarbons to be sourced from within the group. Possible hydrocarbon source rocks in the Cambrian and Ordovician Arbuckle Group were deposited in the rapidly subsiding aulacogen, and were buried to depths in the “oil window” (6,000-13,000 ft) from Middle Ordovician to Late Pennsylvanian time (Johnson and Cardott, 1992). Total organic carbon (TOC) data for the Arbuckle from Trask and Panode (1942) report 0.1-1.3 percent TOC in 81 Arbuckle samples from 16 wells, with lower values reported by Cardwell (1977). The Signal Mountain Formation, which was deposited in a deeper water setting than the rest of the Arbuckle, has shales with TOC values up to 1.26 percent and may have greater potential (Donovan and Critchfield, 2001; fig. 12). The Arbuckle, especially in the deep basin, has gone through the oil-generation window and has lost a substantial amount of the original organic matter that was converted to gas and oil (Johnson, 1992). Thus, Arbuckle rocks with low TOC could have had twice as much at the time of oil generation, according to arguments presented by Johnson (1992). It is also argued that organic-rich rocks in the Arbuckle Group may not yet have been located and (or) analyzed. Gatewood (1992) provided evidence of self-sourcing Arbuckle reservoirs, including production of large quantities of oil and gas 600-1,000 ft or more below the top of the Arbuckle, oil produced beneath salt-water zones in some fields, organic remains in parts of the Arbuckle, and evaporites that serve as caps or seals for underlying dolomite reservoirs.

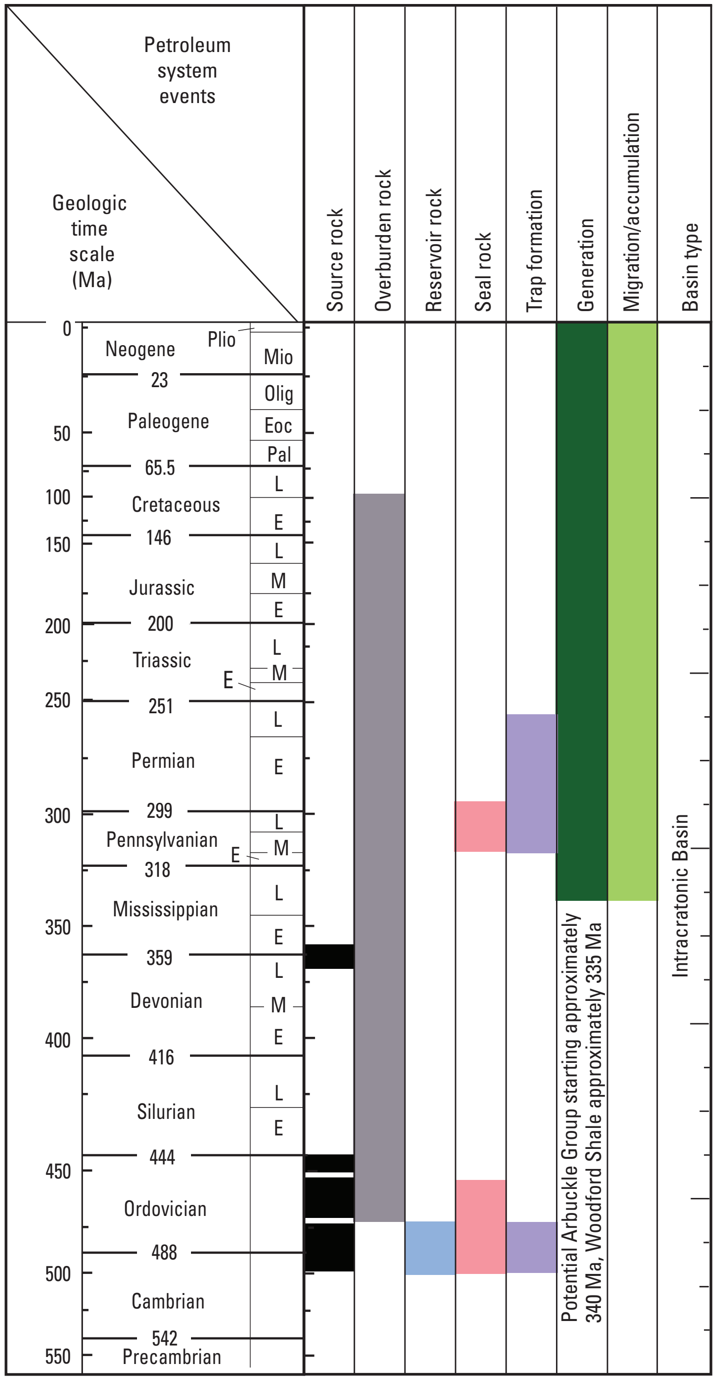

Figure 11. Arbuckle-Ellenburger Asessment Unit events chart showing the timing of source rock deposition and trap formation, and the age of overburden, reservoir, and seal rocks with different color bars (black, source rock; gray, overburden rock; blue, reservoir rock; pink, seal rock; purple, trap formation; dark green, generation; light green, migration accumulation). The chart also depicts the timing of oil generation, migration and accumulation as modeled for various wells in different parts of the Anadarko Basin. Ma, mega-annum; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

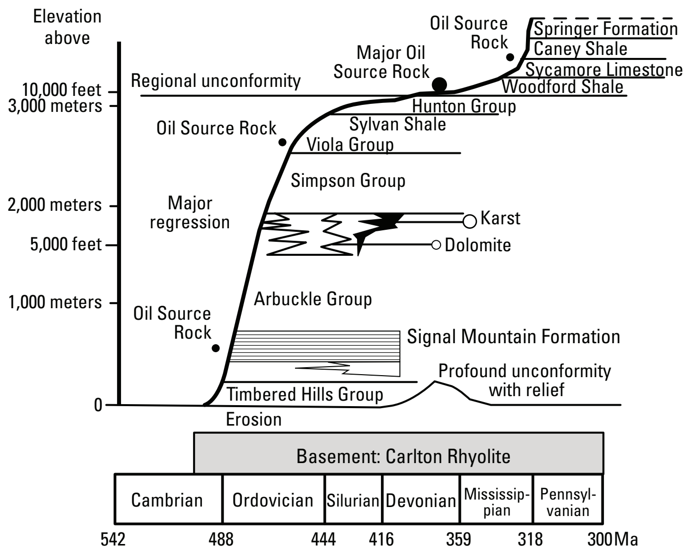

Figure 12. Lower Paleozoic stratigraphy in the southern Oklahoma aulacogen, with a burial-time curve illustrating the position of the Signal Mountain Formation and other hydrocarbon source rocks present in the Anadarko Basin. Modified from Donovan and Critchfield (2001). Ma, millions years before the present.

Potential Arbuckle source rocks reached the thermal zone of oil generation at approximately 340 million years ago (Ma) in the deep basin, according to the Bertha Rogers 1 one-dimensional (1D) burial history model, and 260 Ma near the Nemaha uplift in the West Edmond SWD 1-24 well (fig. 9). This model used variable heat flow through time, a transformation ratio of 0.1 percent and 0.55 percent R_o. A map of present day Arbuckle percent R_o extracted from the three-dimensional (3D) model of the basin shows the Arbuckle as overmature in the deep basin and in the oil window along the Nemaha uplift and onto the shelf (fig. 13).

Reservoir Rocks of the Arbuckle-Ellenburger Assessment Unit

The Arbuckle Group is an important reservoir rock in the Anadarko Basin, with production from porous dolomite zones and limestones that were exposed to erosion on the crests of basement highs (Ball and others, 1991). Dolomites with high fracture intensity form better reservoirs as the late dolomization enhanced porosity and the dolomites did not undergo burial solution compaction or later cementation (Gao and others, 1992). Erosion of the Arbuckle appears to enhance its porosity and permeability, and fracture networks related to structure facilitate production and may have enhanced karstification (Ball and others, 1991). Known hydrocarbon accumulations are the result of the combined effects of diagenetic reservoir enhancement and proximity to major structural features. Porosity in the Arbuckle Group is variable and difficult to predict (Gao and others, 1992).

Production in the Arbuckle Group is scattered in Oklahoma and on the Kansas shelf and is almost exclusively from dolomitized facies (Johnson and others, 2000). The upper 250 ft is more significantly explored than the lower, main body of the Arbuckle Group (Henry and Hester, 1996). Production in Kansas has largely been on and near the Central Kansas uplift and associated structures (fig.14).

The Ellenburger Group is the Arbuckle equivalent in the Texas Panhandle portion of the basin. They have common lithologic and physical characteristics, including: (1) the producing zone is dolomite, (2) it has secondary porosity, (3) the production is related to structure, and (4) fields have lateral and vertical heterogeneity.

The Arbuckle-Ellenburger AU boundary follows the Anadarko Basin province boundary on the north and west, the faults that define the southern end of the Central Kansas uplift in the northeast, the Nemaha uplift on the east, and the Precambrian fault system along the Arbuckle Mountains to the south (fig. 14). There is scattered production throughout the AU, with exploration mainly focused along structures in the eastern, northeastern, and southern parts of the basin (fig. 14). There is the potential for oil migration from the deep basin onto the shelf, or towards the Texas Panhandle, as well as the possibility of self-sourcing in these areas.

Traps and Seals in the Arbuckle-Ellenburger Assessment Unit

Traps in the Arbuckle Group reservoirs are largely structural, or combination structure-stratigraphic, and most are near the eastern and southern fault systems. Seals for Arbuckle Group reservoirs are low porosity zones of Arbuckle evaporites, argillaceous carbonate, or shale, or overlying tight, impermeable shales of the Simpson Group (fig. 11). There are also areas in the basin where Pennsylvanian sands and shales unconformably overlie producing zones, creating the reservoir seal. Major Arbuckle fields that are producing from structurally controlled dolomite reservoirs are Cottonwood Creek and Haldton fields, as well as Oklahoma City field and Mayfield West field. Significant reserves are in Arbuckle reservoirs in Major County, Oklahoma, which is on the northern shelf of the Anadarko Basin, with oil and gas production since 1945. The primary trapping mechanism in the area is a horst and graben structural fabric, and within each horst block, structural reversals and stratigraphic pinchouts define reservoir geometry (Heyer, 1993). Reservoir lithology is dolomite, with textures ranging from bioclastic grainstones to mudstones. Intracrystalline and intercrystalline porosity is as high as 17 percent, with permeability up to 1.82 millidarcies (mD) (Heyer, 1993).

A substantial amount of gas has been produced from the Arbuckle in Mayfield field, in Beckham County, Oklahoma, and to the northwest in Wheeler County (fig. 14). Wells were drilled on faulted, domal structures with production from fractured Arbuckle carbonates which have undergone leaching, resulting in high porosity development at the unconformity level (Perry, 1990).

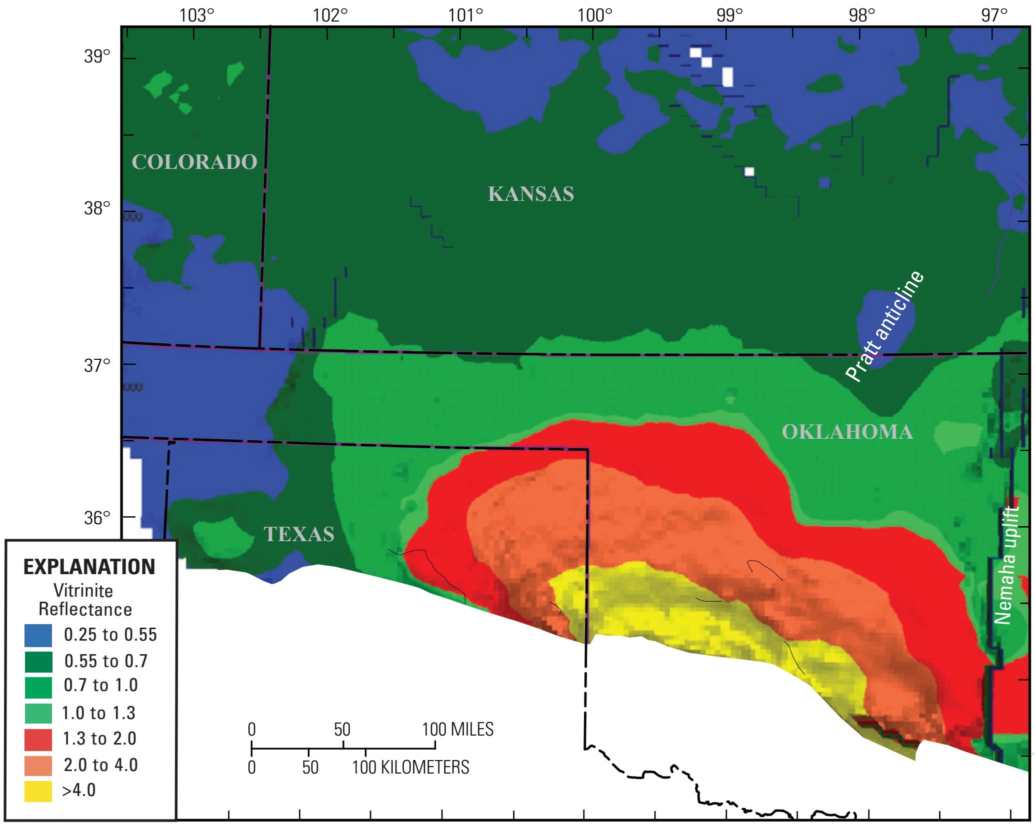

Figure 13. Image showing vitrinite reflectance (% R_o) contours on the Arbuckle Group, extracted from the four-dimensional model of the Anadarko Basin. The burial history model illustrates decompaction through subtle increases in layer thickness backward through time. The vitrinite reflectance profile was calculated using Sweeney and Burnham (1990) kinetics.

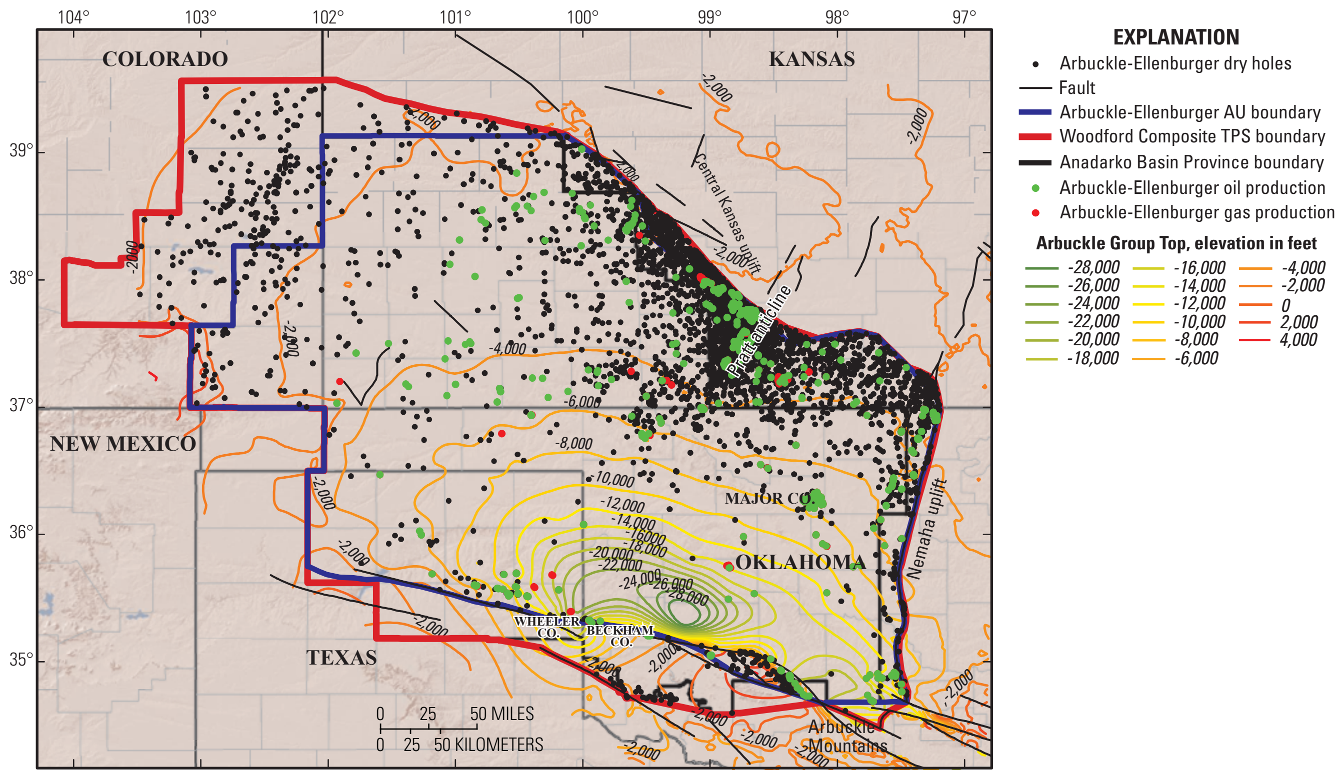

Figure 14. Map showing oil and gas production and dry hole penetrations for the Arbuckle and Ellenburger Groups in the Anadarko Basin Province (IHS Energy Group, 2010). Structure contours are drawn on the top of the Arbuckle Group; contour interval is 2,000 feet. The Anadarko Basin Province boundary is the black line, the Woodford Composite Total Petroleum System (TPS) boundary the red line, and the Arbuckle-Ellenburger Assessment Unit (AU) boundary the blue line.

Sizes and Numbers of Undiscovered Fields in the Arbuckle-Ellenburger Assessment Unit

The Arbuckle Group is not well explored, largely because of its depth, especially in the deep basin. There have been problems with seismic exploration of the Arbuckle because of (1) poor data quality beneath the complex overthrust zones that exist along the southern boundary of the Anadarko Basin (Brown and others, 1991) and (2) the relatively low amplitude of the Arbuckle reflections in the basin compared to the higher amplitude reflections of the overlying strata. Arbuckle wells are characterized by high initial potential, steep decline rates, production of large quantities of oil, and high water-oil ratios.

Cumulative oil production in the Arbuckle-Ellenburger AU is 52 MMBO, with 1.3 MMBO from the Ellenburger Group in Texas (IHS Energy, 2010). Although there is oil production throughout the basin, gas production is limited to the deeper part of the basin, with 285 BCFG produced (IHS Energy, 2010; fig. 14). Production depths range from 3,000 ft to 26,500 ft. The most recent reported discoveries are on the Anadarko shelf, but with low cumulative oil and gas numbers reported by IHS Energy (2010; fig. 15). In commingled fields, which are common in the basin, the Arbuckle composes a relatively small portion of the total production based on a comparison of field data versus Arbuckle accumulation data for a given field (Nehring Associates Inc., 2009).

Nehring Associates Inc. (2009) presented limited data for the Arbuckle-Ellenburger; only 4 of the 24 accumulations in the database have grown reserve accumulation numbers (fig. 15). This is likely because of a historical lack of reporting information from private operators to the state and other agencies for Midcontinent hydrocarbon production. Furthermore, there is a large amount of commingled production in the basin, as well as the incorrect reporting of the producing formation. Nehring field data were used to supplement the database, but are of marginal use because the production from all reservoirs is generally combined for a field, not just that of the Arbuckle-Ellenburger. In cases where the Arbuckle contribution can be determined by combining the field data with the grown data, the Arbuckle is a minor component of the total resource in the majority of the fields.

Using the USGS assessment methodology for undiscovered conventional resources (Klett and others, 2005; Schmoker and Klett, 2005), the mean undiscovered oil and

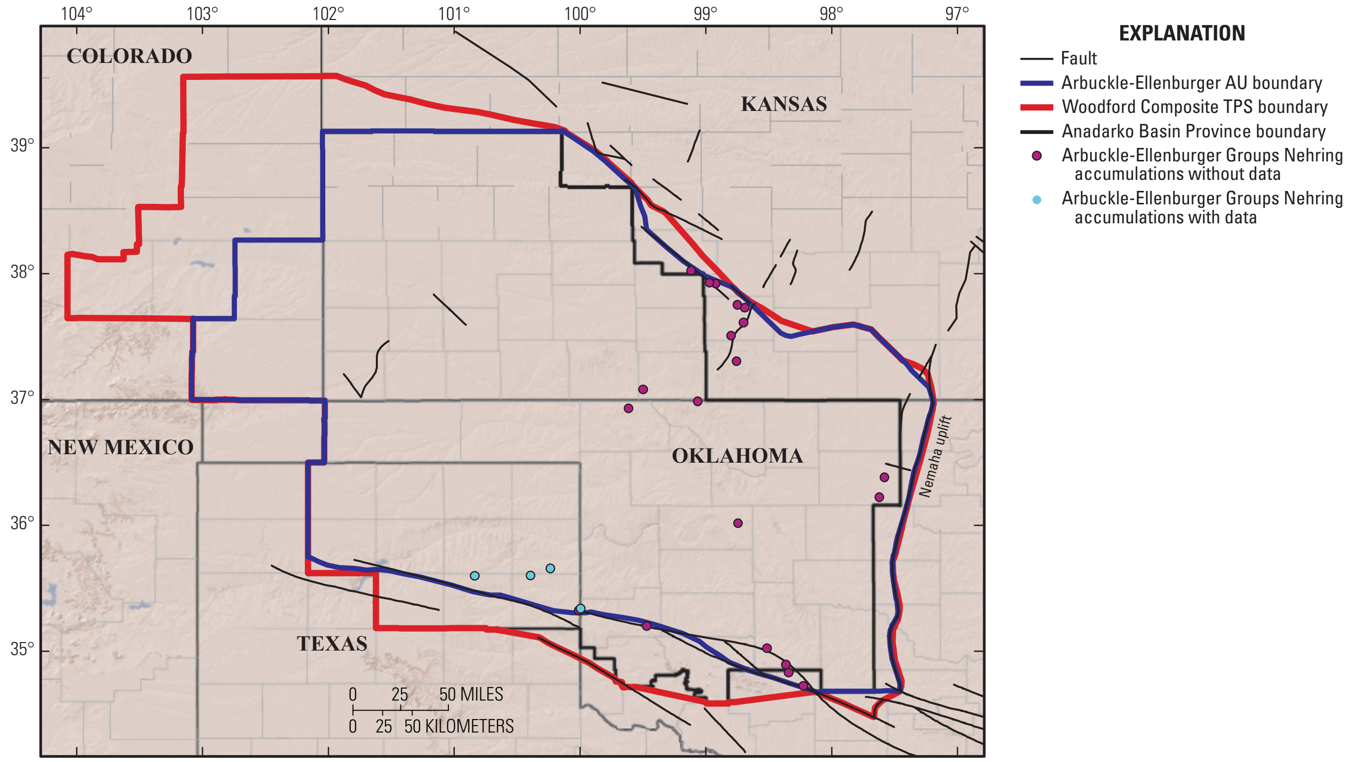

Figure 15. Map showing accumulations for the Arbuckle-Ellenburger Assessment Unit (AU) (Nehring Associates, Inc., 2007). Accumulations without numbers are in purple. TPS, Total Petroleum System.

gas resources for conventional reservoirs in the Arbuckle-Ellenburger AU are estimated at 5.5 MMBO and 181 BCFG (table 1). Estimates of the minimum, median, and maximum numbers of undiscovered accumulations are 1, 2, and 10 for oil, and 1, 10, and 60 for gas. The broad ranges reflect the uncertainty of future potential. The Arbuckle has been penetrated more extensively on the shelf of the basin, where production is predominantly oil (fig. 14). There is more undrilled area in the deep basin along structures; gas production is more likely in the deep basin based on gas versus oil production in the Arbuckle, and the fact that the deep basin is thermally mature to overmature for gas production (figs. 9 and 13). Future oil production will likely be as small accumulations on the shelf, or associated with deeper gas production. The most recent Arbuckle discoveries are on the shelf near the Pratt anticline, but oil numbers are low in these fields, whereas gas fields in the deeper basin are larger, based on field data (Nehring and Associates, Inc., 2009; fig. 15). Large gas fields with Arbuckle production are Mayfield West (23 BCFG grown) and Bradbridge (7 BCFG grown). Production depth has a wide range (3,000 to 26,500 ft) depending on whether the Arbuckle is producing from the deep basin or the shelf (fig. 14).

Estimates of the minimum, median, and maximum sizes of undiscovered oil accumulations are 0.5, 1.0, and 10.0 MMBO. The 0.5 MMBO default signifies that there will be at least one field found greater than the minimum size, and the maximum reflects the uncertainty of Arbuckle accumulation sizes because of the lack of Nehring information. Production by field for the Arbuckle from the IHS database has been small (less than 4 MMBO). Estimates of the minimum, median, and maximum sizes of undiscovered gas accumulations are 3, 6, and 60 BCFG. The maximum reflects the uncertainty with deep gas production in the Arbuckle-Ellenburger, as it is sparsely drilled in the deep basin. The most recent accumulation reported by Nehring Associates, Inc. (2009) data was discovered in 2005. However, there are no Nehring accumulation data provided and none found for the Arbuckle in the IHS database (IHS Energy, 2010).

The future role of the Arbuckle Group is an important question in the development of hydrocarbon resources in Oklahoma, as there may be significant undiscovered resources, especially in the deepest part of the Anadarko Basin, where drilling into the Arbuckle is sparse. There is also potential for future production downdip from the central Kansas production areas, or along migration routes the hydrocarbons generated in the deep basin followed through Oklahoma. The Texas Panhandle is also a viable area for exploration, as the Arbuckle is deep enough there to have possibly self-sourced.

Simpson Group

The Middle Ordovician Simpson Group overlies the Arbuckle Group in the Anadarko Basin, and the rocks represent a departure from carbonate deposition because of an influx of clastic sediments. Simpson Group strata in Oklahoma are clean quartzose sandstones interbedded with thick, shallow-water marine limestones and thin to moderately thick greenish-gray shales (fig. 16; Flores and Keighin, 1989; Johnson, 1991). In Kansas, the Simpson is a sequence of clastics and sandy carbonate rocks. Fine- to coarse-grained clastic sediments were derived from the uplifted Canadian Shield to the north and east when sea level was lowered during the Middle Ordovician; the windblown sediment was carried southward and covered the emergent carbonate shelf (Johnson, 1991). As sea level rose, sand was reworked into an extensive and sheet-like transgressive deposit in marine shoreface and tidal flat environments, which is overlain by marine shales and carbonates. Successive sea level fluctuations during the remainder of Simpson time produced a succession of sands, shales and limestones (Johnson, 1991). Clastic and carbonate rocks are dominant to the north, and offshore facies persist to the south (fig. 17).

The total thickness of Simpson Group rocks ranges from 100 to 300 ft on the basin shelf, to 2,300 ft in the basin depocenter (fig. 18). The Simpson is divided into five formations, in ascending order: (1) the Joins Formation, (2) the Oil Creek Formation, (3) the McLish Formation, (4) the Tulip Creek Formation, and (5) the Bromide Formation (figs. 2 and 16). Each has a basal sandstone facies and upper mudstone-siltstone-limestone facies (fig. 16). The basal sandstones of the Simpson are regionally extensive sheet-like bodies, ranging in thickness from 50 to 200 ft. Other sandstones are less continuous and cannot be traced for long distances laterally. In the subsurface of central Oklahoma, some of the sandstones are referred to as “Wilcox sands” (Johnson, 1991); the “Second Wilcox” is commonly correlated to the basal Bromide sand body (Rottmann, 1997).

The Joins Formation is the exception in that it lacks the sandstone facies present in the upper Simpson Group formations, and is mainly carbonate that was deposited in a shallow marine environment during the post-Arbuckle sea-level lowering in the remaining finger of the carbonate sea in Oklahoma (fig. 19; Denison, 1997). Over a large area of Oklahoma the Joins Formation was embayed by the basal Oil Creek Formation sandstones. The basal Oil Creek sandstone is overlain by shale and limestone, the latter of which is a reservoir in some areas of the basin. The basal McLish Formation sandstone is one of the most widespread and persistent quartz-rich sandstones of the Simpson Group. The McLish Formation grades into limestones, dolomites, and shales, and represents a continuation of clear-water shallow-marine sedimentation (Suhm, 1997). The Tulip Creek Formation has a basal sandstone body overlain by shale, and the uppermost Bromide Formation consists of varying amounts of sandstone, limestone, dolomite, and shale. The Bromide basal sandstone is the most areally

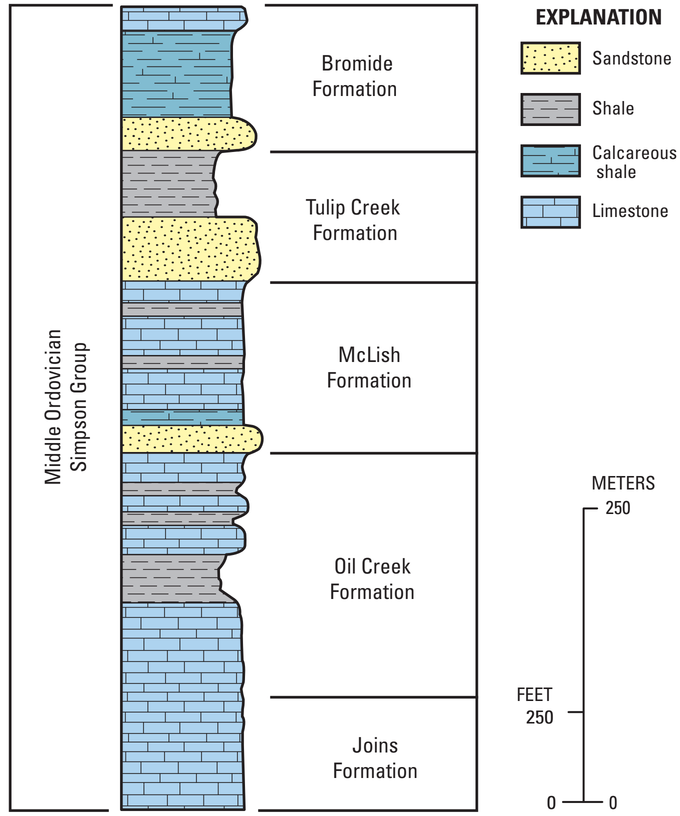

Figure 16. Stratigraphic section of Simpson Group rocks (modified from Flores and Keighin, 1989).

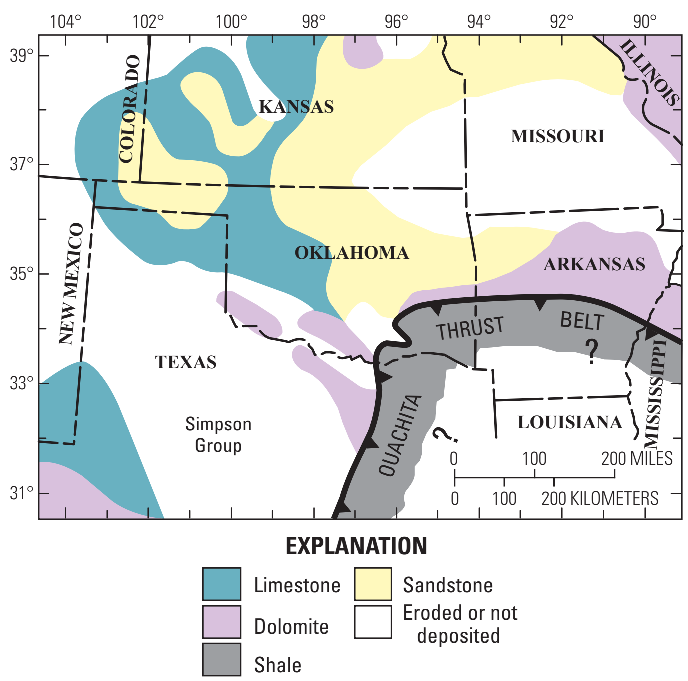

Figure 17. Image showing major lithologies of Ordovician Simpson Group strata in the southern midcontinent (modified from Northcutt and Johnson, 1997).

extensive of the Simpson sandstones, and the contact with the overlying Viola Group is distinct based on the change to clean, crystalline limestone (Suhm, 1997).

In the Kansas portion of the Anadarko Basin, the Simpson is divided into six informal stratigraphic units that are correlated with the McLish and Bromide Formations. The McLish Formation corresponds to the two lower units and the Bromide Formation to the upper four units (Doveton and others, 1990; Charpentier and Doveton, 1991). The absence of the Joins, Tulip Creek, and Oil Creek Formations reflects the change from proximal shoreface facies in the deeper basin to offshore facies near the Pratt anticline (fig. 19; Charpentier and Doveton, 1991).

Source Rocks of the Simpson Group

Oil samples from the Middle Ordovician Simpson Group have the characteristics of Ordovician oils. The Woodford Shale is also a likely source rock for the Simpson Group reservoirs (figs. 7 and 20; Burruss and Hatch, 1989). Faults juxtapose the Woodford and Simpson in the basin, and migration from the Woodford Shale in the deep basin also charged Simpson reservoirs (Smith, 1997).

Simpson Group shales have been identified as a hydrocarbon source rock for the Oklahoma basin (fig. 3) by Adler and others (1971), Webster (1980), Hatch and others (1986), and Wavrek (1989). Philippie (1981) showed that shales of the Simpson Group acted as the source for oils in the stratigraphically older rocks of the Ellenburger Group in west Texas. Hatch and others (1986) also interpreted Simpson shales to be the probable source for Viola and Simpson Groups reservoirs in the Forest City Basin of Kansas and Nebraska.

Burruss and Hatch (1989) identified potential source rocks in the shales of the Simpson Group as containing Type I and II kerogen. Sparse sampling on the Kansas shelf indicates as much as 14 percent of the Simpson shales may be of source rock quality (greater than 1 percent TOC; Burruss and Hatch, 1989). Organic material in the Simpson Group is algal, and potentially improves in Kansas, where it is on the shelf. However, Simpson shales on the shelf are only marginally mature for oil and potential is considered poor to moderate (fig. 7; Burruss and Hatch, 1989). Quality is moderate in the deep basin where Simpson shales have reached maturity.

Reservoir Rocks in the Simpson Group Assessment Unit

The blanket-like sandstones with interbedded shales are the dominant reservoir facies within the Simpson Group. The Simpson Group is most productive from its sandstone units, but it also contains some carbonate reservoirs that are highly productive locally. Carbonate rocks within the lower Simpson yield oil and gas, especially in karsted reservoirs. All of the Simpson formations are productive to varying degrees. To the north in south-central Kansas, the Simpson increases in thickness west of the Pratt anticline and becomes dominated by sandy, cherty dolomite, which accounts for the loss of production in that area of the basin (Lynn Watney, written commun., 2010).

Reservoir porosity in producing sandstones ranges from 10 to 30 percent, with permeabilities ranging from 15 to 300 (mD) (Ball and others, 1991; Johnson, 1991). Reservoir quality is highest in well-sorted sandstones that are absent of clay, and which have had dissolution of intergranular carbonate cement during burial (Pollastro, 1989). The Second Wilcox (Bromide) is the principal producing unit of the Simpson on the central Oklahoma shelf, where overlying impermeable strata create stratigraphic traps when the sandstones are upthrown against impermeable strata and a fault seal occurs (Rottmann, 1997).

The Simpson AU boundary follows the Simpson subcrop on the northwest, the province boundary on the west, the faults that the define the southern end of the Central Kansas uplift in the northeast, the Nemaha uplift on the east, and the Precambrian fault system along the Arbuckle Mountains to the south (fig. 18). Production is concentrated on the eastern edge of the basin and to the north along the Central Kansas uplift. There is also production in the southeast corner of the basin along the Precambrian fault system.

Traps and Seals in the Simpson Group Assessment Unit

Simpson Group sandstones have produced substantial volumes of hydrocarbons from structural traps, especially along the Nemaha uplift on the eastern edge of the basin (fig. 18). On the Nemaha uplift, production is on the flanks of structural highs from erosionally truncated sandstone that is sealed by overlying Pennsylvanian shales. Multiple Simpson fields produce along these complex structures, such as the Oklahoma City, Golden Trend, and Sho-Vel-Turn fields. The Oklahoma City field produces from a large anticline near the south end of the Nemaha uplift, bounded on the east by a normal fault (Northcutt and Johnson, 1997). There is a large amount of commingled production in these fields.

Historically, Simpson exploration has been largely related to structural traps, with little exploration for possible stratigraphic traps related to unconformities, porosity development, and pinchouts of porous sandstone and carbonates. There may also be significant potential for stratigraphic traps that lie off structure and below seismic resolution (Candelaria and others, 1997).

Simpson reservoir seals are interbedded Simpson shales and tight sandstones or carbonates (fig. 20). Also, overlying Pennsylvanian shales on the flanks of structural highs form seals where the underlying strata have been removed by erosion.

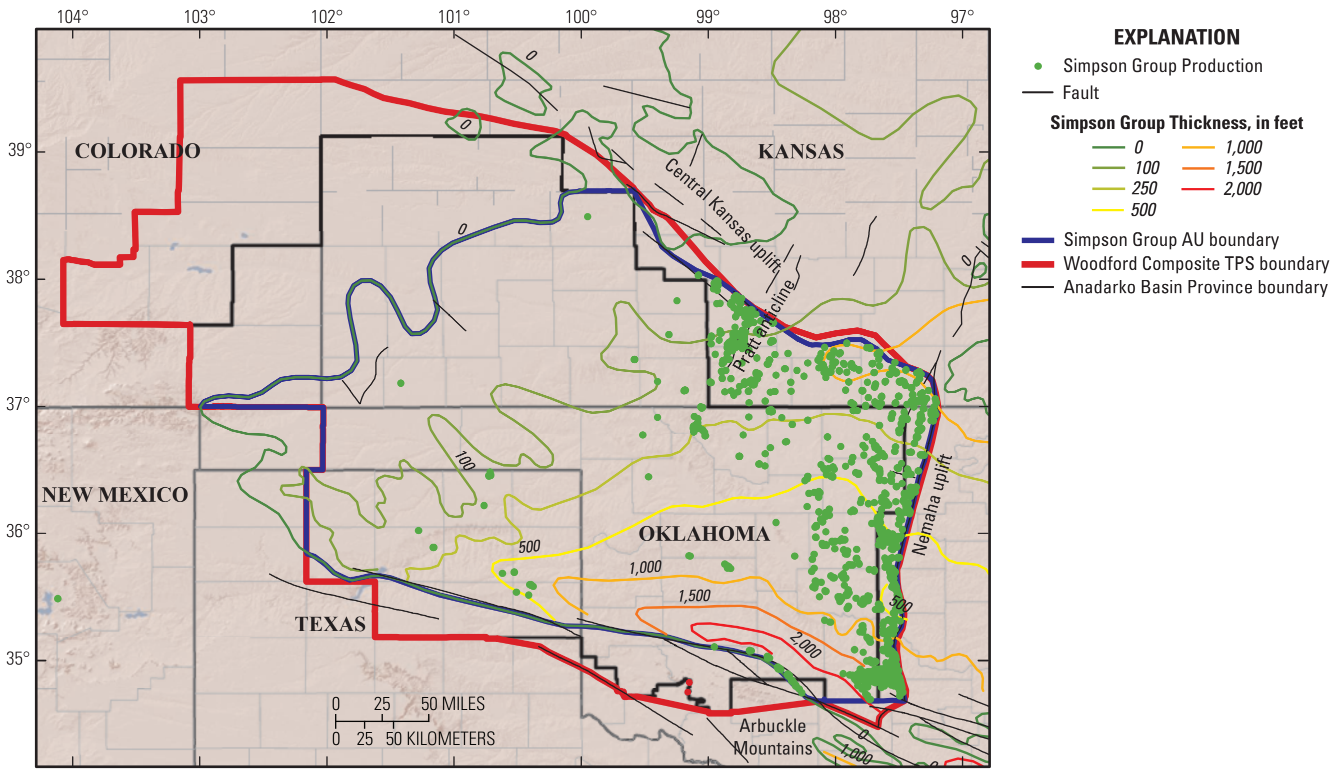

Figure 18. Map showing production from and thickness of the Simpson Group; contour interval is 500 feet.

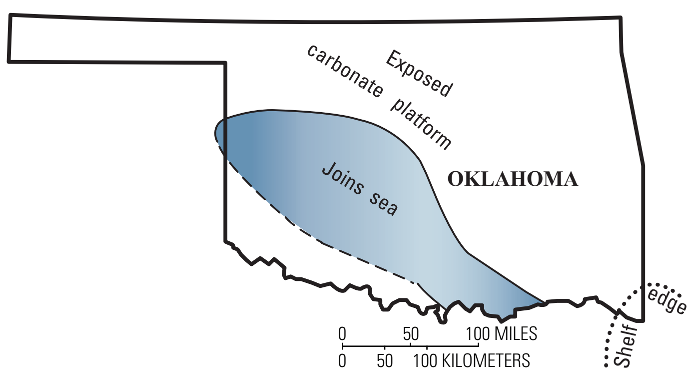

Figure 19. Image showing approximate distribution of the Joins sea during Ordovician time (modified from Denison, 1997).

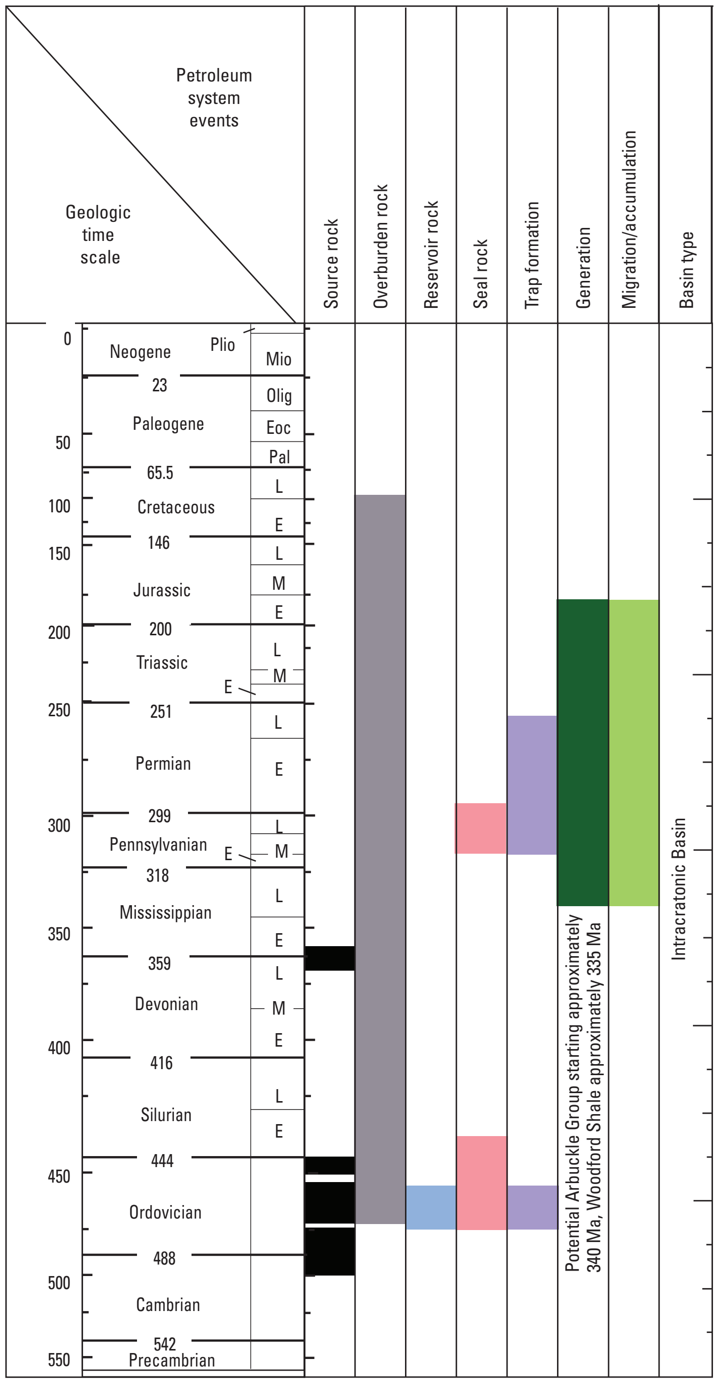

Figure 20. Simpson Goup Assessment Unit events chart showing the timing of source rock deposition and trap formation, and the age of overburden, reservoir, and seal rocks with different color bars (black, source rock; gray, overburden rock; blue, reservoir rock; pink, seal rock; purple, trap formation; dark green, generation; light green, migration accumulation). The chart also depicts the timing of oil generation, migration and accumulation as modeled for various wells in different parts of the Anadarko Basin. Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

Sizes and Numbers of Undiscovered Fields in the Simpson Group Assessment Unit

The Simpson reservoirs are of limited lateral and vertical extent, but important enough to enable individual wells to produce more than 1 MMBO (Northcutt and Johnson, 1997). Production is commonly commingled with other reservoirs, especially reservoirs in the Viola Group. Nehring accumulation data (Nehring Associates, Inc., 2009) indicates that individual fields in the Simpson produce approximately 0.5 to 8.0 MMBO in the basin. There is limited gas data available. There has been substantial penetration of the Simpson Group in south-central Kansas and near the Nemaha uplift, and scattered sporadic drilling throughout the remainder of the AU (fig. 21). There has been little drilling in the deep basin, near the basin depocenter.

Cumulative oil production in the Simpson AU is 470 MMBO (IHS Energy Group, 2010). There is oil production throughout the basin, whereas gas production is limited to the deeper part of the basin, with 1.2 TCFG produced (IHS Energy, 2010; fig. 21). Production depths range from 3,000 to 17,400 ft in the structurally deepest part of the basin (fig. 21). There is an overlap in the oil and gas production, with production concentrated on the eastern and southern parts of the basin, and accumulations split between oil and gas.

The Nehring database (Nehring Associates, Inc., 2009) lists 105 Simpson accumulations, but only 18 have accumulation data (17 oil and 1 gas; fig. 22). As with the Arbuckle, this is likely because of the reporting of commingled production, or the erroneous reporting of the producing formation. Nehring field data (Nehring Associates, Inc., 2009) were used to supplement the database, but field data are of marginal use because it includes all producing reservoirs for a field, not just the Simpson Group.

Using the USGS assessment methodology for undiscovered conventional resources (Klett and others, 2005; Schmoker and Klett, 2005), we estimated the mean undiscovered oil resources for conventional reservoirs in the Simpson Group AU at 5 MMBO and 125 BCFG (table 1). These estimates are based partly on data for 18 discovered accumulations that exceeded the minimum size of 0.5 MMBO (Nehring Associates, Inc., 2009). The distribution of the number of undiscovered oil accumulations is estimated to have a minimum of 1, a median of 3, and a maximum of 10. The estimated minimum, median, and maximum numbers of undiscovered gas accumulations exceeding the minimum size are 3, 6, and 60, respectively. The Simpson has been penetrated extensively on the shelf near the Oklahoma-Kansas border, along the Nemaha uplift, and on other structures in the basin (fig. 21). There are also dry holes and wells with minor production in the Texas Panhandle and into south-central Kansas, where the Simpson becomes dominated by chert (Doveton and others, 1990; Charpentier and Doveton, 1991). There is more undrilled area in the deep basin along structures in the same region where the Arbuckle is sparsely drilled. Future oil and gas production is likely limited on the shelf, as it has been extensively explored. The most recent Simpson discoveries were in the mid-1980s, suggesting that the interest and potential in the Simpson is waning.

The estimated minimum, median, and maximum sizes of undiscovered oil accumulations are 0.5, 0.8, and 8.0 MMBO. The 0.5 MMBO default signifies that there will be at least one field discovered greater than the minimum size, and the maximum reflects the maximum size of a potential undiscovered oil accumulation, and the largest grown oil field reported (Nehring Associates, Inc., 2009). Oil production per field for the Simpson is generally less than 2 MMBO. Estimated minimum, median, and maximum sizes of undiscovered gas accumulations are 3, 6, and 60 BCFG. The maximum number reflects the uncertainty of deep gas production in the Simpson, similar to the Arbuckle-Ellenburger, as both are sparsely drilled in the deep basin.

Viola Group

Simpson Group sandstones and limestones are overlain by the Upper Ordovician limestones of the Viola Group. Following a brief marine withdrawal, Viola seas transgressed over the exposed upper Bromide carbonates of the Simpson Group, and deposition was in a broad, shallow, epicontinental sea (Denison, 1997). The Viola is a marine limestone sequence deposited on a carbonate platform (figs. 4 and 23), and is widespread in the Anadarko Basin. It contains chert at several stratigraphic levels and is highly fossiliferous (Johnson and others, 2000). There is terrigenous detritus in the lower Viola in the aulacogen, and the strata grade upward into clean, skeletal limestones (Johnson, 1991). The vertical change indicates an upward decrease in water depth and corresponding increase in energy level and aerobic activity (Johnson and others, 2000). Viola strata are 500-800 ft thick in the aulacogen, and thin to 50-500 ft on the shelf (fig. 24). The rift margin played an important role in the thickness and facies of the Viola carbonates. The Viola Group is absent in the northern and western parts of the basin (fig. 24).

In the southern Anadarko Basin, the Viola Group consists of the lower Viola Springs Formation and the upper Welling Formation (fig. 2), and represents a shallowing-upward sequence (Denison, 1997). Within the aulacogen, the Viola Springs comprises organic-rich, finely laminated lime mudstones deposited in deeper water, and the Welling is pelmatozoan-rich grainstones deposited in shallow water (Denison, 1997). Outside the aulacogen, the basal Viola Springs lithology is packstone and wackestone.

Viola carbonate deposition ended abruptly as the system was flooded with clays of the overlying Sylvan Shale. The Sylvan is a widespread green to greenish-gray shale sequence that ranges from 300 to 400 ft thick in the aulacogen and from 30 to 200 ft thick in most shelf areas (Johnson and Cardott, 1992; fig. 25). The formation was included in the Viola Group AU for this assessment, although there is sparse, insignificant production despite numerous penetrations (fig. 25). Minor accumulations attributed to the Sylvan Shale by IHS Energy (2010) are likely erroneously reported and are from other units.

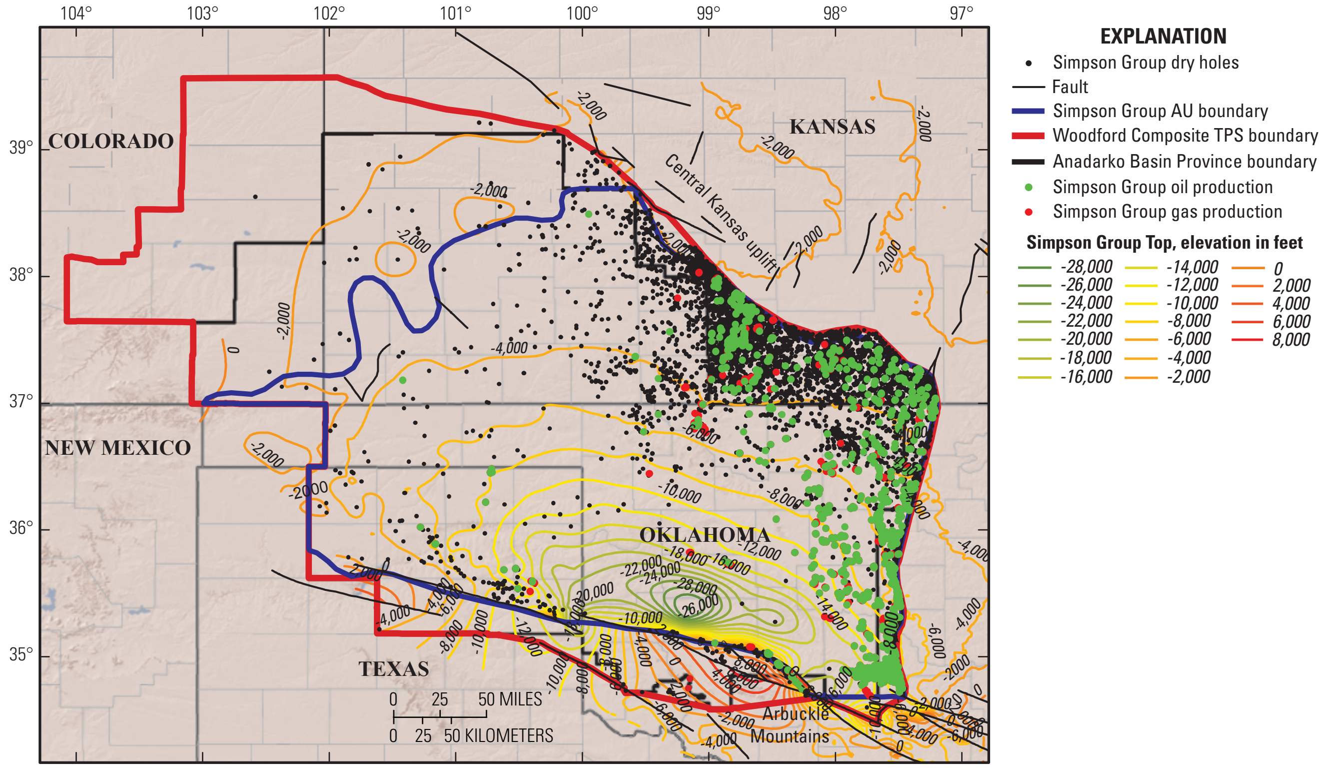

Figure 21. Map showing oil and gas production and dry hole penetrations from the Simpson Group in the Anadarko Basin Province (IHS Energy Group, 2010). The structure contours are drawn on the top of the Simpson Group; contour interval is 2,000 feet. The Anadarko Basin Province boundary is the black line, the Woodford Composite Total Petroleum System (TPS) boundary the red line, and the Simpson Group Assessment Unit (AU) Boundary the blue line.

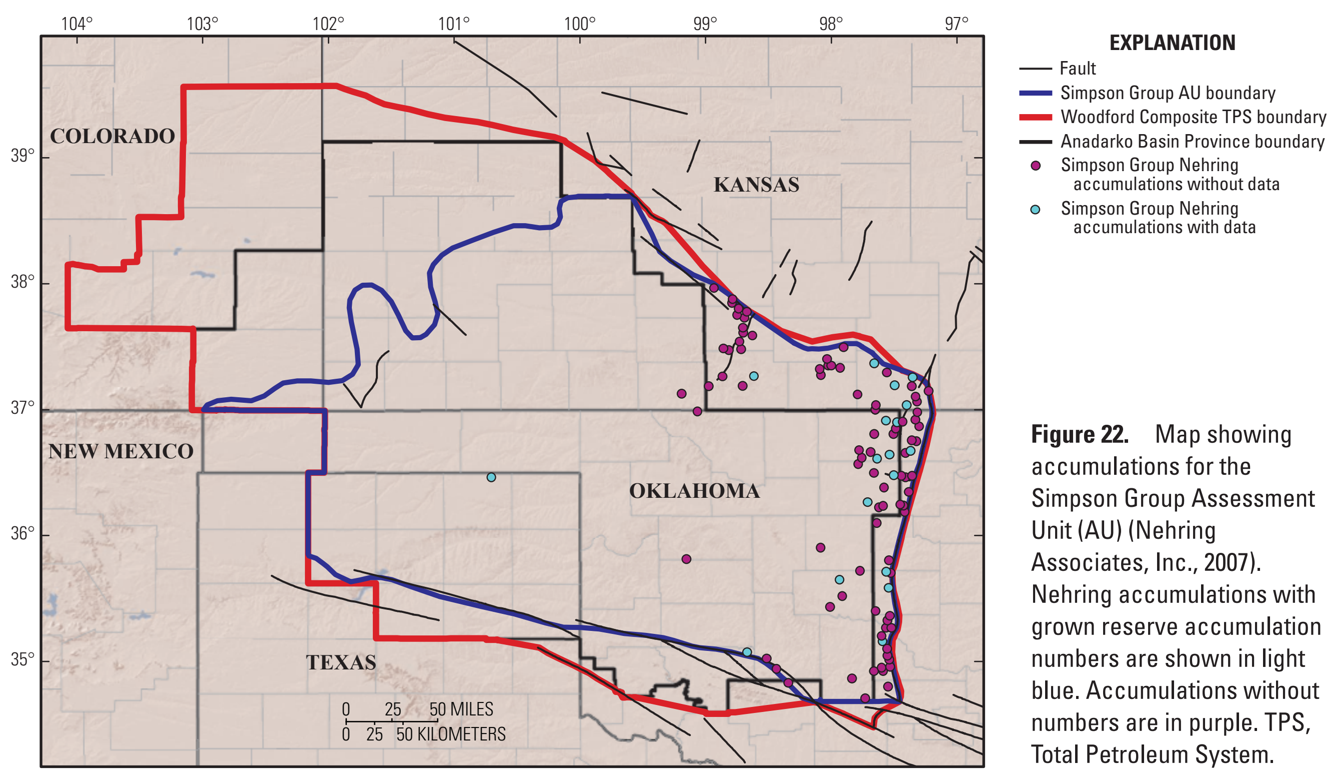

Figure 22. Map showing accumulations for the Simpson Group Assessment Unit (AU) (Nehring Associates, Inc., 2007). Nehring accumulations with grown reserve accumulation numbers are shown in light blue. Accumulations without numbers are in purple. TPS, Total Petroleum System.

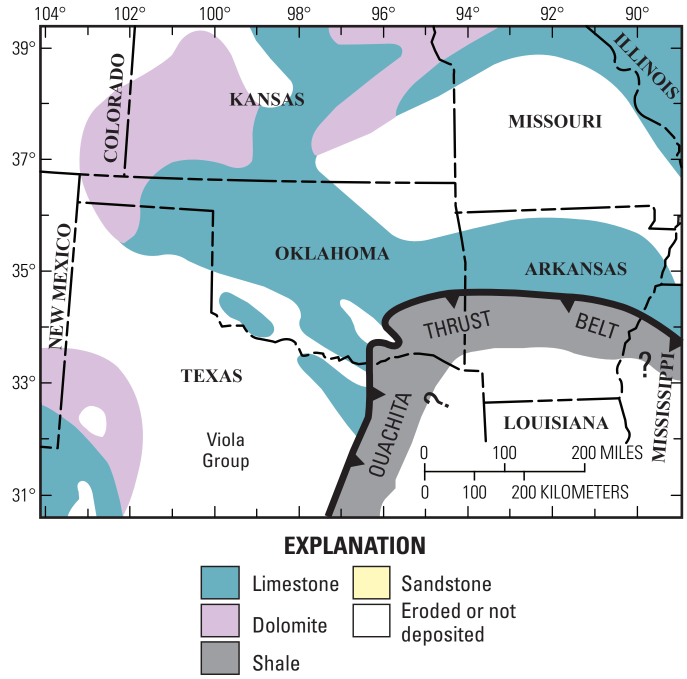

Figure 23. Image showing major lithologies of the Ordovician Viola Group strata in the southern midcontinent (modified from Northcutt and Johnson, 1997).

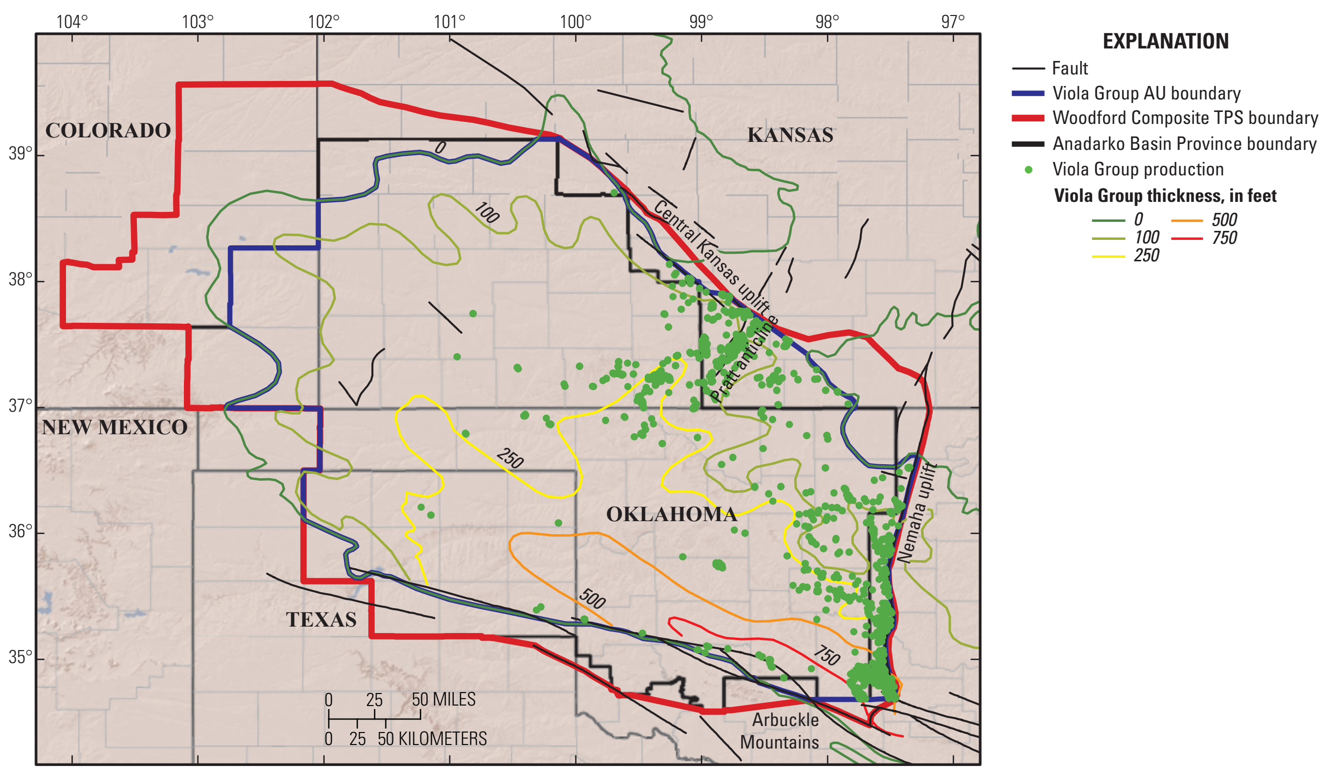

Figure 24. Map showing production from and thickness of the Viola Group; contour interval is variable.

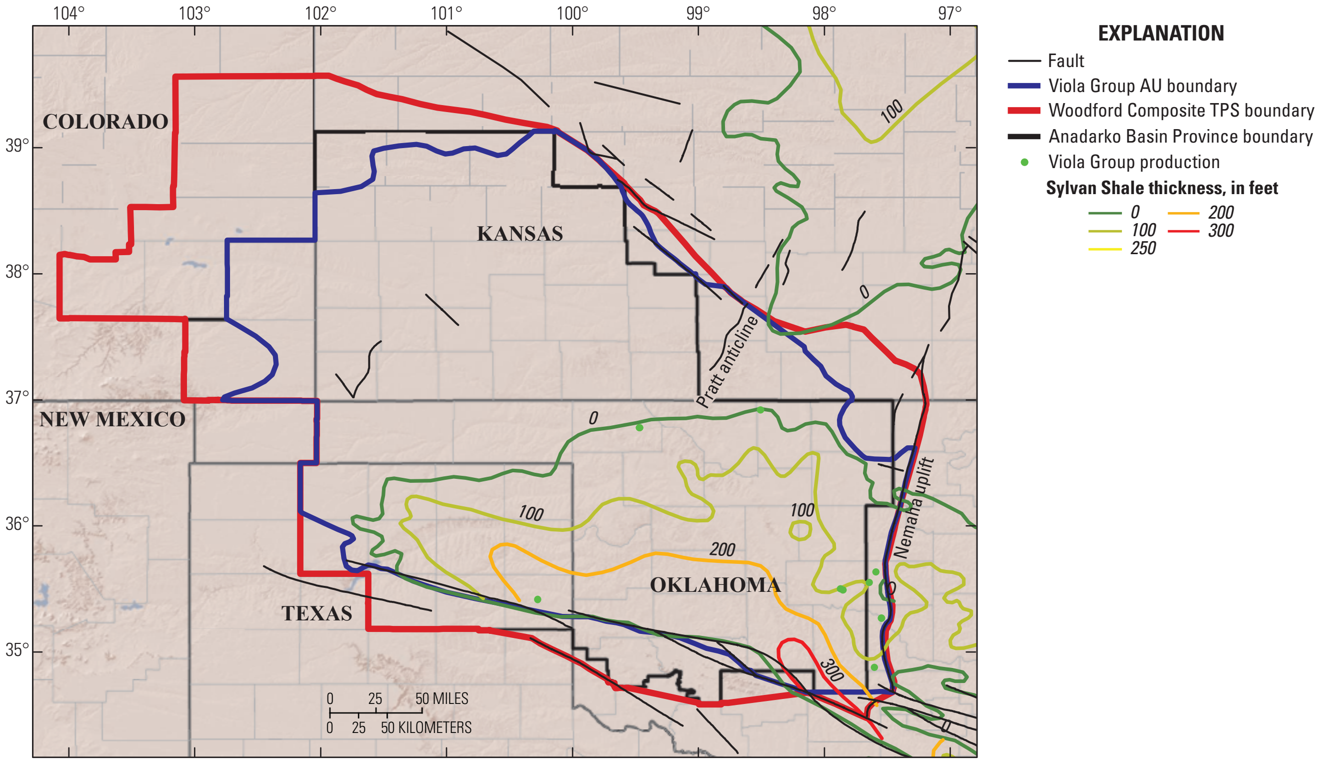

Figure 25. Map showing production from and thickness of the Sylvan Shale; contour interval is 100 feet.

Source Rocks of the Viola Group Assessment Unit

The Woodford Shale is the apparent source rock for Viola reservoirs, though there may be some self-sourcing as well as contributions from other Ordovician source rocks, such as the Simpson (figs. 7 and 26). Thin source beds that were sampled in the lowermost Viola Springs Formation have an average TOC of approximately 1 percent, with Type II kerogen (Denison, 1997; Wang and Philip, 1997). However, these data were disputed by Brown and Sentfle (1997) as a consequence of other studies indicating higher organic contents within the laminated marls of the Viola (average TOC of 2.4 percent) and basal chert (average TOC of 1.3 percent; see Wavrek and others, 1997). The Viola was reported as a source rock for oil in the Pauls Valley area of the Anadarko Basin by Jones and Philip (1990).

Data on the Sylvan Shale indicate that the source-rock potential is poor to moderate (Johnson and Cardott, 1992). The Sylvan contains Type II kerogen with low TOC (less than 1 percent; Burruss and Hatch, 1989).

Reservoir Rocks in the Viola Group Assessment Unit

Viola reservoirs are in thick sequences of limestones and dolomites that have been subjected to fracturing and dissolution, with karst features and zones of vuggy porosity. The Viola ranges from about 4,000 to 13,000 ft in depth in the basin (fig. 27). Karstification occurred following Sylvan and Hunton deposition when the Viola was exhumed in southern Oklahoma (Sykes and others, 1997). Karst features include conduit-filling breccias, solution enlarged fractures, crackle breccias, vugs, and channels (Sykes and others, 1997). Surface karstic features are also common. Selective dolomitization also enhanced porosity and reservoir quality in the Viola.

Reservoirs of the Viola Group may have primary and secondary porosity, and fracture systems are developed as a function of the brittle nature of the carbonate. The highest porosity is in intercrystalline, moldic, and vuggy subtidal dolomitic mudstones and wackestones (Newell, 2000). Porosity averages 8–10 percent, but can be as high as 23 percent in dolomitized reservoirs in south-central Kansas (Newell, 2000).

The Viola is absent in the northern and western Anadarko Basin, and the subcrop and province boundary define the assessment unit in those parts of the basin (fig. 24). The AU boundary is defined by the faults that delineate the southern end of the Central Kansas uplift in the northeast, the Nemaha uplift on the east, and the Precambrian fault system along the Arbuckle Mountains to the south (fig. 24).

Traps and Seals in the Viola Group Assessment Unit

Viola accumulations in the Anadarko Basin are commonly in structural or combination traps near the Central Kansas uplift and on the Nemaha uplift where the Viola is overlain by the Sylvan Shale or unconformably by Pennsylvanian shales (Carlson and Newell, 1997). The structural traps are in the same areas as the Simpson Group reservoirs. Production trends in south-central Kansas are in areas where dolomitized units are preserved on the crests of local anticlines (Newell, 2000). There is substantial Viola production in Fitts pool, to the southeast of the Anadarko Basin, on the western edge of the Arkoma Basin, where the structure is a large, fault-bounded anticlinal fold. Stratigraphic variations resulting from localized movement during deposition can provide north-south closure for these structural traps. Stratigraphic traps may also be present where porous wedges of dolomitized Viola are enclosed by nonporous packstone and grainstone beds.

The primary seals in the Viola Group are the overlying Sylvan Shale, which has low porosity and permeability, or interbedded tight, impermeable limestone of the Viola (fig. 26). Oil and gas fields are also found where Viola reservoirs subcrop beneath the basal Pennsylvanian angular unconformity in south-central Kansas (Newell, 1997).

Sizes and Numbers of Undiscovered Fields in the Viola Group Assessment Unit

The Viola Group is not considered as significant a reservoir as the Simpson Group, though it yields oil and gas from thick sequences of carbonates that are fractured and have solution-enhanced porosity (Northcutt and Johnson, 1997). Production is from locally dolomitized sections on structures tested for Simpson and Arbuckle production. Most of the production is in the eastern basin, along the Nemaha uplift and near the Central Kansas uplift, where the Simpson Group produces (figs. 24 and 27).

The Viola has been extensively penetrated along the eastern and northern basin boundaries (fig. 27). Production is commonly commingled with other reservoirs, and formation water is produced with the oil. Hydraulic fracturing of the Viola reservoirs have been important to reservoir development (Johnson and others, 2000). The Viola has fair to good matrix porosity, but low permeability in many areas of the basin, requiring fracturing for production. The Viola is being pursued as a horizontal drilling candidate (Fritz and others, 1993).

There is little reservoir information reported for the Viola Group in the Nehring database (Nehring Associates, Inc., 2009); of the 29 accumulations only 1 has reported oil accumulation data (fig. 28). Cumulative oil production from the Viola Group AU is 112 MMBO (IHS Energy, 2010). Cumulative gas production is 505 BCF (IHS Energy, 2010). Production depths range from 4,000 to 18,000 ft in the deepest basin. There is an overlap in the oil and gas production, with both concentrated on the eastern and northeastern parts of the basin (fig. 27).

Using the USGS assessment methodology for undiscovered conventional resources (Klett and others, 2005; Schmoker and Klett, 2005), it is estimated that the undiscovered oil and gas resources for conventional reservoirs in the Viola Group AU have a mean of 5 MMBO and 30 BCFG (table 1). The estimated minimum, median, and maximum numbers of (1) undiscovered oil accumulations exceeding the minimum size (0.5 MMBO) are 1, 2, and 10; and (2) undiscovered gas accumulations exceeding the minimum size (3 BCFG) are 1, 2, and 10. Like the Simpson, the Viola has been penetrated extensively on the shelf near the Oklahoma-Kansas border, along the Nemaha uplift, and on other structures in the basin (fig. 27). There is undrilled area in the deep basin along structures in the same region where the Arbuckle and Simpson are sparsely drilled. Future oil and gas production is likely limited on the shelf, as it has been extensively explored along the structures. The maximum number of oil and gas accumulations was raised to account for possible deep basin drilling. The most recent Viola discoveries were in 2000, though no data were reported by Nehring Associates, Inc. (2009) for these fields.

The estimated minimum, median, and maximum sizes of undiscovered oil accumulations are 0.5, 1.0, and 5.0 MMBO. The 0.5 MMBO default signifies that there will be at least one field found greater than the minimum size, and the maximum reflects the maximum size of a potential undiscovered oil accumulation, based on field data, as there is only one oil accumulation reported for the Viola Group AU (Nehring Associates, Inc., 2009). Oil production by field for the Viola is generally less than 3 MMBO. The distribution of sizes of undiscovered gas accumulations was estimated to have a minimum of 3 BCFG, a median of 6 BCFG, and a maximum of 30 BCFG. The maximum reflects the uncertainty with deep gas production in the Viola Group.

Hunton Group

The Silurian-Devonian was a time of widespread marine-carbonate deposition in the Midcontinent, and strata were deposited as a relatively thin veneer of limestones and dolomites in a ramp environment (fig. 29). Sea-level changes caused the migration of facies and generated the lateral distribution and vertical succession of carbonate strata (Al Shaieb and Puckette, 2002). The Hunton Group is a sequence of limestones, dolomites, and lesser clastic rocks of Late Ordovician to Early Devonian age (Al Shaieb and Puckette, 2002; fig. 2). Several distinct depositional environments are interpreted

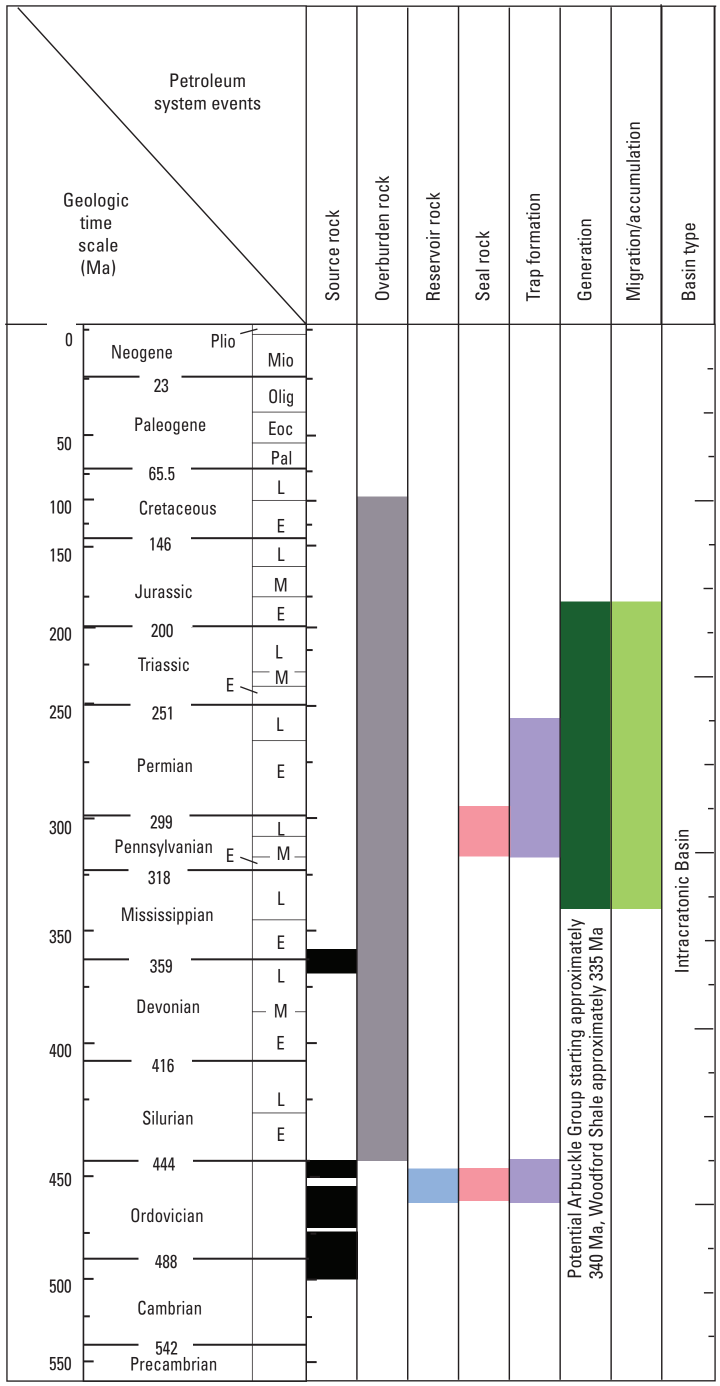

Figure 26. Viola Group Assessment Unit events chart showing the timing of source rock deposition and trap formation, and the ages of overburden, reservoir, and seal rocks with different color bars (black, source rock; gray, overburden rock; blue, reservoir rock; pink, seal rock; purple, trap formation; dark green, generation; light green, migration accumulation). The chart also depicts the timing of oil generation, migration and accumulation as modeled for various wells in different parts of the Anadarko Basin. Ma, mega-annum; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

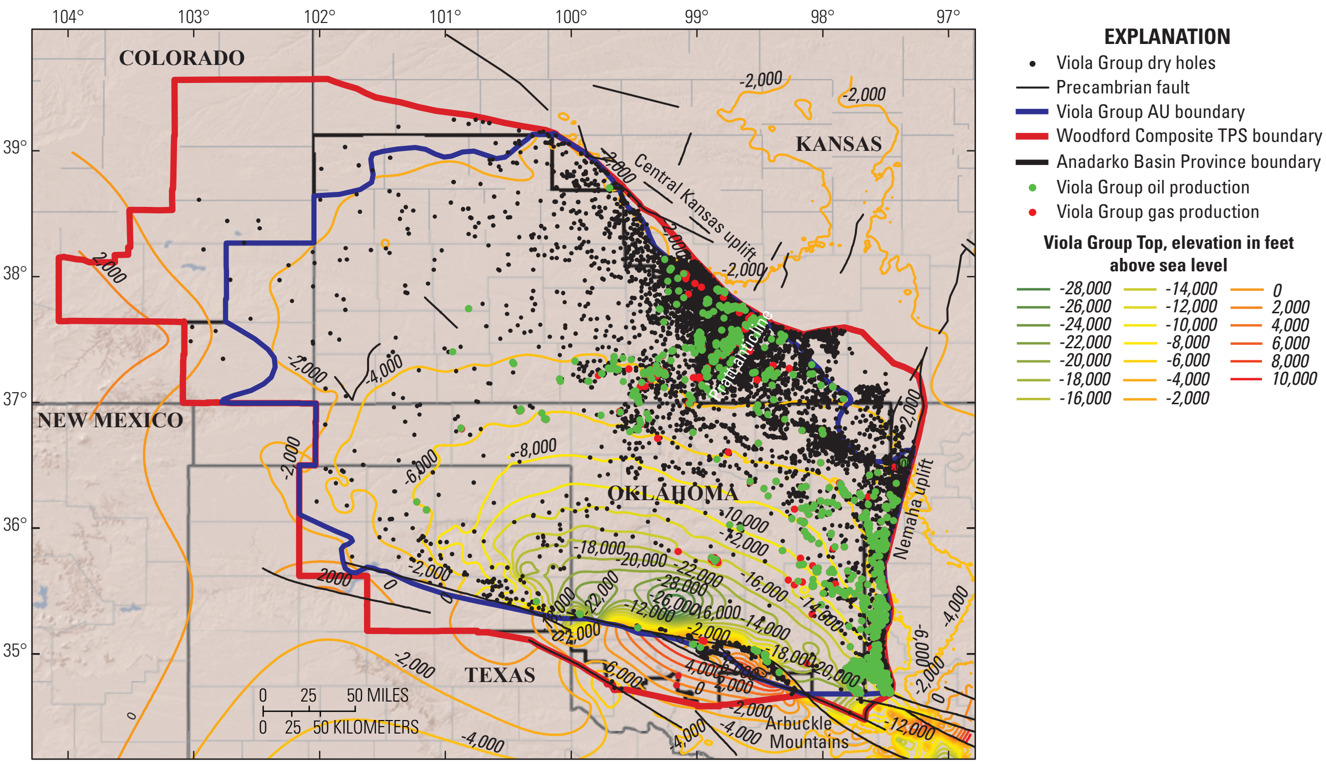

Figure 27. Map showing oil and gas production and dry hole penetrations for the Viola Group in the Anadarko Basin Province (IHS Energy Group, 2010). Structure contours are drawn on the top of the Viola Group; contour interval is 2,000 feet. The Anadarko Basin Province boundary is the black line, the Woodford Composite Total Petroleum System (TPS) boundary the red line, and the Viola Group Assessment Unit (AU) boundary the blue line.

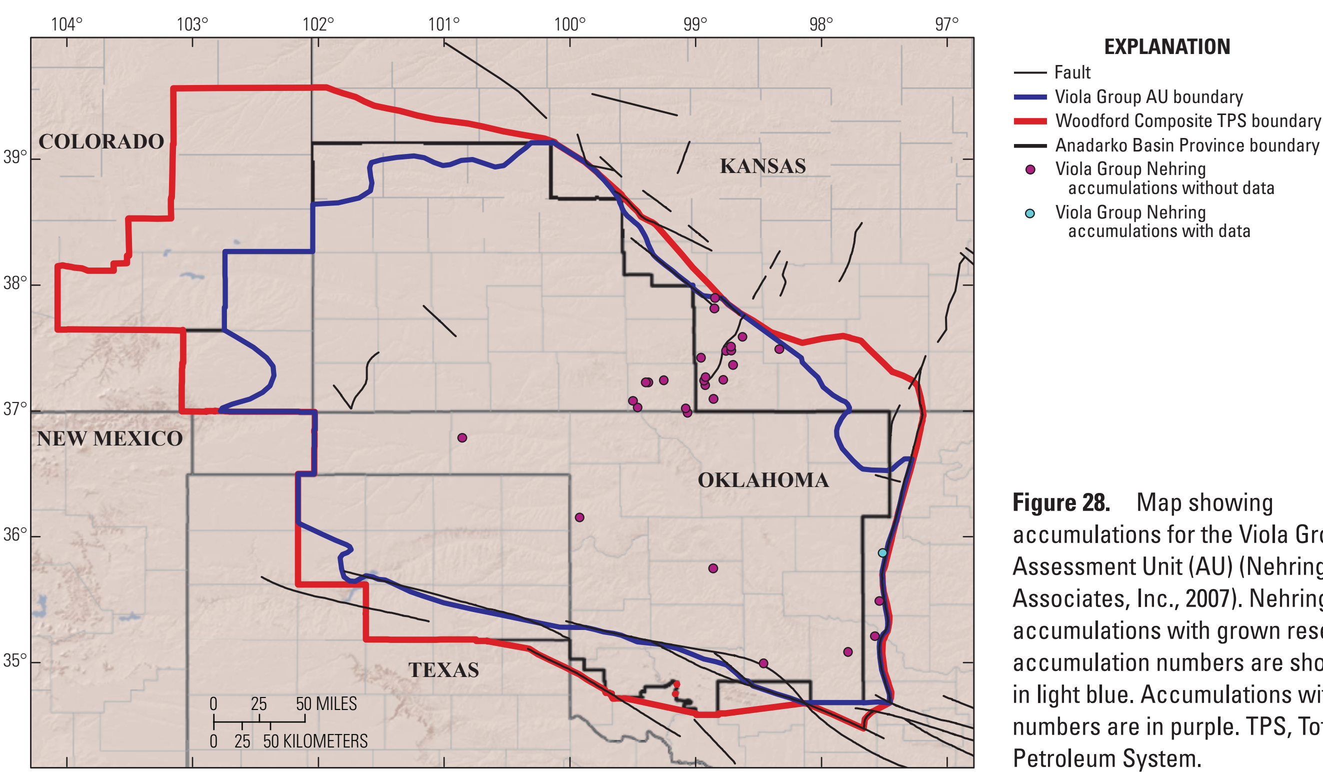

Figure 28. Map showing accumulations for the Viola Group Assessment Unit (AU) (Nehring Associates, Inc., 2007). Nehring accumulations with grown reserve accumulation numbers are shown in light blue. Accumulations without numbers are in purple. TPS, Total Petroleum System.

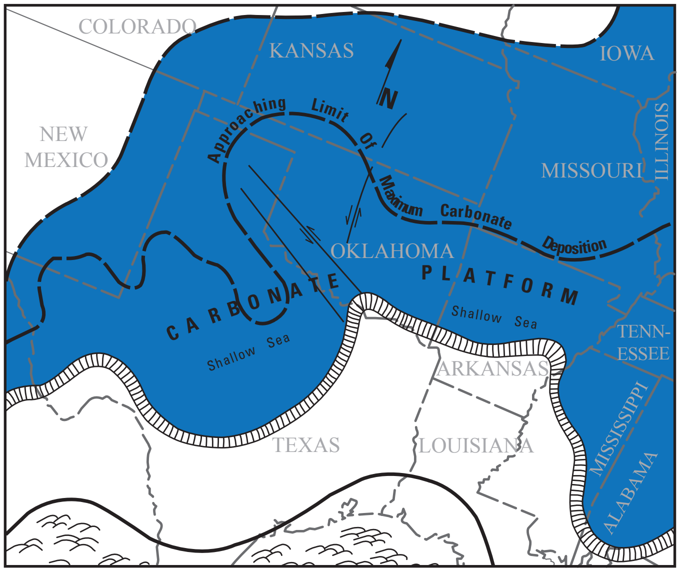

Figure 29. Image showing depositional setting during Hunton time in the midcontinent (modified from Fritz and Medlock, 1994).

from Hunton strata, including upper intertidal to supratidal, upper subtidal to lower intertidal, and subtidal facies (Fritz and Medlock, 1994; fig. 30). These facies are in shallowing-upward cycles or parasequences. The Hunton comprises a series of progradational sequences that built generally southward across the carbonate ramp (Fritz and Medlock, 1994); predominantly subtidal rock, bioclastic, and oolitic facies that are less argillaceous and more bioturbated than the Arbuckle Group, the Hunton Group is divided into a number of formations (fig. 31). The basal unit in the southern Anadarko Basin of Oklahoma is the Ordovician Keel Formation, which resulted from eustatic shoaling of sea water with no significant terrigenous sedimentation, and has patchy distribution in Oklahoma (Johnson, 1991). The Keel is part of the informal Chimneyhill subgroup, which also contains the overlying Silurian Cochrane and Clarita Formations, which are dolomitic limestones and dolomite (fig. 31). The clean skeletal limestones and dolomites of the Chimneyhill are overlain by the argillaceous and silty limestones and dolomites of the Silurian Henryhouse and Silurian–Devonian Bois d'Arc Formations (Haragan Formation equivalent). The Henryhouse reservoirs are dolomitized intertidal facies (Al Shaieb and Puckette, 2002). In central and southern Oklahoma, they are overlain by the Devonian Frisco Formation (fig. 32). The Frisco Formation consists of skeletal packstone and grainstones, whose main components are pelmatozoans, brachiopods, and local corals (Morgan and Schneider, 1981). There are several intra-Hunton unconformities, including the Silurian–Devonian contact, and at the base of the Frisco Formation (fig. 31).

Following Hunton deposition, a pre-Woodford unconformity developed that is widespread in the Midcontinent (Johnson, 1989). This unconformity surface is one of the few in the Midcontinent in which the erosional geometry includes preserved incised channel features (Rottmann, 2000c). The inundation of Devonian seas was initially confined to erosional channels, filling them with Woodford Shale and preserving them.

The Hunton conformably overlies the Sylvan Shale and is unconformably overlain by either the main body of the Woodford Shale or locally by the basal informal Misener sandstone of the Woodford, which is Late Devonian in age (fig. 2). The Misener was deposited on the post-Hunton unconformity in a marine environment, accumulating within preexisting fluvial channels (fig. 33). The sandstones are of the same source as the Simpson sandstones to the north and east, with the detritus being transported south as the early Woodford sea transgressed. The Misener is a fine-grained quartz sandstone with some dolomite, interbedded with Woodford-like shale.

The Hunton thickens from a wedge edge near the Kansas-Oklahoma border to more than 1,600 ft in Washita and Beckman Counties, Oklahoma, in the deepest part of the basin (fig. 34). The Hunton is typically 100 to 400 ft thick on the northern shelf, where it is highly dolomitized (Johnson and others, 2000). The depositional extent of the Hunton has been modified by erosion (fig. 32).

Source Rocks of the Hunton Group Assessment Unit

The Hunton Group is not known to contain source rocks for hydrocarbons in the Anadarko Basin (Johnson and Cardott, 1992). However, the Woodford Shale, which lies unconformably on the Hunton (fig. 2) and has excellent source rock quality is considered to be the primary source for Hunton reservoirs throughout the basin (figs. 7 and 35). Vitrinite reflectance data indicates that the Woodford is mature for the generation of both oil and gas, especially in the deep basin (fig. 8). Woodford hydrocarbons likely migrated up through the deep basin into Hunton reservoirs, although there is some indication from one-dimensional burial history models that there could be sourcing from the Woodford along the Nemaha uplift on the eastern edge of the basin (fig. 9). It is also likely that there is some contribution of Ordovician oil into the Hunton Group reservoirs as well, based on analyzed Hunton reservoir oils (J.R. Hatch, oral commun., 2010).

Reservoir Rocks in the Hunton Group Assessment Unit

The Hunton Group is a significant oil reservoir on the northern Anadarko Basin margin and a major gas producer in the deep (greater than 15,000 ft) basin (fig. 36). Reservoir development is largely facies dependent in the Hunton Group (Fritz and Medlock, 1994), though the wide range of depositional environments and diagenetic changes were also favorable for reservoir development. Typical facies for reservoir units are low-relief skeletal buildups and oolite shoals, both of which underwent some post-depositional dolomitization (Johnson and others, 2000).

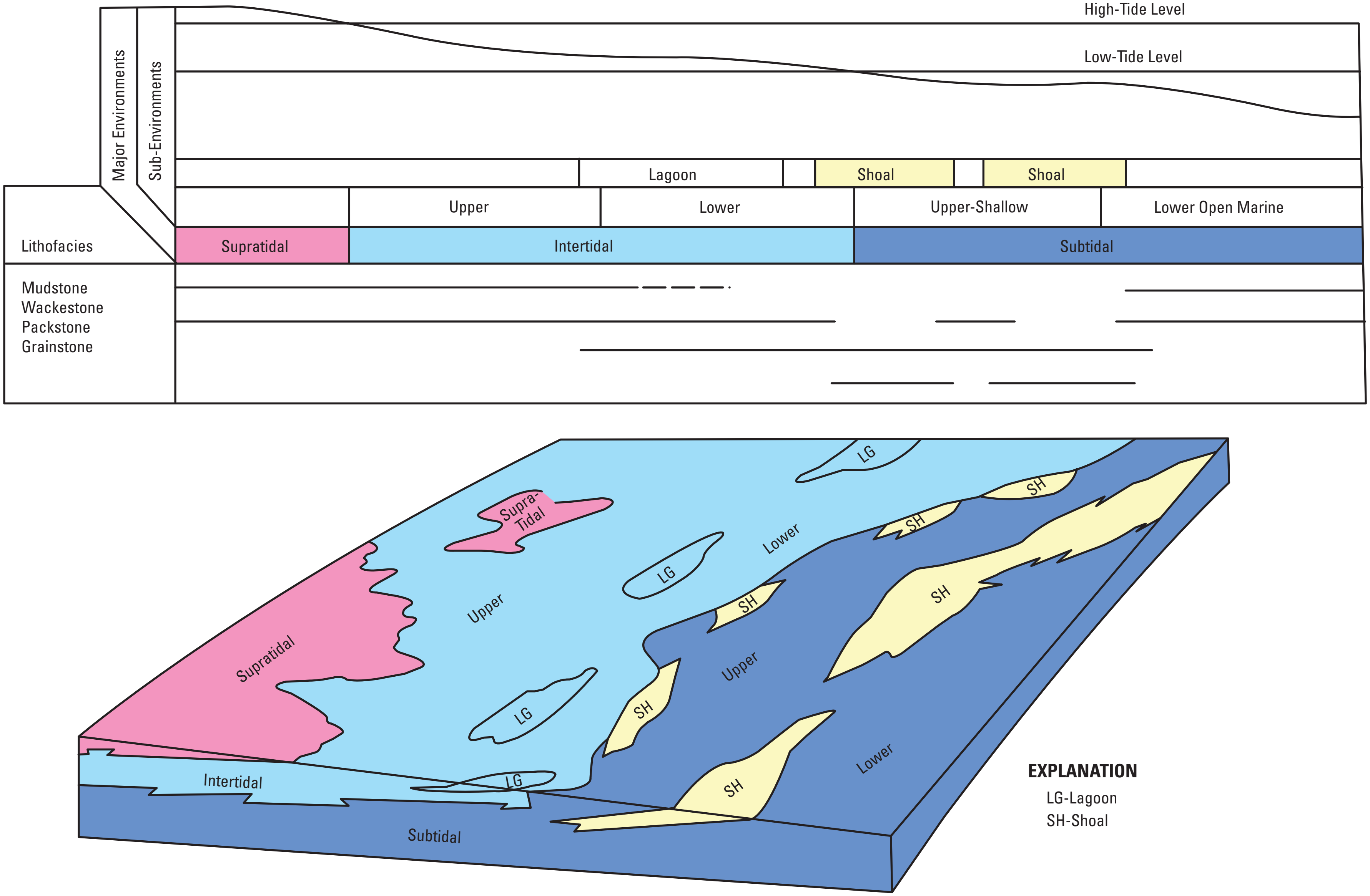

Figure 30. Depositional model for Chimneyhill subgroup through Bois d'Arc Formation strata of the Hunton Group (modified from Fritz and Medlock, 1994).

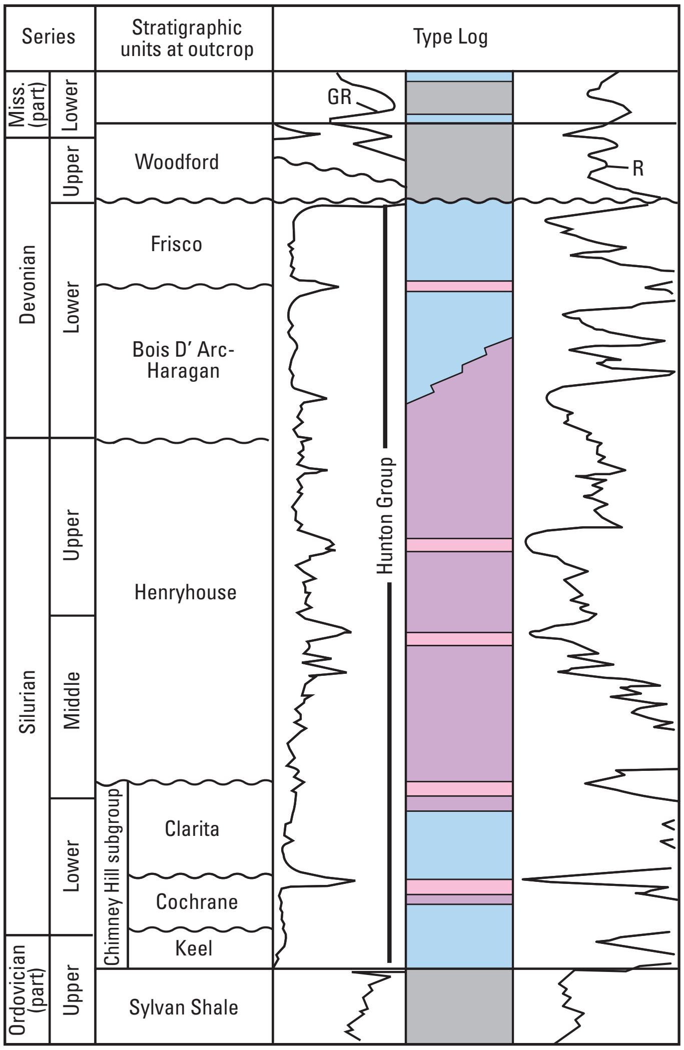

Figure 31. Type log of the Hunton Group in central Oklahoma; gray are shales, pink are calcareous shales, blue are limestones, and purple represents dolomite (modifed from Fritz and Medlock, 1994). GR, gamma-ray; R, resisitivity; Miss., Mississippian.

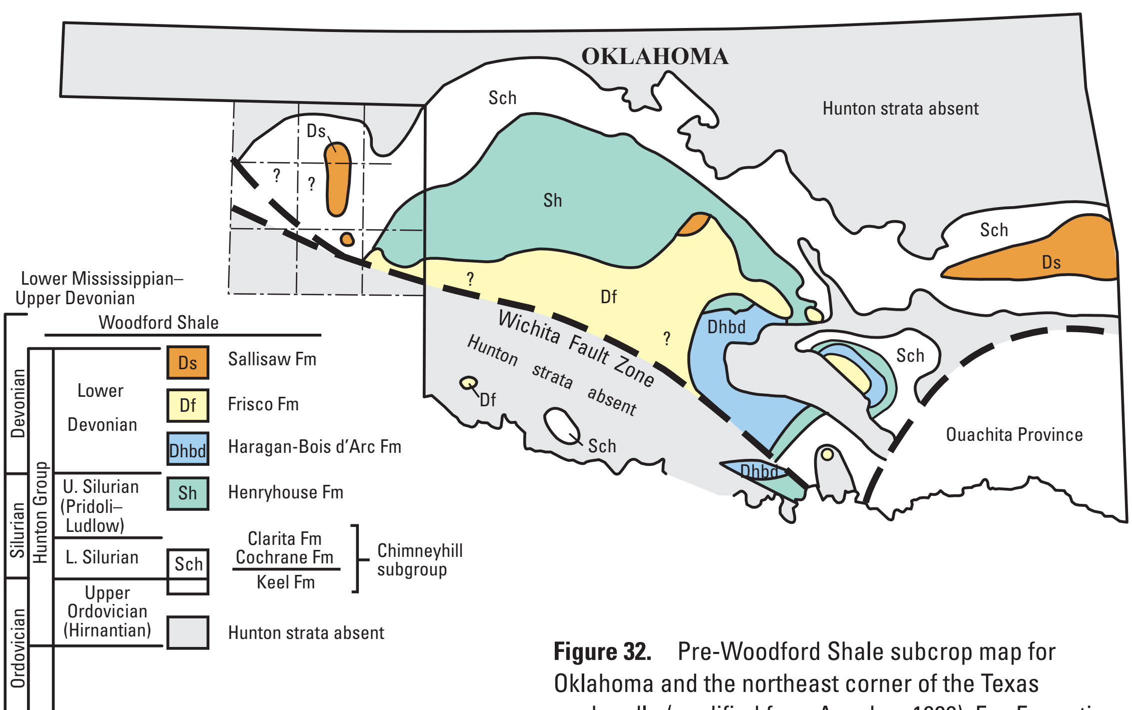

Figure 32. Pre-Woodford Shale subcrop map for Oklahoma and the northeast corner of the Texas panhandle (modified from Amsden, 1989). Fm, Formation.

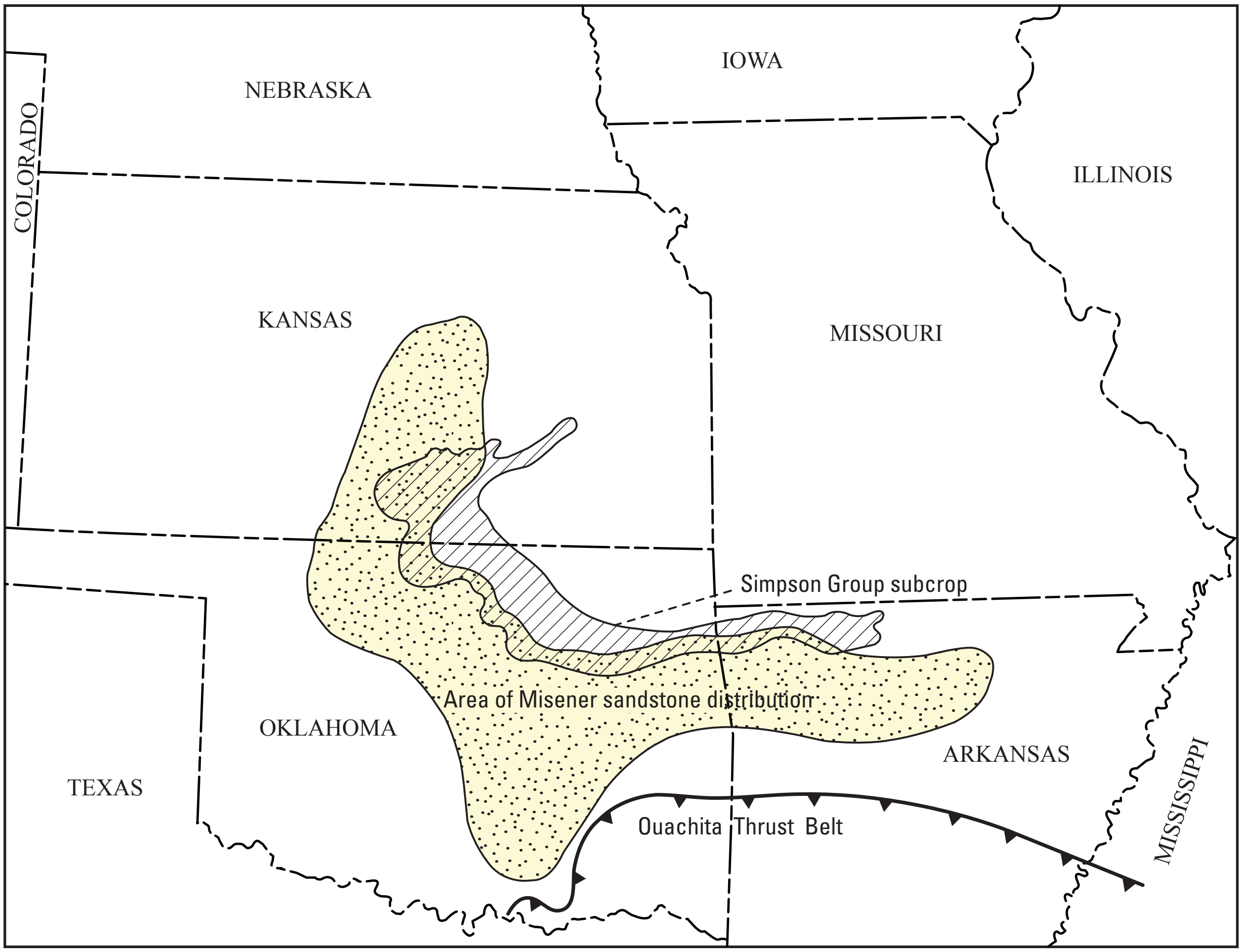

Figure 33. Image showing approximate distribution of the informal Misener sandstone of Woodford Shale and its relation to the Simpson Group subcrop (modifed from Kuykendall and Fritz, 1993).

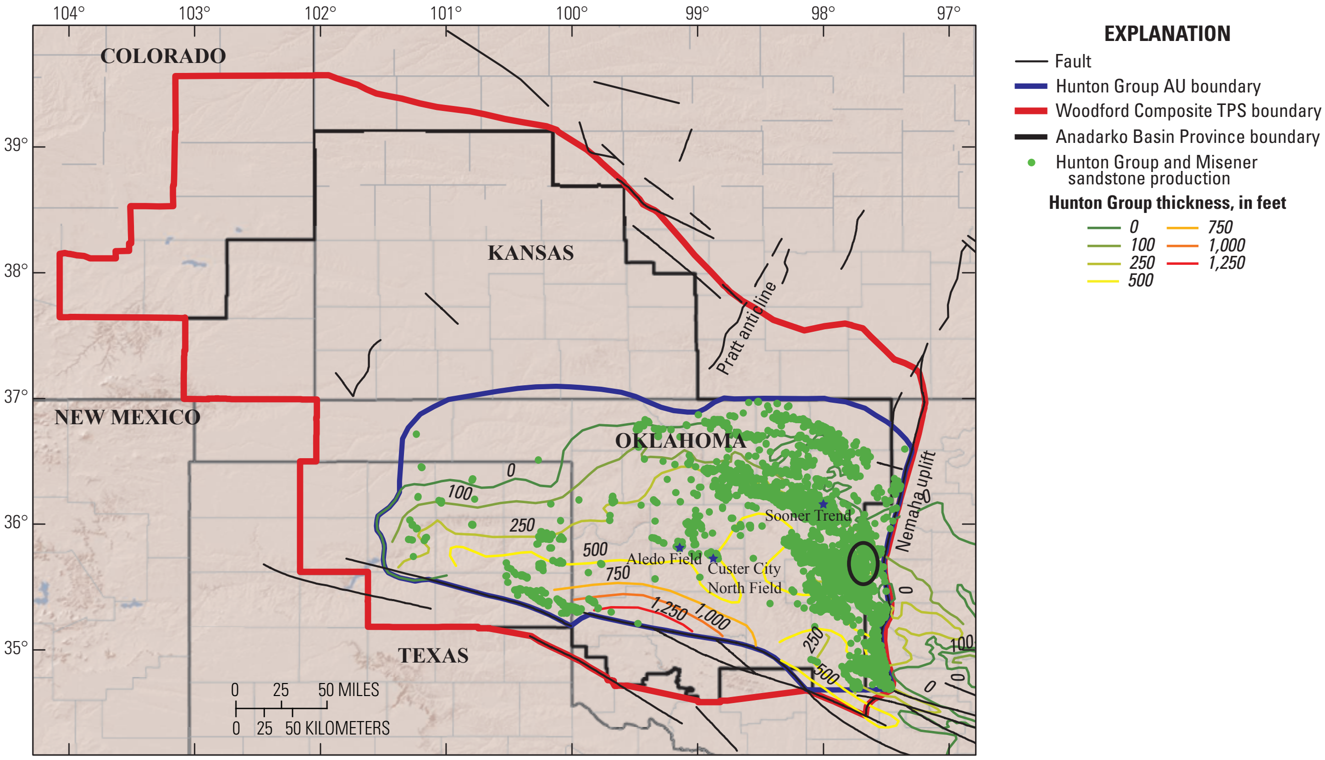

Figure 34. Map showing production from the Hunton Group and informal Misener sandstone of the Woodford Shale, and Hunton Group thickness; contour interval is 250 feet. Black oval is the West Edmond field. TPS, Total Petroleum System; AU, Assessment Unit.

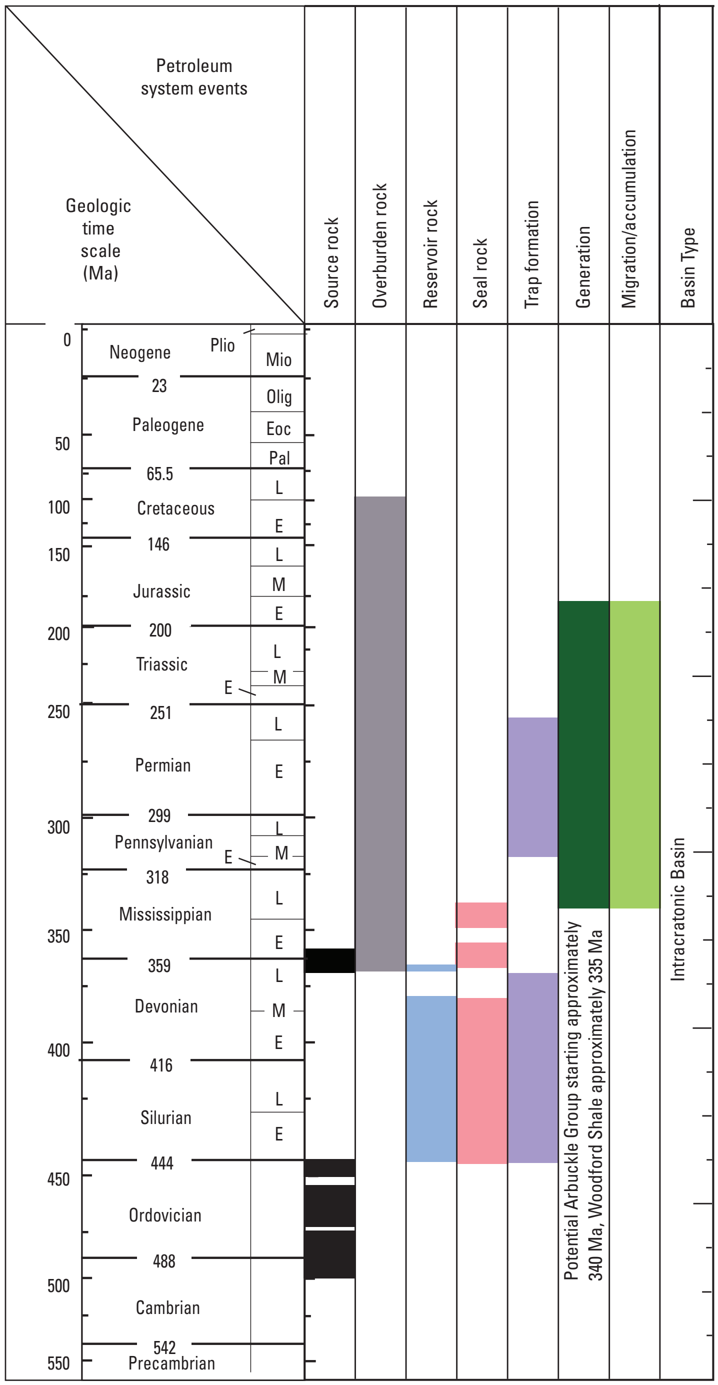

Figure 35. Hunton Group Assessment Unit events chart showing the timing of source rock deposition and trap formation, and the age of overburden, reservoir, and seal rocks with different color bars (black, source rock; gray, overburden rock; blue, reservoir rock; pink, seal rock; purple, trap formation; dark green, generation; light green, migration accumulation). The chart also depicts the timing of oil generation, migration and accumulation as modeled for various wells in different parts of the Anadarko Basin. Ma, mega-annum; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

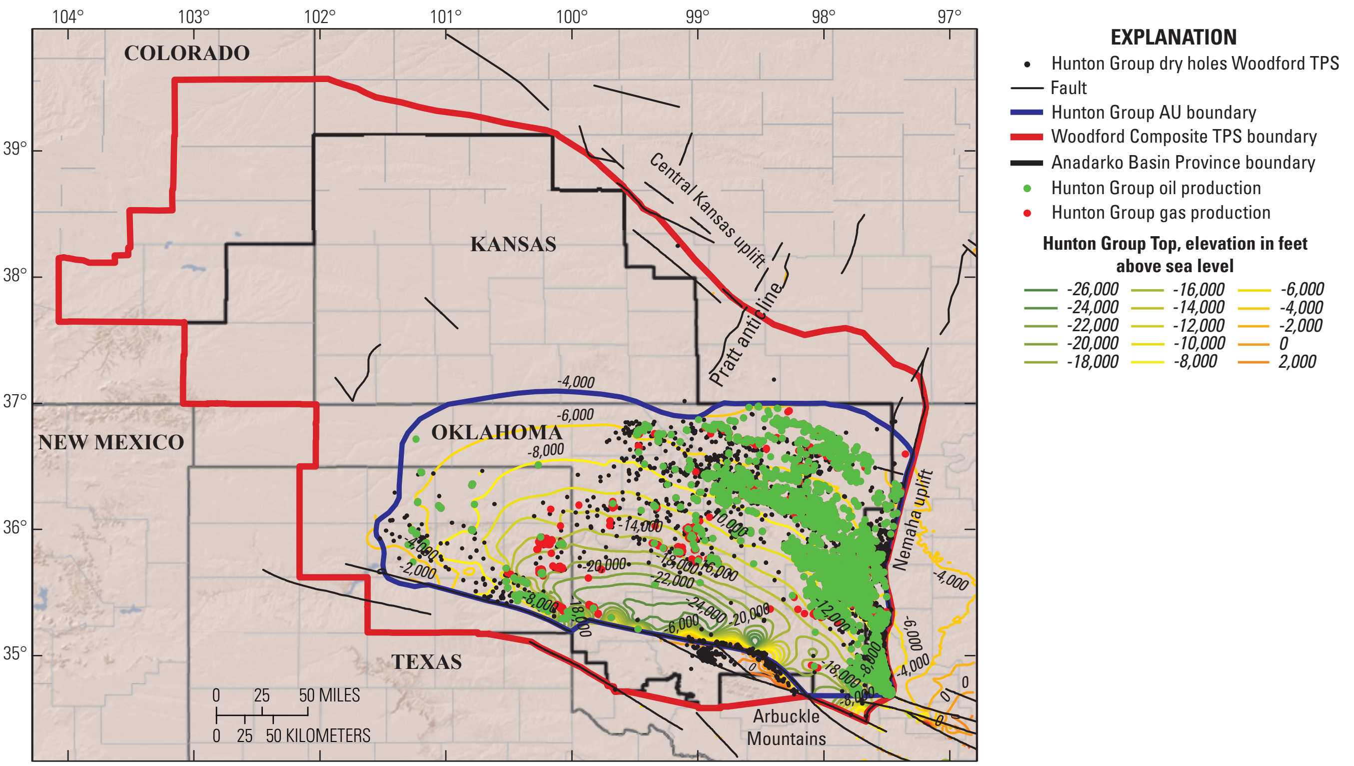

Figure 36. Map showing oil and gas production and dry hole penetrations for the Hunton Group and informal Misener sandstone of the Woodford Shale in the Anadarko Basin Province (IHS Energy Group, 2010). Structure contours are drawn on the top of the Hunton Group; contour interval is 2,000 feet. The Anadarko Basin Province boundary is the black line, the Woodford Composite Total Petroleum System (TPS) boundary the red line, and the Hunton Group Assessment Unit (AU) Boundary the blue line.

Fracturing, dolomitization, and dissolution are important factors for porosity development in the Hunton. Most Hunton reservoirs are in dolomitized rock. Upper subtidal and lower intertidal facies are dolomitized and have higher porosity (Wilson and others, 1991). Porosity ranges from 3 to 12 percent with an average of 8.6 percent over a depth range of 9,000 to 19,500 ft (Ball and others, 1991). Significant porosity formation in the Hunton is commonly in oolitic dolomitized grainstones and dolomitized burrowed wackestones and packstones (Fritz and Medlock, 1994). The exception is the Frisco Formation (fig. 31), which is sparsely dolomitized and generally has interparticle and intraparticle porosity combined with moldic to vuggy porosity, as it has undergone multiple diagenesis phases (Fritz and Medlock, 1994; Medlock, 1984). Hydrocarbon accumulations in the Frisco are mainly in stratigraphic traps situated downdip of the areas where the formation has been severely truncated (Morgan and Schneider, 1981). Some giant fields that produce from the Devonian Frisco Formation include the Fitts and West Edmond fields. The West Edmond field in northwest Oklahoma County produces where the Hunton is truncated on the west flank of the Nemaha uplift.

Most Hunton fields are west of the Nemaha uplift on the northeastern shelf of the Anadarko Basin. Another major region of production is in central Oklahoma (Johnson and others, 2000; fig. 34), and on the north flank of the Anadarko Basin, including the Sooner Trend, Aledo, and Custer City North fields. Unlike the Arbuckle, Simpson, and Viola, where production is largely dependent on structures, the Hunton production is unique in that it extends away from structural features. There has also been a substantial amount of production near the Hunton erosional edge near the Kansas-Oklahoma border.

Production from the Misener sandstone has been concentrated in the northeast corner of the AU, especially in Garfield, Grant, and Alfalfa Counties (fig. 37). Most of the production from the unit is reported commingled with that of the Hunton Group. It is a common target where present because of its shallow depth.

The Hunton Group AU boundary is defined by the Nemaha uplift on the east, the Precambrian fault system along the Arbuckle uplift to the south, and the Hunton subcrop and production to the east and north (fig. 34). The AU boundary was drawn slightly beyond the subcrop to account for remnant islands of Hunton carbonates that may have production potential.

Traps and Seals in the Hunton Group Assessment Unit

Most Hunton accumulations are in structure-stratigraphic combination traps, typically formed by the truncation of porous carbonate across structural noses (Fritz and Medlock, 1994). Most structures containing Hunton strata produce from the Hunton, but truncation traps are most common (Johnson and others, 2000). Another reservoir configuration in the Hunton Group is trapping by permeability barriers that are the result of facies changes along structural noses or faults. The upper surface of the Hunton is sculpted by the regional pre-Woodford unconformity, and these erosional structures also shape the traps on the basin margin (Ball and others, 1991). Weathering of the Hunton Group that occurred during pre-Woodford time and Pennsylvanian time also increased porosity and permeability.

The overlying Devonian–Mississippian Woodford Shale is a seal for the Hunton carbonates in the majority of the areas of the basin where the Hunton Group is present (fig. 35). However, the Woodford Shale is absent in some areas, and Mississippian strata form a seal for Hunton Group reservoirs in the Oklahoma and Texas Panhandles. There are also tight, low-porosity intervals within the Hunton Group that form intraformational seals for some reservoirs. Traps for the Misener sandstone are mainly stratigraphic, with some minor structural influence. Seals are likely interbedded shales.

Sizes and Numbers of Undiscovered Fields in the Hunton Group Assessment Unit

The Hunton Group is a prolific oil- and gas-producing unit in the Midcontinent. Some of the greatest potential for Hunton Group production is in the deepest parts of the Anadarko Basin, and some of the deepest gas fields in the world are located in the Hunton Group at depths below 20,000 ft along the Oklahoma-Texas border (Fritz and Medlock, 1994; fig. 36). Gas recovery in the basin increases with depth. Well spacing does not seem to have a significant effect on gas recovery, and most spacing on deep wells is 640-acre units (Smith and others, 2000).

The Hunton Group is a heterogenous reservoir, with a large amount of vertical and lateral variability. It is well explored and penetrated through most of the AU, but it is underexplored in the southwestern and north-central parts of the AU, where potential may exist, especially in stratigraphic plays (fig. 36).

There are 81 Nehring accumulations reported for the Hunton Group and Misener sandstone (fig. 38). Of these, 6 oil fields and 18 gas fields have accumulation data reported in the Nehring database (Nehring Associates, Inc., 2009). Cumulative oil production in the Hunton Group AU is 290 MMBO in the Hunton Group and 55 MMBO from the Misener sandstone (IHS Energy, 2010). Cumulative gas production is 5 TCFG from the Hunton and 127 BCFG from the Misener (IHS Energy Group, 2010). Production depths range from 4,000 ft to over 25,000 ft in the deepest part of the basin (fig. 36). There is an overlap in the oil and gas production, especially along the east-northeast AU boundary and in the Texas Panhandle.

Using the USGS assessment methodology for undiscovered conventional resources (Klett and others, 2005; Schmoker and Klett, 2005), it is estimated that the undiscovered oil resources for conventional reservoirs in the Hunton Group AU have a mean of 9 MMBO and 310 BCFG (table 1). Estimates of the minimum, median, and maximum numbers of (1) undiscovered oil accumulations exceeding the minimum size are 1,

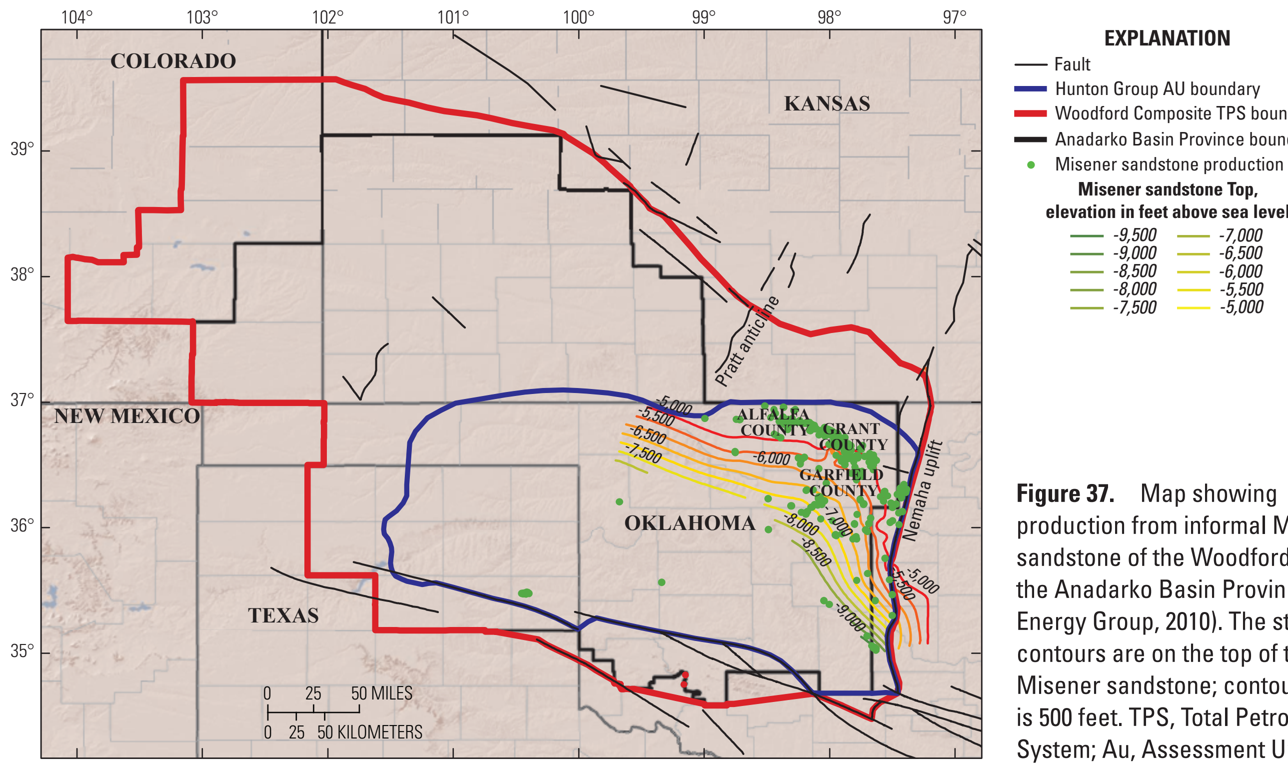

Figure 37. Map showing production from informal Misener sandstone of the Woodford Shale in the Anadarko Basin Province (IHS Energy Group, 2010). The structure contours are on the top of the Misener sandstone; contour interval is 500 feet. TPS, Total Petroleum System; Au, Assessment Unit.

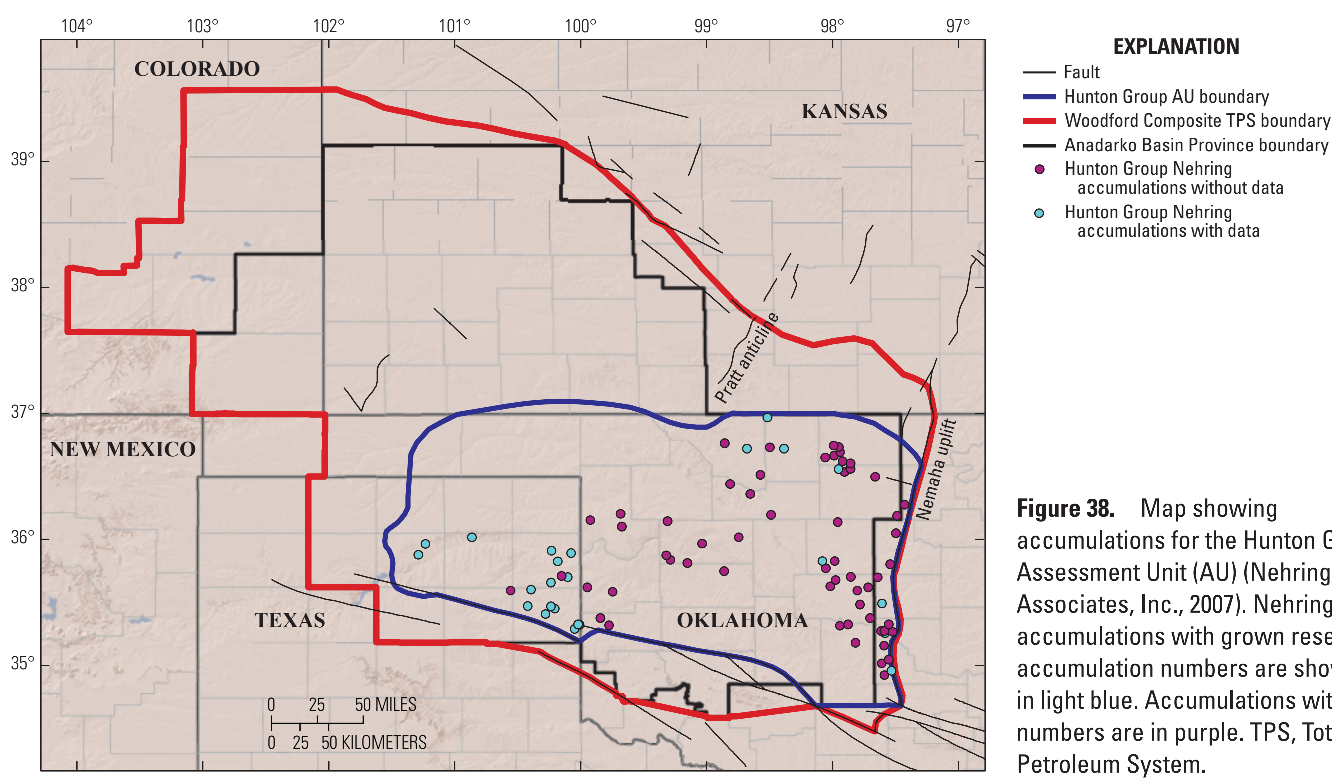

Figure 38. Map showing accumulations for the Hunton Group Assessment Unit (AU) (Nehring Associates, Inc., 2007). Nehring accumulations with grown reserve accumulation numbers are shown in light blue. Accumulations without numbers are in purple. TPS, Total Petroleum System.

3, and 15 and (2) undiscovered gas accumulations exceeding the minimum size are 1, 10, and 50. The Hunton has been well-explored on the shelf and along the Nemaha uplift, and in the southwest part of the AU in the Texas Panhandle (fig. 36). There is undrilled area in the deep basin along structures in the same region where the Arbuckle, Simpson, and Viola are sparsely drilled. There is potential, especially for gas, in this region of the basin from karstification of the Hunton during channelization in pre-Woodford time. These channels were later filled in with Woodford Shale. In the deep basin, these potential gas reservoirs have not been explored.

Estimates of the minimum, median, and maximum numbers for the sizes of undiscovered oil accumulations are 0.5, 1.0, and 20 MMBO. The 0.5 MMBO default signifies that there will be at least one field discovered greater than the minimum size, and the maximum reflects the large sizes of some of the historical Hunton oil accumulations, such as West Edmond field (100 MMBO), and along the Sooner trend (380 MMBO commingled; Nehring Associates, Inc., 2009). Estimates of the minimum, median, and maximum numbers for the sizes of undiscovered gas accumulations are 3, 10, and 200 BCFG. The maximum is raised to account for deep basin gas potential.

The Viola Group has produced 112 MMBO and 505 BCFG, with reservoirs in limestones and dolomites that have been subjected to fracturing and dissolution to create secondary porosity. Production is in areas similar to the Simpson, along the eastern part of the Anadarko Basin. Traps are structural and combination structural-stratigraphic, and seals are the overlying Sylvan Shale or interbedded tight carbonates of the Viola Group. The Viola reservoirs are sourced by Ordovician source rocks and the Woodford Shale. Undiscovered potential is in the deep basin, in areas similar to the Arbuckle and Simpson.

The Hunton Group has produced 290 MMBO and 5 TCFG. Reservoirs are in carbonates of the Hunton Group and sandstones of the Misener. Misener sandstones are dominant reservoirs within the Hunton AU, producing 55 MMBO and 127 BCFG. Production is in a more limited area because of erosion of the Hunton throughout much of the basin; it is concentrated along the northeast and east portion of the AU. Traps are structural and stratigraphic and seals are interbedded tight carbonates of the Hunton and the overlying Woodford Shale. Source rocks for the Hunton reservoirs are the Woodford Shale, with possible contributions from Ordovician rocks. Undiscovered potential is in the deep basin, especially for reservoirs within the Hunton Group.

Conclusions

The Woodford Composite TPS includes the conventional Arbuckle-Ellenburger Group, Simpson Group, Viola Group and Hunton Group AUs. The Cambrian-Ordovician Arbuckle and Ellenburger Groups have produced 52 MMBO and 285 BCFG as of this assessment, with reservoirs concentrated in dolomitized Arbuckle strata on the shelf of the Anadarko Basin in Kansas and Oklahoma. The reservoirs are concentrated along structures and in combination structural-stratigraphic traps. Seals are low porosity zones of the Arbuckle Group or overlying, impermeable shales of the Simpson Group. The Arbuckle reservoirs are primarily sourced by the Woodford Shale, with contribution from Ordovician source rocks. The source rock potential of the Arbuckle Group has been debated, and it is suggested that the Arbuckle Group is self-sourcing. The results of 1D and 3D modeling indicate the Arbuckle Group is overmature in the deep basin and in the oil window on the basin shelf. Undiscovered potential exists in the undrilled areas in the deep basin along the flanks of structures. Gas production is likely in the deep basin, where the Arbuckle Group is mature to overmature for gas production.

The Simpson Group has produced 470 MMBO and 1.2 TCFG, with reservoirs in blanket sandstones with high porosity and permeability, and minor contributions from carbonate reservoirs. Production is concentrated in structural traps along the eastern edge of the basin and up into Kansas south of the Central Kansas uplift. Seals are interbedded tight carbonates and shales. The Simpson reservoirs are sourced by Ordovician source rocks and the Woodford Shale. Source rock potential of the Simpson is considered moderate. Undiscovered potential exists in the undrilled deep basin.

References Cited

Adler, F.J., Caplan, W.M., Carlson, M.P., Goebel, E.D., Henslee H.T., Hick, I.C., Larson, T.G., McCracken, M.H., Parker, M.C., Rascoe, G., Jr., Schramm, M.W., and Wells, J.S., 1971, Future petroleum provinces of the mid-continent, *in* Cram, I.H., ed., Future petroleum provinces of the United States—Their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 2, p. 985–1120.

Al Shaieb, Z., and Puckette, J., 2002, Sequence stratigraphy of Hunton Group ramp facies, Arbuckle Mountains and Anadarko Basin, Oklahoma, *in* Johnson, K.S., ed., Platform carbonates of the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 131–137.

Amsden, T.W., 1989, Depositional and post-depositional history of middle Paleozoic (late Ordovician through early Devonian) strata in the ancestral Anadarko Basin *in* Johnson, K.S., ed., Anadarko Basin Symposium: Oklahoma Geological Survey Circular 90, p. 143–146.

Ayan, D., Bucheit, A.K., Kulow, M.J., and Donovan, R.N., 2000, Preliminary cyclic stratigraphy of the Upper Arbuckle Group in the Richard's Spur Quarry, Slick Hills, Oklahoma *in* Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 97–102.

Ball, M.M., Henry, M.E., and Frezon, S.E., 1991, Petroleum geology of the Anadarko Basin region, Province (115), Kansas, Oklahoma, and Texas: U.S. Geological Survey Open-File Report 88–450W.

Bartram, J.G., Imbt, W.C., and Shea, E.F., 1950, Oil and gas in Arbuckle and Ellenburger Formations, mid-continent region: American Association of Petroleum Geologists Bulletin, v. 34, p. 682–700.

Bebout, D.G., W.A. White, T.F. Hentz, and M.K. Grasmick, eds., 1993, Atlas of major mid-continent gas reservoirs: Bureau of Economic Geology, 85 p.

Brown, R.L., Everett, R., and Tadepalli, S., 1991, Special seismic exploration techniques for Arbuckle exploration: Oklahoma Geological Survey Circular 92, p. 183–184.

Brown, A.A., and Sentfle, J.T., 1997, Source potential of the Viola Springs Formation, southern limb of the Arbuckle anticline, Arbuckle Mountains, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 102.

Brown, S.W., and Swetland, P.J., 1992, Arbuckle oils—an overview *in* Johnson, K.S. and Cardott, B.J., eds., Source rocks in the southern Midcontinent: Oklahoma Geological Survey Circular 93, p. 175.

Burruss, R.C., and Hatch, J.R., 1989, Geochemistry of oils and hydrocarbon source rocks, greater Anadarko Basin: Evidence for multiple sources of oils and long-distance oil migration, *in* Johnson, Kenneth S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 53–64.

Candelaria, M.P., Handford, C.R., and Reed, C.L., 1997, Sequence stratigraphic model for the Simpson Group of the southern Midcontinent: Key to a new stratigraphic play, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Survey Geological Circular 99, p. 218–223.

Cardott, B.J., 1989, Thermal maturation of the Woodford Shale in the Anadarko Basin, *in* Johnson, Kenneth S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 32–46.

Cardwell, A.L., 1977, Petroleum source-rock potential of Arbuckle and Ellenburger Groups, southern mid-continent, United States: Quarterly of the Colorado School of Mines, v. 72, no. 3, 134 p.

Carlson, M.P., and Newell, K.D., 1997, Stratigraphy and petroleum production of the Simpson and Viola (Ordovician) in Kansas and Nebraska *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 58–64.

Charpentier, R.R., and Doveton, J.H., 1991, Stratigraphy and facies in the Middle Ordovician Simpson Group, southwestern Kansas and western Oklahoma, *in,* Johnson, K.S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 Symposium: Oklahoma Geological Survey Circular 92, p. 211.

Denison, R.E., 1997, Contrasting sedimentation inside and outside the southern Oklahoma aulacogen during the Middle and Late Ordovician, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 48–57.

Donovan, R.N., 2000, Initiation of the Arbuckle Platform-view from the Slick Hills, Oklahoma: in Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 47–56.

Donovan, R.N., and Critchfield, R., 2001, The Signal Mountain Formation—A source rock in hiding *in* Johnson, K.S. and Merriam, D.F., eds., Petroleum systems of sedimentary basins in the southern Midcontinent, 2000 Symposium: Oklahoma Geological Survey Circular 106, p. 71–80.

Doveton, J.H., Charpentier, R.R., and Metzger, E.P., 1990, Lithofacies analysis of the Simpson Group in south-central Kansas: Kansas Geological Survey, Petrophysical Series no. 5, 34 p.

Flores, R.M., and Keighin, C.W., 1989, Petrology and depositional facies of siliciclastic rocks in the Middle Ordovician Simpson Group, Mazur well, southeastern Anadarko Basin, Oklahoma: U.S. Geological Survey Bulletin 1866–E, 45 p.

Fritz, R.D., and Medlock, P.L., 1994, Sequence stratigraphy of the Hunton Group as defined by core, outcrop, and log data: Bulletin Houston Geological Society, 11 p.

Fritz, R.D., Johnson, C.I., and Medlock, P.L., 1993, Application of horizontal drilling in fractured carbonates of Oklahoma, *in* Johnson, K.S. and Campbell, J.A., eds., Petroleum-reservoir geology in the southern Midcontinent, 1991 symposium: Oklahoma Geological Survey Circular 95, p. 66–68.

Gao, G., Land, L.S., and Folk, R.L. 1992, Meteoric modification of early dolomite and late dolomitization by basinal fluids, Upper Arbuckle Group, Slick Hills, southwestern Oklahoma: American Association of Petroleum Geologists Bulletin, v. 76, n. 11, p. 1649–1664.

Gatewood, L.E., 1992, Can carbonates be source rocks for commercial petroleum deposits? *in* Johnson, K.S. and Cardott, B.J., eds., Source rocks in the southern Midcontinent: Oklahoma Geological Survey Circular 93, p. 270–281.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Bleeker, W., and Lourens, L.J., 2004, A new geologic time scale with special reference to Precambrian and Neogene: Episodes, v. 27, p. 83–100.

Haq, B.U., and Van Eysinga, F.B., 1998, Geological time table: Elsevier Science, Amsterdam, New York, 1 chart.

Hatch, J.R., Rice, D.D., Burruss, R.C., Schmoker, J.W., and Clayton, J.L, 1986, Thermal maturity modeling and geochemical characterization of hydrocarbon source rocks, oils, and natural gases of the Anadarko Basin, *in* Carter, L.M.H., ed.: U.S. Geological Survey Circular 974, p. 21–23.

Henry, M.E., and Hester, T., 1996, Maps showing petroleum exploration intensity and production in major Cambrian to Ordovician reservoir rocks in the Anadarko Basin: U.S. Geological Survey Miscellaneous Field Studies Map MF-2313.

Heyer, J., 1993, Trapping mechanisms in Arbuckle sediments, eastern Major County, Oklahoma: Fort Worth Geological Society Transactions and Abstracts, p. 43–54.

Higley, D.K., Gaswirth, S.B, Abbott, M.M., Charpentier, R.R., Cook, T.A., Ellis, G.S., Gianoutos, N.J., Hatch, J.R., Klett, T.R., Nelson, P., Pawlewicz, M.J., Pearson, O.N., Pollastro, R.M., and Schenk, C.J., 2011, Assessment of undiscovered oil and gas resources of the Anadarko Basin Province of Oklahoma, Kansas, Texas and Colorado: U.S. Geological Survey Fact Sheet 2011–3003, 2 p.

IHS Energy Group, 2009, IHS energy well database: Unpublished database available from IHS Energy, 15 Inverness Way East, Englewood, CO 80112.

IHS Energy Group, 2010, Petroleum Information/Dwights petroROM Rocky Mountain Region production data on CD-ROM: IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO, 80112.

Johnson, K.S., 1989, Geologic evolution of the Anadarko Basin *in* Johnson, K.S., ed., Anadarko Basin Symposium: Oklahoma Geological Survey Circular 90, p. 3–12.

Johnson, K.S., 1991, Geologic overview and economic importance, *in* Johnson, K.S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 symposium: Oklahoma Geological Survey Circular 92, p. 3–14.

Johnson, K.S., 1992, Discussion between audience and panel on the subject: can carbonates be source rocks for commercial petroleum deposits? *in* Johnson, K.S., and Cardott, B.J., eds., Source rocks in the southern Midcontinent: Oklahoma Geological Survey Circular 93, p. 283–286.

Johnson, K.S., and Cardott, B.J., 1992, Geologic framework and hydrocarbon source rocks of Oklahoma *in* Johnson, K.S., and Cardott, B.J., eds., Source rocks in the southern Midcontinent: Oklahoma Geological Survey Circular 93, p. 21–37.

Johnson, K.S., Hinshaw, G.C., and Northcutt, R.A., 2000, Petroleum production from platform carbonates of Oklahoma, *in* Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 1–11.

Jones, P.J., and Philip, R.P., 1990, Oils and source rocks from Pauls Valley, Anadarko basin, Oklahoma, U.S.A.: Applied Geochemistry, v. 5, p. 429–448.

Klett, T.R., Schmoker, J.W., and Charpentier, R.R., 2005, U.S. Geological Survey input-data form and operational procedure for the assessment of conventional petroleum accumulations: U.S. Geological Survey Digital Data Series 69–D, 7 p.

Kuykendall, M.D., and Fritz, R.D., 1993, Misener Sandstone: Distribution and relationship to late/post-Hunton unconformities, northern shelf, Anadarko Basin, *in* Johnson, K.S., ed., Hunton Group core workshop and field trip: Oklahoma Geological Survey Special Publication 93-4, p. 117–134.

Lindsay, R.F., and Koskelin, K.M., 1991, Arbuckle Group depositional parasequences *in* Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 symposium: Oklahoma Geological Survey Circular 92, p. 71–84.

Medlock, P.L., 1984, Depositional environment and diagenetic history of the Frisco and Henryhouse Formations in central Oklahoma: Oklahoma State University, unpublished M.S. thesis, 146 p.

Morgan, W.A., and Schneider, R.E., 1981, Subtle porosity and traps within Frisco Formation (Devonian, Hunton Group): Geologic-seismic waveform approach, example from West El Reno field, Canadian County, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 65, p. 960–961.

Nehring Associates, Inc., 2009, The significant oil and gas fields of the United States: Nehring Associates, Inc., P.O. Box 1655, Colorado Springs, CO, 80901.

Newell, K.D., 1997, Correlation and distribution of reservoir and sealing facies within the Viola Formation, south-central Kansas, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 247–259.

Newell, K.D., 2000, Depositional and diagenetic controls on porosity development in the Ordovician Viola Formation, south-central Kansas, *in* Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 107–115.

Northcutt, R.A., and Johnson, K.S., 1997, Major Simpson and Viola oil and gas reservoirs in Oklahoma *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 48–57.

Perry, C.C., 1990, New Arbuckle frontier opens: Oil and Gas Journal, v. 88, p. 56.

Philippie, G.T., 1981, Correlation of crude oils with their oil source formations using high resolution GLD C6-C7 component analyses: Geochimica et Cosmochimica Acta, v. 45, p. 1495–1513.

Pollastro, R.M., 1989, Mineralogic and textural relations in deeply buried rocks of the Simpson Group (Middle Ordovician)—Implications in diagenesis and petroleum geology, *in* Johnson, K.S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 194–208.

Price, L.C., 1997, Minimum thermal stability levels and controlling parameters of methane, as determined by C_{15}+ hydrocarbon thermal stabilities, *in* Dyman, T.S., Rice, D.D., and Westcott, P.A., eds., Geologic controls of deep natural gas resources in the United States: U. S. Geological Survey Bulletin 2146-K, p. 135–176.

Rascoe, B., and Adler, F.J., 1983, Permo-Carboniferous hydrocarbon accumulations, mid-continent, U.S.A.: American Association of Petroleum Geologists Bulletin, v. 67, p. 979–1001.

Rottmann, K., 1997, Stratigraphy, paleogeomorphology, and structure of Simpson, Viola, and Mississippian strata and their integral relationships to “Second Wilcox” production in Lincoln and Logan counties, Oklahoma, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 137–154.

Rottmann, K., 2000a, Structure map of Hunton Group in Oklahoma and Texas Panhandle: Oklahoma Geologic Survey Special Publication 2000–2, pl. 3.

Rottmann, K., 2000b, Isopach map of Woodford Shale in Oklahoma and Texas Panhandle: Oklahoma Geologic Survey Special Publication 2000–2, pl. 2.

Rottmann, K., 2000c, Defining the role of Woodford-Hunton depositional relationships in Hunton stratigraphic traps of western Oklahoma, *in* Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 139–146.

Schmoker, J.W., and Klett, T.R., 2005, U.S. Geological Survey assessment concepts for conventional petroleum accumulations, chap. 19 of USGS Southwestern Wyoming Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series 69–D, 6 p.

Smith, P.W., 1997, Structural and Stratigraphic factors that influence Simpson Group production in central Oklahoma, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Circular 99, p. 111–136.

Smith, P.W., and Woods, T.J., 2000, Effects of depth on quality of gas-well completions in carbonate reservoirs of the Anadarko Basin and shelf areas, *in* Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 25–45.

Smith, P.W., Hendrickson, W.J., and Williams, C.M., 2000, Production and reservoir characteristics of selected Hunton Fields in the Anadarko Basin, *in* Johnson, K.S., ed., Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 147–156.

Suhm, R.W., 1997, Simpson stratigraphy of the southern Midcontinent, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 3–38.

Sullivan, K.L., 1985, Organic facies variation of the Woodford Shale in western Oklahoma: Shale Shaker, v. 35, no. 4, p. 76–89.

Sweeney, J.J., and Burnham, A.K., 1990, Evaluation of a simple model of vitrinite reflectance based on chemical kinetics: American Association of Petroleum Geologists Bulletin, v. 74, p. 1.559–1.570.

Sykes, M., Puckette, J., Abdalla, A., and Al-Shaieb, Z., 1997, Karst development in the Viola Limestone in southern Oklahoma, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 66–75.

Trask, P.D., and Patnode, H.W., 1942, Source beds of petroleum: American Association of Petroleum Geologists, Tulsa, 566 p.

von Almen, W.E., 1970, Palynomorphs of the Woodford Shale of south central Oklahoma with observations on their significance in zonation and paleoecology: East Lansing, Michigan, Michigan State University, Ph.D. dissertation, 179 p.

Walper, J.L., 1977, The geotectonic evolution of the Wichita aulacogen, Oklahoma, *in* Henry, G.E., ed., Basins of the Southwest, phase 2: North Texas Geological Society, p. 192–211.

Wang, H.D., and Philip, R.P., 1997, A geochemical study of Viola source rocks and associated crude oils in the Anadarko Basin, Oklahoma, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 81–101.

Wavrek, D.A., 1989, Characterization of oil types along Hewitt trend, Carter County, Oklahoma: Implications for future exploration (abs.): American Association of Petroleum Geologists, v. 73, p. 424.

Wavrek, D.A., Garcia, M.A., and Ferebee, C.D., 1997, The Viola Group as a petroleum system: Implications for horizontal-drilling prospects, *in* Johnson, K.S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 78–86.

Webb, G.W., 1976, Oklahoma City oil—Second crop from preserved subunconformity source rocks: American Association of Petroleum Geologists Bulletin, v. 60, p. 115–122.

Webster, R.E., 1980, Evolution of the southern Oklahoma aulacogen: Oil and Gas Journal, v. 78, p. 150–172.

Williams, J.A., 1992, Can carbonates be source rocks for commercial petroleum deposits? *in* Johnson, K.S. and Cardott, B.J., eds., Source rocks in the southern Midcontinent: Oklahoma Geological Survey Circular 93, p. 267.

Wilson, J.L., Fritz, R.D., and Medlock, P.L., 1991, The Arbuckle Group—Relationship of core and outcrop analyses to cyclic stratigraphy and correlation *in* Johnson, K.S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 symposium: Oklahoma Geological Survey Circular 92, p. 61–63.