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Chapter 6

Petroleum Systems and Assessment of Undiscovered Oil and Gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—Woodford Shale Assessment Units

By Debra K. Higley, Troy A. Cook, and Mark J. Pawlewicz

Chapter 6 of 13

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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Petroleum Systems and Assessment of Undiscovered Oil and Gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—Woodford Shale Assessment Units

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Abstract

The Woodford Composite Total Petroleum System in the Anadarko Basin Province includes assessment units of Cambrian through Lower Mississippian oil and gas reservoirs. Two of the assessment units are continuous (unconventional)—the Woodford Shale Gas assessment unit and The Woodford Shale Oil assessment unit of the Upper Devonian and Lower Mississippian Woodford Shale. Assessment unit boundaries were defined based on extent, thickness, and levels of thermal maturation of this reservoir/source unit. The assessment units are self-sourced from this rich petroleum source rock, with thermal maturity ranging from marginally mature for oil generation on the basin shelf to overmature for gas generation in the deep basin. The Woodford Shale Oil assessment unit boundary is approximated by the extent of the Woodford Shale in the basin; mean assessed resources are 393 million barrels of oil, 1.963 trillion cubic feet of gas (TCFG), and 59 million barrels of natural gas liquids. The Woodford Shale Gas assessment unit is located in the deep basin of Oklahoma and Texas. The assessment unit area includes a Woodford Shale thickness of approximately 75 feet (25 meters) and greater, and a transformation ratio of 0.99 percent based on Woodford hydrous pyrolysis kinetics modeling; this corresponds to a vitrinite reflectance of about 1.2 percent. Mean undiscovered assessed resources for the Woodford Shale Gas assessment unit are 15.973 trillion cubic feet of gas and 192 million barrels of natural gas liquids.

Introduction

The U.S. Geological Survey (USGS) completed an assessment of the undiscovered oil and gas resource potential of the Anadarko Basin Province of western Oklahoma and Kansas, northern Texas, and southeastern Colorado (fig. 1). The province area includes the Las Animas arch of southeastern Colorado, part of the Palo Duro Basin of Texas, and the Anadarko Basin. This assessment is hereafter referred to as the 2011 assessment, which corresponds to the publication release date of the results (Higley and others, 2011). Results of the geologic analysis and resource assessment are based on the geologic elements of each defined total petroleum system (TPS), including hydrocarbon source rocks (source-rock maturation, hydrocarbon generation and migration), reservoir rocks (sequence stratigraphic and petrophysical properties), hydrocarbon traps (trapping mechanisms and timing), and seals. Using this geologic framework, the USGS defined 2 TPS and 12 included Assessment Units (AUs), and quantitatively estimated the undiscovered oil and gas resources within these 9 conventional and 3 continuous AUs (table 1). TPSs and AUs are listed below.

Woodford Composite TPS 505801:

1. Arbuckle-Ellenburger, AU 50580101
2. Simpson Group, AU 50580102
3. Viola Group, AU 50580103
4. Hunton Group, AU 50580104
5. Mississippian, AU 50580105
6. Woodford Shale Gas, AU 50580161
7. Woodford Shale Oil, AU 50580162

Pennsylvanian Composite TPS 505802:

1. Morrowan-Atokan, AU 50580201
2. Desmoinesian, AU 50580202
3. Missourian-Permian, AU 50580203
4. Greater Granite Wash Composite, AU 50580204
5. Thirteen Finger Limestone–Atoka Shale Gas, AU 50580261

Continuous AUs are the Devonian and Mississippian (1) Woodford Shale Gas and (2) Woodford Shale Oil of the Woodford Composite TPS, and (3) the Pennsylvanian Thirteen Finger Limestone–Atoka Shale of the Pennsylvanian

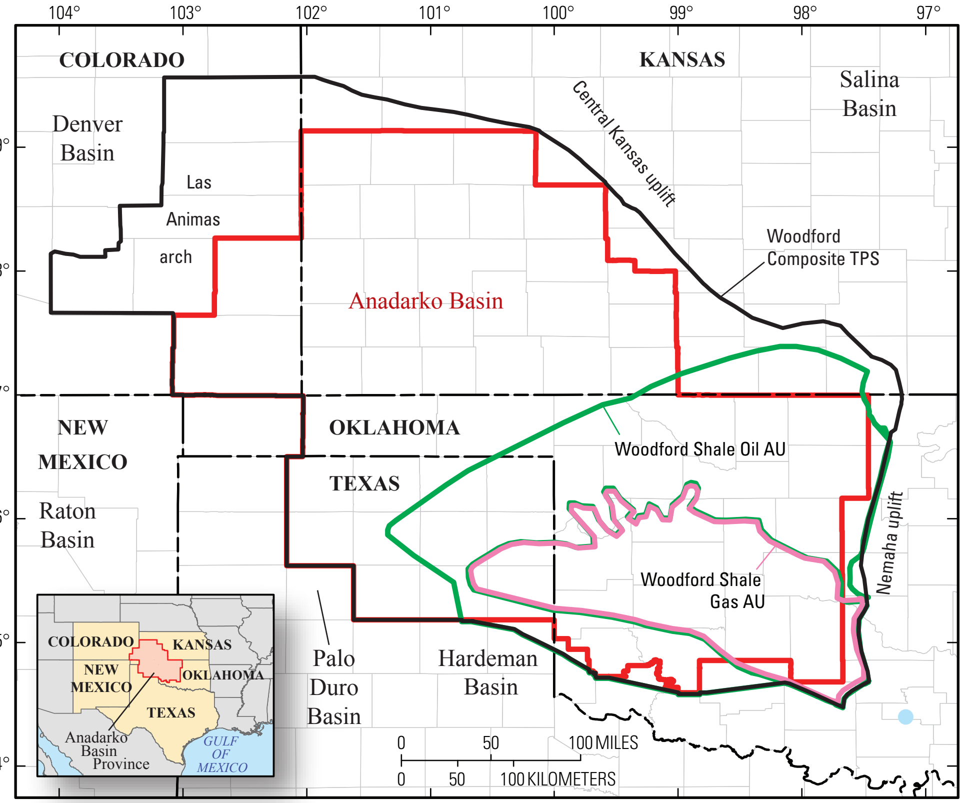


Figure 1. Map showing boundaries of the Anadarko Basin (red line) and the Woodford Composite Total Petroleum System (TPS). The contained Woodford Shale Oil and Woodford Shale Gas AUs are discussed in this chapter of the report. Green AU boundary approximately encloses all Woodford Shale within the province. The Henry House Creek quarry and State Route 77D outcrop locations are marked by the blue dot near the southeast corner of the figure. Background is surface elevation.

Composite TPS. The Woodford Shale Oil and Woodford Shale Gas AU assessment and geologic review are included in this chapter of the report. Description of the Thirteen Finger Limestone–Atoka Shale Gas AU is included in Higley (2014a, 2014b), and associated oil resources are assessed as conventional within the Morrowan-Atokan AU. The stratigraphic chart shows units within the Woodford Composite TPS (fig. 2).

The Woodford Composite TPS encompasses all included AU boundaries, although only the Woodford Shale Gas and Woodford Shale Oil AUs are shown in figure 1. Assignment of Woodford AU boundaries and assessment results were based primarily on (1) the lateral extent and thickness of the Woodford Shale, (2) timing and degree of thermal maturation of the Woodford Shale based on one-dimensional and four-dimensional (4D) petroleum system models of the basin (Higley, 2014a) and published vitrinite reflectance data, and (3) faults and other structures that would limit or enhance oil and gas accumulations. The “fingers” appearance of the Woodford Shale Gas AU boundary partly reflects Woodford deposition in eroded channels of the unconformably underlying Silurian-Devonian Hunton Group. Results of the oil, gas, and natural gas liquids (NGL) assessment are in table 1 and Higley and others (2011).

The 4D petroleum system model consists of stacked grids of lithostratigraphic units that are referred to as layers. Each layer extends across the study area, a requirement of the PetroMod® petroleum system modeling software. This means that the highest elevation from the underlying layers is displayed if the modeled unit(s) has limited lateral extent. Model construction and data sources are discussed in Higley (2014a) and Higley and others (2014). Maps and models were generated using Dynamic Graphics® Earthvision® (Dynamic Graphics® and Earthvision® are registered trademarks of Dynamic Graphics, Inc.) and PetroMod® software (Schlumberger, 2011). PetroMod® software was used for 1D and 4D petroleum system models. Data sources for Woodford Shale isopach and structure surfaces include Rottmann (2000a, 2000b), well-log picks from about 100 wells across the basin, and edited formation tops from IHS Energy (2009a, 2009b).

Table 1. Anadarko Basin Province assessment results are listed by name and code of total petroleum system (TPS) and assessment unit (AU).

[Resources are undiscovered oil, gas, and (or) natural gas liquids. MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids. Type refers to mainly oil or gas accumulations in the assessment unit. Fractiles are fully risked estimates. F95 denotes a 95-percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive only under the assumption of perfect positive correlation]

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

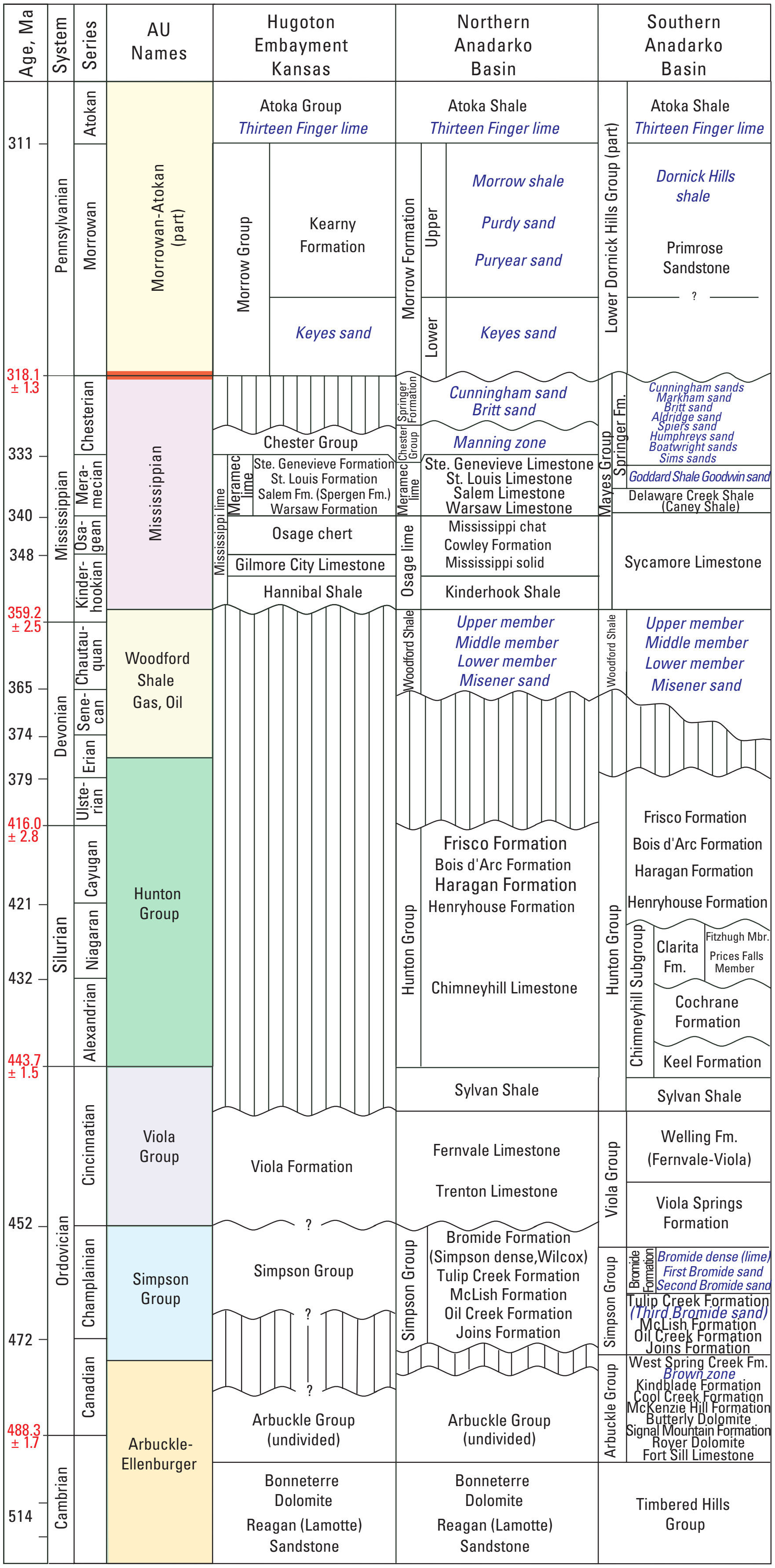


Figure 2. Generalized surface and subsurface stratigraphic columns for the Anadarko Basin Province. The horizontal red line divides assessment units (AUs) and total petroleum systems (TPSs) into those of the (above) Pennsylvanian Composite TPS and (below) Woodford Composite TPS. Italics (blue text) indicate 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 (1995). Ages in millions of years before present (Ma) from Haq and Van Eysinga (1998) and Gradstein and others (2004) (red text). Intervals with vertical bars and wavy horizontal lines represent time periods of nondeposition and (or) erosion. Formation, Fm.; Member, Mbr.

Geologic Setting of the Anadarko Basin Province

The Anadarko Basin Province includes (1) the Anadarko Basin, a south-dipping asymmetric basin; (2) the southwest-northeast-trending Las Animas arch, and (3) part of the southeast-dipping Palo Duro Basin. The province is bounded on the southeast by the Arbuckle uplift and Marietta-Ardmore Basin, on the east by the Nemaha uplift and Salina Basin, on the north by the Central Kansas uplift, on the west by the Denver and Raton Basins, and on the south by the eroded Amarillo and Wichita Mountain uplifts (fig. 3). The Nemaha uplift consists of a discontinuous series of block-faulted uplifts, most of which are 5 to 20 miles long (north-south) and 3 to 5 miles wide, and forms the axis and western boundary of the broad, gently raised Central Oklahoma platform (Johnson, 1989) that separates the Anadarko and Ardmore Basins. Elevation on the top of the Woodford Shale in the province ranges from about -2,500 feet (ft) [-760 meters (m)] on the southern Kansas shelf, to -27,000 ft (-8,000 m) in the deep basin of southern Oklahoma. Extent of the Woodford Shale within the Anadarko Basin Province is approximated by the Woodford Shale Oil AU boundary in figure 3. The formation is mostly absent because of erosion in the Nemaha, Wichita Mountain and Amarillo uplifts, although the AU includes an area of Woodford in the Wichita Mountain uplift proximal to the fault zone. The Woodford Shale also is present northeast of the province in the Salina Basin of Kansas, and is commonly named the Chattanooga Shale. The Woodford Shale in the Arkoma Basin is also a petroleum source and reservoir rock. The Woodford Shale layer was contoured using the data and fault systems of Rottmann (2000a, 2000b), who showed the Woodford contact with the bounding fault of the Wichita Mountain uplift to be north of the Precambrian faults of Adler and others (1971). Because of this, Woodford contours terminate basinward of the fault system of Adler and others (1971) (fig. 3).

Southern Oklahoma was initially described by Shatski (1946) as a failed Cambrian aulacogen. The deepest part of the Anadarko Basin is along and north of this rift zone and is proximal to its southern margin along the Wichita Mountain uplift (fig. 3). This southern Oklahoma aulacogen (Rascoe and Adler, 1983) was emplaced on the Precambrian craton as described by Ham and others (1964) and is about 100 miles (mi) [160 kilometers (km)] wide and 300 mi (480 km) long.

Most of Late Cambrian through Mississippian time was marked by a broad epicontinental sea (Johnson and others, 1988) that extended across most of the southern Midcontinent area, including the Anadarko Basin. Rates of basin subsidence were elevated in the Cambrian but decreased during the Silurian, Devonian, and Early Mississippian, one reason why Hunton and Woodford rocks are relatively thin (Feinstein, 1981; Johnson and others, 1988; Johnson, 1989) and of limited areal extent. Following Hunton Group deposition and prior to Woodford Shale deposition, the entire area was emergent and subjected to extensive erosion, and the Amarillo and Wichita Mountain uplifts began to form as positive tectonic features (Eddleman, 1961). Early Mississippian seas advanced from the southeast and stable conditions again prevailed with deposition of mostly marine Mississippian carbonates (Eddleman, 1961). Ball and others (1991) indicated that the Mississippian Period closed with regional uplift and erosion that marked the onset of the Wichita orogeny; the associated erosional unconformity further removed Devonian strata on structural highs around the basin margin, and truncated formations as deeply as the Arbuckle Group. Figure 4 shows generalized paleogeography near the end of Woodford deposition. Euxinic seas of the Late Devonian–Early Mississippian were replaced by shallow, well-oxygenated marine waters in which fossiliferous (commonly crinoidal, and some oolitic) limestones were deposited, some of which were interbedded with shale and siltstone (Johnson, 1989). Depth of water during Woodford deposition is estimated at 160 to 1,300 ft (50 to 400 m) (Krystyniak and Paxton, 2006) to less than 500 ft (150 m) (Kirkland and others, 1992).

Various tectonic events strongly influenced rates of sediment deposition, sediment sources, depositional environments, erosion, and especially burial depths of reservoir, seal, and source rocks. During Late Mississippian to Pennsylvanian time, rapid rates of subsidence coincided with tectonic development of the Anadarko Basin and the Wichita Mountain uplift (Ball and others, 1991; Al-Shaieb and others, 1994). Present basin configuration was impacted by movement of the late Paleozoic Wichita Mountain fault zone and the Ouachita thrust plate (Amsden, 1975, 1989). Depth of burial through time is the main control on thermal maturation of petroleum source rocks, although oil and gas generation is also influenced by factors such as basement heat flow and thermal conductivity of lithofacies.

Petroleum Source and Reservoir Rocks

Thickness of the Woodford Shale varies greatly across the province. It ranges up to 375 ft thick and averages 40 ft based on Rottmann (2000b), well-log picks from about 100 wells across the basin, and edited formation tops from IHS Energy (2009a, 2009b) (fig. 5). Increased thickness of the Woodford Shale and Hunton Group strata southward is probably related more to basin subsidence than sediment supply (Amsden, 1989). Greatest thickness of the Woodford is in the southern part of the basin in Oklahoma, largely as fill within eroded channels of the underlying Hunton Group. This is also the basin area that is most thermally mature for gas generation. Areas within the AUs (fig. 1) in which the Woodford is absent or thin resulted from erosion or nondeposition, and there are a few erosional remnants outside the Woodford Shale Oil AU boundary. Smooth contours near the southeastern corner of figure 5 reflect limited data and variable thicknesses because of extensive faulting. The Misener sand is an informal lower unit of the Woodford Shale (fig. 2) that is located mainly in the northeastern part of the basin in Oklahoma and

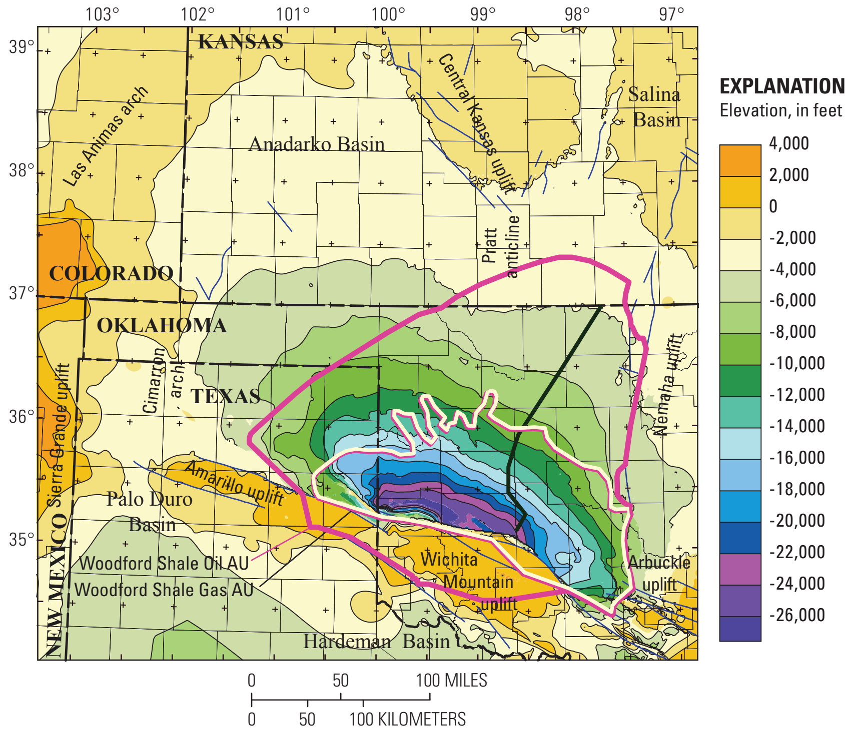


Figure 3. Map showing elevation on the top of the Woodford Shale in the 4D model layer. Extent of the Woodford Shale in the Anadarko Basin is approximated by that of the Woodford Shale Oil AU (pink line). Contours outside this boundary represent the highest elevation of underlying model layers. The Woodford Shale is also located east and northeast of the basin. The Woodford Shale Gas AU boundary (white line) corresponds to a thickness of about 75 feet (25 meters) and a transformation ratio of 0.99 percent, based on Woodford hydrous pyrolysis modeling. The black line corresponds to location of the southwest to northeast cross sections in figure 12. Precambrian faults (dark blue lines) and named structures are from Adler and others (1971).

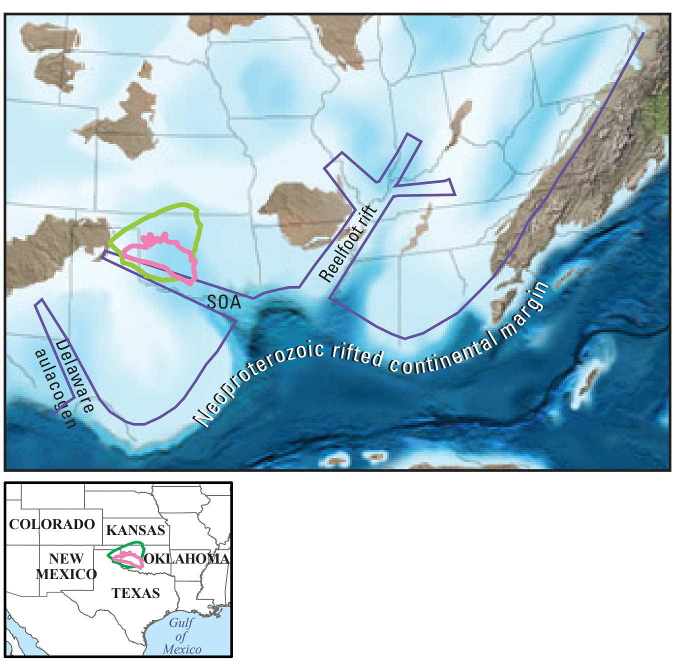


Figure 4. Generalized paleogeography at 360 million years before present showing marine influx (blue) near the end of Woodford Shale deposition (modified from Blakey, 2011). Ground surface is shades of brown. Superimposed Neoproterozoic and early Paleozoic rifts and continental margin (modified from Shatski, 1946; Perry, 1989) (purple line) shows possible Cambrian failed southern Oklahoma rift (SOA) along the southern boundary of and southeast of the Woodford Shale Gas assessment unit (AU) (pink line). The SOA approximates the northern border of the Wichita Mountain and Amarillo uplifts. Green line is the Woodford Shale Oil AU. Woodford extent is not shown outside of the Anadarko Basin Province.

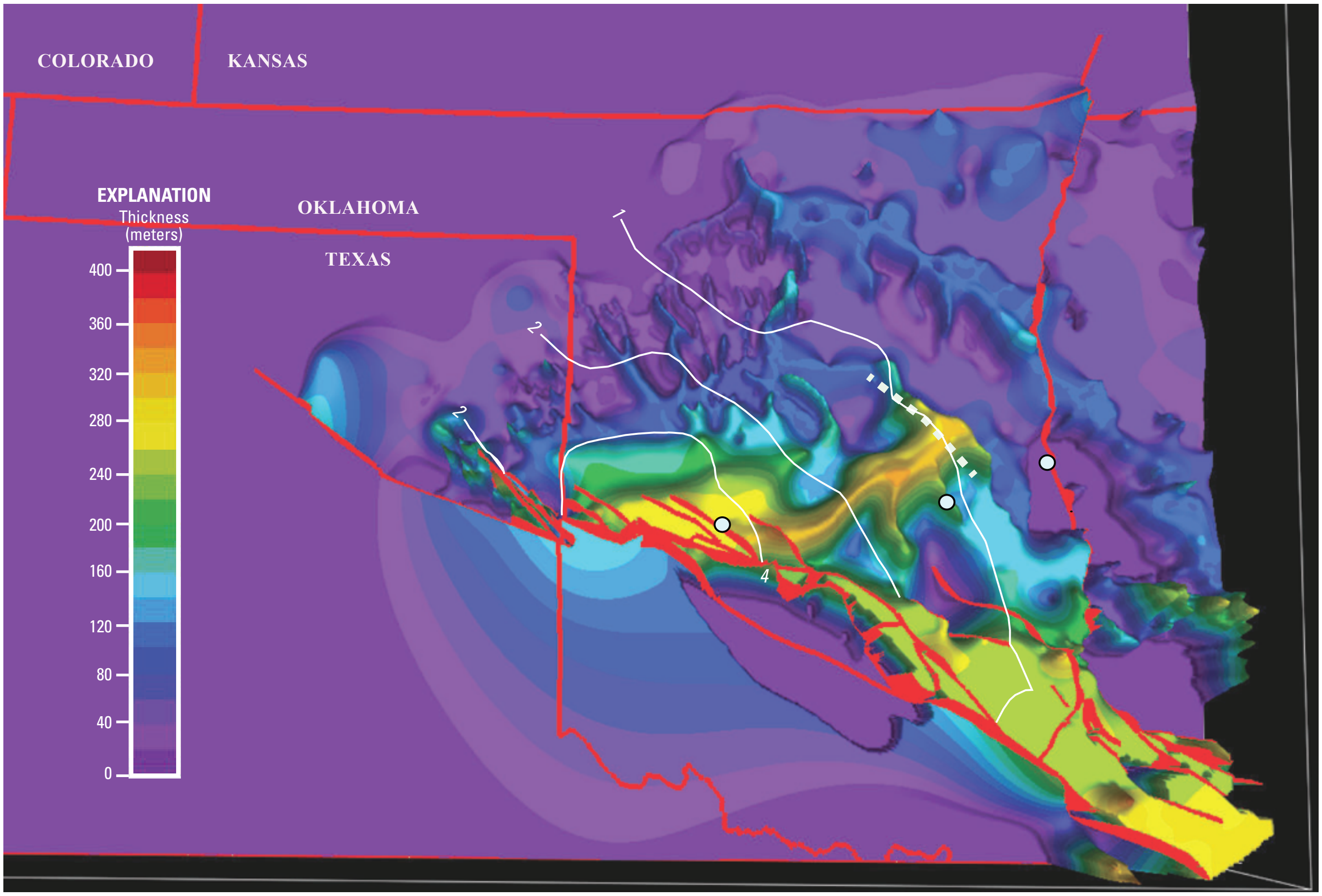


Figure 5. Three-dimensional isopach image of the Woodford Shale in the Anadarko Basin. Vitrinite reflectance (% R_o) contours (white lines) from figure 11 approximate the end of oil generation at about 1% R_o, to onset of dry gas generation at 2% R_o, and overmature for petroleum generation at 4% R_o. Well locations (white dots) are, from left to right, Bertha Rogers 1, Petree 1, and Streeter 1. Woodford thickness is derived from Rottmann (2000b, pl. 2), analysis of more than 100 well logs, and edited formation tops from IHS Energy (2009a, 2009b). Faults (red) are from Rottmann (2000a, pl. 3). Image is tilted and 1,300 times vertical exaggeration.

Kansas; petroleum resources of this unit were evaluated with the Hunton Group AU (Gaswirth and Higley, 2014). Primary reasons for this assignment were that Misener sand reservoirs are conventional, and much of the petroleum production was reported as commingled with that of the Hunton Group.

The primary petroleum source rock for the Woodford Composite TPS is the Woodford Shale; additional sources may include limestones and (or) shales from the Mississippian Mayes Group, and the Ordovician Viola Formation (or Group) and Simpson Group (Hatch and others, 1987; Burruss and Hatch, 1989) (fig. 6). The Woodford Shale and other petroleum source rocks are discussed in more detail in Higley (2014a).

The Woodford Shale consists of upper, middle, and lower informal members of carbonaceous silica-rich fissile and non-fissile shales (von Almen, 1970; Sullivan, 1983, 1985; Hester and others, 1990; Lambert, 1993; Krystyniak and Paxton, 2006). Kirkland and others (1992, fig. 3) indicated Woodford Shale lithofacies in northwest Kansas and southeast Nebraska are more carbonate rich than those of the deep Anadarko Basin. Based primarily on data from outcrops in the Arbuckle Mountains (fig. 3) and well core, Egenhoff and others (2011) determined that the upper shale member represents a downslope extension of a carbonate or carbonate-siliciclastic shallow marine system into deeper water siliciclastics. Egenhoff and others (2011) indicated that (1) the upper shale member is composed primarily of laminated silt-rich mudstones with lag deposits; and (2) these facies grade progressively basinward into finer-grained laminated mudstones and, (3) most distally, into quartz-rich radiolarian cherts that are intercalated with laminated mudstones. The non-fissile strata include phosphatic and siliceous shales, dolomite beds, phosphatic nodules, and rare chert beds (Krystyniak and Paxton, 2006). Fissile shale can also contain dolomite beds and phosphate nodules, such as in the upper member outcrop

Figure 6. Generalized stratigraphic column for the Anadarko Basin Province, with petroleum source rocks identified with brown text. Increases in source rock potential are indicated by larger numbers. Petroleum source rocks may be more oil-prone (green) or gas-prone (red). Chart is modified from Burruss and Hatch (1989) and Hatch (oral commun., 2010). Italicized text indicates informal names. Vertical lines show a generalized time range of unconformity from Bebout and others (1993, fig. 5). Gp., Group; Fm., Formation.

at the Henry House Falls quarry (fig. 7). These fissile shales are thin-bedded and laterally continuous. The fissile and non-fissile shales exhibit different fracture behavior; shale from the upper member is thin-bedded and fairly friable (fig. 7), whereas the non-friable lower-member siliceous shale is more competent (figs. 8 and 9). Chert beds within the shales display different fracture patterns, competence, and orientations than the bounding shales (fig. 9).

Outcrop studies by Roberts and Mitterer (1992) and Krystyniak and Paxton (2006) determined that siliceous shale samples yield low weight percent total organic carbon (TOC) and fissile samples yield high TOC values. Outcrops and well cores were sampled at numerous locations across Oklahoma and Arkansas, including 11 in the Anadarko Basin Province, by Comer and Hinch (1987) in their analysis of source rock richness and hydrocarbon expulsion from the Woodford Shale; their results showed that for interbedded black shale and chert, the chert beds contain relatively less TOC, but more bitumen and hydrocarbons than the shale. This suggests that, whereas both the shale and chert beds can be hydrocarbon sources, the shale was more efficient at expelling petroleum and the chert beds were better traps. Comer and Hinch (1987) described fractures that occur within the Woodford throughout their study area; these include fractures filled with bitumen, which are most common in the Arbuckle Mountain uplift and proximal Marietta-Ardmore Basin, the frontal zone of the Ouachita system, and in the southern part of the Anadarko Basin, where late Paleozoic orogenic activity was intense. Fractures filled with bitumen are also in central Oklahoma (along the Nemaha Ridge), where tectonic activity was of less certain timing and style (Comer and Hinch, 1987).

Figure 7. Photograph showing outcrop of Woodford Shale is as much as 231 feet. thick and is located on private property in the Henry House Falls quarry, sec. 6, T. 2 S., R. 1 E., on the south side of the Arbuckle uplift (Paxton, 2007) (fig. 1). Shown is a portion of the upper member of the Woodford Shale. It was described by Paxton (2007) as an organic-rich finely laminated fissile shale. The three resistant lighter-colored beds at Stan Paxton's thigh level are finely crystalline dolomite with hydrocarbon saturation. Spherical phosphate nodules are present above the upper dolomite layer. The upper member at this location is about 55 percent siliceous beds, 44 percent fissile beds, and 1 percent dolomite zones.

Figure 8. Photographs showing outcrop of a slightly overturned lower member of Woodford Shale beds next to State Route 77D, in NE ¼ sec. 30, T. 1 S., R 2 E., Murray County, Oklahoma (fig. 1). Stratigraphically up is to the left on the road-cut image. Red arrow on the upper right points to a fault and associated fault gouge, some of which is saturated with hydrocarbon. This section, as described in Paxton and Cardott (2008), strikes N. 70o W and dips 68o to the southwest, is highly siliceous, and was highly susceptible to fracturing during the structural deformation. Strata are generally less fissile than those in figure 7.

Figure 9. Photograph showing detail of fracture patterns in the lower member of the Woodford Shale at the State Route 77D outcrop photo from Paxton and Cardott (2008) (fig. 1). Spacing and orientation of fracture patterns in the dark gray siliceous shale differ from those in the underlying light-colored chert-rich facies.

The Woodford Shale includes abundant type A amorphous type II kerogen (partially equivalent to the liptinite [exinite] maceral group) with the remaining primarily type III kerogen (vitrinite) and type I kerogen (*Tasmanite alginite*) (Lewan, 1983; Thompson and Dembicki, 1986; Crossey and others, 1986; Comer and Hinch, 1987; Burwood and others, 1988; Cardott, 1989, p. 35; Krystyniak and Paxton, 2006). A generalized composition of the Woodford Shale based on Abouslei-man (2008) is 37 percent quartz, 26 percent illite, 15 percent kerogen, 17 percent carbonate, and 5 percent kaolinite. TOC content for the upper Woodford ranges from 0.8 weight percent (wt%) up to 17 wt% and is highly variable vertically and laterally across the province based on data from Comer and Hinch (1987), Burruss and Hatch (1989), Hester and others (1990), Price (1997), Krystyniak and Paxton (2006), Joseph Hatch (oral commun., 2010), and data from the USGS Energy Geochemistry Data Base (2010, *http://energy.cr.usgs.gov/prov/og/*) (fig. 10). Hester and others (1990) used log-derived formation density for 99 wells across the Anadarko Basin area to assign average TOC values of 3.2, 5.5, and 2.7 wt% for the respective lower, middle and upper members of the Woodford Shale; variation in TOC was not influenced by formation thickness, but by increased depth and thermal maturation with associated depletion by generation and expulsion of petroleum.

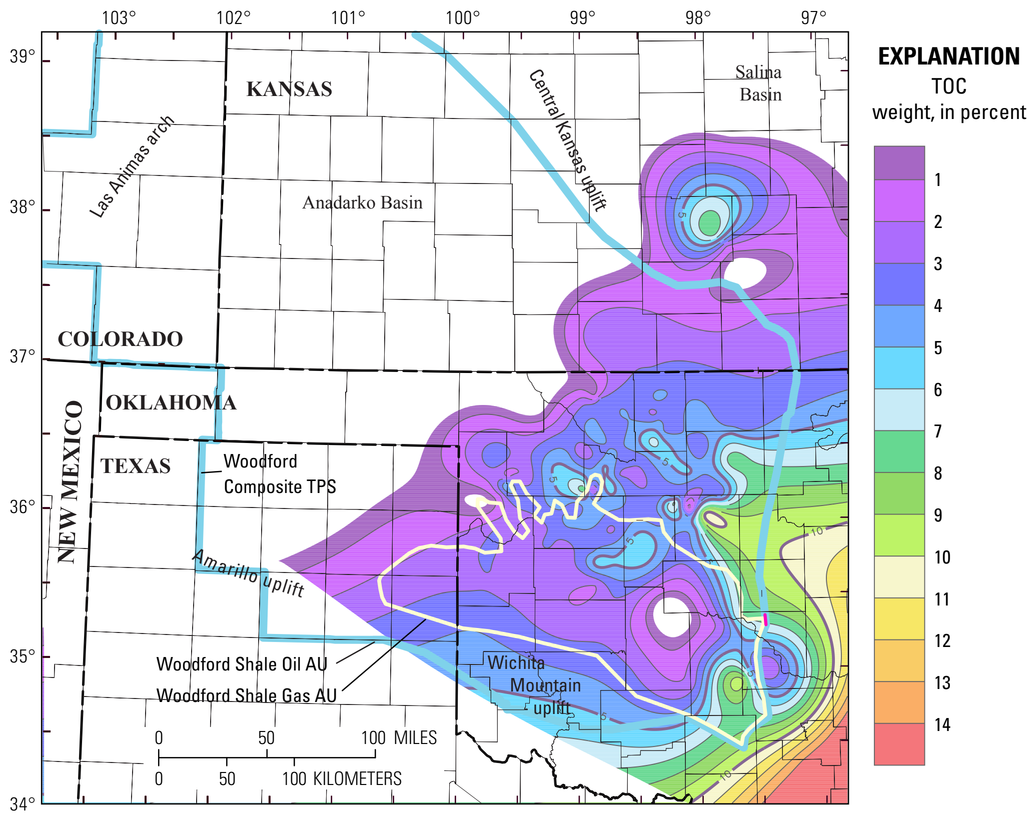


Figure 10. Map showing total organic carbon (TOC) for the Woodford Shale based on data from Burruss and Hatch (1989) and mean estimated values from Hester and others (1990). TOC ranges from 0.08 to 14.05 wt% and averages 3.7 wt% based on core and well log density calculations from 123 wells. There is considerable TOC variation, but almost the entire area that is thermally mature for petroleum generation contains greater than 2 wt% TOC. Decrease in TOC in the deep basin is partly the result of elevated levels of thermal maturation. Oil and gas generation depletes TOC and hydrogen indices (HI)—the fuels for petroleum—so original TOC and HI values would have been greater. Pink lines are Precambrian faults from Adler and others (1971).

Thermal Maturation

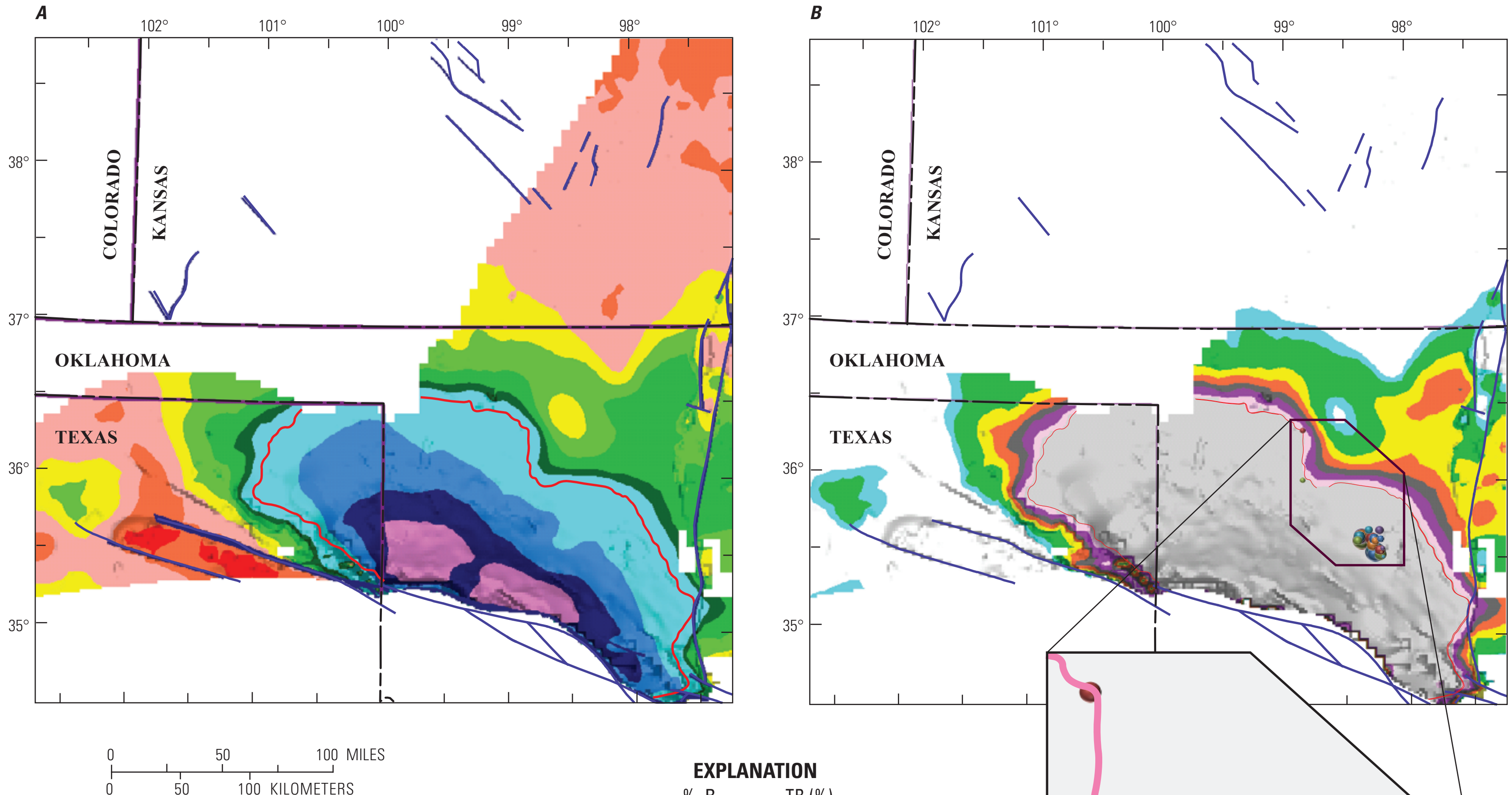
The Woodford Shale is thermally mature for oil generation to overmature for gas generation over most of the Oklahoma and eastern Texas Panhandle portions of the Anadarko Basin Province (fig. 11). Levels of thermal maturation were based on 1D and 4D petroleum system models and contoured R_o data from the Woodford Shale from Cardott (1989), Price (1997), and two wells in the Edmond West field provided by Chesapeake Energy and Mark Pawlewicz. Part of the area proximal to the Nemaha uplift is thermally immature for oil generation from the Woodford Shale based on Cardott (1989) R_o data but marginally mature to mature based on R_o measurements for the West Edmond SWD 1-24 (0.55 percent mean R_o) and Streeter 1 (0.75 percent mean R_o) wells from Brian Cardott and Mark Pawlewicz, respectively. The West Edmond SWD 1-24 sample was also analyzed by Chesapeake Energy on January 10, 2008, with an estimated mean 0.83 percent R_o and range of 0.44 to 0.96 percent R_o based on Rock Eval pyrolysis Tmax values for 19 samples of the Woodford Shale interval. The models were preferentially calibrated to measured R_o data on the Woodford Shale. Extent of our modeled thermally mature source rocks is somewhat greater than that of Cardott (1989). The area of thermally mature Woodford Shale was also expanded slightly based on calibration of 1D and 1D extracted models (Gaswirth and Higley, 2014; Higley, 2014a) to incorporate areas in Oklahoma that are petroleum productive from the Woodford Shale, under the assumptions that the reservoir is self-sourced and internal lateral migration is minimal. The Woodford Shale may also be subject to R_o suppression based on Price and Barker (1985) and Cardott (1989), which could result in higher values than those recorded and displayed by Cardott (1989). These factors are discussed in more detail in Higley (2014a).

Carter and others (1998) determined that oil generation from the Woodford Shale began as early as Late Mississippian in the western basin. Burial history models for two wells from the deep Anadarko Basin were used by Carter and others (1998) to determine that the Woodford Shales were thermally mature for oil generation by the end of the Permian; their burial history model for the northern shelf area of Oklahoma did indicate that the Woodford Shale has been in the early oil generation zone since Early Permian time.

The modeled onset of oil generation and expulsion from the Woodford Shale in the deep basin was about 330 million years ago (Ma), based on generated volumes of oil through time. Onset through completion of hydrocarbon generation is highly dependent on burial depth, which varies greatly across the basin. Figure 12 shows two-dimensional extractions from the 4D model that display thermal maturation through time for a south-north cross section. Displayed are transformation ratios (TR) that range from 0.1 percent at onset, 50 percent at peak, and 99 percent at completion of oil generation (Higley, 2014a, fig. 18). The 99-percent TR boundary corresponds to about 1.2 percent R_o based on Lewan and Ruble (2002) Woodford Shale hydrous pyrolysis kinetics; this represents the transition from primarily oil to only gas generation. Modeled R_o contours are also shown for the generalized onsets of dry gas (about 2 percent R_o), and overmaturity for gas generation (about 4 percent R_o) based on secondary cracking reactions (Tsuzuki and others, 1999; Higley, 2014a). Methane gas is stable in the Woodford Shale of the deep basin, based on thermodynamic calculations and constraints by Takach and others (1987) and Barker and Takach (1992), even considering the almost 28,000 ft current depth of the Woodford Shale in the Bertha Rogers 1 well (fig. 5) and greater than 30,000 ft maximum burial depth of the unit in the basin. Although this indicates that methane is probably present in the deepest portion of the Woodford Shale Gas AU, it does not address the effects of elevated pressure and decreased pore size and permeability on the stored volumes of gas.

Oil generation began about 330 Ma and slightly deeper in the basin than the 330 Ma-cross section image (fig. 12). By 300 Ma, the Woodford Shale on this section ranged from thermally immature to overmature for oil generation, and by 250 Ma the range was marginally mature for oil to overmature for gas generation. Because 250 Ma was approximately the time of maximum burial depth, changes in maturation from 250 Ma to 0 Ma were fairly minor. The present-day Woodford Shale and Thirteen Finger Limestone model layers range from marginally mature for oil to overmature for gas generation. As is the case with Carter and others' (1998) research, thermal maturation is strongly influenced by burial depth and temperature. Basement heat flow affects the wavy character of contours in the figure 12 thermal maturation cross sections, with areas of decreased heat flow exhibiting less thermal maturation. This relation is also displayed in Higley (2014a, figs. 39 and 40). Some of the "bumps" in the thermal maturation profiles were explained by Gallardo and Blackwell (1999) as associated with the thermal conductivity structure of the basin and heat generation properties of basement rocks. Cardott and Lambert (1985) and Cardott (1989) observed that the highest R_o values in the Woodford Shale are about 19–25 mi (30–40 km) north of the deepest part of the basin and change rapidly over a small lateral distance. Heating history is also influenced by lithologies, for example, evaporites are thermally conductive and thick sections can "cool" underlying strata, whereas coals and shales are thermal insulators that increase heat of underlying rocks. Within the Anadarko Basin, coals are thin and sparse and evaporite sequences are relatively thin, so these lithologies would have minimal impact on heating history. Shales are more common, particularly in the Pennsylvanian section, and would have functioned as thermal blankets for underlying strata. Morrowan black shales compose as much as 60 percent of the rocks in the Oklahoma portion of the province (Wang and Philp, 1997), and the Morrowan section is as much as 4,000 ft thick in the deep Anadarko Basin, thinning northward onto the shelf (Adler and others, 1971; Johnson, 1989).

Hydrocarbons from the Woodford AUs are self-sourced. Oil migration within the Woodford Shale is probably limited because of the low permeability; consequently, migration is predominantly expulsion outward to bounding carrier (reservoir) beds. Petroleum migration is preferentially from higher to



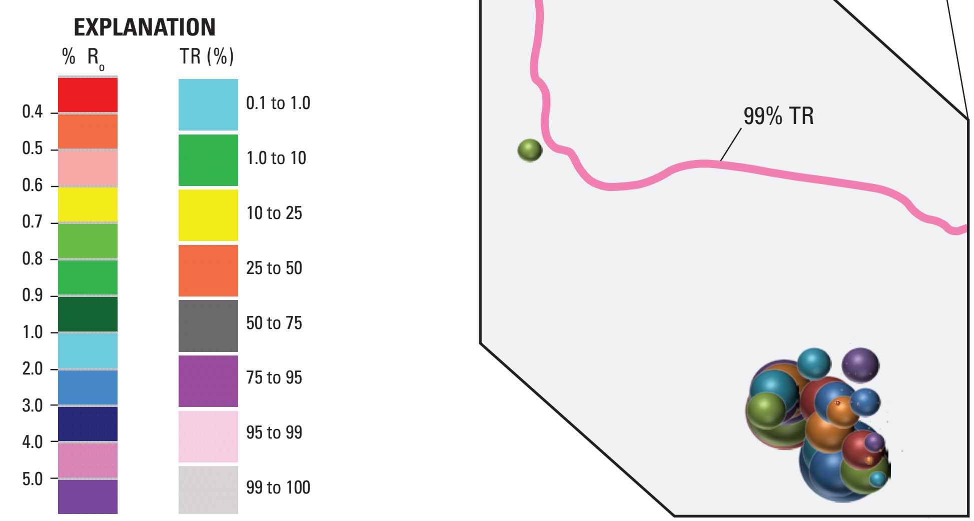
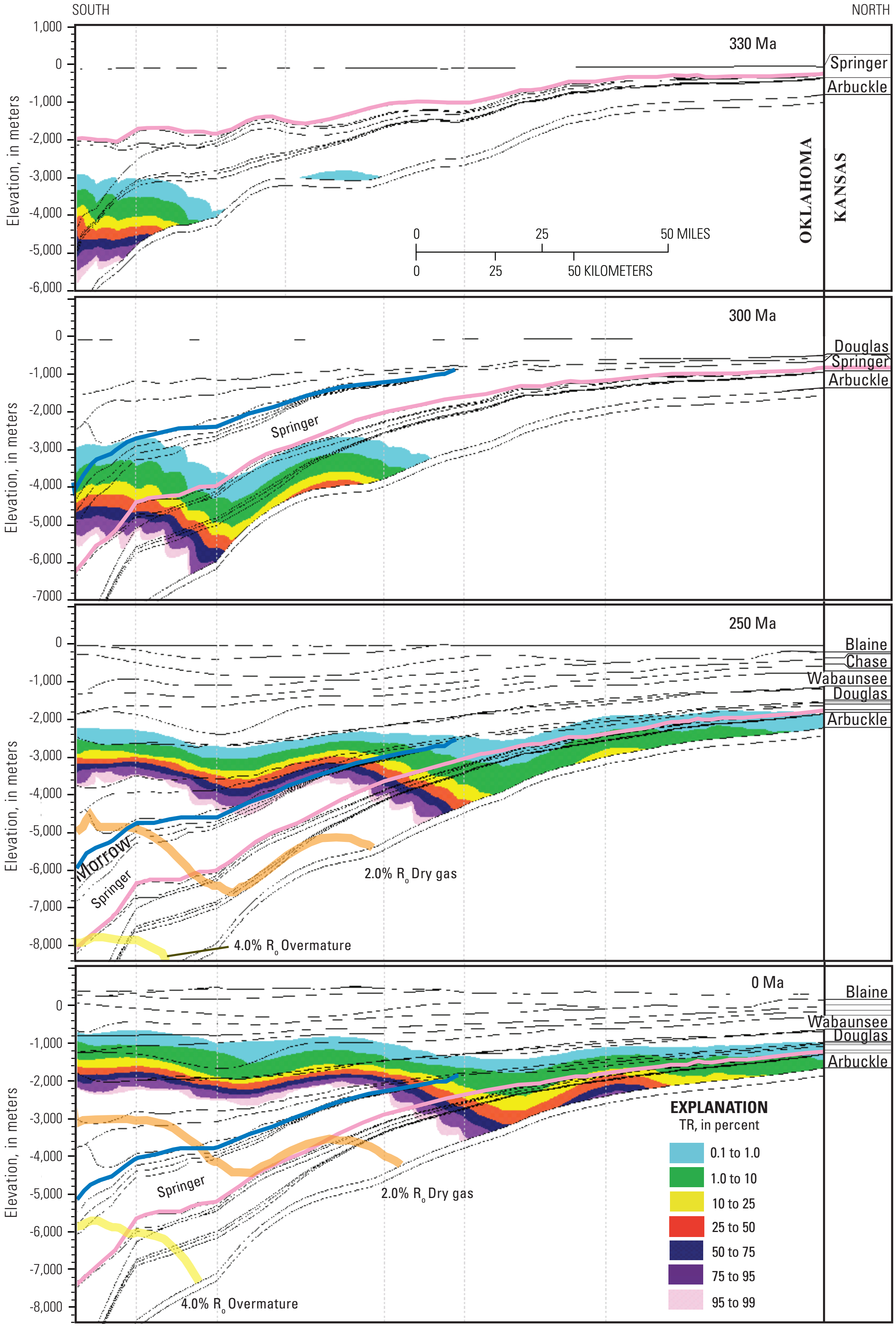


Figure 11. Maps showing *A*, calculated vitrinite reflectance (% R_o) (Sweeney and Burnham, 1990) and *B*, transformation ratios (% TR) for the Woodford Shale from the four-dimensional petroleum system model. The three-dimensional rendering results in variable shading within contours. Pink contour line on the % R_o map and the gas-oil ratio (GOR) inset corresponds to the 99% TR end of oil generation. The inset bubble symbols are GOR, with larger bubbles representing greater GOR. Greatest thermal maturation is in the deep basin of Oklahoma and Texas, whereas most of Colorado and Kansas is immature for oil generation, as characterized by an R_o of about 6 percent and TR of 0.1 percent and greater. Blue lines are Precambrian faults from Adler and others (1971).


SOUTH
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2.0% R_o Dry gas
4.0% R_o Overmature
0 Ma
Blaine
Wabaunsee
Douglas
Arbuckle
Springer
2.0% R_o Dry gas
4.0% R_o Overmature
Elevation, in meters
EXPLANATION
TR, in percent
0.1 to 1.0
1.0 to 10
10 to 25
25 to 50
50 to 75
75 to 95
95 to 99

Figure 12. South to north thermal maturation cross sections showing transformation ratios (% TR) through time based on Woodford Shale hydrous pyrolysis kinetics from Lewan (1983, 1985), and Lewan and Ruble (2002). Pink and dark blue lines are the respective Woodford Shale and Thirteen Finger lime model layers. Cross section location is in figure 3. Modeled vitrinite reflectance (R_o) lines mark the boundaries for generation and overmaturity for dry gas. Millions of year ago, Ma.—Previous page

lower pressure environments, regardless of whether those are underlying or overlying strata. Oil and gas within the Woodford Shale mainly represent saturation from nonexpelled hydrocarbons and that within faults and fractures. Because this is a reservoir, albeit with low permeability, there is also the potential of hydrocarbons migrating into the Woodford from deeper in the basin or from other source rocks, especially gas, because of its mobility. However, it is unlikely that other petroleum source rocks contributed petroleum to the Woodford Shale, because it is currently overpressured relative to underlying strata in the deep basin (Al-Shaieb and others, 1994) and has probably been overpressured since it was mature for hydrocarbon generation.

Comer and Hinch (1987) estimated the volume of expelled oil from their Woodford Shale study area by subtracting the TOC-normalized volume of hydrocarbons in black shale from the corresponding amount in chert. Their calculations also incorporated the Woodford Shale subcrop area and source rock total thickness, density and TOC concentration, as well as the density and amount of the expelled oil. Their calculated expulsion efficiency was between 27 and 50 percent. Estimated volume of expelled oil was 22 billion barrels from about (1) the eastern one-third of the Anadarko Basin, (2) the Marietta-Ardmore Basin, and (3) the western two thirds of the Central Oklahoma platform (Comer and Hinch, 1987, fig. 1). Figure 13 shows oil generation through time for the Oil Creek Formation, Woodford Shale, and Thirteen Finger lime petroleum source rocks (fig. 2). The curves are displayed as onset to completion, rather than volumes, partly because thickness of the Oil Creek layer is generalized and does not represent

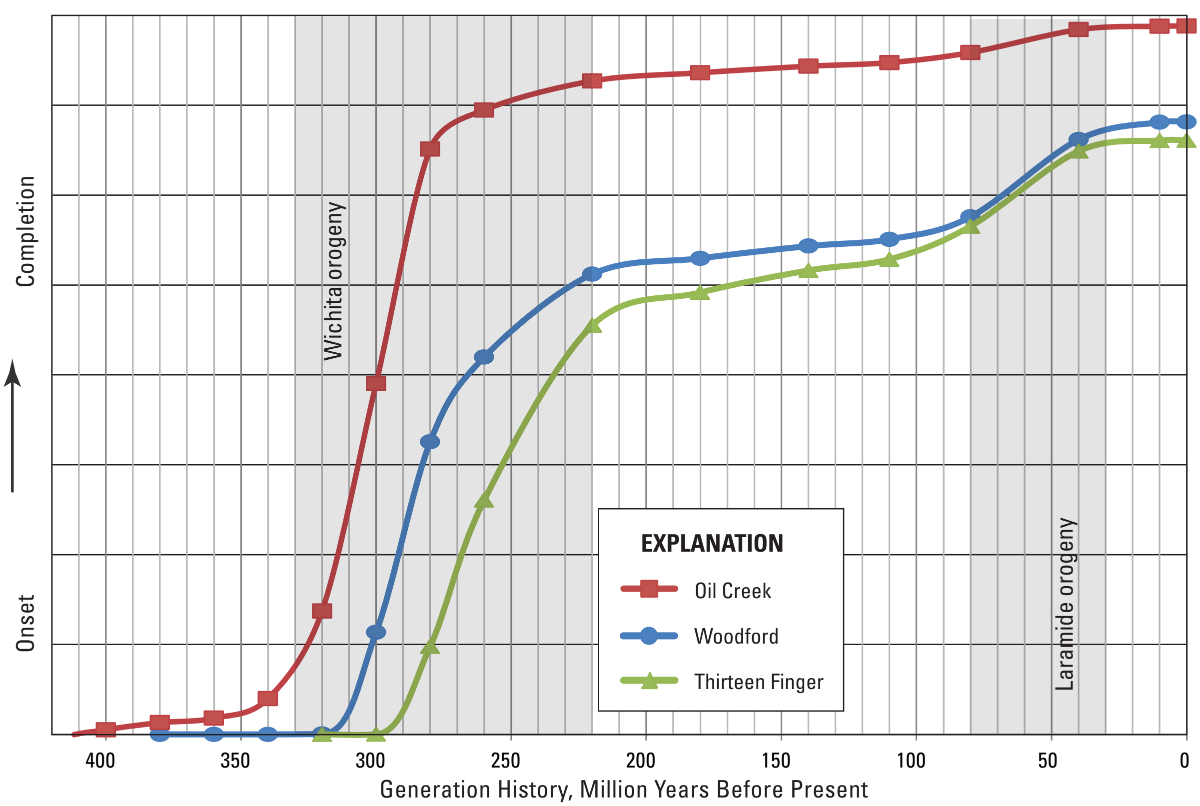

Figure 13. History of petroleum generation from the Oil Creek Formation, Woodford Shale, and Thirteen Finger lime (fig. 2) source layers in the four-dimensional petroleum system model. History is based on Woodford hydrous pyrolysis kinetics (Lewan and Ruble, 2002). Shaded area brackets the main period of peak oil generation from the Woodford Shale. Early oil generation from the Oil Creek layer, prior to about 70 million years ago, is in a narrow strip in the model that is proximal to the Wichita Mountain uplift. This strip exceeds maximum depth of the formation and is primarily the result of areas of poor data control in the area bordering the fault zone. The error could have been removed by clipping the four-dimensional model extent to the basin axis and northward, but less of the model would have been visible and usable.

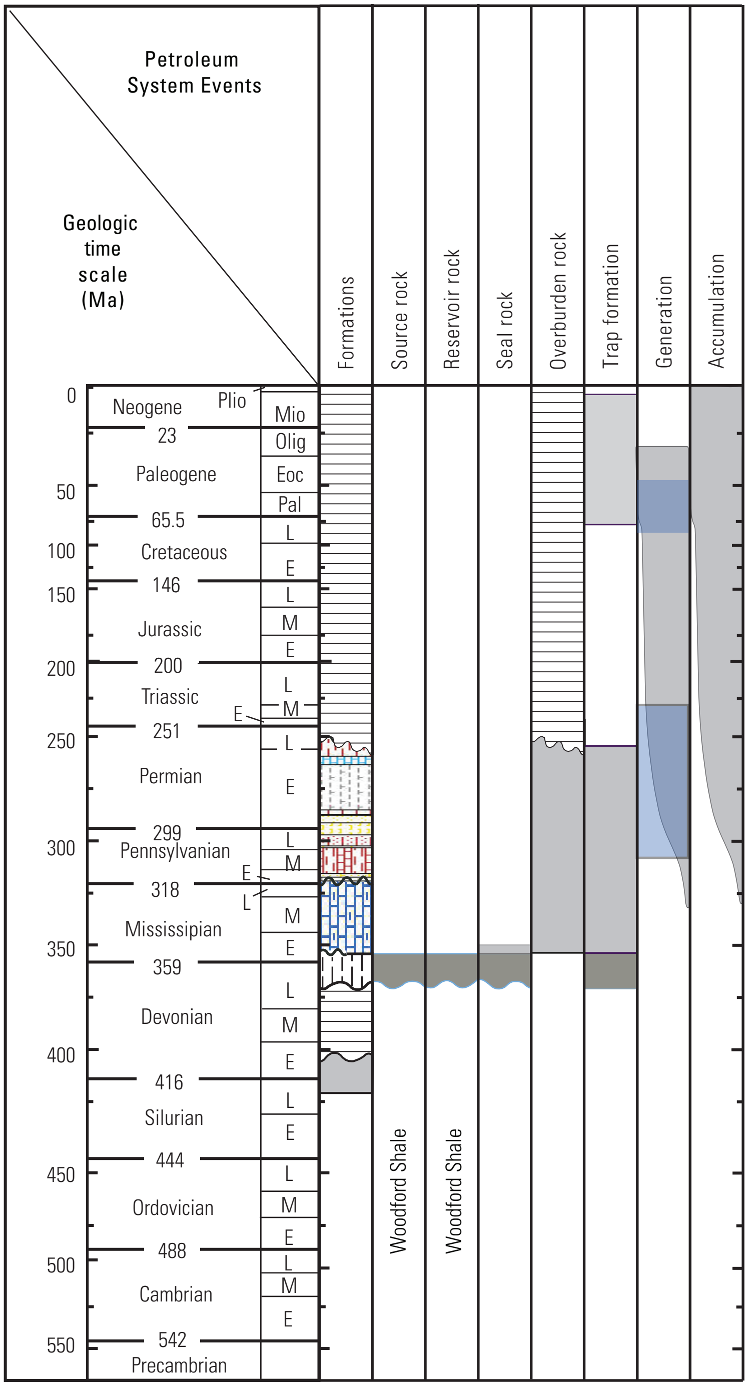

Figure 14. Events chart for the Woodford Shale Gas assessment unit (AU) and Woodford Shale Oil AU. Timing of oil and gas generation, migration, and accumulation is based primarily on vitrinite reflectance and transformation ratios through time from one-dimensional and four-dimensional (4D) models (Higley, 2014a). Timing of oil generation (gray polygon) is also based on (unpublished) volumes of petroleum generated through time using the 4D model; peak generation from the Woodford Shale (blue bars) is from about 310 to 230 million of years before present (Ma). A second phase of generation from about 80 to 50 Ma is associated with deposition and erosion of strata associated with the Laramide orogeny. Lithofacies assignments in the "Formations" row are intended only to show periods of unconformities (wavy and horizontal lines) and deposition. Plio, Pliocene; Mio, Miocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

the actual thickness of the source interval. Peak oil generation from the Woodford Shale was from about 310 to 230 Ma. Because Anadarko is a deep basin with a shallow shelf, age ranges for petroleum generation vary laterally as well as vertically, allowing for longer periods of oil and gas generation, migration, and trapping across the basin. A second period of Woodford oil generation from about 80 to 50 Ma is associated with Laramide deposition, uplift, erosion, and subtle tilting of the basin. The petroleum system events chart for the Woodford Shale Oil and Woodford Shale Gas AUs (fig. 14) shows time periods of deposition of source, reservoir, seal, and overburden strata. Timing of hydrocarbon generation, migration, and accumulation are derived mainly from the Higley (2014a) petroleum system models (fig. 13, table 2). The curves are displayed as onset to completion, rather than volumes, partly because thickness of the Oil Creek layer is generalized and does not represent the actual thickness of the source interval. Peak oil generation from the Woodford Shale was from about 310 to 230 Ma. Because Anadarko is a deep basin with a shallow shelf, age ranges for petroleum generation vary laterally as well as vertically, allowing for longer periods of oil and gas generation, migration, and trapping across the basin. A second

Table 2. Oil generation onset for the Anadarko Basin four-dimensional model, and onset and completion dates in millions of years before present (Ma) for the Bertha Rogers 1 and Petree Ranch 1 one-dimensional models based on Woodford Shale hydrous pyrolysis kinetics (Lewan and Ruble, 2002). The Douglas Group overlies the youngest potential petroleum source rocks in figure 6. The HP kinetics-based onset of oil generation is 0.1% TR and completion is 99% TR. Oil generation histories in the four-dimensional model were recorded at 10 million year increments, so the plus symbol indicates onset was before the listed age.

	Four Dimensional Model	Bertha Rogers 1		Petree Ranch 1	
	Onset	Onset	End	Onset	End
Virgilian (Douglas Group)	270	100			
Thirteen Finger limestone	+300	290	265	270	
Woodford Shale	330	330	310	290	200
Oil Creek Formation	+370	340	320		

period of Woodford oil generation from about 80 to 50 Ma is associated with Laramide deposition, uplift, erosion, and subtle tilting of the basin. The petroleum system events chart for the Woodford Shale Oil and Woodford Shale Gas AUs (fig. 14) shows time periods of deposition of source, reservoir, seal, and overburden strata. Timing of hydrocarbon generation, migration, and accumulation are derived mainly from the Higley (2014a) petroleum system models (fig. 13, table 2).

Traps and Seals

The Woodford Shale Gas AU southern boundary includes a small portion of the overthrust belt that borders the Amarillo–Wichita Mountain uplift (fig. 3). Gas potential within wells in this area is influenced by complex faulting and fracturing that would likely enable leakage of gas from the Woodford Shale, adversely impacting production of gas. The area was included because Woodford intervals in this area are probably within the oil and gas generation windows, and some wells encounter repeated strata because of the faulting. For example, the Apache Gas Unit No. 1 vertical well penetrates the Woodford at least 4 times and at depths that range from about 1,900 to 19,000 ft.

The Woodford Shale AUs are within the Anadarko Basin area defined by Nelson and Gianoutsos (2014) as overpressured. Al-Shaieb and others (1994) outlined an overpressured megacompartment that is primarily in the Oklahoma and Texas portions of the basin; the diagenetically enhanced basal seal is stratigraphically controlled and seems to coincide with the Woodford Shale. Overpressuring occurs in all reservoirs between the top seal at depths of about 7,500 to 10,000 ft (2,290 to 3,050 m) to the base of the Woodford Shale, with return to normal pressure in the underlying Hunton Group (Al-Shaieb and others, 1994). Overpressure probably assists petroleum production from the Woodford Shale if natural and induced fractures are open. Effects of overpressure on lateral and bounding seals are dependent on their competence. Al-Shaieb and others (1994) indicated that the megacompartment complex is composed of sealed overpressured reservoirs with pressure gradients that exceed the normal gradient of 10.515 thousand Pascals per meter (kPa/m) [0.465 pounds per square inch per foot (psi/ft)]; the megacompartment, including the Woodford Shale, is sealed to the south by a vertical cementation zone associated with the frontal fault zone of the Wichita Mountain uplift and by the convergence of the top and basal seals along its eastern, northern, and western boundaries. The overlying Kinderhook Shale probably provides a seal across its extent in the eastern basin.

Petroleum Production History

Distribution of oil and gas wells from the Woodford Shale is shown in figures 15 and 16. Gas production is located primarily within the Woodford Shale Gas AU and oil within the Woodford Shale Oil AU. Estimated mean undiscovered resources from the 2011 assessment are (1) 15.973 trillion cubic feet of gas (TCFG) and 192 million barrels of natural gas liquids (MMBNGL) for the Woodford Shale Gas AU; and (2) 393 million barrels of oil (MMBO), 1.963 TCFG, and 59 MMBNGL for the Woodford Shale Oil AU. The Woodford Shale was included in the 1995 play assessment of the Anadarko Basin as the Woodford/Chattanooga/Arkansas Novaculite play, which was described by J. Schmoker in Henry and Hester (1995) as a hypothetical continuous play with no production or assigned estimates of undiscovered resources. The Misener sand (fig. 16) of the basal Woodford Shale was separately assessed in 1995 as the Devonian Misener sandstone oil play with mean undiscovered accumulations of 4.1 MMBO (Henry and Hester, 1995). The Misener sand for the 2011 assessment was not assessed separately, but was included within the conventional Hunton Group AU (table 1) (Gaswirth and Higley, 2014).

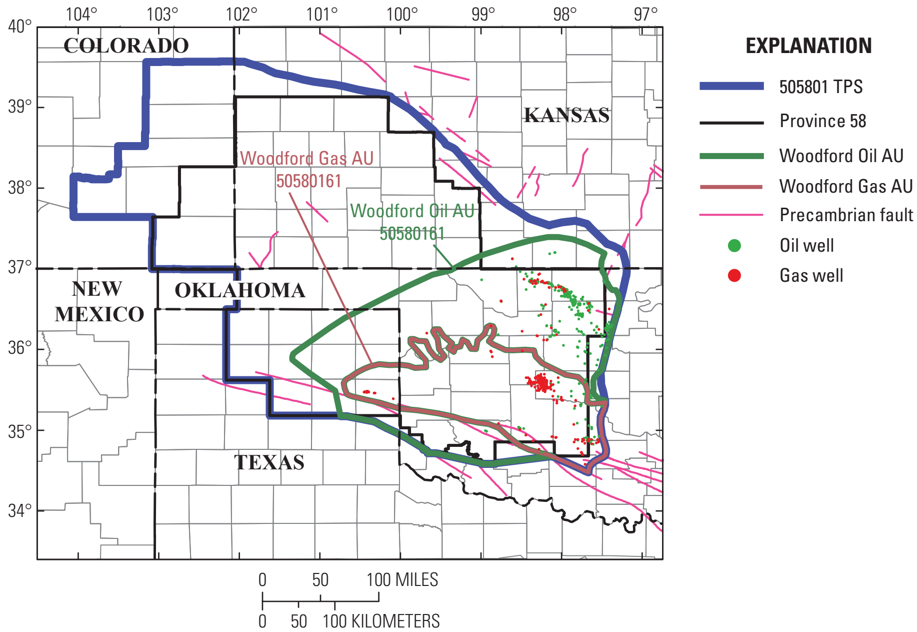

Figure 15. Map showing oil and gas wells that produce from the Devonian-Mississippian Woodford Shale Oil and Woodford Shale Gas assessment units (AUs) in the Anadarko Basin Province (code number 58) (IHS Energy, 2009a, 2010, 2011). Shown also are AU code numbers. Some wells include production from other units, primarily the Silurian-Devonian Hunton Group, Devonian informal Misener sand, and Mississippian strata. The Woodford Composite TPS code is 50580. Precambrian faults (pink) are from Adler and others (1971).

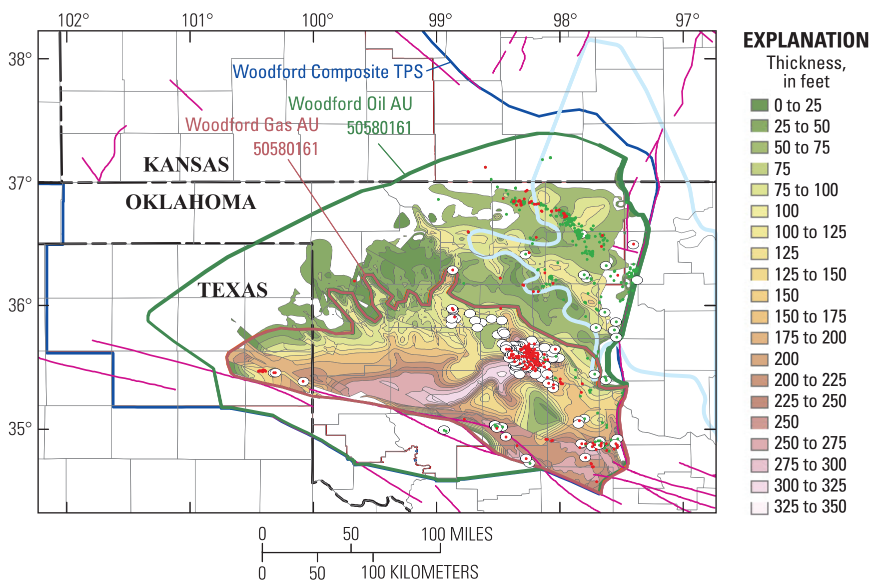

Figure 16. Map showing oil wells (green dots) and gas wells (red dots) that produce from the Woodford Shale in the Anadarko Basin Province (IHS Energy, 2009a, 2010, 2011). White dots are wells that are productive only from the Woodford Shale based on a November 2011 retrieval of data from IHS Energy (2011). White dot wells that do not contain oil or gas wells were added to the IHS database since the January data retrieval. Extent of the Woodford Shale in the province is approximated by the Woodford Oil AU line. Thickness was derived from Rottmann (2000b, pl. 2), analysis of more than 100 well logs, and edited formation tops from IHS Energy (2009a, 2009b). The Kansas portion of the province contains variable thicknesses of Woodford Shale, and the Oklahoma and Texas portions have several small erosional remnants. The generalized location of the informal Misener sand (light blue line) in the lower part of the Woodford Shale (fig. 2) is modified from Amsden and Klapper (1972) and IHS Energy (2009a, 2009b). The Misener sand exhibits variable thickness and distribution, and is also present in isolated lows in the eroded, karst surface of the Hunton Group (Gaswirth and Higley, 2014). Pink lines are Precambrian faults from Adler and others (1971).

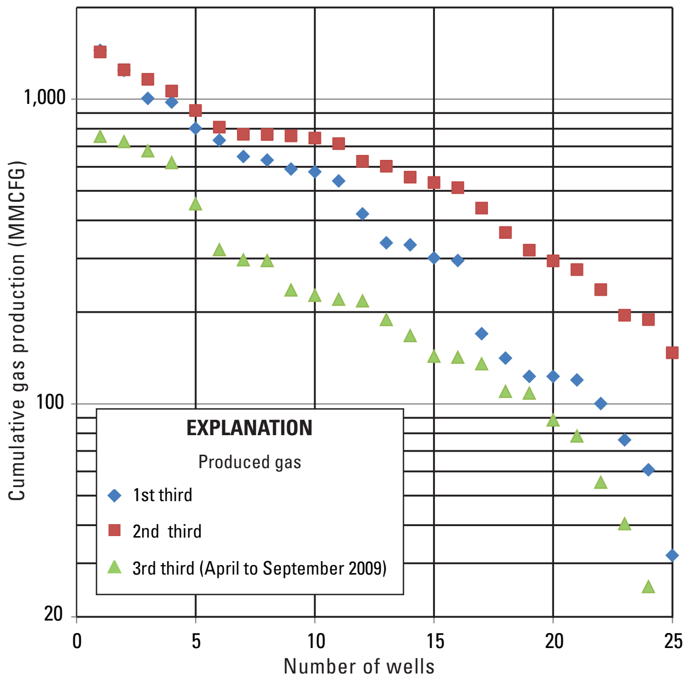

Figure 17. Discovery thirds for 74 wells with reported cumulative gas production from only the Woodford Shale from 1946 to September, 2009 (IHS Energy, 2010). The apparently poor production from the 3rd third is misleading, and actual performance is probably greater, particularly with the present focus on horizontal wells. Reasons for the spread in data include that early production likely incorporates (unreported) oil and gas from the conventional basal Misener sand of the Woodford shale and (or) bounding reservoirs, and the 3rd third only represents 6 months of Woodford Shale gas from 24 wells. Average gas/oil ratio of the above data set is 237,000 cubic feet of gas per barrel of oil. Million cubic feet of gas, MMCFG.

The 2011 assessment incorporated multiple databases of well and field history and production that included IHS Energy (2009a, 2009b, 2010) and Nehring and Associates, Inc. (2009). Cumulative production from the Woodford Shale across the province was about 2 MMBO and 34 BCFG, based mainly on data from IHS Energy (2010). Woodford Shale oil and gas has been mostly from vertical wells, with the production commonly reported commingled with the Hunton Group, Misener sand, Sycamore Limestone, and other units. Of the 130 total wells, there were about 49 horizontal Woodford Shale completions (IHS Energy, 2009a, 2010). Future Woodford Shale wells are expected to be mainly horizontal. Gas-oil ratio averaged about 237,000 cubic feet of gas/barrel of oil for 55 Woodford Shale wells in the province that did not report commingled production (IHS Energy, 2009b). Cumulative gas production for discovery thirds (fig. 17) shows largest gas production for the second third of production history. Largest decrease is for the last third of production history; however, the curves provide only limited information because of the short time range of production. Eighty-eight gas and 21 oil wells, respectively, with Woodford-only production were used to calculate estimated ultimate recovery (EUR) for the Woodford Shale Gas and Woodford Shale Oil AUs (IHS Energy, 2011). Contoured gas EURs are shown in figure 18. Present-day distribution of production for the Woodford Shale Gas AU is scattered across the formation extent, but gas production is concentrated in areas where R_o values are greater than 1.2 percent (fig. 18). The isolated blue dot of greater than 5,000 MMCFG (fig. 18) appears to be in an area of lower thermal maturity, but there are no proximal R_o samples, so the value here could be greater than indicated by the contours. The modeled TR through this point is 100 percent and R_o is 1.3 percent. Methodology for determining EUR is in Cook (2004).

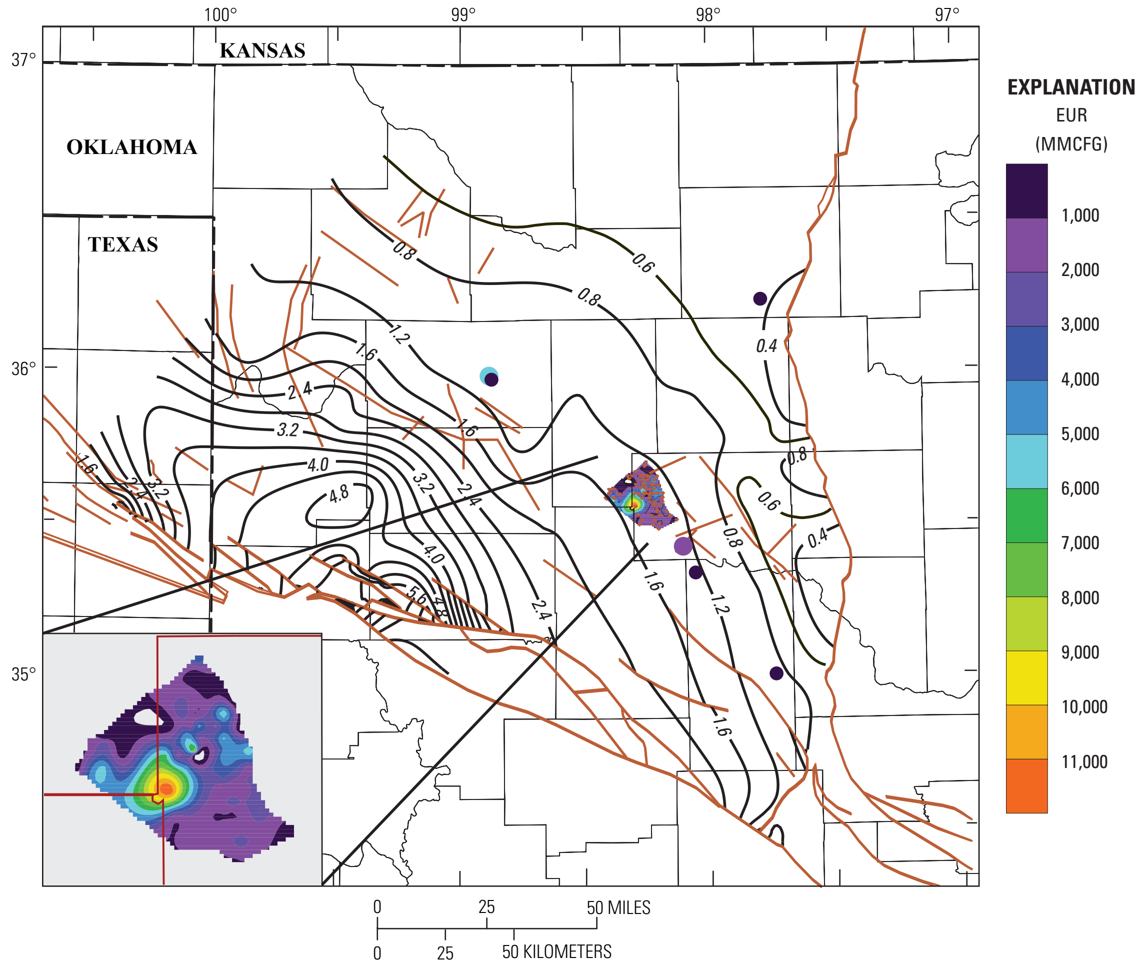

Figure 18. Map showing Woodford Shale calculated gas estimated ultimate recoverable (EUR) ranges from about 0.1 million (MMCFG) to 11.9 billion cubic feet of gas for 76 wells based on production history from IHS Energy (2010). The dense cluster of wells has contoured values, whereas those outside are measured values. Inset map of contoured values is magnified 300 percent. Most gas production is located at the 1.2% R_o and greater Woodford Shale contours created using data from Cardott (1989), Price (1997), Chesapeake Energy Corporation (2009), and Mark Pawlewicz. Faults (brown lines) on the underlying Hunton Group (Rottmann, 2000a) were used to create the Woodford layer and to contour R_o values.

Conclusions

The Devonian-Mississippian Woodford Shale is an important petroleum source rock and reservoir in the Anadarko Basin Province. The formation consists of upper, middle, and lower informal members of carbonaceous silica-rich shales, and a lower informal Misener sand. The shale members contain fissile and non-fissile shale, including chert beds, all of which can exhibit different fracture behavior. Elevation on the top of the Woodford Shale ranges from about -2,500 ft (-760 m) on the southern Kansas shelf, to -27,000 ft (-8,000 m) in the deep basin of southern Oklahoma. Thickness of the Woodford Shale ranges up to 375 ft and averages 40 ft. Greatest thickness is within eroded channels of the underlying Hunton Group. Present-day total organic carbon (TOC) content for the upper Woodford ranges from about 0.8 wt% to 17 wt%.

Hydrocarbons in the Woodford Shale Gas and Woodford Shale Oil AUs are self-sourced. Gas production is concentrated in areas where R_o values are greater than 1.2 percent, based mainly on the 4D model. Lateral migration distances are minor because of the low permeability within the source rock and primary expulsion is from this source outward to bounding carrier beds. Oil generation from the Woodford Shale began in the deep basin of southern Oklahoma about 330 Ma, based on 1D and 4D petroleum system models; peak oil generation was from about 310 to 230 Ma. Because Anadarko is a deep basin that has a shallow shelf, age ranges for generation vary laterally as well as vertically. These time ranges allowed for longer periods of oil and gas generation, migration, and trapping across the basin. A second period of Woodford oil generation from about 80 to 50 Ma is associated with Laramide deposition, uplift, erosion, and subtle tilting of the basin.

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