Chapter 7
Petroleum Systems and Assessment of Undiscovered Oil and Gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—Mississippian Through Permian Assessment Units

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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—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—Mississippian Through Permian Assessment Units

By Debra K. Higley

Abstract

The Anadarko Basin Province includes the Anadarko Basin of western Oklahoma, western Kansas, and northern Texas, the Las Animas arch of southeastern Colorado, and the Palo Duro Basin of Texas. This is a mature petroleum province for conventional oil and gas reserves and resources. Two total petroleum systems were defined for the province. The Woodford Composite Total Petroleum System includes Cambrian through Mississippian strata, and the Pennsylvanian Composite Total Petroleum System comprises Pennsylvanian through Permian strata. This chapter of the report details assessment results and associated methodology for conventional and continuous resources for defined assessment units (AU) of Mississippian through Permian strata within the total petroleum systems. Mean undiscovered conventional resources for Mississippian through Permian assessment units in the Anadarko Basin Province total 77 million barrels of oil (MMBO), 1,934 billion cubic feet of gas (BCFG), and 60 million barrels of natural gas liquids (MMBNGL).

Total petroleum system assessment methods of analysis resulted in mean undiscovered resources of 17 MMBO, 417 BCFG, and 11 MMBNGL for the Mississippian Assessment Unit (AU) of the Woodford Composite Total Petroleum System (TPS). Mean undiscovered continuous gas resources for the Thirteen Finger Limestone–Atoka Shale Gas AU are 6.850 trillion cubic feet of gas (TCFG) and 82 MMBNGL. Undiscovered oil resources for the Thirteen Finger limestone and Atoka Shale are incorporated in the conventional Morrowan-Atokan AU. Mean undiscovered conventional resources for the Pennsylvanian Composite TPS include:

a. 15 MMBO, 332 BCFG, and 7 MMBNGL for the Morrowan–Atokan AU;

b. 6 MMBO, 118 BCFG, and 4 MMBNGL for the Desmoinesian AU;

c. 23 MMBO, 258 BCFG, and 8 MMBNGL for the Missourian–Permian AU

d. 16 MMBO, 809 BCFG, and 30 MMBNGL for the Desmoinesian through Permian Greater Granite Wash Composite AU

Introduction

The U.S. Geological Survey (USGS) recently completed an assessment of the undiscovered oil and gas resource potential of the Anadarko Basin Province of western Oklahoma, western Kansas, northern Texas, and southeastern Colorado (fig. 1). The province area covers 59,861 square miles and includes the Anadarko Basin, Las Animas arch, and Palo Duro Basin. This is hereafter referred to as the 2011 assessment, which corresponds to the publication date of the assessment results by Higley and others (2011). Results of the assessment and geologic analysis (table 1) are based on the geologic elements that are used to define each total petroleum system (TPS), including hydrocarbon source rocks (source-rock maturation, hydrocarbon generation and migration), reservoir rocks (sequence stratigraphy and petrophysical properties), and hydrocarbon traps (trap formation and timing).

Using this geologic framework, the USGS defined the Woodford Composite TPS and Pennsylvanian Composite TPS and nine conventional and three continuous assessment units (AU), and quantitatively estimated the undiscovered oil and gas resources within each AU. The AU code numbers and assignments to TPSs are listed below. Those detailed within this chapter of the report are highlighted in bold text and AU boundaries are shown in figure 1 and the figure 2 stratigraphic column of Devonian through Permian units. The Woodford Shale Oil AU and Woodford Shale Gas AU are discussed in Higley and Cook (2014a); they are included

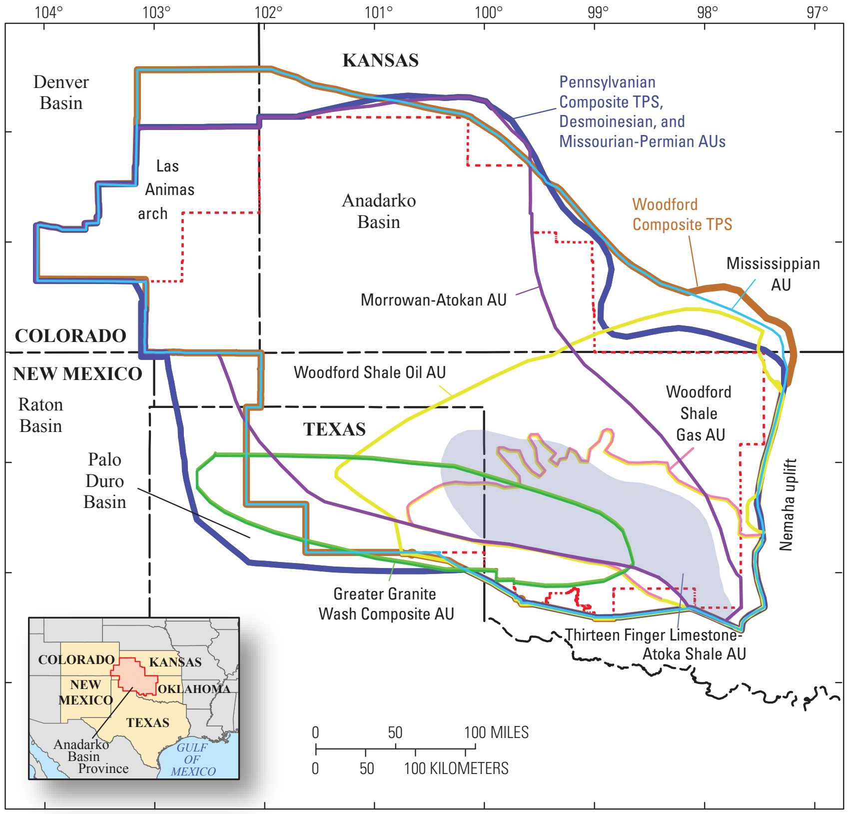


Figure 1. Map showing Anadarko Basin (red dashed line) and boundaries of total petroleum systems (TPS) and assessment units (AU) that are described in this chapter of the report. The Desmoinesian and Missourian-Permian AUs share a common boundary with the Pennsylvanian Composite TPS, with the exception that the AUs include a “donut hole” that is the Greater Granite Wash Composite AU. There are common boundaries for most AUs.

Table 1. Anadarko Basin Province assessment results are listed by name 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. Field 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

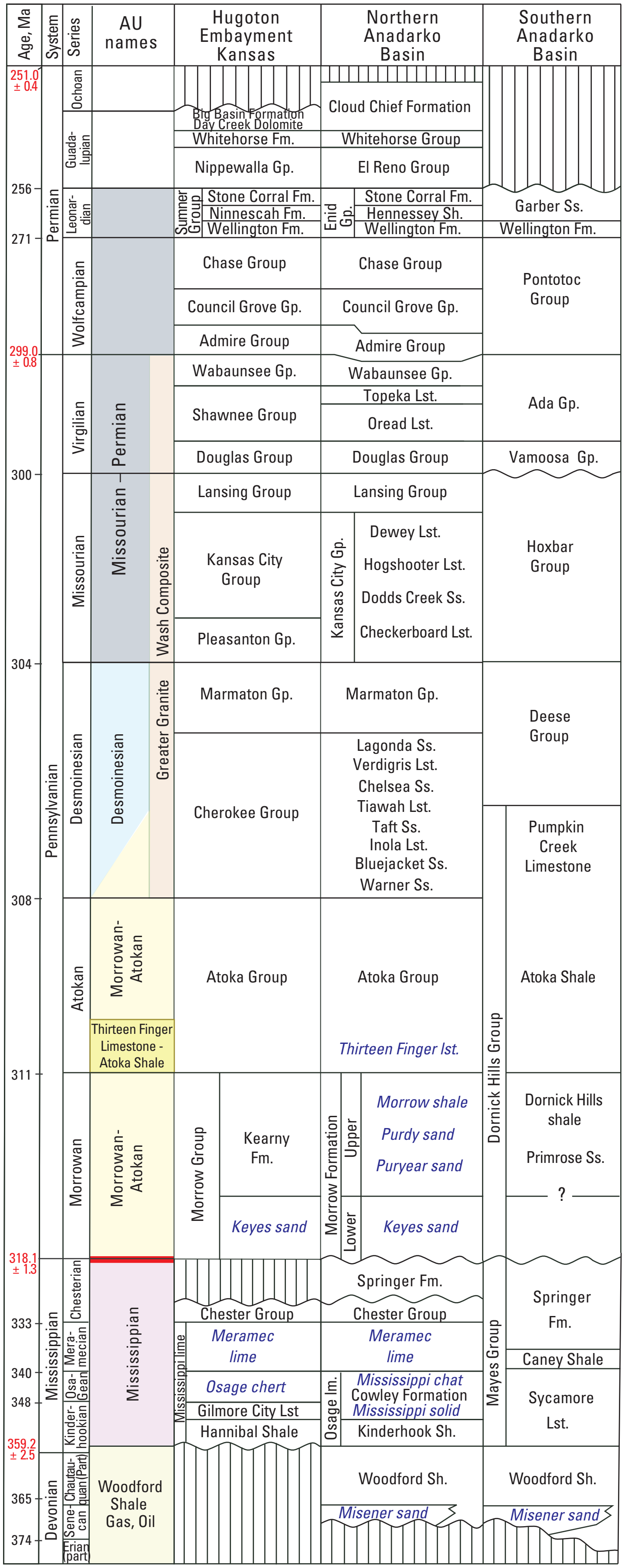


Figure 2. Generalized stratigraphic columns for Devonian through Permian strata in the Anadarko Basin Province. Assessment unit (AU) names and generalized divisions are split at the horizontal red line into (upper) Pennsylvanian Composite Total Petroleum System (TPS) and (lower) Woodford Composite TPS. Italics (blue text) and lowercase names indicate informal status. The Devonian Misener sand was evaluated as part of the Hunton Group AU (Gaswirth and Higley, 2014). Extension of the Morrowan-Atokan AU into the Desmoinesian reflects the unclear boundary of the Atoka Shale in the southern basin. Modified from Bebout and others (1993) and Henry and Hester (1995). Ages in millions of years from Haq and Van Eysinga (1998), and Gradstein and others, (2004) (red text). Fm.; Formation, Gp.; Group, Lst.; Limestone, lm.; lime, Sh., Shale, Ss.; Sandstone.

in figure 1 because they delineate major petroleum source rocks in the basin.

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

Geologic Setting of the Anadarko Basin Province

Structural and isopach surfaces used in this chapter of the report and for building a four-dimensional (4D) petroleum system model (Higley, 2014; Higley and others, 2014) were constructed using edited formation tops data from (1) more than 220 wells across the province; (2) IHS Energy (2009, 2010a); (3) Kansas Geological Survey (2010, *http://www.kgs.ku.edu/PRS/petroDB.html*); and (4) maps and data from Fay (1964), Rascoe and Hyne (1987), Robbins and Keller (1992), Cederstrand, and Becker (1998), Andrews (1999a, 1999b, 2001), and Rottmann (2000a, 2000b). Rock unit ages and lithologies for surfaces and stratigraphic columns are commonly generalized; sources of information include Denison and others (1984), Ludvigon and others (2009), and the National Geologic Map Database (2011, *http://ngmdb.usgs.gov/Geolex/*). Figures within this chapter of the report may variously have feet or meters as vertical scales. Metric scales are mainly used for the one-dimensional (1D), two-dimensional, and 4D petroleum system models, largely because of ease in using the modeling software. Vertical scale of most contour maps and of well-log cross sections are in feet because that is traditionally used in the United States. Tilted three-dimensional (3D) images generally do not have map scales because edges would have different scales, with the associated clutter.

Structural History

The Anadarko Basin Province, which also incorporates the Las Animas arch and Palo Duro Basin, is located in western Kansas, western Oklahoma, northern Texas, and southeastern Colorado. The Anadarko Basin is the deepest in the onshore United States and markedly asymmetrical, with Precambrian basement ranging in depth from more than 40,000 feet (ft) at the basin axis in southern Oklahoma, to surface exposures on the broad shelf in the proximal Central Kansas uplift (CKU) of Kansas. The basin is bounded on the southeast by the Marietta-Ardmore Basin, on the east by the Nemaha uplift and Salina Basin, on the north by the CKU, and on the south by the eroded Amarillo–Wichita Mountain uplift (fig. 3). Western boundaries are the Denver and Raton Basins (fig. 1). The Nemaha uplift consists of a discontinuous series of block-faulted segments, each of which is about 5–20 mile long (north-south) and 3–5 mile wide, and forms the axis and western boundary of the broad, gently raised Central Oklahoma platform (Johnson, 1989) that separates the Anadarko Basin from the Ardmore Basin. The platform contains Precambrian and pre-Pennsylvanian rocks that are unconformably overlain by Desmoinesian and Missourian age strata (Rascoe and Adler, 1983).

Schatski (1946) stated that southern Oklahoma was initially an aulacogen. The latest Precambrian to earliest Cambrian structural setting of southern Oklahoma is considered to be that of a failed linear rift (aulacogen) of an inferred plate tectonic triple junction (Burke, 1977; Perry, 1989), the common name of which is the Southern Oklahoma aulacogen. Axis of the resulting southern Oklahoma trough extended northwest from the paleocontinental eastern margin through the area now occupied by the Ardmore Basin and Arbuckle Mountains, the Wichita Mountains and vicinity, and into the northern Panhandle of Texas (Perry, 1989). At the close of the rifting phase, the aulacogen began to cool and subside (Feinstein, 1981). From Cambrian to Mississippian time, the area of the Anadarko Basin was located near the equator and predominantly covered by warm, shallow seas with mostly carbonate deposition (Wang and Philp, 1997). A passive continental margin existed outward from the trough during this time period (Nicholas and Rozendal, 1975; Keller and others, 1983). More than 3.3 kilometers (km) [11,000 feet (ft)] of Cambrian through Lower Devonian rocks were deposited over the axis of the aulacogen in the region of the Wichita and southwestern Arbuckle Mountains (Ham, 1973).

The Late Mississippian (probably Chesterian) was marked by renewed tectonism (Perry, 1989). Major plate collision between the North American plate and either Gondwana or an intervening microplate resulted in onset of the Ouachita orogeny and formation of the ancestral Rocky Mountains (Kluth and Coney, 1981; Kluth, 1986). Ball and others (1991) indicated the Mississippian Period closed with regional uplift and erosion that marked the start of the Wichita orogeny. Near the end of Mississippian time, the seas retreated to the deeper areas of the geosyncline because of upwarping of the Wichita

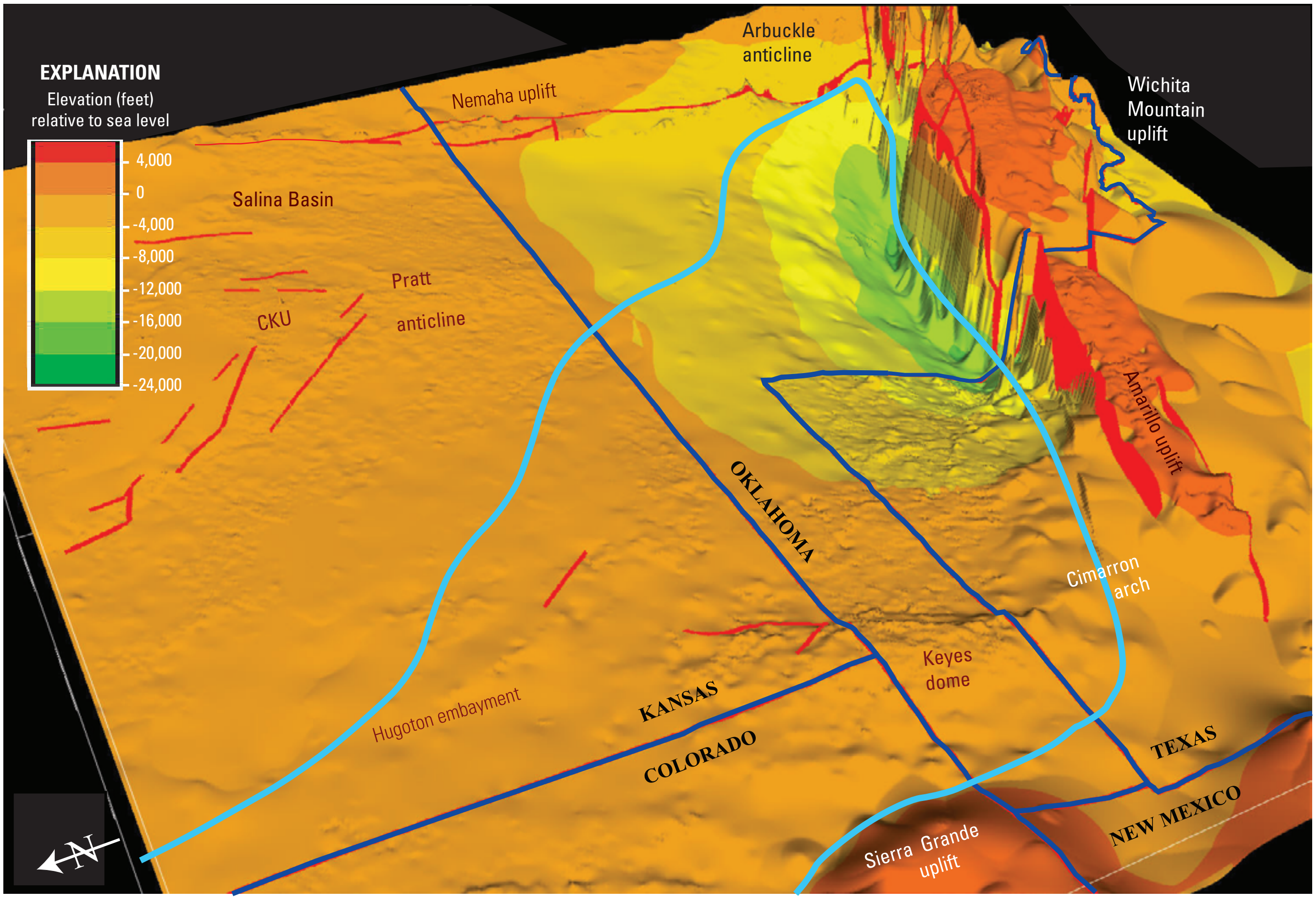


Figure 3. View to the southeast of elevation on the top of the informal Thirteen Finger limestone model layer (Higley and others, 2014b). Areal extent of the Thirteen Finger limestone is approximated by the light blue line. Major structures are labeled. CKU is Central Kansas uplift. The Las Animas arch (not shown) is north of the Sierra Grande uplift. The deep basin of Oklahoma and Texas is approximated by -6,000 feet elevation and deeper. Precambrian faults (red) are from Adler and others (1971). Faults bordering the Wichita Mountain uplift are vertical for 4D model purposes only, and subcropping strata on the uplift are unknown because of insufficient data. Data sources for this surface include formation picks from well logs and edited IHS Energy (2009, 2010a) formation tops. Vertical exaggeration is 18 times.

Mountain and Amarillo uplifts, elevation of the CKU, and subsequent emergence of the shelf areas, including the Oklahoma Panhandle and portions of the Texas Panhandle (Owen, 1975).

There is distinctive Precambrian layering on seismic profiles recorded south of the Wichita Mountains that is not visible under the Anadarko Basin. The Proterozoic basin containing that layering may have been bounded on its north side by a Precambrian fault that was probably twice reactivated during formation of the Southern Oklahoma aulacogen—once during the late Precambrian (?)–Early Cambrian extension, and again during Pennsylvanian compression (Brewer and others, 1983). Pennsylvanian compression resulted in crystalline basement rocks of the Wichita Mountains being thrusted northeastward over the basin along a series of deep faults (about 20- to 24-km depths) with moderate (average 30° to 40°) southwesterly dips (Brewer and others, 1983). Thrusting was northward toward the rapidly subsiding Anadarko Basin (Johnson, 1989). During the Early Pennsylvanian to Permian Ouachita and Wichita orogenies, Texas and Oklahoma moved northward and the Wichita Mountains and Amarillo arch were uplifted and thrust over the southern margins of the southern Oklahoma aulacogen and its superimposed basin, the southern Oklahoma trough (Ball and others, 1991). Figure 4 shows the generalized sequence of development from the Precambrian through Permian as the southern Oklahoma aulacogen proceeded from rifting into the Wichita Mountain uplift.

The Ouachita and Wichita orogenies were responsible for (1) folding and faulting of the Ouachita foldbelt in the Midcontinent, (2) subsidence of the Arkoma Basin, (3) emergence of the Amarillo, Wichita Mountain, and Nemaha uplifts;

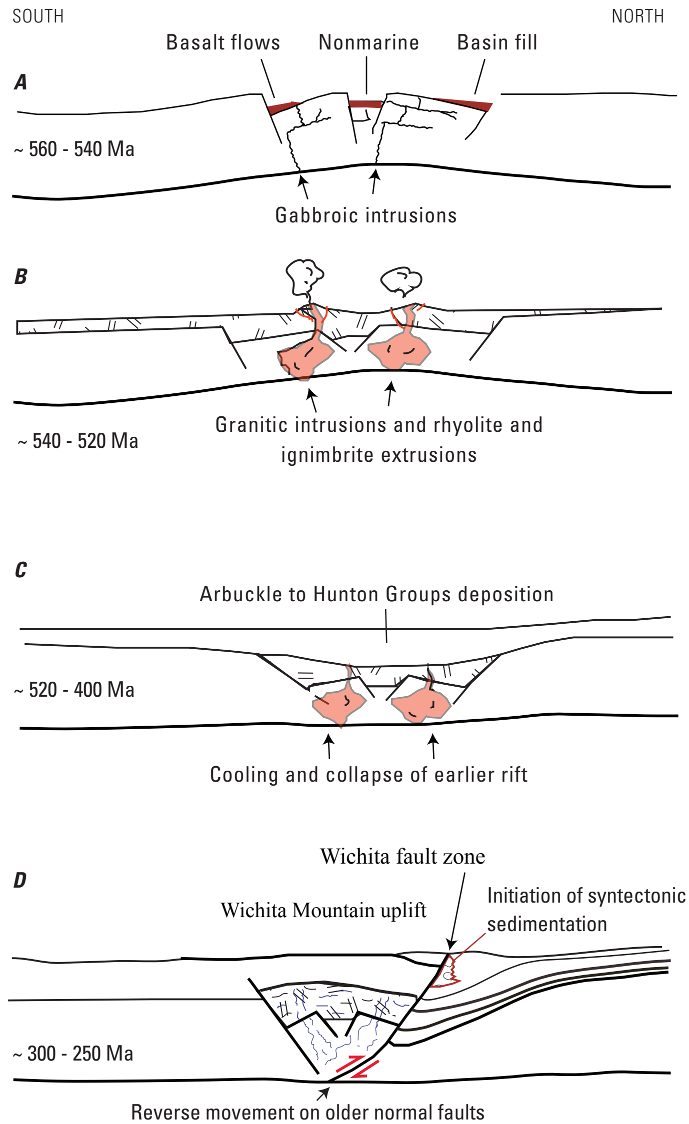


Figure 4. South-north generalized cross sections showing stages of development of the southern Oklahoma aulacogen (*A*, *B*) (modified from Gilbert, 1983; Perry, 1989), southern Oklahoma trough (*C*), and Anadarko Basin and bounding Wichita Mountain uplift and fault zone (*D*).

(4) uplift of the Cimarron arch and structures along the Las Animas arch; and (5) uplift of the Apishapa (Rascoe and Adler, 1983). The Anadarko Basin thus began to assume its present asymmetrical form (Owen, 1975). Associated faulting started at the southeast area of the basin in early Morrowan time (Ham and Wilson, 1967), whereas farther west it began in late Morrowan time; faulting persisted through the rest of the Pennsylvanian and probably died out during the Early Permian (Johnson, 1989). There is some evidence of left-lateral displacement associated with thrusting, but thrusting was most important in developing en echelon folds; strike-slip faulting was relatively minor and late, with most occurring during the Permian (Perry, 1989; Ball and others, 1991).

Pennsylvanian downwarping of the Anadarko Basin was at least partially the result of thrust loading, in contrast with interpretations of Pennsylvanian structures resulting from mainly vertical movements along high-angle faults (Brewer and others, 1983). Maximum structural displacement between the Wichita Mountain uplift and the basin floor exceeds 9,144 meters (m) (30,000 ft) (Al-Shaieb and others, 1994). Downwarping of the basin and compaction through time resulted in increased thickness of strata proximal to the Wichita Mountain and Amarillo uplifts. The Woodford Shale through Desmoinesian interval in particular has a pronounced wedge shape with a northwest-trending axis (fig. 5). Continued Permian filling of the Anadarko Basin following Pennsylvanian thrust loading may have resulted from compaction and dewatering of the thick Upper Mississippian and Pennsylvanian sediments (Perry, 1989). Compaction would have been greatest in the deep basin because these strata were thickest, with associated increased rate of deposition compared to shelf areas.

The current Rocky Mountains formed in the area of the eroded core of the Ancestral Rocky Mountains during the Laramide orogeny of Late Cretaceous and early Tertiary time. The orogeny raised and imparted an eastward and southeastward tilt to the entire region, with associated withdrawal of the Cretaceous epicontinental sea (Owen, 1975; Johnson, 1989) following deposition of the Upper Cretaceous Pierre Shale. Sorenson (2005) indicated that the Laramide orogeny may also

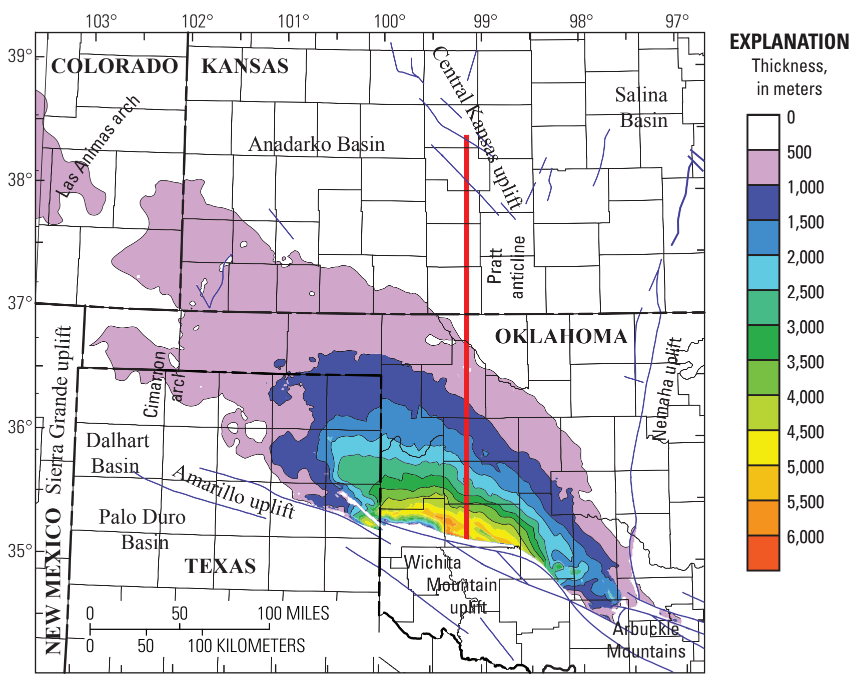


Figure 5. Map showing thickness of strata between the Hunton and Desmoinesian model layers ranges from less than 500 meters (1,640 feet) over most of the Kansas shelf to more than 5,000 meters (16,400 feet) in the deep basin of Oklahoma. This wedge of Woodford Shale and younger rocks is oriented northwest-southeast, similar to that of Woodford Shale thermal maturation contours. Precambrian faults (blue lines) and named structures are from Adler and others (1971).

have influenced petroleum migration in the basin, specifically redistribution of Panhandle field fluid columns with northward spilling of gas into the Hugoton embayment.

Mostly alluvial sediments of the Miocene to Pliocene Ogallala Formation were deposited on an erosional surface of largely Permian, and Mesozoic strata in the western one-half of the basin (Seni, 1980; Johnson and others, 1988). Mesozoic units are present mostly in the Colorado and western Kansas portion of the province, with only scattered erosional remnants in Oklahoma and Texas.

Petroleum Production History

With more than 220,000 drill holes (IHS Energy, 2010a), the Anadarko Basin Province is in a mature state of exploration and development. Horizontal well completions for reported Oklahoma wells increased from less than 5 percent in 2002 to almost 30 percent in 2010 (Boyd, 2011, fig. 6). The Desmoinesian granite wash (Mitchell, 2011) and Devonian–Mississippian Woodford Shale are preferentially completed as horizontal wells. Anadarko is also an old exploration basin, dating back to the early 1900s for the still-productive panhandle, Cement, and numerous other fields (fig. 6). Historical exploration focus was for conventional oil and gas, and exploration is fairly recent for continuous (unconventional) accumulations.

Grouping of stratigraphic units into TPSs and AUs was affected by the quality and distribution of well and production data in the province. Production from most wells in the basin is reported as commingled from multiple units, and reservoir strata are sometimes misnamed. This commingling exists for small and large fields, and can extend across considerable formation ranges, such as for the Cement field of the deep basin in Oklahoma that has produced more than 186 million barrels of oil (MMBO) and 1.3 billion cubic feet of gas (BCFG) from Silurian through Permian strata (IHS Energy, 2010b). The Sooner trend of Oklahoma has yielded more than 334 MMBO, 2.3 trillion cubic feet of gas (TCFG), and no reported water from the Cambrian–Ordovician Arbuckle Group through Virgilian rock units (IHS Energy, 2010b). Produced water is almost exclusively reported for Colorado and Texas, and not for Kansas and Oklahoma. Commingling also influenced populating the Nehring and Associates, Inc. (2009) database on petroleum fields because of the difficulty in assigning production and associated data to rock units. Most Permian production in the Kansas portion of the basin is reported in the IHS Energy (2010b) database as Permian, as opposed to listing the lithostratigraphic unit name(s). As such, data are inadequate to assign production to, for example, the Chase or Council Grove Groups in the Hugoton and Guymon fields that have together produced more than 79 MMBO and 26 TCFG from Wolfcampian and Leonardian reservoirs. Figures 6*A* and 6*B* show oil and gas wells for Pennsylvanian through Permian production in the province; similar maps are presented for the Mississippian AU and other AUs. Although there is extensive well coverage, actual produced volumes and locations are adversely modified by reporting errors and commingling of production from multiple formations.

Mean undiscovered conventional resources that were assessed for Mississippian through Permian strata in the Anadarko Basin Province total 77 MMBO, 1,934 BCFG, and 60 million barrels of natural gas liquids (MMBNGL) (table 1). Oil and gas in the Anadarko Basin were assessed in 1995 (Henry and Hester, 1995) with mean undiscovered resources of 45.7 MMBO and 604.7 BCFG for their Mississippian through Permian plays (5812 through 5827). Primary reasons for the differences between these assessment results include: (1) technological advances have increased recovery of petroleum from existing fields and from undiscovered accumulations; (2) the increased contribution from unconventional (continuous) reserves and resources; and (3) assessment methodology and play/AU boundaries are different for the 1995 and 2011 assessments. For example, the Las Animas arch and Palo Duro Basin were assessed separately in 1995, whereas the Las Animas arch and most of the Palo Duro Basin were included in the Anadarko Basin Province for 2011. Well history and production data quality, although still variable, have improved since the 1995 assessment.

Application of the TPS assessment methodology resulted in mean undiscovered resources for the Mississippian AU of the Woodford Composite TPS of 17 MMBO, 417 BCFG, and 11 MMBNGL. Mean undiscovered oil and gas resources from the 1995 Anadarko Basin assessment totaled 14.0 MMBO and 133.2 BCFG for the Henry and Hester (1995) Lower Mississippian Stratigraphic Oil and Gas, Upper Mississippian Stratigraphic Oil and Gas, and Springer Stratigraphic Oil and Gas plays. Mean undiscovered resources were 4.4 MMBO and 0 BCFG for the Mississippian Carbonate play in the Las Animas arch (Keighin, 1995). Ball and Henry (1995) assessed one play for the Palo Duro Basin, the Upper Paleozoic play that included all Mississippian through Permian strata for which mean undiscovered resources were 4.9 MMBO and 0 BCFG.

Undiscovered oil resources for the Thirteen Finger limestone and Atoka Shale are included with the conventional Morrowan-Atokan AU. Mean undiscovered resources for the Thirteen Finger Limestone–Atoka Shale Gas continuous AU are assessed separately and are 6.850 TCFG and 82 MMBNGL. Undiscovered conventional resources for the Pennsylvanian Composite TPS include:

a. 15 MMBO, 332 BCFG, and 7 MMBNGL for the Morrowan-Atokan AU;

b. 6 MMBO, 118 BCFG, and 4 MMBNGL for the Desmoinesian AU;

c. 23 MMBO, 258 BCFG, and 8 MMBNGL for the Missourian-Permian AU;

d. 16 MMBO, 809 BCFG, and 30 MMBNGL for the Greater Granite Wash Composite AU.

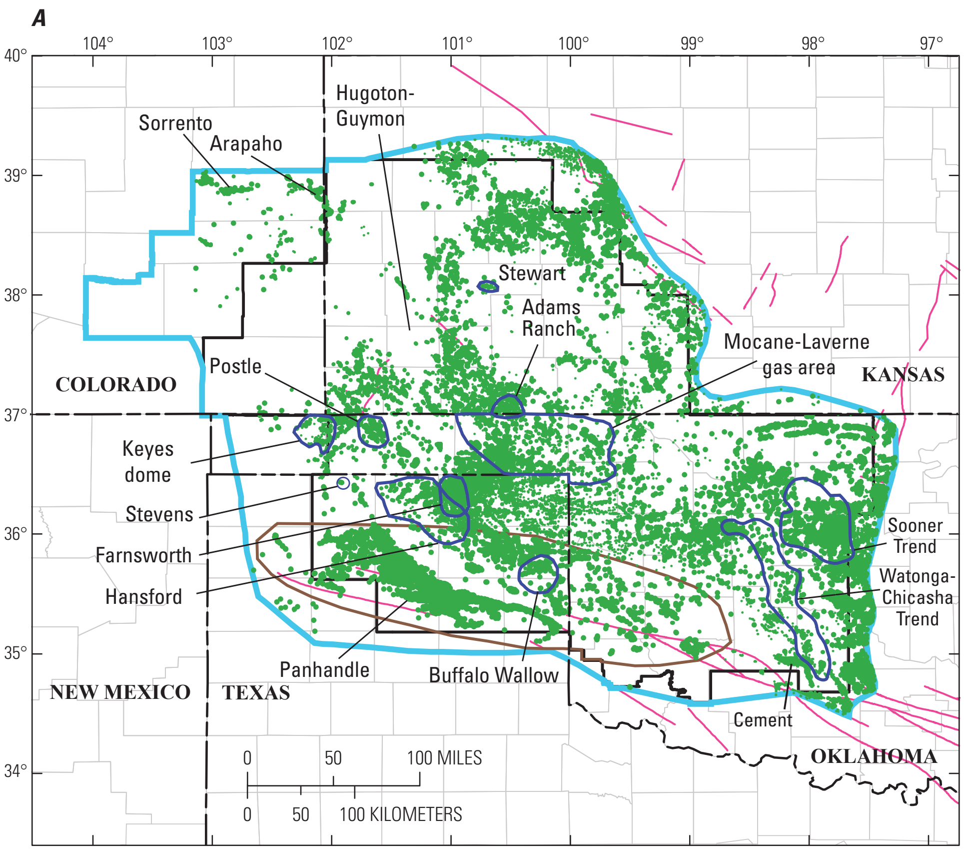
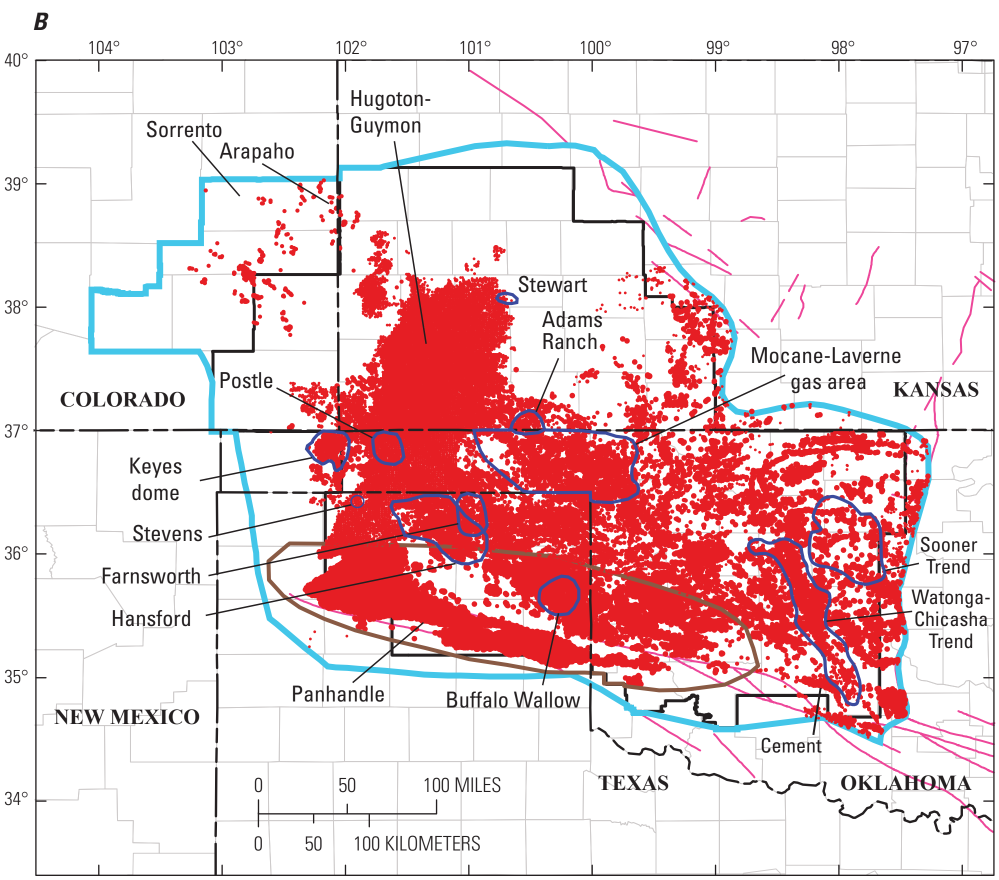


Figure 6. Maps showing *A*, Oil and *B*, gas wells that produce from Pennsylvanian and (or) Permian strata in the Anadarko Basin Province (IHS Energy, 2010a, 2010b). Generalized field locations are from IHS Energy (2010a) and Bebout and others (1993). Also shown are the Greater Granite Wash Composite Assessment Unit (AU) and Pennsylvanian Composite Total Petroleum System (TPS) boundaries. Precambrian faults are from Adler and others (1971).



Petroleum Source Rocks and Thermal Maturity

Petroleum source and potential source rocks in the Anadarko Basin include Ordovician through Missourian marine shale and limestone (fig. 7). Petroleum source rocks and thermal maturation history are discussed more fully in Higley (2014). The Woodford Composite TPS encompasses Ordovician through Mississippian petroleum source rocks and is named for the principal source rock in the province. The Pennsylvanian Composite TPS includes all Pennsylvanian petroleum source rocks. Primary reasons for this generalized TPS division are that (1) geochemical research in the basin has been focused on the Woodford Shale, with lesser information on other possible petroleum source rocks, and (2) the three source rocks with moderate to good hydrocarbon potential (Burruss and Hatch, 1989, p. 57) are the (a) Ordovician Simpson Group shale, (b) Devonian–Mississippian Woodford Shale, and (c) Pennsylvanian black shales. Organic-carbon values for thick shales in the Springer and Morrow Formations range from 0.5 to 3.4 percent; kerogen is Type III, indicating that it is mostly gas prone (Rice and others, 1989). Atokan, Desmoinesian, and Virgilian petroleum source rocks are mainly Types II and III kerogen (Rice and others, 1989). Figure 2 displays the Morrow as Morrow Group in western Kansas, and as Morrow Formation in the northern and southern Anadarko Basin; it is referred to as Morrow Formation in this report. The Atoka interval has group status in the Hugoton embayment and northern Anadarko Basin, and is the Atoka Shale and Pumpkin Creek Limestone of the Dornick Hills Group in the deep basin (fig. 2). It will be called Atoka Group in this chapter of the report. Discussions of Atoka shale refer to included shale intervals.

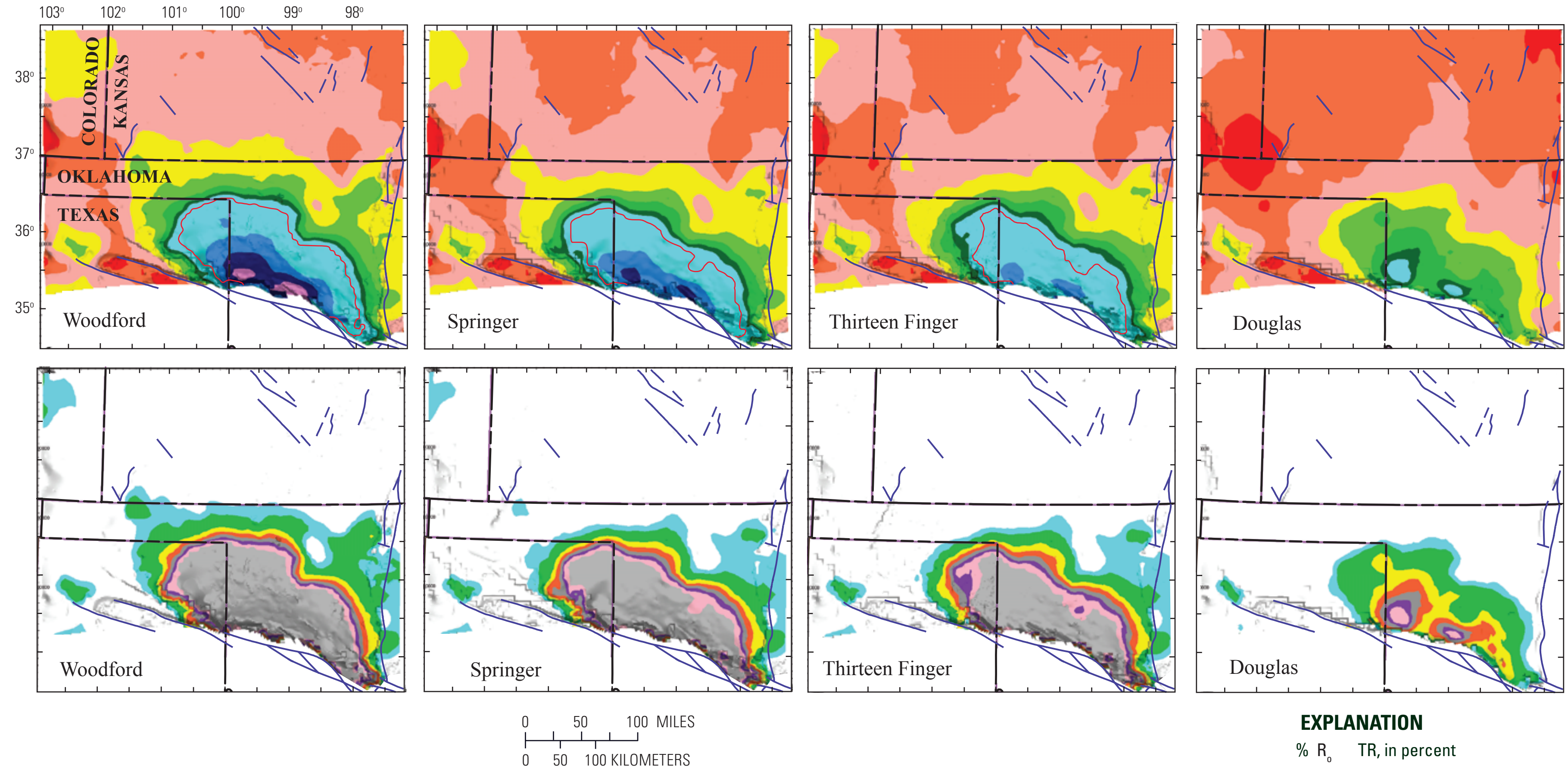
The three highlighted zones in figure 7 correspond to assigned hydrocarbon source rocks in the 4D petroleum system model. These generalized source intervals were chosen and based partly on the Burruss and Hatch (1989) determination of three oil types in the Anadarko Basin; their analyzed crude oils appeared to correlate with extracts from Ordovician, Devonian, and Pennsylvanian source rocks. The Atokan Thirteen Finger limestone was chosen to represent the Pennsylvanian hydrocarbon source rocks because the thickness and extent of this high gamma interval across the province. Morrowan black shales compose as much as 60 percent of the Morrow Formation in the Oklahoma portion of the province (Wang and Philp, 1997), but it would have been more difficult to define and map a specific petroleum source interval within the Morrow Formation across the basin.

Timing of generation, migration, and accumulation of oil and gas are derived from the Higley (2014) petroleum system models (fig. 8, table 2). Schlumberger (2011) PetroMod® software was used for 1D and 4D petroleum system models. Within the Ordovician Simpson Group Oil Creek, Devonian-Mississippian Woodford, and Atokan Thirteen Finger petroleum source rocks in the 4D model, the Oil Creek Formation primarily sources Cambrian through Ordovician petroleum accumulations, the Woodford Shale is the major source for Devonian, Mississippian, and lower Morrowan accumulations, and the Thirteen Finger limestone is the main source for middle Morrowan through Permian accumulations (Higley, 2014). As is shown in figure 7, numerous other petroleum source rocks across the basin are potential contributors to reservoirs. 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® software. This means that underlying layers are displayed if the modeled unit(s) has limited lateral extent. Model construction is discussed in Higley (2014) and Higley and others (2014b). Figure 8 shows modeled vitrinite reflectance (R_o) and transformation ratio (TR) 3D images at present day for the Woodford through Douglas model layers that contain the source rocks that contributed oil and gas for Mississippian through Permian reservoirs. The TR maps record the beginning to the end of oil generation based on hydrous pyrolysis (HP) kinetics, and the R_o images show assigned

Table 2. Oil generation onset for the Anadarko Basin 4D model, and onset and completion dates in millions of years before the present (Ma) for the Bertha Rogers 1 and Petree Ranch 1 1D models based on Woodford Shale hydrous pyrolysis (HP) kinetics (Lewan and Ruble, 2002). The Douglas Group overlies the youngest potential petroleum source rocks in figure 7. The HP kinetics-based onset of oil generation is 0.1 percent transformation ratio (TR) and completion is 99 percent TR. Oil generation histories in the 4D model were recorded at 10-Ma 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		

Figure 7. Generalized stratigraphic column for the Anadarko Basin Province, with hydrocarbon source rocks highlighted (brown text). Increases in source rock potential are indicated by larger numbers. The expected hydrocarbons column heading indicate whether the source rock is more oil or gas prone. Blue highlights source intervals used in the four-dimensional petroleum system model. Vertical lines show a generalized time range of unconformity from Bebout and others (1993, fig. 5). Chart is from J. Hatch (oral commun., 2010, and modified from Burruss and Hatch (1989). Gp., Group; Fm., Formation.



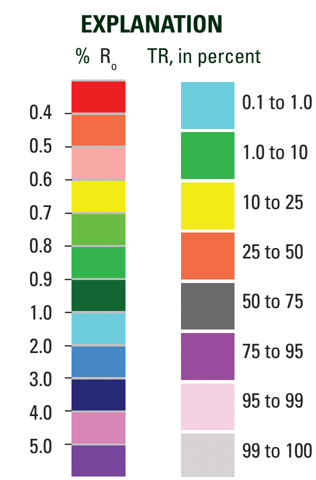


Figure 8. Images showing present-day thermal maturation of Woodford to Douglas model layers using Woodford HP transformation ratio (% TR) kinetics (Lewan and Ruble, 2002) and vitrinite reflectance (% R_o) (Sweeney and Burnham, 1990). Each layer extends across the study area, including units located outside of the petroleum source rocks. As an example, the Kansas portion of the Springer and Thirteen Finger layers are almost identical because these units are absent over much of this area and the thermal maturity reflects that of the underlying mostly Viola and Simpson Groups strata. The vitrinite reflectance contours in equivalent layers in chapter 3 (fig. 26) are limited to the extent of those strata, and also exhibit slightly different thermal maturation patterns, which largely represents a somewhat newer version of the model. Changes in thermal maturity on the shelf areas of Kansas and Colorado are also minor because of shallow burial relative to the deep basin of Oklahoma and Texas; source rocks are mostly immature for oil generation at less than 0.6% R_o. Thermal maturity for source rocks in the deep basin of Oklahoma and Texas ranges from mature for oil generation, to overmature for gas generation at about 4% R_o and greater. Red contour lines on the R_o images mark the 99 percent transformation ratio that is approximately equivalent to 1.2% R_o. Precambrian faults (Adler and others, 1971) are shown as blue lines.

levels of maturation based on Sweeney and Burnham (1990) algorithms. The respective R_o and TR values in figure 8 are not identical, but the good agreement of levels of thermal maturation is largely because of calibrating the model to available downhole temperature and thermal maturation data. Primary conclusions from the images are (1) thermal maturity of Oklahoma and Texas ranges from immature for oil generation to overmature for gas generation, although production of gas from the deep basin indicates all or most of the area is within the limit of gas preservation; (2) the Colorado and Kansas portions of the province are almost exclusively immature to marginally mature for oil generation. Elevated thermal maturation in Colorado is associated with elevated basement heat flow (Higley, 2014); (3) the Douglas layer represents lower Virgilian strata, that are younger than the petroleum source rocks in figure 7, but if this layer contains source rocks in the deep basin they would mainly be immature to mature for oil generation; and (4) the primary factor that controls the degree of thermal maturation is depth of burial, which is mainly why the Woodford Shale is mature for oil and gas generation over a larger area than shallower units.

Reservoir Rocks

Mississippian Assessment Unit

A broad epicontinental sea extended across most of the southern Midcontinent from Late Cambrian through Mississippian time (Johnson and others, 1988). The Anadarko Basin Province area was a broad embayment that received a thick sequence of carbonates interbedded with thinner shales and sandstones (Johnson, 1989). Mississippian strata in the province are mainly limestones, cherty limestones, and shales that were deposited in shallow-marine environments (Craig and others, 1979; Frezon and Jordan, 1979; Mapel and others, 1979; Johnson and others, 1988). Thickness of the Mississippian is greatest in the deep basin of Oklahoma and Texas, where the Chesterian section can exceed 5,000 ft in thickness, and pre-Chesterian Mississippian rocks can be more than 2,000 ft thick (Adler and others, 1971). Craig and Connor (1979) indicated the total thickness of the Mississippian section along the northern shelf is about 1,000-2,000 ft. The Mississippian isopach (fig. 9) exhibits southeastward thickening from the Kansas and Colorado shelf to the deep basin. The irregular contours partly represent variations that resulted from subtracting the Mississippian and Woodford structure grids (layers) and (or) areas of poor data control.

Erosion of Springer Formation strata (fig. 2) over the Nemaha uplift resulted from pre-Pennsylvanian orogenic uplift (Johnson, 1989). The crest of the uplift has Precambrian and pre-Pennsylvanian rocks unconformably overlain by Desmoinesian and Missourian strata (Rascoe and Adler, 1983). Perry (1989) indicated that initial evidence of late Paleozoic tectonism is the abrupt pinchout of Springer strata in the adjacent western Ardmore Basin. This epeirogenic event caused gentle, widespread uplift and erosion over the Midcontinent; Mississippian and older Paleozoic rocks were eroded from the Cambridge arch, north of the province, and parts of the CKU, and from shelf areas bordering the Anadarko Basin and Arkoma Basin, to the east (Rascoe and Adler, 1983).

The angular unconformity that resulted from the Late Mississippian epeirogeny, separates Mississippian carbonate strata from the overlying Morrow Formation (Bowen and Weimer, 2003), except in the deep part of the basin where they conformably overlie lithologically similar Springer strata (Johnson, 1989). Because of the lithologic similarities, it can be difficult to determine the Springer-Morrow contact in the basin (Johnson, 1989). Keighin and Flores (1989) identified three depositional facies for the Springer and Morrow Formations that include (1) fluvial-influenced coastal (FIC), (2) tidal-influenced nearshore (TINS), and (3) mixed tidal and non-tidal marine influence (MT/NTM).

The Mississippian AU extends across the province, with petroleum production from Kinderhookian through Chesterian strata. Reservoir rocks are mostly Lower Mississippian carbonates through Upper Mississippian sandstones and carbonates. Mississippian oil and gas wells are shown in figure 10. Springer Formation oil and gas are produced from thrust fault-bounded blocks on the northern flank of the Wichita Mountain uplift (Alder and others, 1971). Potential resources on the uplift should be predominantly oil because of shallower burial than the adjacent Anadarko Basin. There is also scattered petroleum production on and parallel to the Nemaha uplift. Horizontal drilling in Mississippian strata includes oil and gas wells (IHS Energy, 2012). Sixty percent of the 276 horizontal wells in the province were completed after 2010; these are scattered within existing fields and also include lightly explored areas close to the eastern Kansas/Oklahoma border in the province (fig. 10*A*). Horizontal wells completed in 2010 or later were not incorporated into the Higley and others (2011) assessment of undiscovered resources in the province; this is about 80 percent of the wells. Mississippian cumulative production across the basin is mainly oil with more than 1.16 BBO, 15.9 TCFG, and 277 million barrels of water (MMBW) from more than 29,000 leases in 2,357 fields (IHS Energy, 2010a, 2010b). Water production was reported only for Colorado and Texas. Exploration and development started early for Mississippian reservoirs (fig. 11). The earliest exploration for petroleum in the basin was the Cement field in 1917 (fig. 6), a faulted anticline in the deep basin that has produced oil and gas from Cambrian through Permian reservoirs (Davis and Northcutt, 1989). Exploration and development increased in the late 1950s with a continuing upward trend.

Discovery-thirds plots show the distribution of first, second, and third thirds of completion dates for Mississippian oil and gas fields. The division into thirds is based on early field discoveries frequently being the largest oil and gas accumulations, with later field sizes being smaller. Discovery thirds is also based on mathematically grown, as opposed to known, sizes of accumulations. This is incorporated because initial reserves of conventional accumulations are commonly

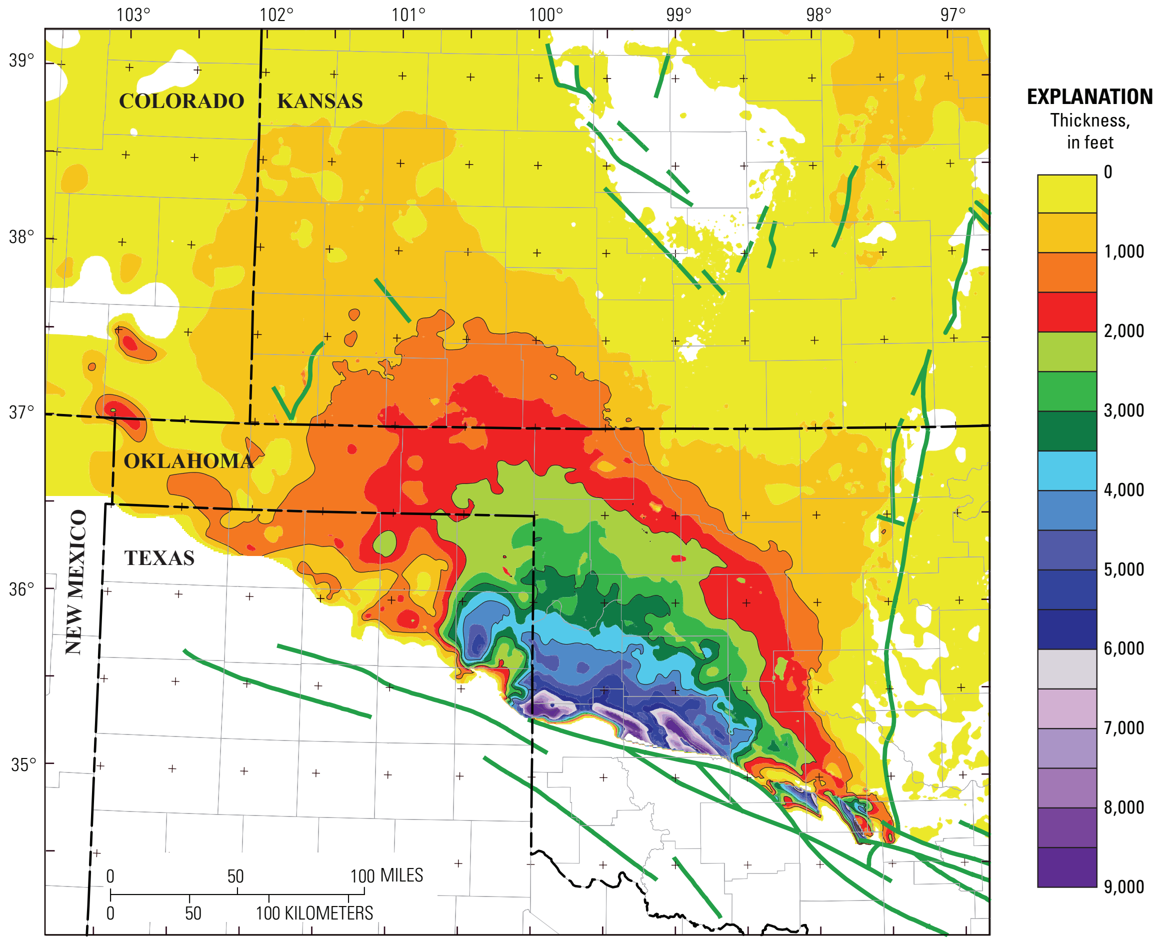


Figure 9. Isopach map of Mississippian to Woodford petroleum system model layers, which approximates the thickness of Mississippian rocks across the study area. Blank areas indicate missing strata or insufficient data. Extent of the Woodford Shale is approximated by the Woodford Shale Oil AU boundary in figure 1. Irregular contours are mainly because of subtraction of these unfiltered (unsmoothed) layer grids. Precambrian faults (green lines) are from Adler and others (1971).

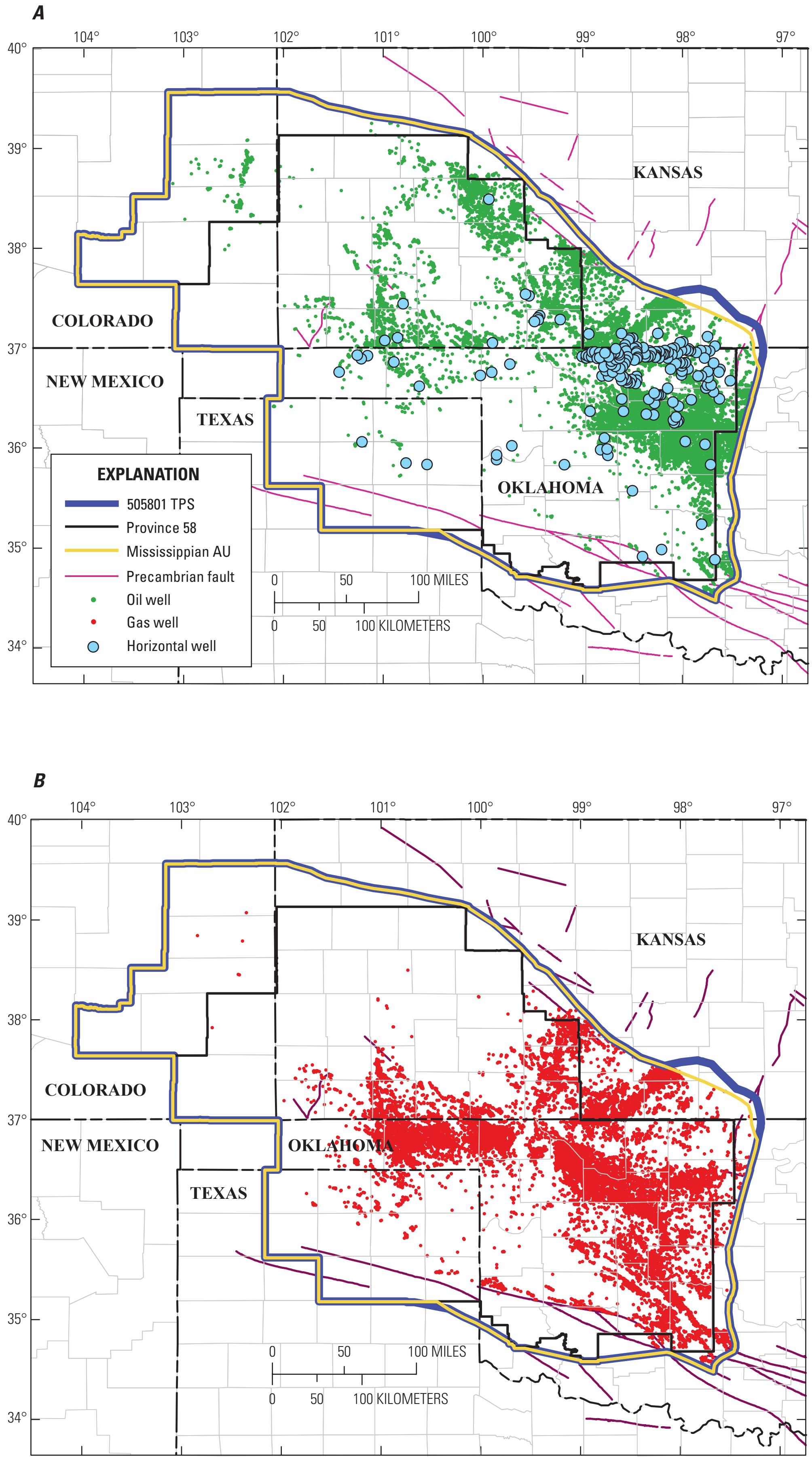


Figure 10. Maps showing *A*, Oil and *B*, gas wells that produce from the Mississippian AU in the Anadarko Basin Province (IHS Energy, 2010b). Also shown in figure 10A are 276 horizontal wells drilled into Mississippian strata; 166 of these were completed after 2010 (IHS Energy, 2012).

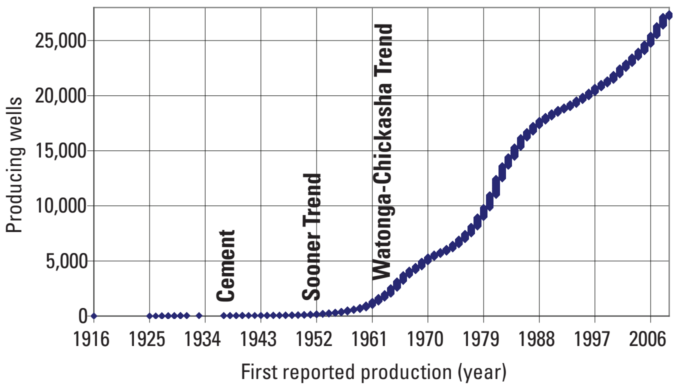


Figure 11. Cumulative number of producing wells by year for the Mississippian AU (IHS Energy, 2010a, 2010b). Some of the wells include production from units other than Mississippian. Onset of production from this AU for several major fields is also shown. Locations are in figure 6.

underestimated. The development success of an AU is measured by sizes of accumulations through time. The Mississippian AU discovery thirds oil and gas production plots show that, even with the mature status of exploration, that the latest discoveries exhibit similar grown accumulation sizes to the early and middle discoveries (fig. 12). This indicates that the AU has continuing potential for resources, even considering its fairly mature exploration status. The discovery trends also continue from the smallest to the largest accumulations. Discovery thirds for oil and gas accumulations (fig. 12) (Nehring and Associates, Inc., 2009) only show a few of the fields that produce from Mississippian units. Shown fields should produce oil and gas almost exclusively from the Mississippian, with lesser reported commingled production from other units.

Trapping mechanisms for the AU are structural, stratigraphic, and a combination of the two. Structural traps are evidenced by the linear trends of some of the oil and gas production in the deep basin, proximal to the greatest thickness of Mississippian strata. This is also the area that is overmature for oil generation, but is within the gas generation and preservation windows (Higley, 2014). Probable Mississippian petroleum source rocks include strata within the informal Osage lime and Springer Formation (fig. 7). Organic-carbon values for thick shales in the Mississippian Springer and Pennsylvanian Morrowan producing intervals range from 0.5 to 3.4 wt %; however, the kerogen is mostly Type III indicating that it is primarily gas-prone (Hatch and others, 1986; Rice and others, 1989) (fig. 2). Mississippian oil generally

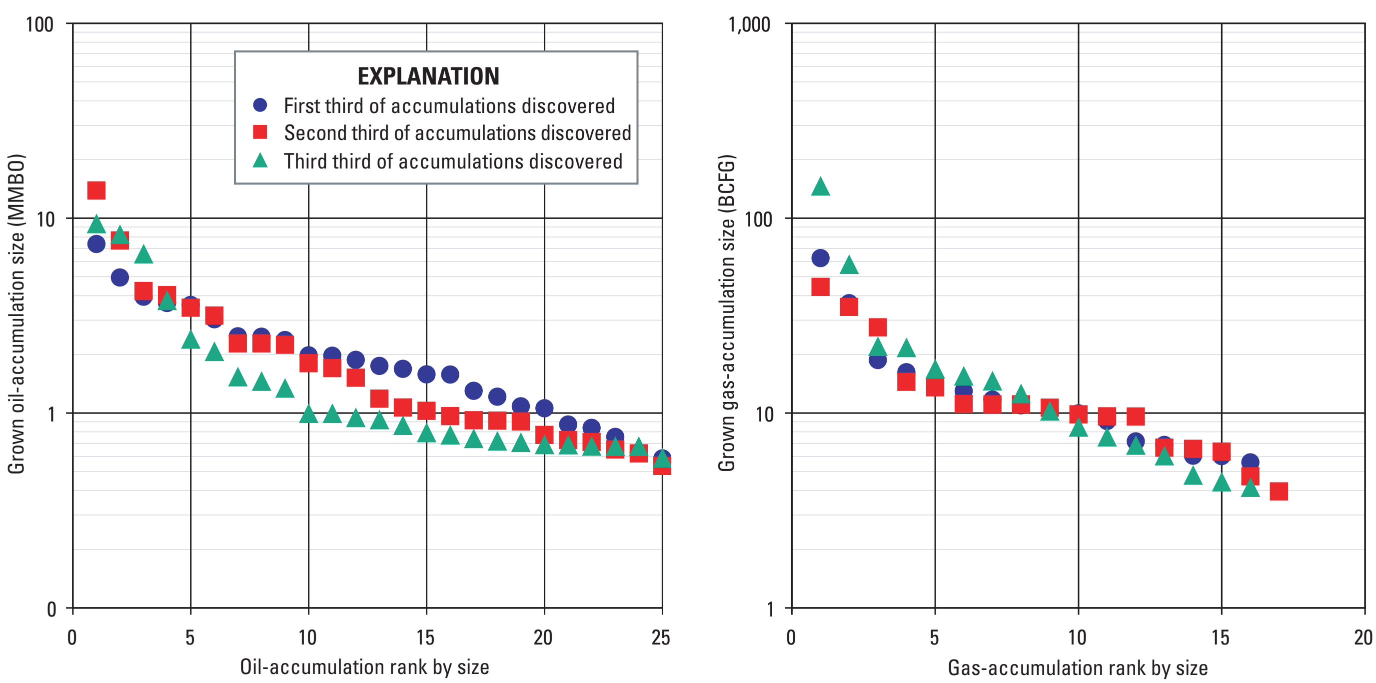


Figure 12. Grown gas and oil accumulation sizes for discovery thirds of the Mississippian Assessment Unit of the Woodford Composite Total Petroleum System. Although this is a mature assessment unit, the oil accumulations only show a minor drop for the third of discoveries, and the gas accumulation history is stable. Data are from the Nehring and Associates, Inc. (2009) field database, which has limited information for the Mississippian fields. MMBO, million barrels of oil; BCFG, billion cubic feet of gas.

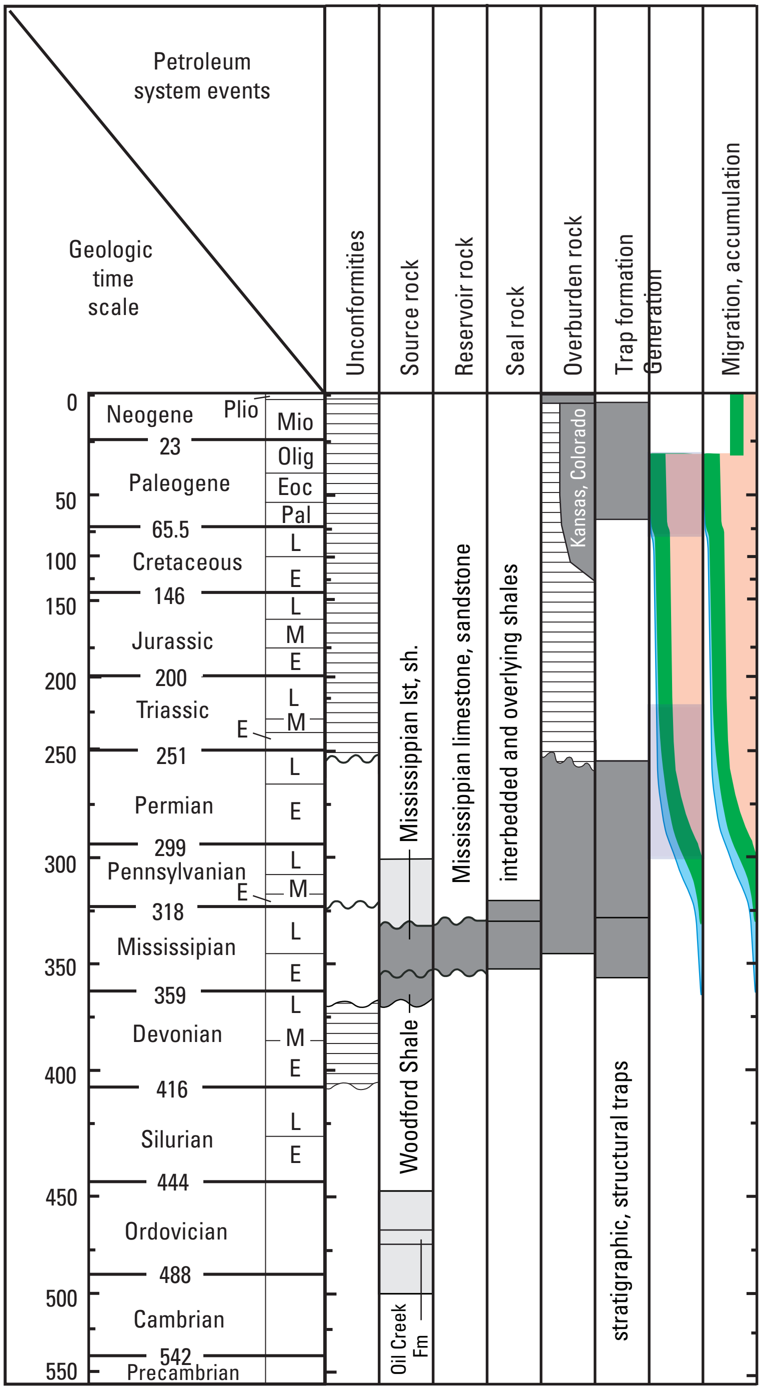


Figure 13. Petroleum system events chart for the Mississippian Assessment Unit of the Woodford Composite Total Petroleum System. Timing of oil and gas generation, migration, and accumulation is based primarily on Higley (2014) petroleum system models. Potential petroleum source rocks (fig. 7; Hatch and others, 1986) are light gray rectangles. Primary petroleum source rock for the Mississippian AU is the Woodford Shale (Rice and others, 1988a, 1988b; Higley, 2014). The informal Osage lime and Springer Formation are potential petroleum sources for the AU. Times of peak generation from the Oil Creek Formation (blue), Woodford Shale (green) and Thirteen Finger limestone (tan) source rocks are within blue shaded rectangles. Paleogene trap formation, migration, and accumulation are based on Laramide generation and potential remigration associated with erosion and basin tilting. Unconformities, wavy and horizontal lines; lst, limestone; sh., shale; Fm., Formation; Plio, Pliocene; Mio, Miocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

correlates with extracts of the Woodford Shale (Rice and others, 1988a, 1988b). The underlying Woodford Shale is also the predominant petroleum source rock for the Mississippian AU based on petroleum system modeling (Higley, 2014). Associated gases from Silurian, Devonian, and Mississippian carbonates from the Sooner trend were from depths as great as 9,678 ft (2,950 m) and were generated from Type II kerogen; gases are isotopically lighter (mean $\delta^{13}C_1$ value is -43.9 percent) and chemically wetter (mean C_{2+} value is 14 percent) than those derived from Type III kerogen at equivalent levels of thermal maturity (Rice and others, 1988a, 1988b). The petroleum system events chart for the Mississippian AU (fig. 13) shows time periods of source, reservoir, seal, and overburden strata, and trap formation. Timing of generation, migration, and accumulation of oil and gas are derived from Higley (2014) petroleum system models (fig. 14, table 2).

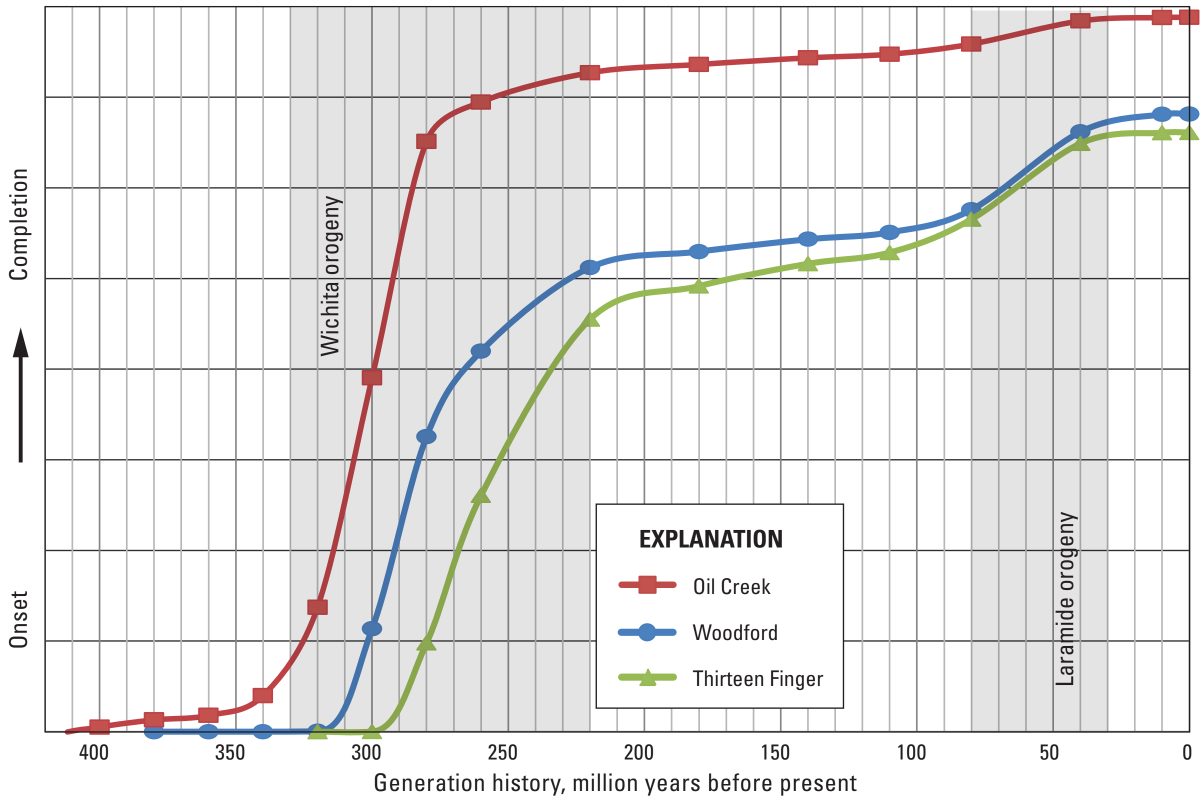


Figure 14. History of petroleum generation from the Oil Creek Formation, Woodford Shale, and informal Thirteen Finger limestone source layers in the four-dimensional (4D) petroleum system model. History is based on Woodford hydrous pyrolysis kinetics (Lewan and Ruble, 2002). Gray bars delineate periods of peak generation. Early oil generation from the Oil Creek layer, prior to about 370 million years ago, is in a narrow band that is proximal to the Wichita Mountain uplift. This band exceeds maximum depth of the formation and is because of areas of poor data control in the area bordering the fault zone. The error could have been removed by clipping the 4D model extent to the basin axis and northward, but less of the model would have been visible and usable.

Morrowan-Atokan Assessment Unit

The boundary of the Pennsylvanian Composite TPS (505802) and contained Morrowan-Atokan AU (50580201) are shown in figure 1. The AU approximates the extent of the contained assessed Morrow Formation and Atoka Group (fig. 2). The Colorado portion is limited by TPS and AU boundaries of the adjacent Denver Basin Province, for which Paleozoic AUs were assessed in 2002 (Higley and Cox, 2007; Higley and others, 2007).

By Early Pennsylvanian, as much as 10,000 ft (3,050 m) of Springer-Morrow and Atoka sediments were deposited in the basin (Rascoe and Adler, 1983; Al-Shaieb and others, 1994). The Morrow and Atoka Groups are each as much as 4,000 ft thick in the deep Anadarko Basin, thinning northward onto the shelf (Adler and others, 1971; Johnson, 1989). By the end of Permian time, more than 20,000 ft of Pennsylvanian and Permian sediments were deposited in the deep Anadarko Basin (Jorgensen, 1989). Morrowan and Atokan strata were deposited on a broad low-relief shelf in Colorado and Kansas, and a subsiding deep basin in the Oklahoma and Texas portions of the province (figs. 3 and 15). The approximate Atokan onset of the Cimarron arch (fig. 5) is characterized by Morrowan rocks unconformably overlain on the crest by lower Desmoinesian strata (Rascoe and Adler, 1983). Lower Morrow strata pinch out along the flanks of the arch, but deposition of overlying Morrow sediments was associated with marine influx (Abels, 1959).

Morrow Formation and Atoka Group reservoirs are mostly marine and nonmarine sandstone and calcareous sandstone, with lesser limestone beds. Morrow Formation sediment supply was from the Sierra Grande uplift, Ancestral Rocky Mountains, Nebraska, and CKU (Swanson, 1979). The lower Morrow Formation consists of shallow-marine shales, sandstones, and limestones that were deposited under transgressive conditions and onlap the eroded Mississippian

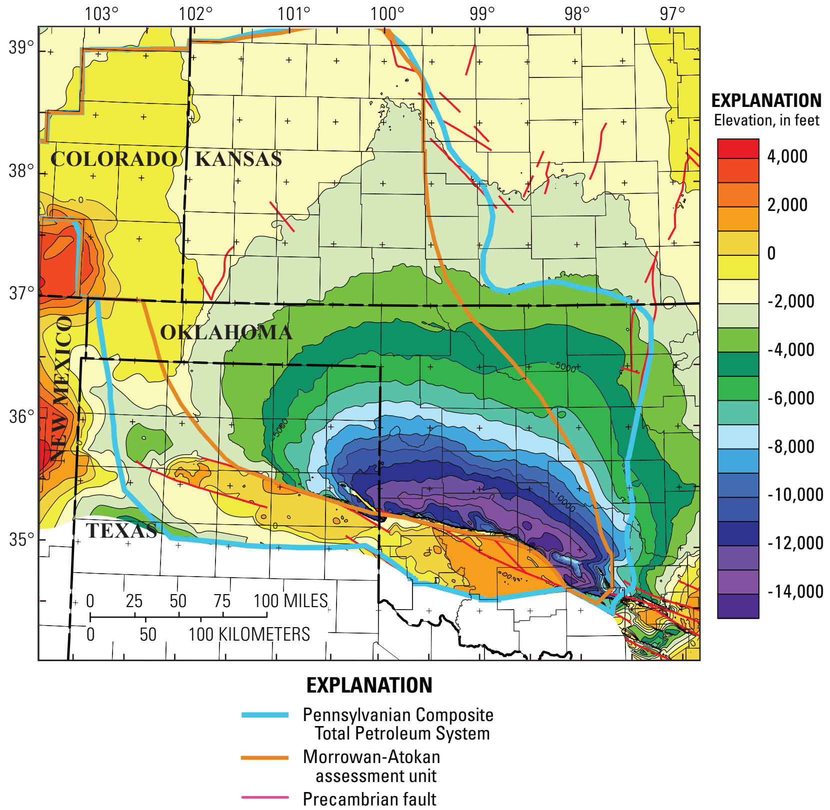


Figure 15. Map showing elevation on the top of the Atoka model layer. Extent of Morrowan and Atokan strata within the Pennsylvanian (Penn.) Composite Total Petroleum System (TPS) is approximated by the Morrowan-Atokan Assessment Unit (AU) boundary and in figure 3 elevation of the basal Thirteen Finger limestone. Elevation is relative to sea level. Precambrian faults are from Adler and others (1971).

rocks toward the north and northeast (Johnson, 1979). Upper Morrow strata in the western part of the basin were primarily a deltaic sequence that prograded toward the southeast, resulting in deposition of mainly shales with lenticular, discontinuous sandstones, minor conglomerates, and thin coals and limestones (Swanson, 1979). Abels (1959) identified thin coal beds in the upper third of the Morrow Formation in the panhandle area of Texas and Oklahoma, and in southwestern Kansas. This area is mainly thermally immature for oil generation, so it is unlikely that the coals would have provided thermogenic natural gas.

The Morrowan on the shelf is characterized by marine to fluvial "clean, relatively well-sorted, non-glauconitic, and non-calcareous sandstone" (Adams, 1964), and the Hugoton field, Panhandle field, and Las Animas areas are mainly fluvial and shoreline sandstone reservoirs (Al-Shaieb and Walker, 1986). Bowen and Weimer (2003) described a compound incised-valley fill in western Kansas and eastern Colorado that contains three facies tracts with unique reservoir characteristics: (1) an updip facies tract of predominantly amalgamated fluvial channel sandstones overlies (2) a transitional facies tract of fluvial channel sandstones and interbedded finer-grained estuarine sandstones, and (3) a downdip facies tract of fluvial channel sandstones isolated in estuarine shale. Traps in their study are combination, structural, and stratigraphic; the structural component is where valley-fill deposits cross anticlines, or the trend of the valley-fill deposits bends against structural strike. Reservoir compartmentalization can result from erosional truncation and subsequent deposition of strata, and lateral facies change from shale to sandstone in these elongate accumulations.

Morrowan strata in the deep basin were deposited in low-energy environments and consist primarily of argillaceous, poorly sorted, glauconitic, calcareous sandstone (Rascoe and Adler, 1983). The lower permeability and depth of the deep-basin sandstones are associated with decreased exploration and development. These strata are also overpressured with gradients that exceed the normal 0.465 psi/ft gradient as part of the sealed megacompartment complex of Al-Shaieb and others (1994). Morrowan and Atokan intervals exhibit approximately normal pressure on the shelf.

Atokan strata consist of a series of southward-thickening marine shales, sandstones, and limestones that are about 50–200 ft thick in the northern and western parts of the Anadarko Basin (Johnson, 1989). Atokan strata tend to grade laterally into granite wash lithofacies close to the Wichita Mountain uplift, making well-log picks more difficult. The Morrow Formation is disconformably to gradationally overlain by Atokan Thirteen Finger limestone. Morrow and Atoka reservoir seals are primarily overlying and interbedded shales that help create the primarily stratigraphic traps in the province. Morrow Formation sandstones account for most of the pre-Permian oil and gas production in the basin (Davis and Northcutt, 1989). Morrowan plus Atokan production from almost 20,000 leases in 1,461 fields in the AU is approximately 850 MMBO, 26.08 TCFG, and 418.39 MMBW (IHS Energy, 2010a, 2010b).

Almost all reported water production in the province is from Colorado and Texas. Average production per well was about 51.8 thousand barrels of water (16,273 wells) and 1.5 BCFG (18,491 wells); average gas-oil ratio (GOR) for 12,865 wells is 3,530 MCFG/BO (IHS Energy, 2010a, 2010b). Morrow Formation reservoirs in western Kansas and eastern Colorado are largely valley-fill sequences that developed when extensive river systems incised the exposed marine shelf during relative lowstands, and have produced more than 100 MMBO and 500 BCFG (Bowen and Weimer, 2003). Best quality reservoirs are medium- to coarse-grained fluvial sandstones with porosities ranging from 18 to 28 percent and permeabilities of 0.5 to 2.0 Darcy; overlying estuarine reservoirs contain 8 to 18 percent porosity and 10 to 500 millidarcies (mD) permeability (Bowen and Weimer, 2003). An area that also includes the Oklahoma Panhandle and northern Texas produced more than 200 MMBO and 8 TCFG from updip fluvial to deep-water marine strata (Bowen and Weimer, 2004). Production from the Atoka Group (including the Thirteen Finger limestone) is 27 MMBO and 1.7 TCFG (IHS Energy, 2010a, 2010b).

Cumulative production numbers are approximate for the Morrow and Atoka, as well as most other reservoirs in the basin, because of extensive use of multiple completions and reporting of commingled production for multiple units. The first Morrow discovery was from Keyes dome (fig. 6) in 1943, which produced 1.7 MMBO and 500 BCFG through 1985 from the lower Morrow Formation Keyes sand (fig. 2) (Davis and Northcutt, 1989; Oklahoma Geological Survey (OGS) 2011a, fields discovery wells database (FDW). The Watonga-Chickasha trend (figs. 6 and 17), discovered in 1960 in Blaine County, Oklahoma, includes reservoirs of Atokan, Morrowan, and Springer age; production through 1985 was 44 MMBO and 1.8 TCFG from sandstones in varied trap types (Davis and Northcutt, 1989). Since about 1955 trends in drilling and production have been relatively stable, even with the fairly extensive exploration and development of this AU. The discovery thirds of oil and gas fields are shown in figure 18. Discoveries in 1969 through 1978 of the (second thirds) Buffalo Wallow, Stiles Ranch, Allison-Parks, and Briscoe fields increased the associated discovery rate for 200 BCFG discoveries.

The petroleum system events chart for the Morrowan-Atokan AU (fig. 19) shows time periods of petroleum source, reservoir, seal, and overburden strata, and trapping. Timing of generation, migration, and accumulation of oil and gas are derived from Higley (2014) petroleum system models (table 2). Onset of oil generation from potential Morrowan source rocks (fig. 7) would be slightly older than the 300-Ma age of the Thirteen Finger limestone on table 2.

Thirteen Finger Limestone–Atoka Shale Gas Assessment Unit

This is a continuous gas AU. Its boundary was determined based on the areal extent of the informally named Thirteen Finger limestone and overlying Atoka shale (fig. 2) of the Atoka Group (fig. 20), combined with the area that is thermally mature for gas generation based on petroleum system modeling by (fig. 20). Estimated oil resources for the Thirteen Finger limestone and Atoka shale were included as part of the Morrowan-Atokan AU assessment. Thirteen Finger limestone thickness contours that are outside the limits of the Morrowan-Atokan AU shown in figure 20 are extrapolated outside areas of data control. Top, base, and extent of the Thirteen Finger limestone are based mainly on examination of 125 wells across the basin. Elevation on the top of the unit ranges from about -4,000 ft on the shelf areas of Colorado and Kansas to -17,000 ft in the deep basin area of Oklahoma and Texas (fig. 3). Average thickness is 95 ft, and the greatest thickness is in the deep basin and trending northwest toward Colorado (fig. 20). Also shown in figure 20 are locations of figure 21 cross sections.

The Thirteen Finger limestone across the Anadarko Basin Province comprises 75 to 100 ft (23 to 30 m) of cyclical thin marine limestones and shales (Rascoe and Adler, 1983). The “fingers” name is because of its stacked thin shale and carbonate beds with irregular high gamma kicks of 140 American Petroleum Institute (API) and greater on well logs over most of its extent (fig. 21). The Carr and Hentz (2009) described the unit as fissile, organic-rich shale interbedded with fossiliferous wackestones that represent a third-order transgressive systems tract; the thickest, most organic-rich shale in the Atoka, at the top of the unit, is inferred to represent a third-order marine condensed section. They indicated that a third-order highstand systems tract downlaps this condensed section and contains several progradational parasequences that are capped by “conventional” Atoka limestone and dolomite reservoirs. The thin carbonate beds in the basal Atokan Thirteen Finger limestone (fig. 2) are potential reservoirs that are overlain by Atoka Formation shales. The basal Atoka shales that exhibit gamma signatures of greater than 140 API in well logs in areas of the basin, suggest elevated levels of organic matter (fig. 21).

The Thirteen Finger limestone can be correlated across the extent of the underlying Morrow Formation in the province, except where proximal to the Wichita Mountain uplift. This is primarily the result of tilting of strata and increased contribution of clastic sediments relative to that of organic matter. Gamma response in wells in cross section *B–B’* are more pronounced than those in *A–A*’, which suggests less organic matter in the deep basin. Source rocks in *A–A*’ are thermally mature for oil and (or) gas generation, which would deplete the TOC and HI values. Gamma response of the overlying Atoka Group is unremarkable in the *A–A*’ cross section but the *B–B*’ response is similar to that of the Thirteen Finger limestone. The Atoka Group source interval differs in that it is primarily shale, rather than thin limestone and shale beds.

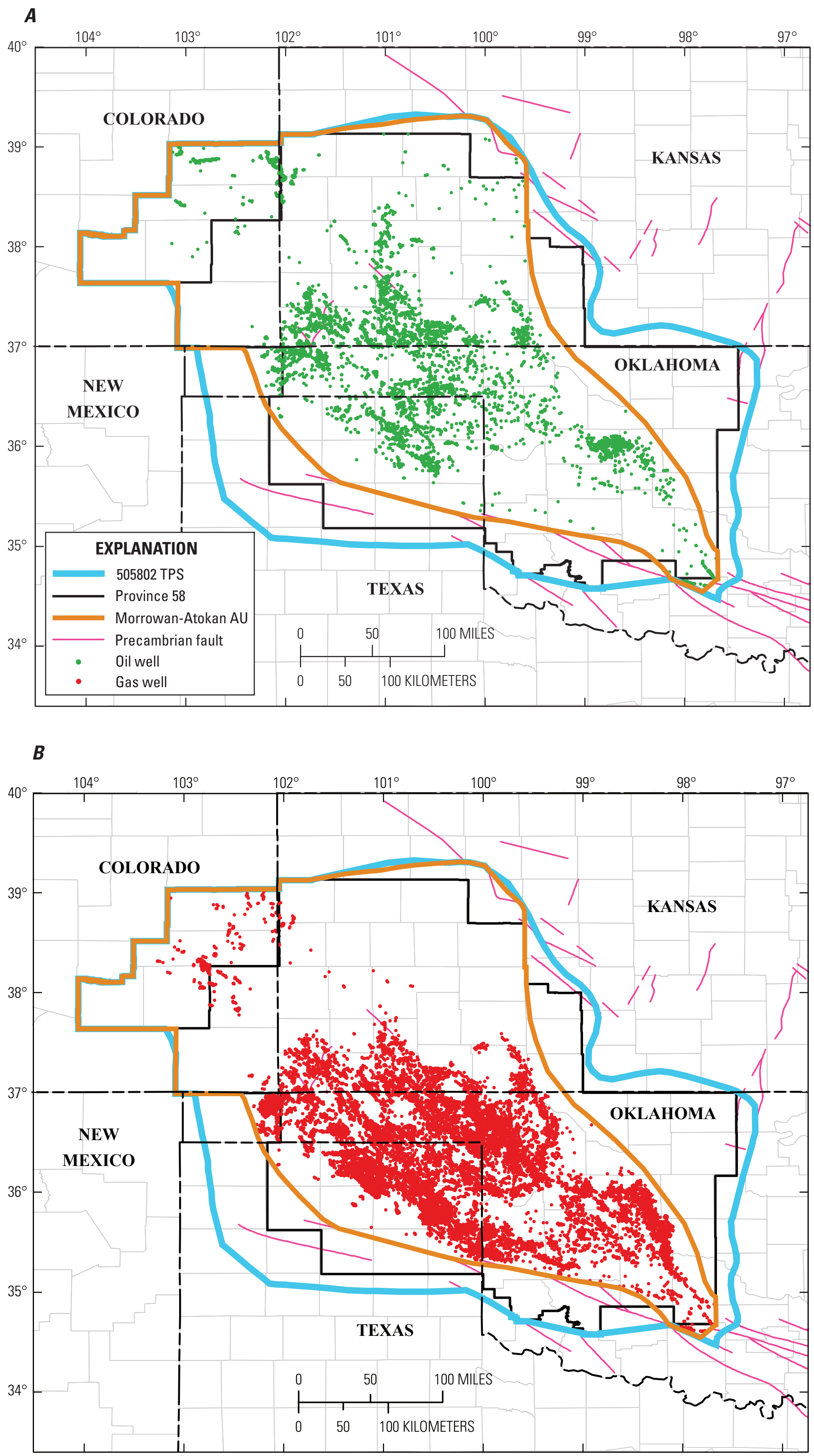


Figure 16. Maps showing *A*, Oil and *B*, gas wells that produce from Morrowan and Atokan reservoirs in the Anadarko Basin Province (IHS Energy, 2010a). The assessment unit (AU) boundary approximates the extent of Morrowan and Atokan strata. Precambrian faults are from Adler and others (1971). TPS, Total Petroleum System.

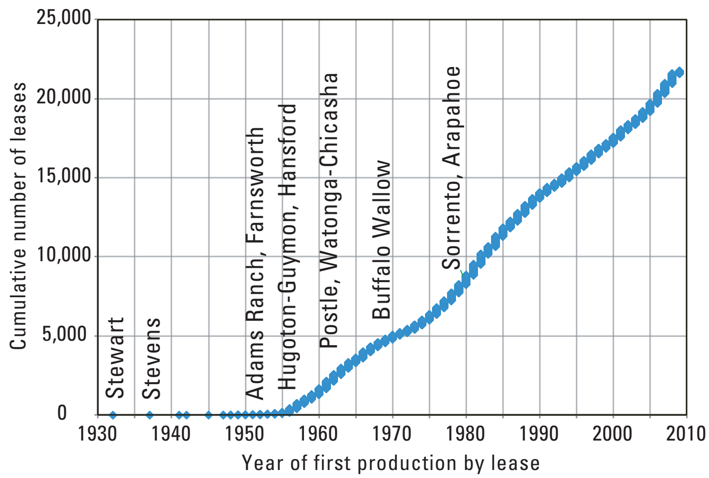


Figure 17. Cumulative number of wells by year that produce from the Morrowan and Atokan (IHS Energy, 2010a, 2010b). Several major fields are also shown by year of discovery; all are shown in figure 6.

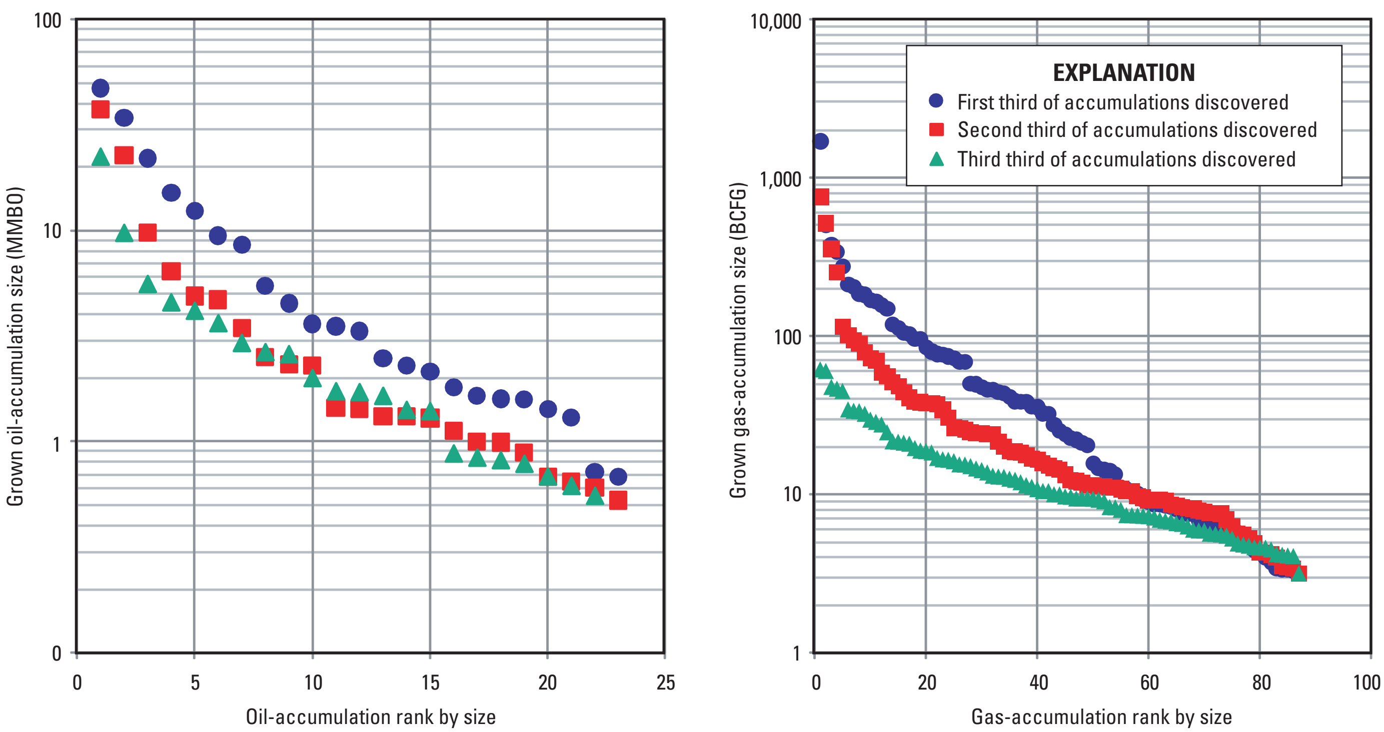


Figure 18. Discovery thirds of grown oil and gas accumulations for the Morrowan-Atokan Assessment Unit (AU) of the Pennsylvanian Composite Total Petroleum System (TPS). This is a mature AU, which is reflected by the generally larger field sizes early in the exploration history (first third) relative to later discoveries (second and third thirds). All thirds show similar trends in field sizes through time. Gas accumulation history is stable for fields less than 10 billion cubic feet of gas (BCFG), but exhibits progressive decline for fields greater than this. Data were constructed using the Nehring and Associates, Inc. (2009) field database, which has limited information for the Morrowan and Atokan fields. The database contains more information on Morrowan and Atokan gas fields than oil fields, as indicated by the data density on the plots. MMBO, million barrels of oil.

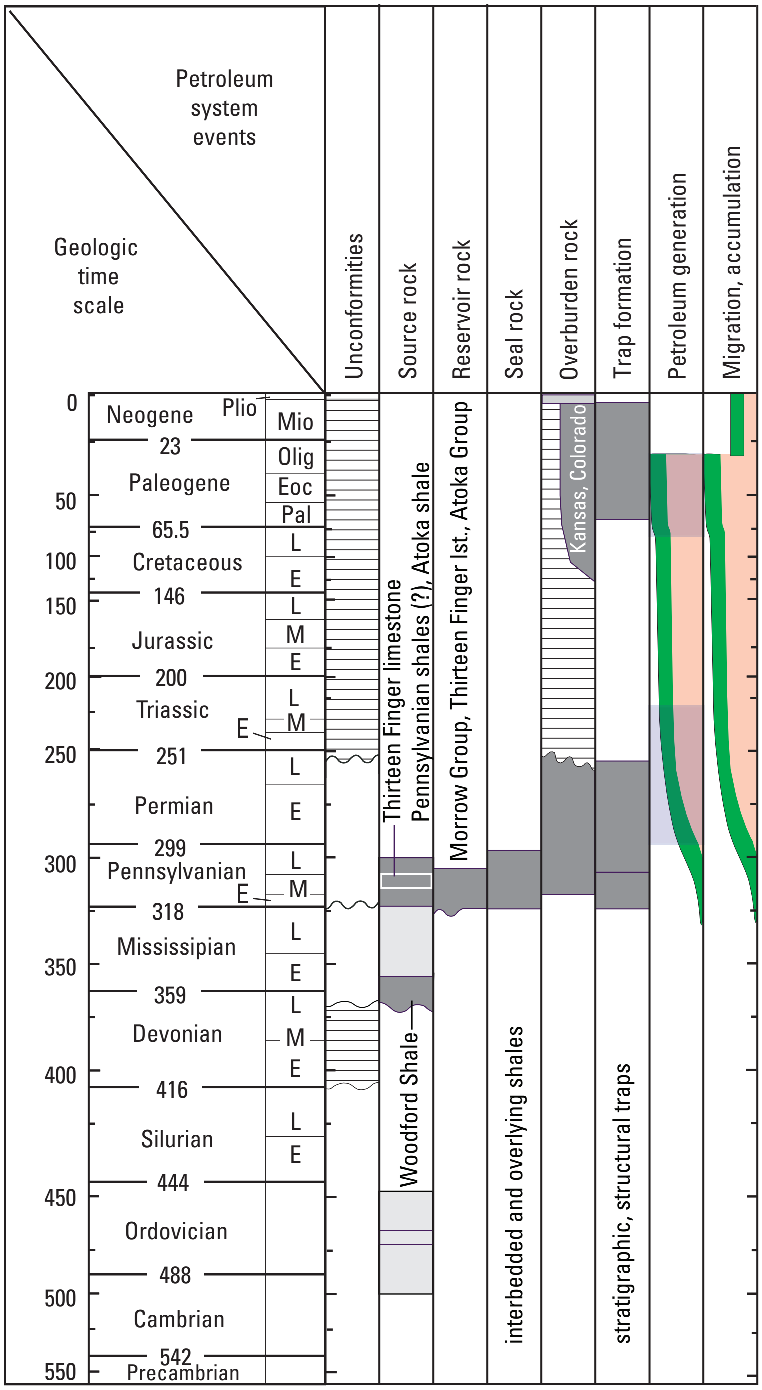


Figure 19. Petroleum system events chart for the Morrowan-Atokan AU of the Pennsylvanian Composite TPS. Woodford Shale (green) and Thirteen Finger limestone (tan) ranges of oil and gas generation, migration, and accumulation are based primarily on the petroleum system models. Potential petroleum source rocks from Hatch and others (1986) are light gray. Time ranges of peak generation (fig. 14) are within blue rectangles. Paleogene trap formation, migration, and accumulation are based on Laramide generation and potential remigration associated with basin tilting. Unconformities, wavy and horizontal lines; lst, limestone; sh., shale; Fm., Formation; Plio, Pliocene; Mio, Miocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

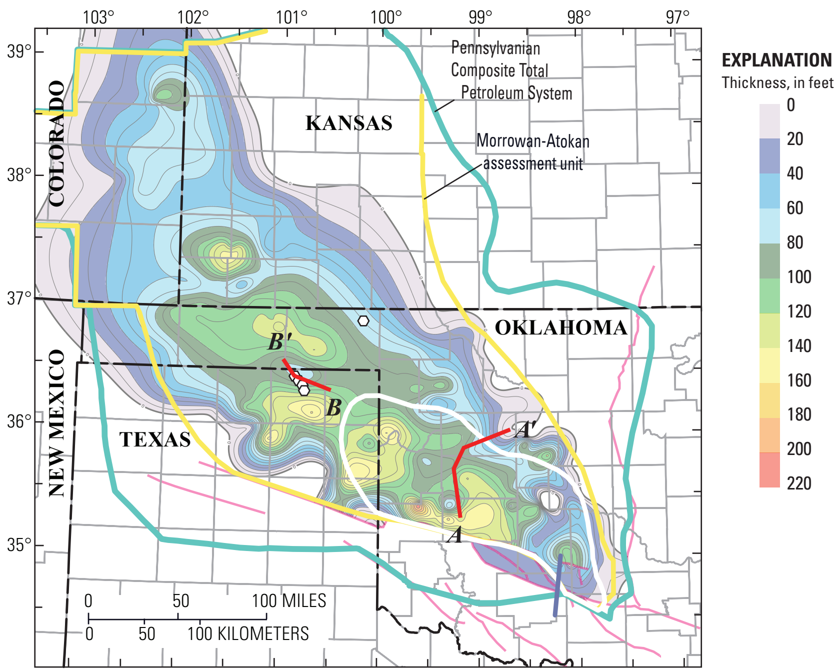


Figure 20. Isopach map of the top of the Thirteen Finger limestone to the Morrow Formation, and the Thirteen Finger Limestone–Atoka Shale Gas AU (white line). Morrow and Thirteen Finger tops are based on Andrews (1999a, 1999b), examination of more than 120 well logs, and edited tops from IHS Energy (2009, 2010a). Morrow Formation faults (pink) are modified from Andrews (1999b). Color contour interval is 20 ft and (black) line contours are 10-feet intervals. Figure 21 cross sections are labeled *A–A′* and *B–B′*. White polygons are Perryton (Texas) and Knowles Northwest (Oklahoma panhandle) oil fields, conventional oil reservoirs from the Thirteen Finger limestone.

There is no recorded continuous gas production in this AU. Within the Morrowan-Atokan AU there is minor conventional oil and associated gas production based on decline curves of petroleum and water production; the Thirteen Finger limestone in the Perryton and Knowles Northwest fields (fig. 20) have cumulative production of about 160,000 barrels of oil, 300 million cubic feet of gas (MMCFG), and 6,900 barrels of water (IHS Energy, 2010b). The fields are also located in an area marginally mature to mature for oil generation from the Thirteen Finger limestone, based on modeled TR and R_o values (fig. 8). Carr and Hentz (2009) indicated that Atoka reservoirs are mainly limestone, and also sandstone, and have been productive since the 1940s in the northwestern part of the Anadarko Basin; operators have recently been drilling horizontally and applying hydraulic-fracture stimulations in the thin (6–27 ft, average 11 ft) carbonate reservoirs to tap adjacent organic-rich shales. Cumulative conventional petroleum production is 185 BCFG and 6.7 MMBO in Ochiltree and Lipscomb Counties, northeast Texas (IHS Energy, 2010b).

The petroleum system events chart (fig. 22) shows the timing of generation, migration, and accumulation of petroleum that are based on petroleum system models of (table 2). Onset of gas generation from the Thirteen Finger limestone and Atoka shale (fig. 7) is probably soon after the 300-Ma onset of oil generation from these petroleum source rocks. The AU boundary (fig. 20) approximates the 0.99 percent TR boundary (fig. 8) that marks the transition from the end of oil generation to gas generation from the Thirteen Finger limestone. Although the Thirteen Finger limestone and Atoka shale are assumed to be the petroleum source rocks for this AU, there could be potential contributions from shales of the underlying Morrow Formation. Also, timing of petroleum generation is based on Woodford hydrous pyrolysis (HP) kinetics. These boundaries would probably be slightly different, either larger or smaller, should HP kinetics values be available that is specific to the Thirteen Finger limestone and Atoka shale.

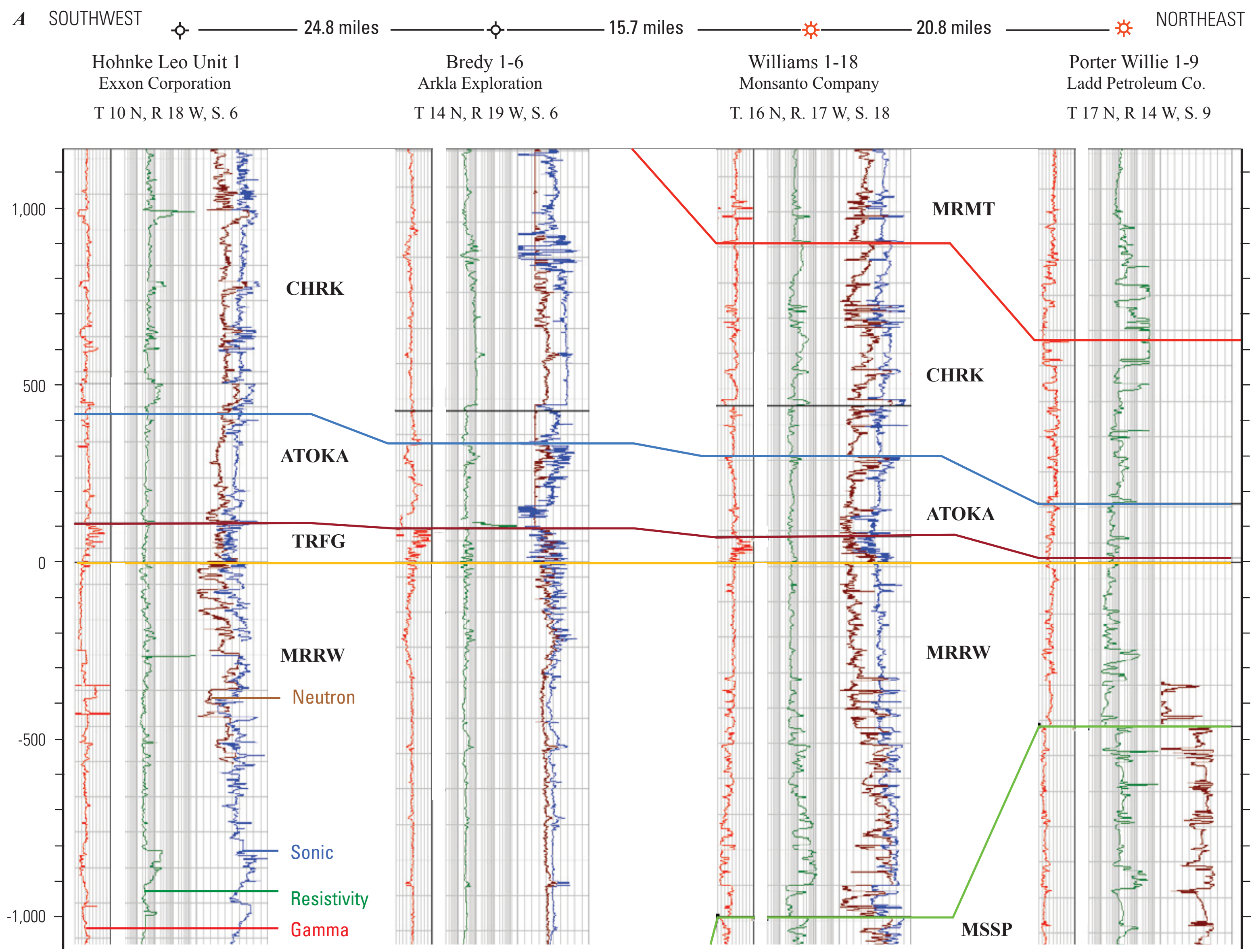


Figure 21. *A*, Southwest to northeast and *B*, southeast to northwest cross sections of the Thirteen Finger limestone (TRFG) of the Pennsylvanian Atoka Group (ATOKA) in the Anadarko Basin. Lines of section are in figure 20. Vertical scale is in feet relative to the base of the Thirteen Finger limestone. MRMT is Marmaton Group, CHRK is Cherokee Group, MRRW is Morrow Formation, and MSSP is top of the Mississippian. Labeled well log traces are gamma (0 to 200 American Petroleum Institute [API]), resistivity, sonic density, and neutron density.

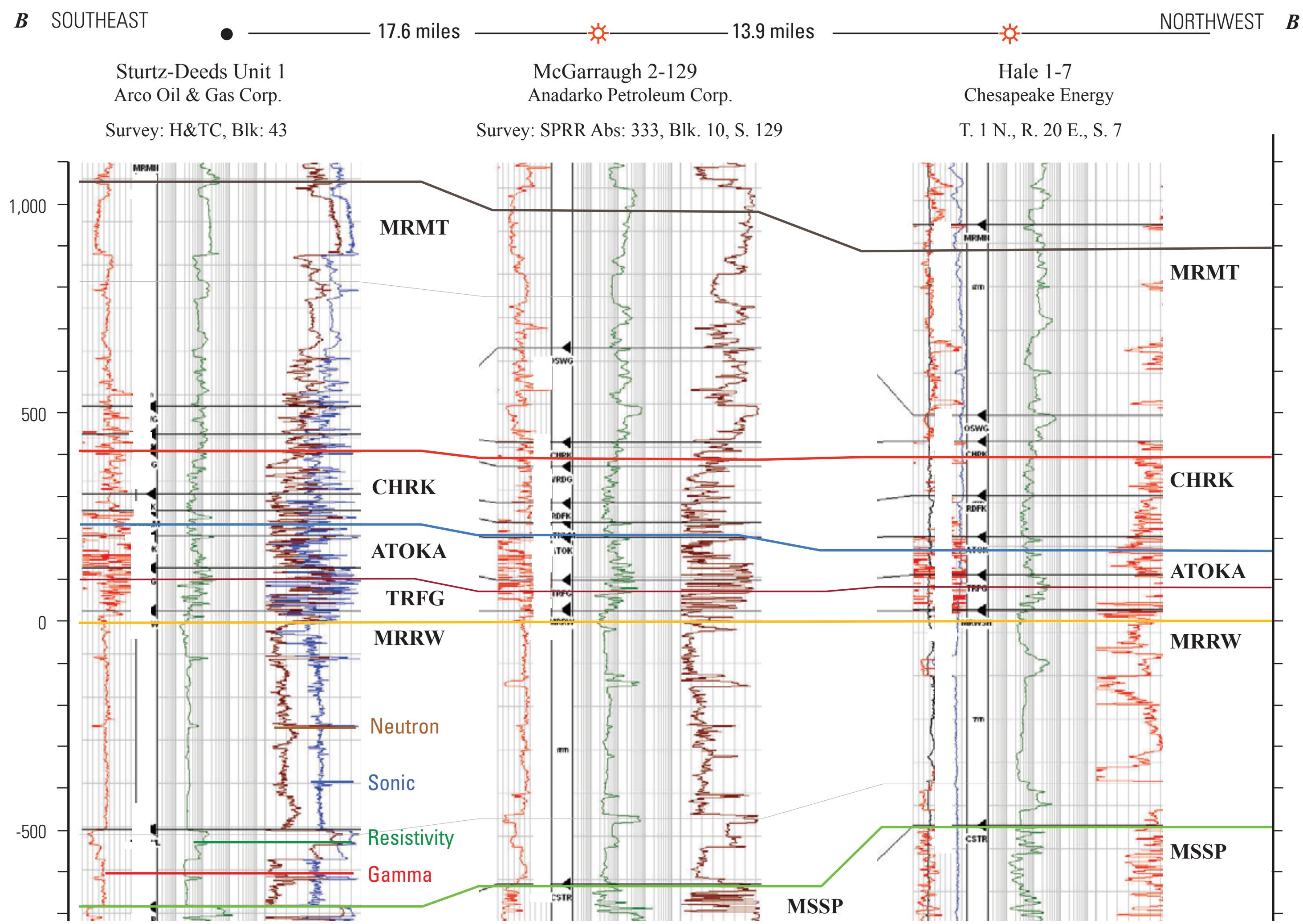


Figure 21. *A*, Southwest to northeast and *B*, southeast to northwest cross sections of the Thirteen Finger limestone (TRFG) of the Pennsylvanian Atoka Group (ATOKA) in the Anadarko Basin. Lines of section are in figure 20. Vertical scale is in feet relative to the base of the Thirteen Finger limestone. MRMT is Marmaton Group, CHRK is Cherokee Group, MRRW is Morrow Formation, and MSSP is top of the Mississippian. Labeled well log traces are gamma (0 to 200 American Petroleum Institute [API]), resistivity, sonic density, and neutron density.—Continued

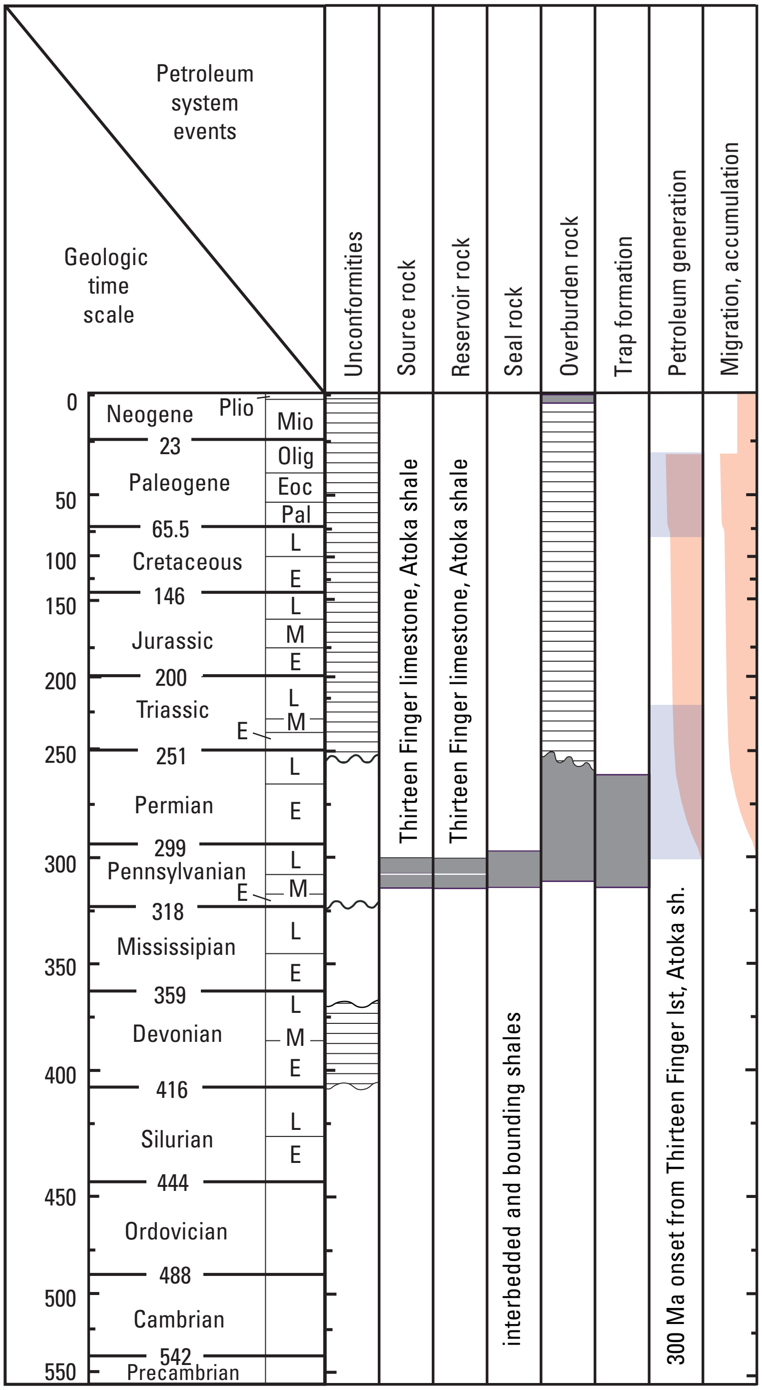


Figure 22. Petroleum system events chart for the continuous Thirteen Finger Limestone–Atoka Shale Gas Assessment Unit (AU) of the Pennsylvanian Composite Total Petroleum System. Timing of basin oil and gas generation, migration, and accumulation is based primarily on the petroleum system models. Thirteen Finger limestone (tan) periods of peak oil and gas generation are shown by the blue rectangles. This AU is located in an overpressured zone of the deep basin (Al-Shaieb and others, 1994). Because of this, Laramide uplift and erosion probably had minimal effect on the pressure environment. Millions of years ago, Ma; Unconformities, wavy and horizontal lines, lst; limestone, sh; shale.

Desmoinesian Assessment Unit

Desmoinesian, Missourian, and Virgilian strata were deposited in transgressive-regressive cycles that periodically inundated the province with alternating thin-bedded predominantly marine sandstones, limestones, and shales; these can be separated into stratigraphic packages of mostly sandstone or mostly limestone reservoirs (Moore, 1979; Rascoe and Adler, 1983). Desmoinesian strata, mainly of the Cherokee and Marmaton Groups (fig. 2) cover the province except where locally removed by erosion. They are absent over most of the Wichita Mountain uplift, in the CKU, Cimarron arch, and the Sierra Grande uplift (fig. 5). The lateral continuity of these strata are visible on well logs, but the Paradox Basin of southeastern Utah provides extensive outcrops to visualize the stacking symmetry and lateral continuity of beds (fig. 23).

Desmoinesian seas covered the entire central Oklahoma arch and the northern shelf area, extending into central Kansas (Johnson, 1989). The shallow sea was estimated at 50 to as much as 100 ft (15 to 23 m) deep (McCrone, 1964). Alluvial plain, deltaic, and incised channels flowed from the north and east southward and westward into the basin; during lowstands the shelf edge was exposed, the streams were incised during extension, and submarine fans were deposited on the basin floor (Anderson, 1991) with subsequent valley-fill deposition as the seal level rose. During temporary stillstands, deltaic conditions developed in the lower stretches of the streams, and relatively thin delta-fringe sands formed sheet-like units; further rise in sea level inundated the stream systems, and estuarine settings preceded widespread shallow marine conditions (Al-Shaieb and others, 1989). Source area for lower Desmoinesian clastics was from the north, whereas upper Desmoinesian strata were sourced from the south for the Arkoma and Anadarko Basins (Rascoe and Adler, 1983). West of the CKU, the lower Desmoinesian consists of an alternating sequence of thin limestones with lesser shale; sandstone is present but not common in this region, and was probably sourced from the Cambrian Reagan Sandstone from the northern CKU and Cambridge arch (Rascoe and Adler, 1983).

The lower Desmoinesian Cherokee Group and correlative strata are mainly marine shale with numerous thin limestones and some lenticular point-bar and channel-fill sandstones. The informal Red Fork sand is the most important reservoir of this group; its stacked channel-fill sandstones are generally coarser grained and thicker than the delta-fringe sandstone and other facies of the group (Al-Shaieb and others, 1994). The informal Prue sand, the uppermost unit of the Cherokee Group was deposited in fluvial, deltaic, and nearshore marine environments (Andrews and others, 1996; Boucher, 2009); it ranges in depth from 3,500 ft on the northern shelf to about 12,000 ft near the Wichita Mountain uplift (Henry and Hester, 1995). The upper Desmoinesian Marmaton Group across the northern Oklahoma shelf area consists almost entirely of limestones, but in the deep Anadarko Basin it is almost entirely clastic sediments that were derived from the Ouachita foldbelt to the south (Krumme, 1981; Rascoe and Adler, 1983). Modeled thickness of the Desmoinesian in the deep basin ranges southward from about 500 ft to more than 3,500 ft. The Marmaton Group comprises in ascending order, Fort Scott Limestone, Englevale Sandstone, and Oologah Limestone (Big lime) (Johnson, 1989) in the northern basin, and sandstones and shales of the Deese Group in the southern basin (fig. 2). Depths to the top of the Marmaton Group range from 3,500 ft on the northern shelf, to about 13,000 ft proximal to the Wichita Mountain uplift (Henry and Hester, 1995). This marine sequence is 200–1,000 ft thick in the north and grades southward in the deep Anadarko Basin into 4,000–5,000 ft of granite wash (Johnson, 1989). Granite wash lithofacies are generalized in the 4D model as the gray clastic sequence in figure 24. Desmoinesian strata in the deep basin were assessed as part of the Greater Granite Wash Composite AU.

The Desmoinesian AU boundary corresponds to that of the Pennsylvanian TPS, with the exception of an area in the deep basin that contains the Greater Granite Wash Composite AU (fig. 25). Oil and gas wells are distributed across the Desmoinesian AU, but are concentrated in the area of the Watonga-Chickasha and Sooner trends in the eastern half of the province, against the Nemaha uplift and, for oil wells, around the CKU. Trap types are structural and (or) stratigraphic. Fields close to the Wichita Mountain uplift are commonly structural, such as the large faulted anticline of the Cement field. Reservoirs are clastic and carbonate beds of the Cherokee and Marmaton Groups, and their lateral equivalents (fig. 2). Reservoirs range in depth from about 4,000 to 12,000 ft (Nehring and Associates, Inc., 2009). Cumulative production in the province is about 747 MMBO, 8.29 TCFG, and 49.4 MMBW from about 14,235 wells in 1,640 fields (IHS Energy, 2010a, 2010b). Average GOR is 18,000 CFG/BO. Three of the larger fields are (1) Cement, for which 85 of 1,345 leases in the field record Desmoinesian production of 1.4 MMBO and 210 BCFG, (2) Postle, which has produced 5.4 MMBO and 9.5 BCFG from 25 Desmoinesian leases, and (3) the Watonga-Chickasha trend, which has produced 2.4 MMBO and 123 BCFG from 180 of the 2,750 total leases (IHS Energy, 2010b) (fig. 25). Because much of the production in the province is reported as commingled from multiple units, volumes should be considered approximate. The discovery thirds plots of grown oil and gas accumulations contain only a few of the Desmoinesian reservoirs in the basin (fig. 26), largely because of the quality of well and production data, so trends in production are difficult to determine. The discovery thirds of oil accumulations appear to have a stable exploration and development history, although four of the five largest oil fields were discovered early in exploration. The gas discovery thirds has too few points to make valid conclusions.

Burruss and Hatch (1989) determined there are three oil types in the basin based on geochemical analysis of 104 crude oils and 190 shale core samples of Cambrian through Pennsylvanian rocks; these oil types are divided into (1) Pennsylvanian, (2) Silurian to Mississippian, and (3) Middle Ordovician Simpson Group reservoirs. This suggests that Pennsylvanian reservoirs are sourced from Pennsylvanian

Figure 23. Photograph showing Desmoinesian outcrop along the San Juan River in the Paradox Basin, southeastern Utah, illustrates carbonate/siliclastic cyclicity and lateral continuity of beds. The informally named middle Desmoinesian "Old Yeller," Desert Creek, and Ismay zones are within the Paradox Formation and are roughly age-equivalent to the upper Cherokee and lower Marmaton Groups in the Anadarko Basin. This section is described in Grammer and others (1996) and is located in about sec. 26, T. 41 S., R. 19 E. Raft is for scale and this north view of the outcrop trends approximately west to east.

shales, although additional research may indicate more complexity. There are also potential petroleum contributions to Desmoinesian reservoirs from Mississippian strata in the northeastern Oklahoma portion of the basin because Morrowan and Atokan rocks are absent there. Oil and gas are concentrated along the Nemaha uplift and Central Kansas uplift, and a broad age range of petroleum source rocks could contribute in these areas because of migration along fault systems and thinning of strata in Kansas. Sampled shales within the Desmoinesian contain a mixture of Types II and III kerogen (Rice and others, 1989). Thermal maturation of potential Desmoinesian source rocks (fig. 7) is approximated by the Thirteen Finger images in figure 8 and shown in Higley (2012, fig. 26). Cherokee and Marmaton Groups petroleum source rocks in the Texas and Oklahoma Panhandles would be slightly less mature than the Thirteen Finger image. Desmoinesian source rocks in the deep basin of Oklahoma and Texas are overmature for oil generation based on TR, and in the wet and dry gas generation windows using modeled vitrinite reflectance. The petroleum system events chart (fig. 28) displays the timing of generation, migration, and accumulation of petroleum based in part on petroleum system models (table 2) (Higley, 2014). Onset of oil generation from Pennsylvanian source rocks for the Desmoinesian AU (fig. 7) approximates the 300-Ma onset of oil generation from Thirteen Finger limestone petroleum source rocks.

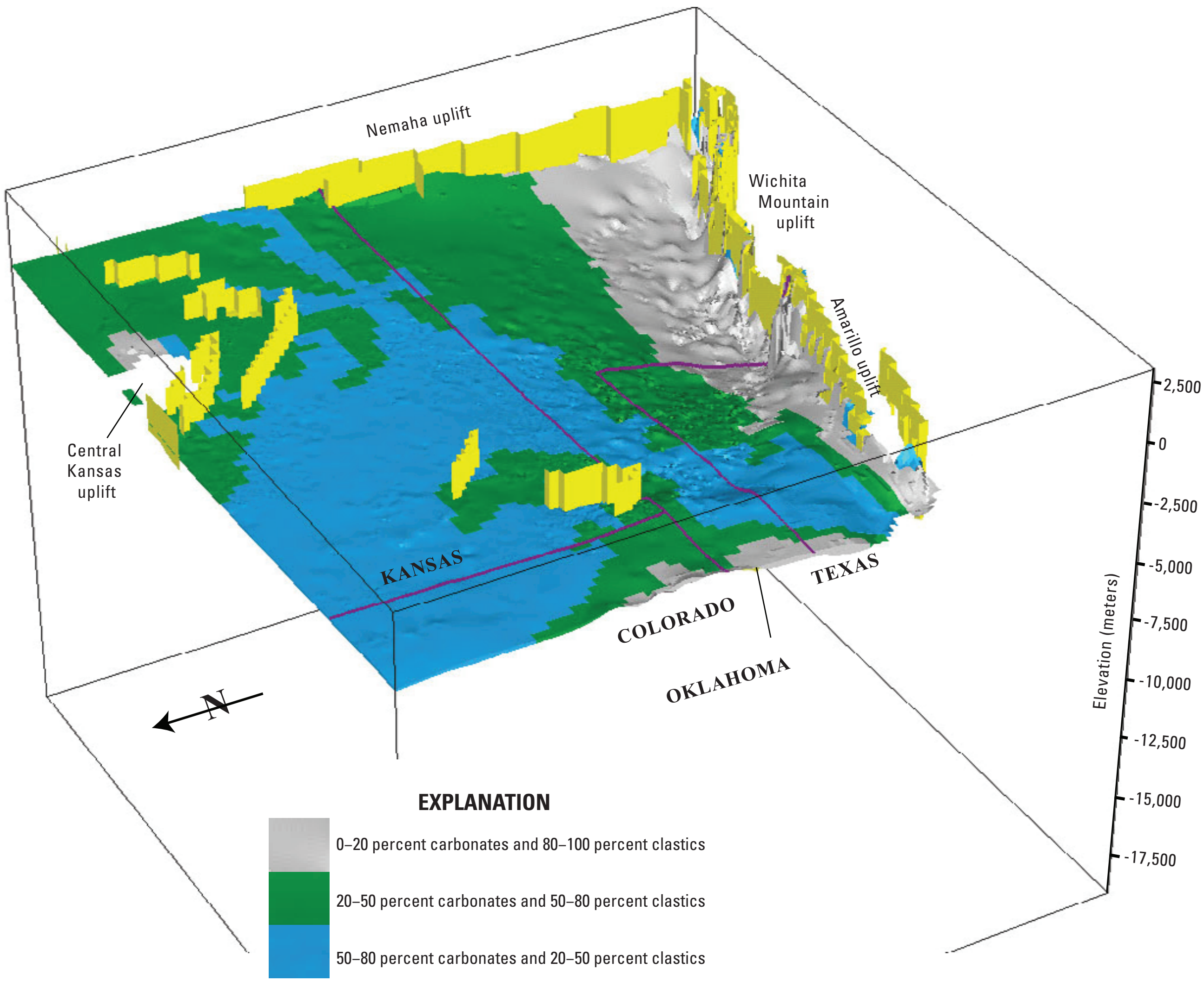


Figure 24. Modeled surface on the Desmoinesian layer shows a broad gentle slope in Colorado and Kansas that deepens near the basin axis, north of the Wichita Mountain uplift. Vertical yellow bars are Precambrian faults, and surface colors are generalized lithofacies from Adler and others (1971) that mainly record increased clastics basinward. White areas do not contain Desmoinesian or underlying Cherokee model layer lithofacies. Vertical exaggeration is 15 times.

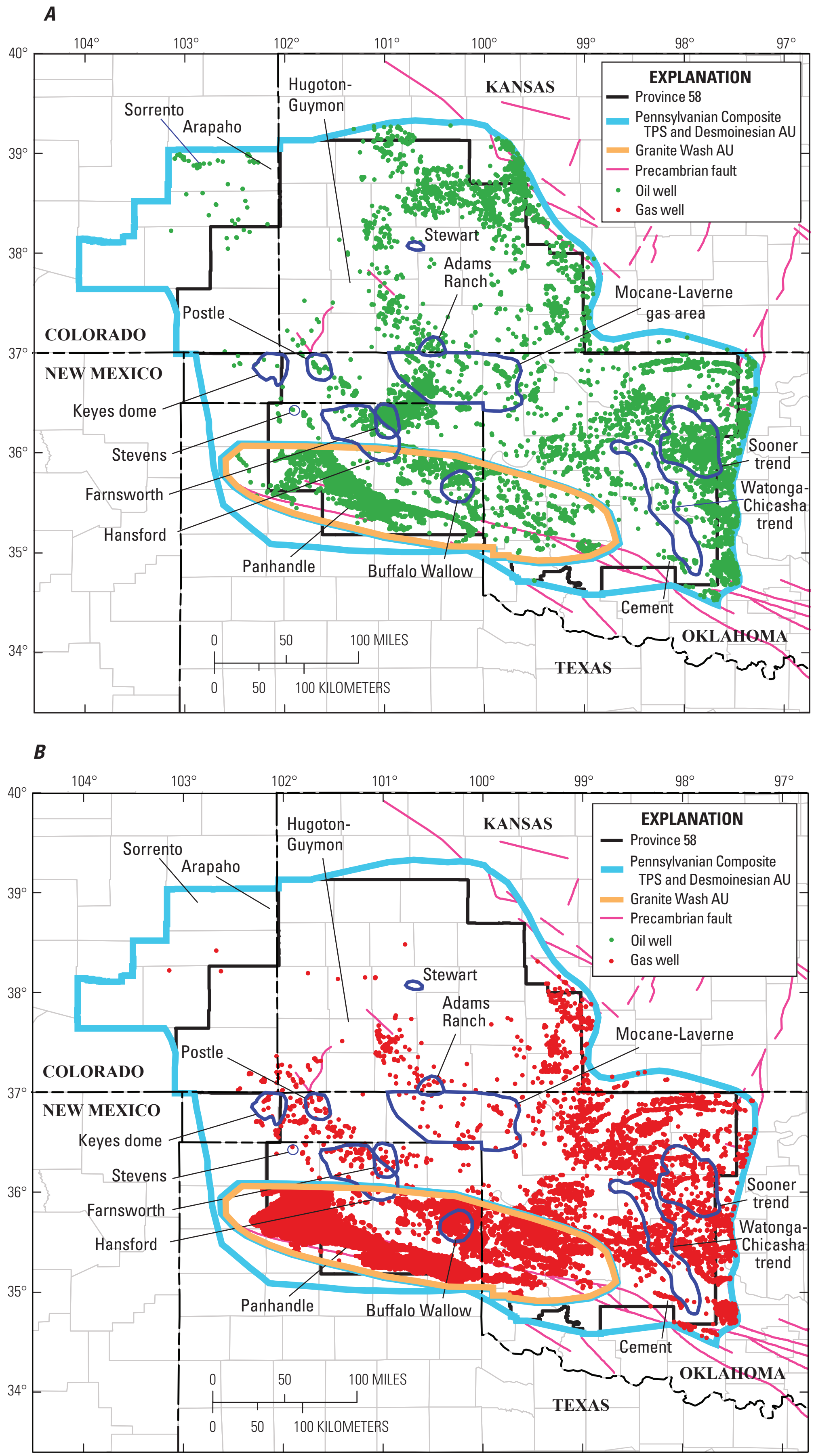


Figure 25. Maps showing *A*, Oil and *B*, gas wells that produce from the Desmoinesian Assessment Unit (AU) Cherokee and Marmaton Groups in the Anadarko Basin Province (IHS Energy, 2010a, 2010b). Generalized field locations are from IHS Energy (2010a) and Bebout and others (1993). The Desmoinesian AU shares a common boundary with the Pennsylvanian Composite Total Petroleum System (TPS). Excluded from the AU is an oval area in the deep basin that is the Greater Granite Wash Composite AU and included wells. Precambrian faults (pink) are from Adler and others (1971).

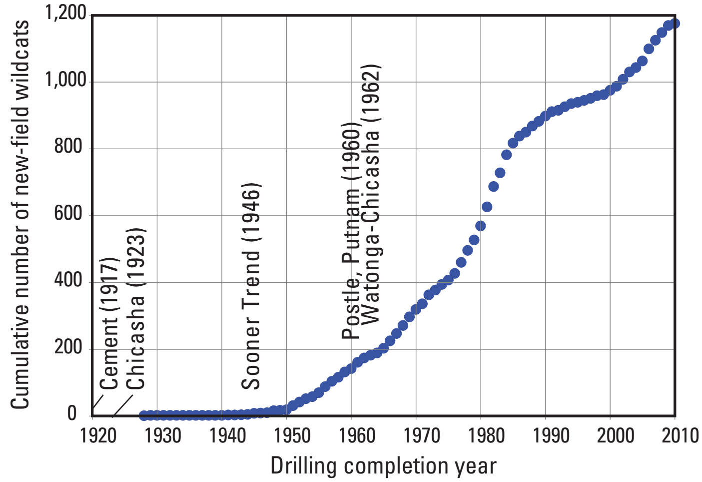


Figure 26. Cumulative number of new-field wildcats by year that produce from the Desmoinesian AU (IHS Energy, 2010a, 2010b). Exploration and development was static until about 1950, after which activity increased and has been fairly steady through time. The displayed major fields by discovery dates produce oil and gas from multiple units and ages. Field locations are shown in figure 25.

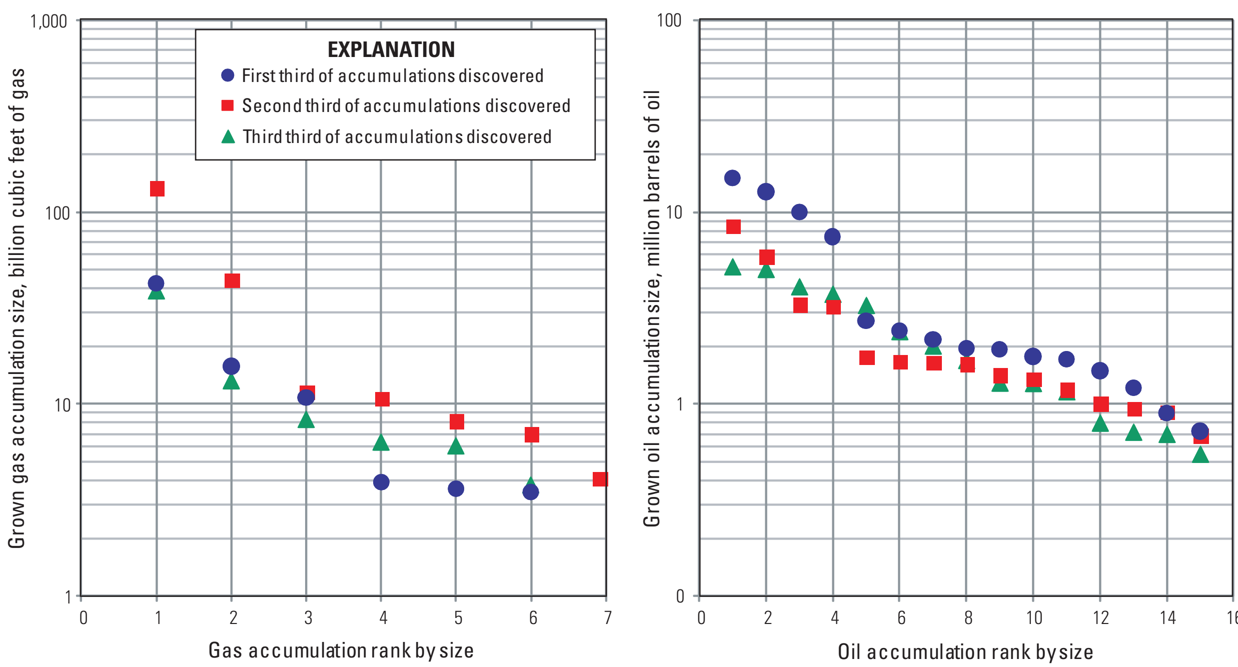


Figure 27. Grown gas and oil accumulation sizes for discovery thirds for the Cherokee and Marmaton Groups reservoirs in the Desmoinesian Assessment Unit (AU) (50580202). This AU has a mature exploration and development status with production from about 1,400 fields in the province (IHS Energy, 2010a, 2010b); however, only a few of these fields are represented on the figure. This paucity of information from the Nehring and Associates, Inc. (2009) is primarily because of reporting of production, mainly as commingled production from multiple units and age ranges. The discovery thirds for oil accumulations show close agreement for fields less than 8 MMBO, and for gas accumulations the limited data suggest that the second third of discoveries was more successful than the first and third thirds.

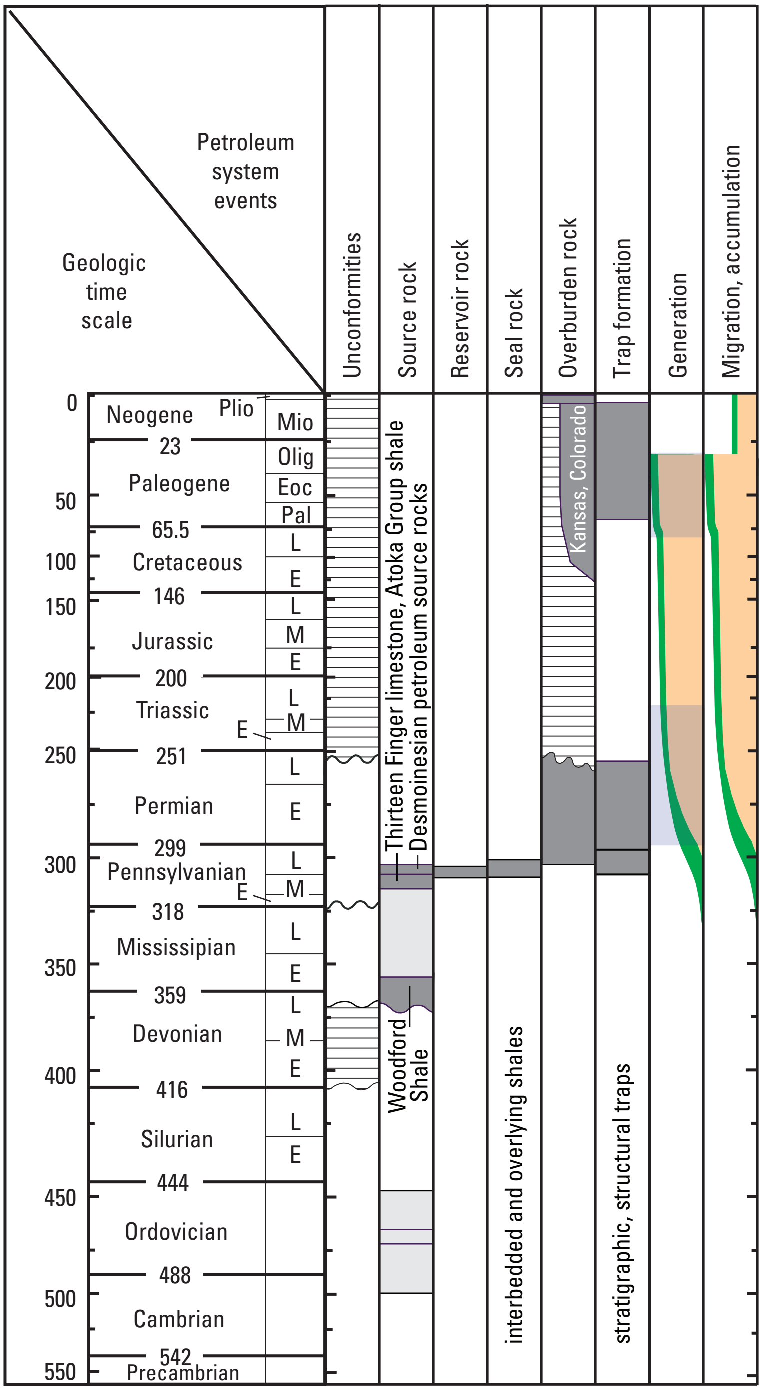


Figure 28. Petroleum system events chart for the Desmoinesian Assessment Unit (AU) of the Pennsylvanian Composite Total Petroleum system (TPS). Potential petroleum source rocks (fig. 7) from Hatch and others (1986) are light gray rectangles. The Thirteen Finger limestone (tan) range of oil and gas generation, migration, and accumulation represents Atokan and younger strata that are the primary petroleum source rocks; the 300-million years ago (Ma) onset of generation is based on the petroleum system one-dimensional and four-dimensional models. Potential oil and gas contributions from older source rocks is bracketed by the Woodford Shale (green) onset of generation of about 330 Ma. Time ranges of peak generation (fig. 14) are within blue rectangles. Paleogene trap formation, migration, and accumulation are based on Laramide generation and potential remigration associated with basin tilting. Unconformities, wavy and horizontal lines; Plio, Pliocene; Mio, Miocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

Missourian-Permian Assessment Unit

The Missourian-Permian AU shares a common boundary with the Pennsylvanian Composite TPS, but excludes the Greater Granite Wash Composite AU in the deep Anadarko Basin (fig. 1). The AU includes Missourian, Virgilian, Wolfcampian, and Leonardian carbonate and clastic reservoirs (fig. 2). Missourian and Virgilian strata were primarily deposited in transgressive-regressive cycles that periodically inundated the province with alternating thin-bedded predominantly marine sandstones, limestones, and shales; these can be separated into stratigraphic packages of mostly sandstone or mostly limestone reservoirs (Moore, 1979; Rascoe and Adler, 1983). Movement and erosion of the Wichita and Amarillo uplifts provided sediment for Missourian and Virgilian strata. Deformation and uplift of the Ouachitas, southeast of the Anadarko Basin, began during the Desmoinesian, and by late Missourian time several delta-front clastic wedges were deposited from streams that drained the Ouachitas and flowed into the eastern part of the Anadarko Basin (Johnson, 1989). Sandstone content increases from west to east in the Oklahoma portion of the basin, and the associated progression from marine to marginal marine indicates uplift with subsequent erosion of the Ouachita foldbelt was a sediment source (Rascoe and Adler, 1983). The Ouachitas continued to contribute clastics to the eastern basin during Virgilian time; a source of coarse detritus for the southeastern basin was provided by rapid rise of the Arbuckle Mountains uplift (Johnson, 1989).

The thickness of Missourian strata ranges from 500 to 1,000 ft in most of the northern shelf and Hugoton embayment area, to more than 2,500 ft at the depocenter in the southeastern Anadarko Basin (Johnson, 1989). The Missourian Series in southwest Kansas and the Oklahoma Panhandle are mostly marine limestones with some shale interbeds that grade to the south and southeast into shales and sandstones with minor carbonate beds; against the Wichita Mountain and Amarillo uplifts they become the thick arkosic and carbonate strata (Johnson, 1989) of the Greater Granite Wash Composite AU. Along the western margin of the Hugoton embayment, the Missourian Series consists of a clastic sequence of shales, siltstones, and sandstones, which are commonly red beds; Virgilian strata in the Hugoton embayment and proximal shelf area to the east are mainly marine limestones interbedded with shale (Johnson, 1989).

The Virgilian sequence ranges in thickness from about 500 to 1,500 ft in the north and west, to more than 4,500 ft in the southeastern corner of the province (Johnson, 1989). Virgilian and Wolfcampian marine carbonates and shales grade westward toward the Sierra Grande uplift into redbeds and sandstones that were sourced mainly from this uplift (Maher, 1953; Roth, 1955). An exception to the normal clastic/carbonate sequences of the Missourian and Virgilian is the middle Virgilian Heebner Shale, which was deposited under deep marine conditions (Al-Shaieb and others, 1994). This laterally continuous interval provides a seal for underlying strata. Post-Heebner Virgilian sedimentation consisted of cyclic carbonates and shales on the Kansas shelf, and of cycles comprising carbonates and thick wedges of terrigenous deltaic strata on the eastern margin of the basin (Rascoe, 1978).

Lower Wolfcampian strata in-filled the sediment-starved Anadarko Basin at the end of the Pennsylvanian; estimated maximum water depth was about 700 ft (213 m) based on thickness of adjacent Virgilian deltaic wedges (Rascoe and Adler, 1983). The Wolfcampian Admire, Council Grove, and Chase Groups strata (fig. 2) cover most of the province, being absent over the Sierra Grande uplift and parts of the Amarillo, Central Kansas, and Wichita Mountain uplifts. The Chase Group in the basin averages about 200 ft in thickness and consists of cyclical limestone, dolomitic limestone, dolomite, red shales, and siltstone lithofacies that become more shaly to the north and west (Ball and others, 1991). Modeled thickness of the Chase layer is about100 to 450 ft thick in the Kansas portion of the basin, and thickens southward to about 800 ft near the Amarillo and Wichita Mountain uplifts. The Council Grove model layer includes the underlying Admire Group; this interval also thickens southward in the basin to as much as 800 ft in the Oklahoma and Texas portions of the basin. Unlike the Chase layer, which is thin in the Colorado portion of the model, the Council Grove and Admire interval has a northeast-trending increase in thickness that corresponds to the eastern flank of the Las Animas arch.

Owen (1975) ascribed evaporite deposition at the end of Wolfcampian time as resulting from landlocked seas. Continued basin subsidence in Guadalupian time resulted in deposition of as much as 1,500 ft of red beds and evaporites in the deep basin; the Wichita Mountain uplift subsided at a somewhat slower rate and all but the highest parts were probably buried by fine clastics (Johnson, 1989). Thicknesses of 100–200 ft of Guadalupian Blaine Formation dolomite, anhydrite, and shale were deposited over almost the entire province during a marine transgression (Johnson, 1989). Leonardian and Guadalupian evaporites of the Wellington and Blaine Formations form important seals for underlying reservoir beds.

Figure 29 shows elevation on the top of the Wolfcampian Council Grove and Chase model layers. Data in the Palo Duro Basin area, south of the Panhandle field (figs. 1 and 29) were insufficient to model this surface. Shown are the basin axis proximal to the Wichita Mountain and eastern Amarillo uplifts, and the north-northwest trend of the flanks of the basin that are important to hydrocarbon migration. Also visible are the structural high of the Amarillo uplift in the Panhandle field area, a slight structural low between the Panhandle and Hugoton-Guymon fields, and the east-southeast tilt of strata in the Hugoton-Guymon fields.

Figure 30 is a tilted view of the present-day top of the Virgilian Douglas model layer with oil and gas migration flow paths. The process and methodology of modeled oil and gas generation, migration, and accumulation is explained in . Petroleum flow paths resemble hydrologic tributaries, with the exception that the flow is generally from deeper to shallower. Drilling depths to the top of the Douglas Group range from about 3,800 ft in the northeastern part of the province

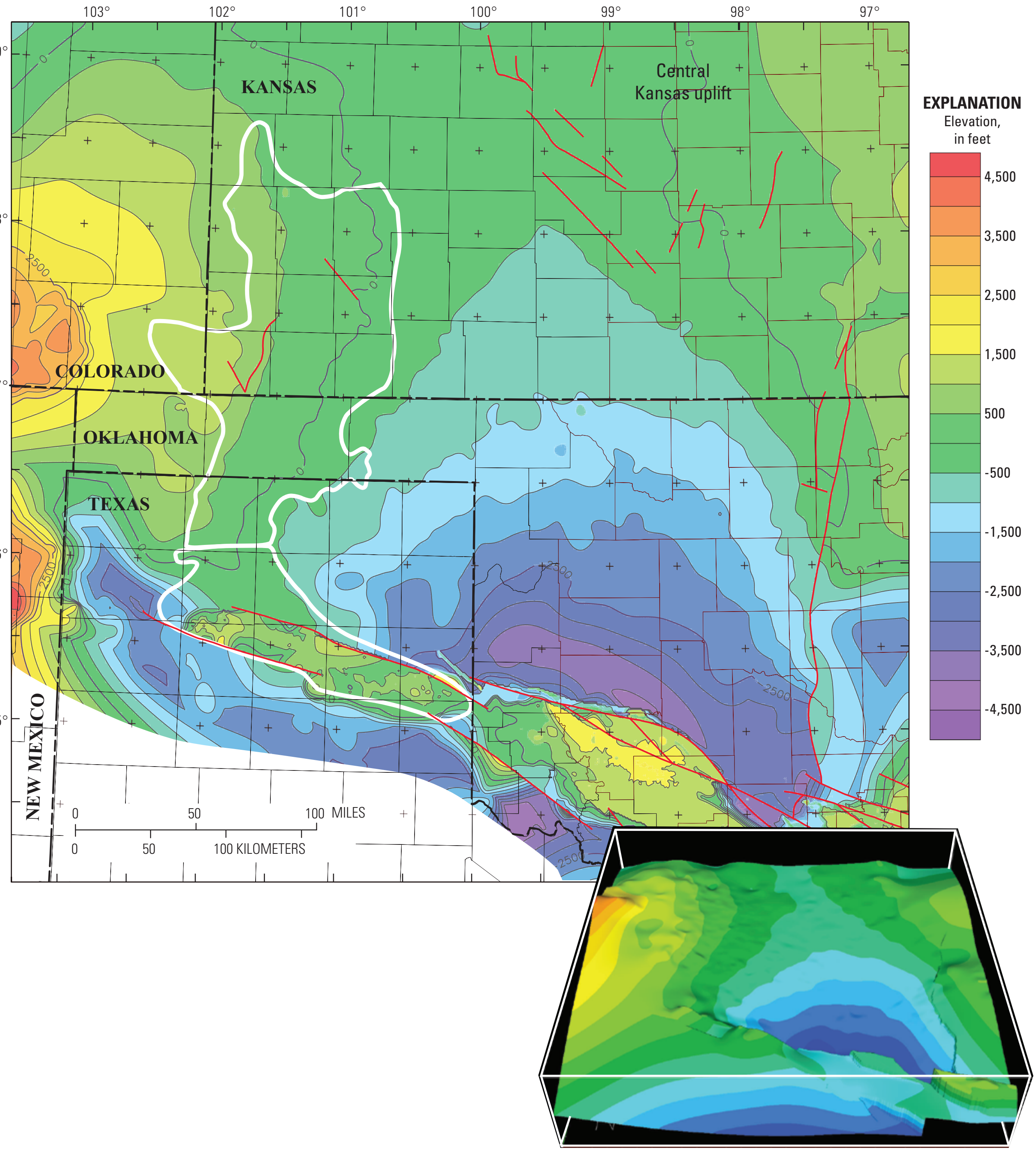


Figure 29. Map showing elevation on the top of the Council Grove model layer for the Anadarko Basin province. Inset image on the top of the overlying Chase layer shows structures on this north-tilted view at 20 times vertical exaggeration. The primary basin axis is proximal to the Wichita Mountain uplift (fig. 24) in Oklahoma and Texas, the secondary axis trends northward along the west flank of the Central Kansas uplift (CKU), which is bounded approximately by displayed faults. White outlines the Panhandle (south) and Hugoton-Guymon (north) field areas (fig. 25). Precambrian faults (red) are from Adler and others (1971).

to about 11,000 ft in the southern basin (Henry and Hester, 1995). Modeling indicates that migration on the Douglas layer is mainly from the deep basin radially outward to the Panhandle-Guymon-Hugoton fields, CKU, Salina Basin, and Nemaha uplift (fig. 30). Hydrocarbon flow follows topography on a layer, which is quite similar to structure on the Council Grove and Chase Groups (fig. 29), across the western and eastern flanks of the basin and up the secondary basin axis to the CKU. Gas flow paths are visible along the western and northwestern boundaries and CKU and mainly represent increase of gas volume because of pressure release proximal to outcrops and at major structures, such as the Sierra Grande uplift and Las Animas arch. Petroleum generation began in the deep basin (fig. 8) but then flowed up the flanks of the basin and toward bounding structures.

Potential Pennsylvanian petroleum source rocks that underlie the Douglas layer in Kansas and most of the Oklahoma and Texas panhandle area are thermally immature for oil generation (fig. 8), so long-distance migration factors into these reservoirs. Lateral migration can exceed 200 km (124 mi), which is the distance between the extent of thermally mature source rocks for the Oil Creek layer and the northern limit of the 4D model. Maximum migration is probably considerably greater because migration pathways tend to follow curved paths through permeable carrier lithofacies and along structures. Also, the wealth of oil and gas resources for the CKU and the Cambridge arch to the north are in areas that are thermally immature for petroleum generation. Because most oil and gas is not trapped in the 4D model, the flow paths are useful for visualizing migration on structural surfaces. The V-shaped areas of low flow to the right and left of the CKU correspond to areas of fewer oil and gas wells in figure 30, but flow also appears to be mostly absent in most of the Panhandle field area. That oil and gas migration flow paths appear west of the Panhandle field indicates that hydrocarbons did flow through this field but did not accumulate in the model.

Missourian-Permian AU oil and gas production is from more than 28,900 leases in 1,820 fields (fig. 31) and totals about 846 BBO, 50 TCFG, and 263 MMBW (IHS Energy, 2010a, 2010b). Because the reservoirs are subject to the same data reporting problems as for other strata in the basin, these numbers should be considered approximate. The Nehring and Associates, Inc. (2009) database contains information on 66 of the oil fields and 93 of the gas fields. This AU also includes oil and gas production from the Palo Duro Basin, and oil production from the Las Animas arch of southeastern Colorado (figs. 5 and 31). The Palo Duro Basin is bounded on the north by the Amarillo uplift (fig. 5), south of the Panhandle field. Oil and gas production, aside from the giant Panhandle-Guymon-Hugoton field complex, is somewhat scattered across the province, particularly in regard to the number of wells that have been drilled. Oil and gas wells are concentrated in the Panhandle field, which is part of the Greater Granite Wash Composite AU (fig. 31); as such, some of the following discussion also applies to that AU. Within the Missourian-Permian AU, oil wells are concentrated in northeast Texas, the Cement, Watonga-Chickasha trend, and Sooner trend fields, and Nemaha uplift of Oklahoma, and near the CKU in Kansas. Gas wells are similarly distributed with the exception of the vast Panhandle-Guymon-Hugoton gas field complex (fig. 31), the largest in North America at 8,500 mi^2; through 1985 it produced more than 48 TCFG, and accounted for about 58 percent of the gas and 26 percent of the oil production in the basin (Davis and Northcutt, 1989). This field complex will be referred to as the Panhandle-Guymon-Hugoton field, even though it includes other fields (fig. 31).

The Panhandle West field in the Panhandle-Guymon-Hugoton field was discovered in 1918, with production from Desmoinesian strata informally named “Big lime” (Mason, 1968) of the Marmaton Group (figs. 2 and 32). Galloway and others (1983) determined that porosity and permeability for the Panhandle field averages 13 percent and 25 mD, at 2,850 ft depth. About 94 percent of the gas but less than 2 percent of the oil production from the Panhandle-Guymon-Hugoton fields is from the Missourian-Permian AU, almost all of it from the Permian, mainly Wolfcampian Council Grove and Chase Groups; most of the oil production is from granite wash in the Panhandle field, with other units producing minor amounts (IHS Energy, 2010a, 2010b). Hugoton-Guymon field production through September 2009 totaled about 1.4 BBO, 51.8 TCFG, and 864 MMBW for all reported Mississippian through Permian units (IHS Energy 2010a, 2010b).

Figure 33 shows estimated ultimate recovery (EUR) values for 1,024 wells across the Hugoton-Guymon portion of the field area. There is considerable variation in EURs, ranging mainly from about 400 to 7,000 MMCFG, and there are no clear trends in production. The EUR discovery thirds (fig. 34) show greatest production for the first third of discovered wells, followed by a progressive decline in EURs for the second and third of discovered wells. This is a complex set of reservoirs, and research by Dubois and others (2006) suggests that additional reserves may result from bypassed pay and by reservoir compartmentalization. Complex stacking, cyclicity, and lateral continuity of Council Grove and Chase Groups lithofacies are shown in figure 35. Average reservoir characteristics of the Chase Group in the field complex, north of about 35.5° latitude, include about 5-mD permeability, 14 percent porosity, 25 percent water saturation, and 45 net feet of productive rock (Mason, 1968). Hugoton field initial reservoir pressure was 485 pounds per square inch (psia) in about 1928 and pressure declined to 360 psia by 1958 and 260 psia by 1968; average formation temperature and depth are 90 °F and 2,700 ft (Mason, 1968).

Discovery thirds of grown oil accumulations for the Missourian-Permian AU (fig. 36) do not decline much through time, aside from effects on the curves of early fields from which 20 MMBO and more was produced. The discovery thirds of gas fields do exhibit decline through time, particularly for larger fields.

Reservoir seals include interbedded shale lithofacies (Morse, 1963; Galloway and others, 1977). Missourian and Virgilian reservoir seals are mainly interbedded and overlying

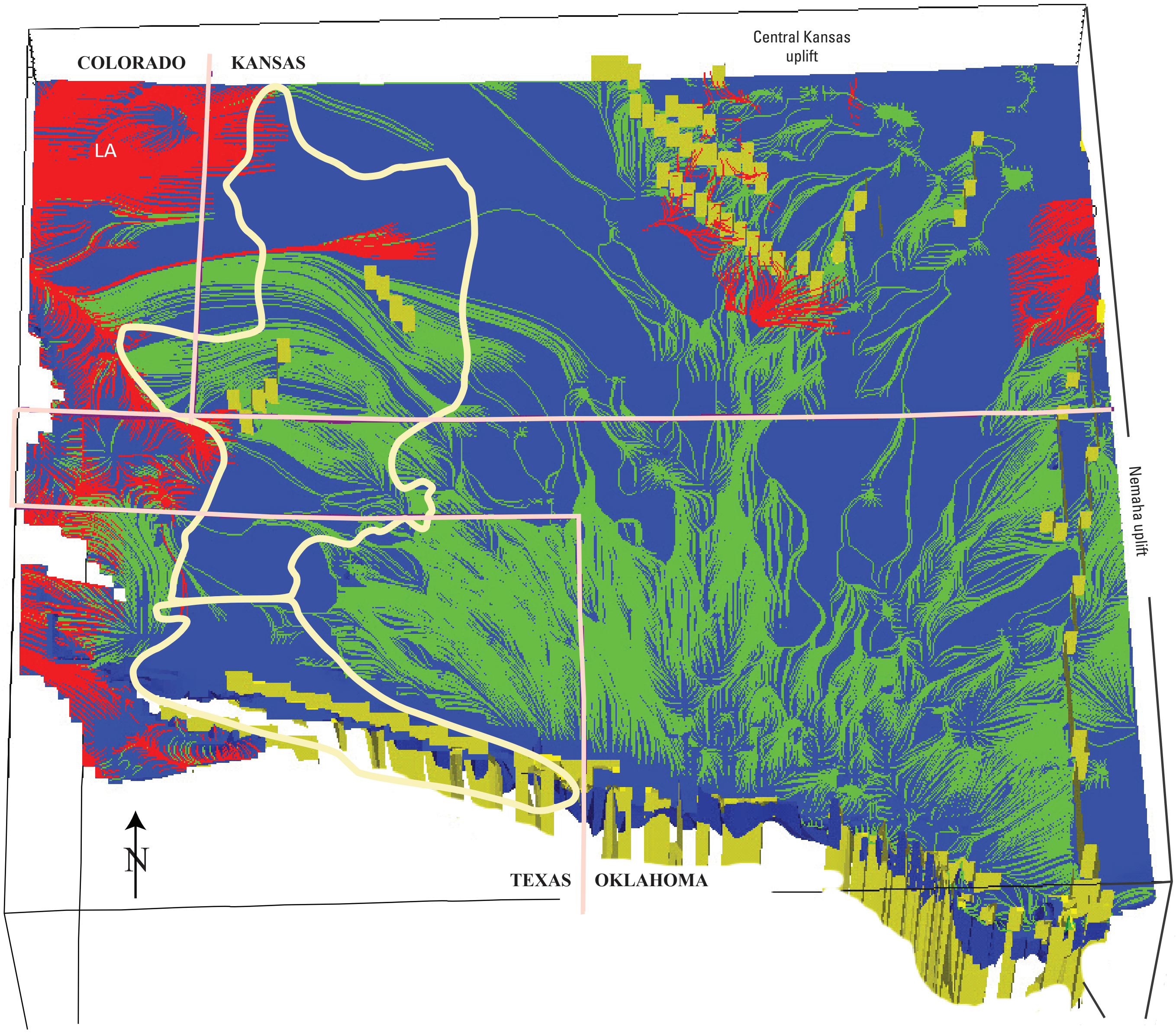


Figure 30. Oil (green) and gas (red) migration flow paths on the Douglas and Permian layers in the four-dimensional petroleum system model at present day. The image is tilted to the north and is at 15 times exaggeration to better show flow paths. Yellow outline is for the generalized locations of the Hugoton and Panhandle fields (fig. 25). In general, flow follows topography on the model layers. Petroleum is generated mostly in the deep basin and flows radially northward. Flow in northern Oklahoma and in Kansas is directed toward the Las Animas arch (LA), Central Kansas uplift (CKU), and Nemaha uplift. Gas flow paths at the western and eastern boundaries of the map and the CKU resulted from decrease in pressure-volume-temperature (PVT) conditions. Greenish-gold vertical bands are Precambrian faults (Adler and others, 1971). These are the only modeled Missourian-Permian Assessment Unit layers that have flow paths, mainly because (1) Heebner layer shale above the Douglas layer provided enough of a seal to prevent upward leakage, (2) the generalized lithologic assignments of other layers, and (3) coarse grid spacing resulted in most generated petroleum migrating out of the model.

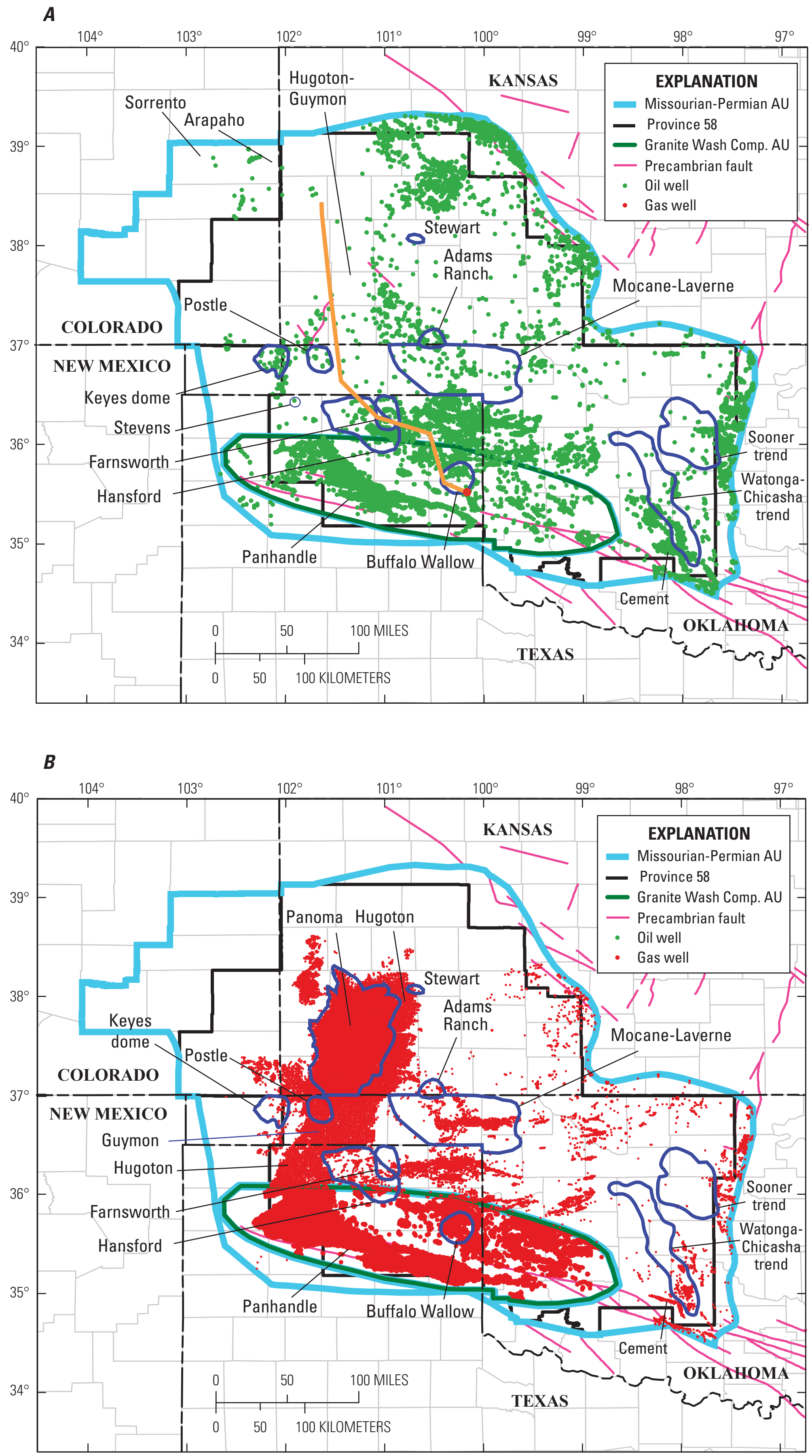


Figure 31. Maps showing *A*, Oil and *B*, gas wells that produce from the Missourian-Permian Assessment Unit (AU) in the Anadarko Basin Province (IHS Energy, 2010a, 2010b). Also shown is the common boundary with the Greater Granite Wash Composite AU boundary and included wells. Generalized field locations are from IHS Energy (2010a) and Bebout and others (1993). Largest gas field is Hugoton-Guymon, which extends northward from the Panhandle field. Gold-colored line on A is the southeast to northwest cross section and (red dot) burial history plot location for figure 39. Precambrian faults (pink) are from Adler and others (1971).

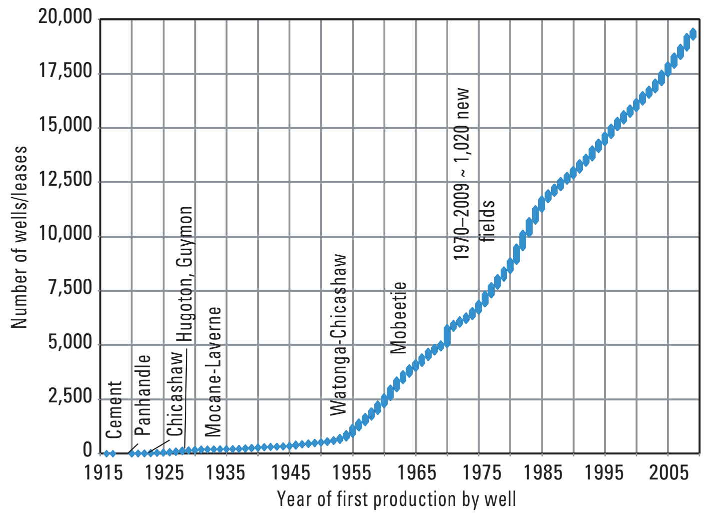


Figure 32. Graph showing production history of the Missourian-Permian Assessment Unit (AU) in the Anadarko Basin Province with some of the major field discovery names and dates (IHS Energy, 2010a, 2010b; Oklahoma Geological Survey, 2011a, 2011b). Exploration and development was relatively slow until discovery of the Watonga-Chickasha field. Development after about 1950 shows the same general trends as those from other AUs.

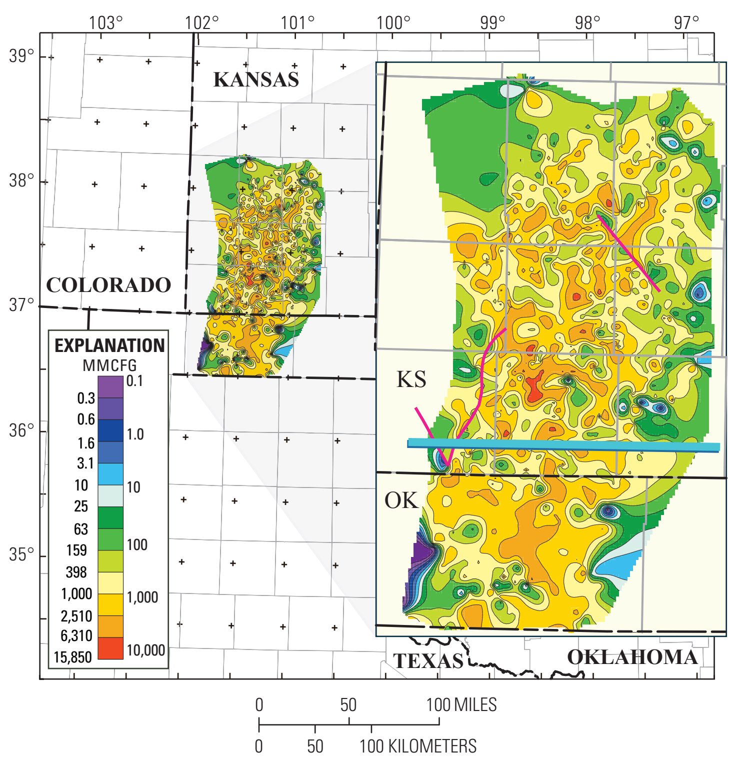


Figure 33. Map showing generalized contours of estimated ultimate gas recovery (EUR) in million cubic feet of gas (MMCFG) from 1,024 leases in the Hugoton and Guymon fields (data from Troy Cook, written commun., 2010). Leases represent single-well production of gas from the Chase and (or) Council Grove Groups. Contours are based on log10 EUR values to better show variability across the area. Horizontal blue line is generalized location of cross sections shown in figure 35. Pink lines are Precambrian faults from Adler and others (1971).

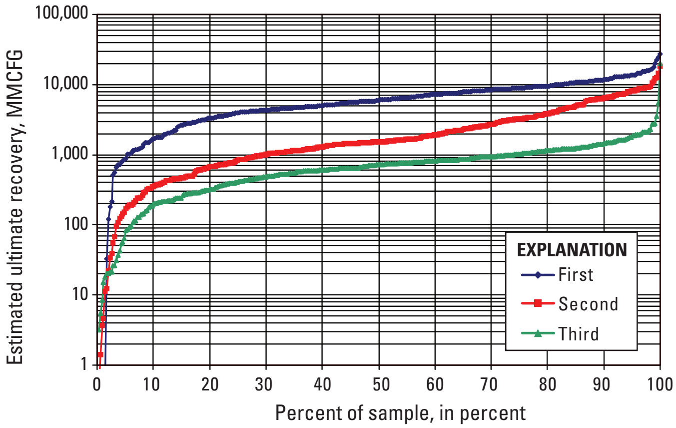


Figure 34. Graph showing discovery thirds of estimated ultimate recovery of gas (EUR) in million cubic feet of gas (MMCFG) for 1,024 wells in the Hugoton and Guymon fields that produce gas from the Chase and (or) Council Grove Groups (T. Cook, written commun., 2010). Data represent leases that have one well per lease and are split into the first, second, and third thirds of onset of production to November 2009, based on data from IHS Energy (2010a, 2010b). The curves indicate that gas production has undergone a steady decline since onset of production. Decline rate is greatest for the more productive wells in the third of EUR.

shales. Seals in Permian reservoirs include overlying shale-evaporite beds in the Leonardian strata, and seals for the Hugoton gas field may include capillary-pressure effects of bounding water. Trap types in this AU are mainly structural and (or) stratigraphic. Oil and gas fields that produce from Missourian rocks have a wide distribution, and are in structural, stratigraphic, and combination traps (Rascoe and Adler, 1983). The Cement field in the deep basin is a faulted anticline that produces from Silurian through Permian strata. The primary trapping mechanism is structural in the Panhandle field but stratigraphic in the Hugoton field, with a hydrodynamic component to both (Owen, 1975). Pippin (1970, p. 211) created a structure map on the granite underlying the Panhandle field that suggested the Amarillo uplift was a great horst block circumscribed almost completely by faults. The Hugoton field is an east-dipping homocline with the western edge being a somewhat steeply dipping monocline. Mason (1968) indicated that Chase and Council Grove Groups strata have a common gas-water contact in the Hugoton field, and that production in the west is limited by updip water and by a permeability decrease in the Chase Group, and on the east by an eastward-dipping gas-water interface.

Absence of an updip seal in the 4D model is indicated by flow of hydrocarbons westward through the Hugoton and Guymon fields (fig. 37); appearance of gas flow paths is largely the result of a decrease in pressure with shallower burial on the west and at the CKU. There were few accumulations with the 4D model, compared to overall production in the province, but production from this AU is generally focused along major Douglas layer flow paths. The overlying Heebner shale layer provided enough of a seal for the 4D petroleum system model to show migration of oil and gas on the underlying Douglas layer (fig. 30). The Heebner Shale is an exception to the normal clastic/carbonate sequences of the Missourian and Virgilian; its deep marine deposition was a period of uncommon Virgilian quiescence (Al-Shaieb and others, 1994). This shale generally is less than 100 ft thick and can be mapped across most of the province; it thickens in the deep basin and proximal to the Nemaha and Arbuckle uplifts shown in figure 5. Rascoe and Adler (1983) indicated the shale is only about 3 ft thick in the northern part of the basin, but increases to about 400 ft in the deep basin.

Petroleum source rocks for the Missourian-Permian AU are probably Pennsylvanian shales and limestones. Rice and others (1988a, 1988b) indicated that Panhandle-Hugoton field nonassociated gases are mostly produced from Permian carbonates at depths less than 900 m (2,950 ft), and that Pennsylvanian and Permian gases display little compositional variation with a range of $\delta^{13}C$ values from -46.4 to -39.9 percent (mean $\delta^{13}C_1$ value is -43.2 percent, mean C_{2+} value is 14 percent). This isotopic composition is comparable to that of thermogenic gas from Atokan and Desmoinesian producing intervals in the central basin (Rice and others, 1989), which indicates Pennsylvanian sources of hydrocarbons. Shales in Virgilian-producing intervals have a mixture of Type II and III kerogen (Rice and others, 1989).

Permian oil and gas from the 4D model are mostly located in and west of the Panhandle through western Hugoton field areas (fig. 37); gas was sourced 56 percent from the Thirteen Finger limestone, 26 percent from the Oil Creek layer, and 18 percent from the Woodford layer. Because the 4D model has far fewer traps or seals than exist in the basin, modeled contributions from the Woodford layer source rocks may not be present with a more complex model. Model reasons for the Oil Creek contribution are that (1) Woodford Shale and Thirteen Finger limestone source rocks are thin to absent north of the Amarillo uplift area; (2) the Woodford through Desmoinesian isopach (fig. 5) is thin in the Texas Panhandle area; (3) Pennsylvanian strata in the Panhandle field area are underlain by up-tilted edges of lower Paleozoic rocks (Mason, 1968), which could allow for greater contributions from deeper source rocks; and (4) this leaky 4D model allows for more vertical and lateral migration than would a more complex model. The Panhandle field contains sweet and sour gases (Owen, 1975), which also suggests contributions from deeper sources than the mostly Type II and III kerogen of Pennsylvanian source rocks.

Measured R_o values of the Upper Devonian–Lower Mississippian Woodford Formation are highest 30 to 40 km (20 to 40 mi) north-northwest of the deepest part of the Anadarko Basin, which is partly the result of the contrast in thermal conductivity between the high-conductivity granite wash strata adjacent to the Wichita uplift and the basinward low-conductivity shale section (Carter and others, 1998). The combination of decreasing heat flow toward the Wichita

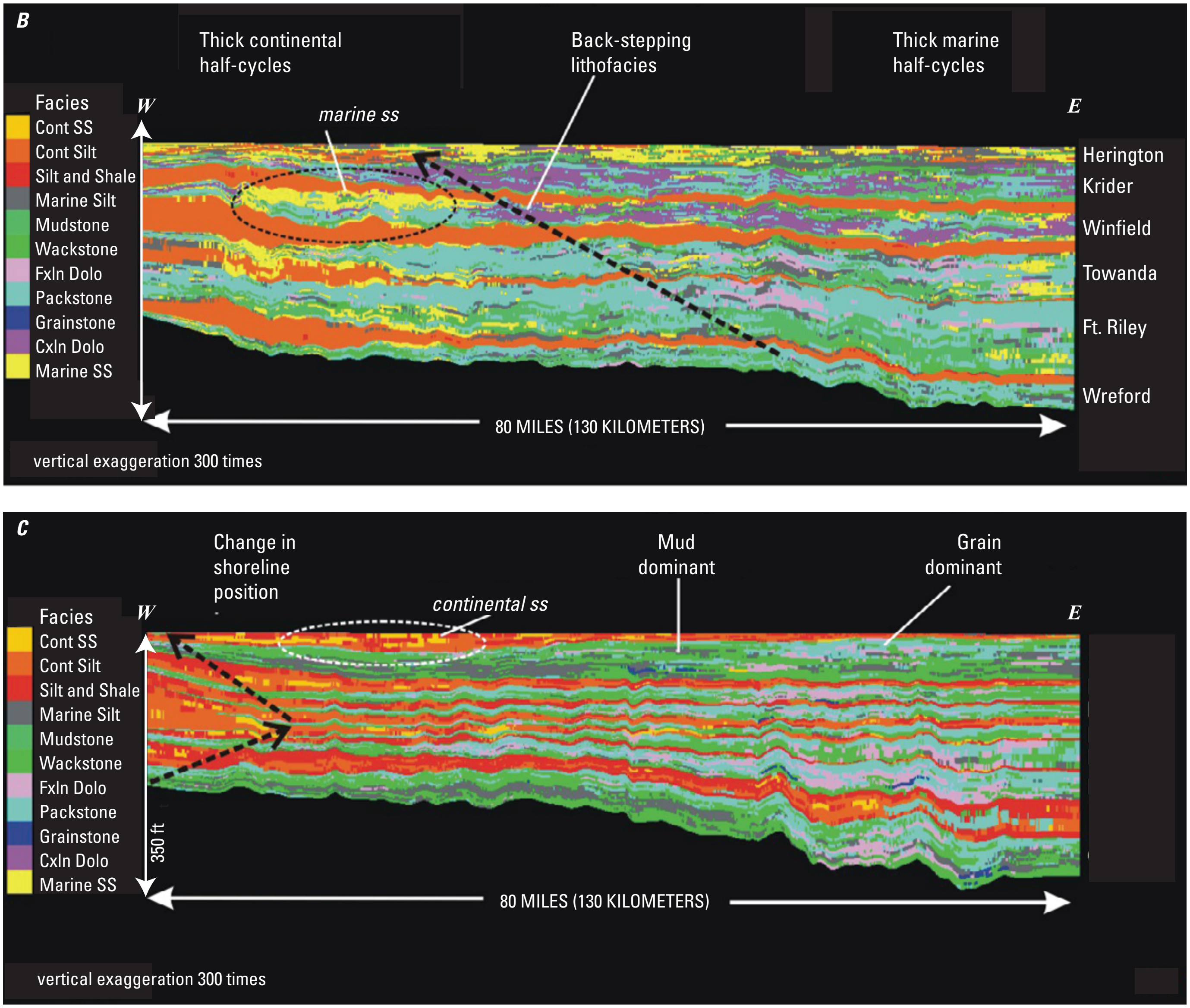


Figure 35. Lithofacies in west to east cross sections across the Hugoton field for the (B) Chase and (C) Council Grove Groups (modified from Dubois, 2007). These stratigraphic cross sections are hung on the top of the Chase (B) and the Council Grove (C), and location is in figure 33. Orange through red layers are continental (Cont) sandstone (SS), siltstone (Silt) and shale. Other colors are marine lithofacies, including fractured (Fxln) and crystalline (Cxln) dolomite (Dolo). Both cross sections show lateral continuity of cyclical beds of marine and continental strata. Marine strata increase in thickness to the east and continental beds thicken westward. Dubois (2007) indicated that large-scale sedimentation patterns and distribution of resultant lithofacies (at the cycle scale) are largely a function of the position on the shelf and reflect the interaction of shelf geometry, sea level, and, possibly, the proximity to siliclastic sources. Lithofacies distribution and cycle-stacking patterns at larger scales may be a function of lower-order cyclicity and a shift from icehouse to greenhouse conditions (upward) during the Lower Permian.

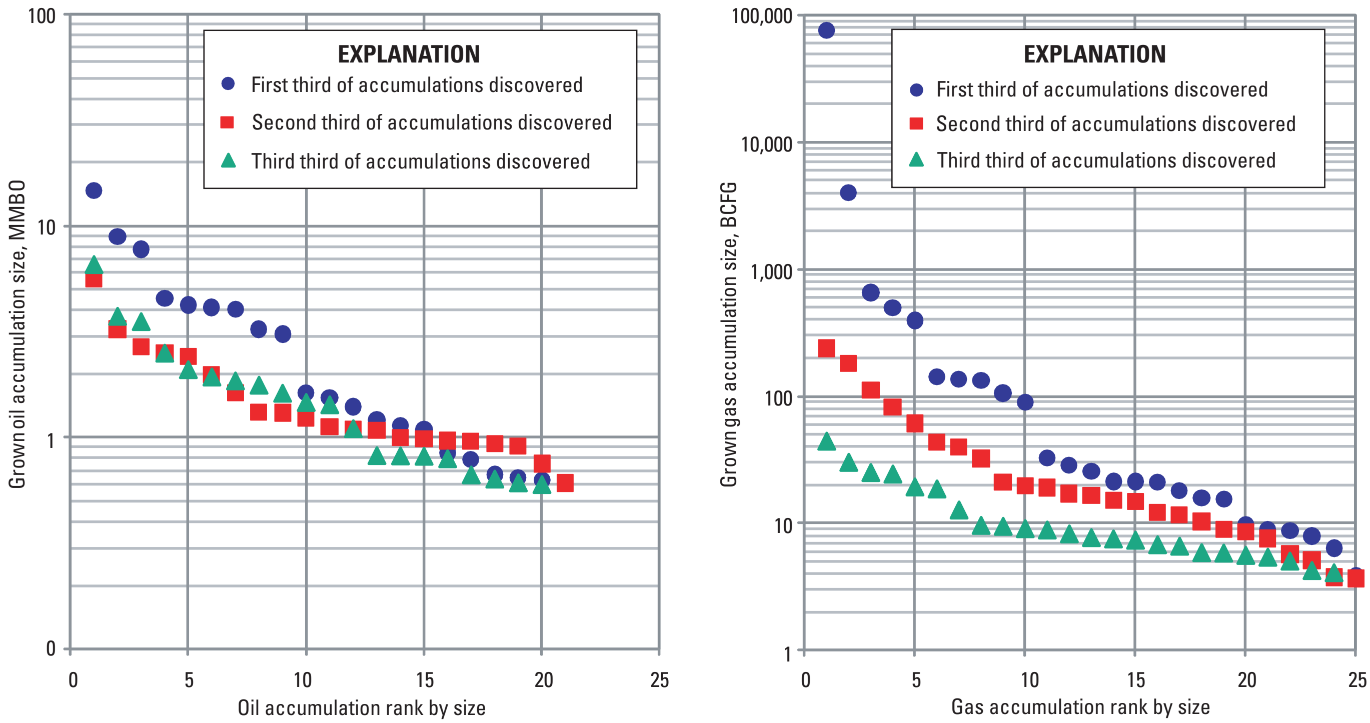


Figure 36. Graphs showing grown oil and gas accumulation sizes for discovery thirds of the Missourian-Permian Assessment Unit (AU) of the Pennsylvanian Composite Total Petroleum System. Only a fraction of the about 1,420 oil and gas fields that produce from this AU are shown, largely because many fields produce from multiple units with reported commingled volumes. Discovery trends are similar of grown oil accumulations less than about 20 million barrels of oil (MMBO). At greater than this volume, the first third of discoveries are larger than those of the second and third thirds. The early development history was marked by the giant Hugoton-Guymon and Panoma gas fields. In general, the gas accumulation chart shows a general decrease through time in field sizes. Billion cubic feet of gas, BCFG.

Mountains and the facies changes in the Pennsylvanian from marine shale to granite wash toward the uplift results in the highest formation temperatures being displaced about 50 km (31 mi) northward into the basin (Gallardo and Blackwell, 1999). Basement heat flow is greater basinward than it is close to the mountain front (fig. 38), which results in the pronounced thermal maturity "bump" in the figure 39 cross section from within the Greater Granite Wash Composite AU northward to Kansas. The associated burial history plot is in an area of low basement heat flow that contains granite wash arkosic strata. The Panhandle field is located on the Amarillo uplift, which exhibits low heat flow (fig. 38) and is thermally immature for hydrocarbon generation (fig. 40). The basin just north of the uplift deepens rapidly and thermal maturation of potential petroleum source rocks within 30 km (20 mi) ranges from mature for oil to gas generation. Some of the model layers are identified in figure 40, but lateral continuity is variable mainly because of faulting and data quality of formation tops used to construct the layers.

The petroleum system events chart (fig. 41) shows the timing of hydrocarbon generation, migration, and accumulation based on petroleum system models (table 2) (Higley, 2014). Onset of oil generation from Pennsylvanian source rocks (fig. 7) approximates the 300-Ma beginning of oil generation from Thirteen Finger limestone petroleum source rocks based on 4D petroleum system modeling. This onset preceded deposition of reservoir rocks from this AU; so the 270-Ma beginning of oil generation for this AU is based on the Higley (2012, table 3) modeled onset of generation from potential Virgilian source rocks.

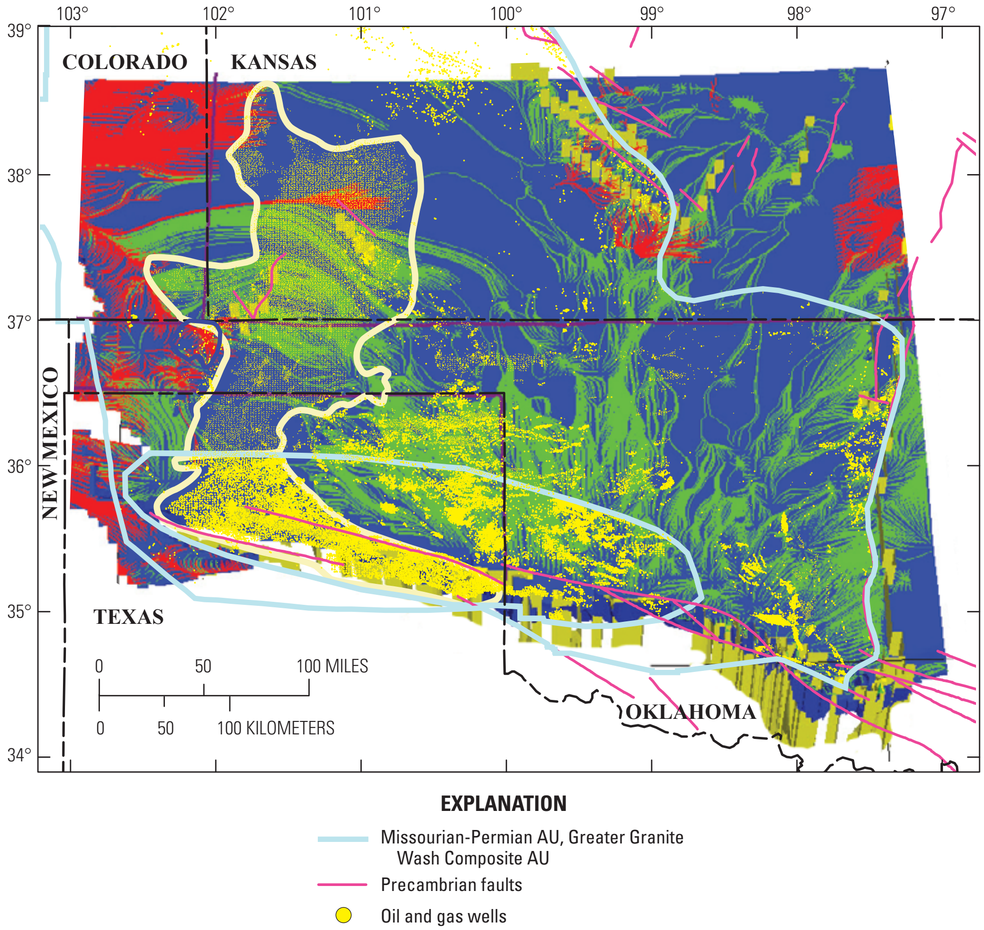


Figure 37. Model image showing oil and gas wells that produce from the Missourian-Permian and Greater Granite Wash Composite assessment units (AU) in the Anadarko Basin Province (IHS Energy, 2010a, 2010b) are superimposed on the image of Douglas plus Permian layer flow paths (fig. 30). In general, areas with less flow have fewer wells. Yellow outline is the Panhandle-Guymon-Hugoton field area, drilling is somewhat faint within the gas fields because of the wider drill spacing than for oil production. Absence of flow paths within the Panhandle field, with their appearance on the west side of the field suggests (invisible) Darcy flow through the reservoir because all potential source rocks are thermally immature in the western Amarillo uplift (fig. 8) (Higley, 2014). Sorenson (2005) also indicated that petroleum migrated southward from the basin into structural traps of the Panhandle field. Precambrian faults are from Adler and others (1971).

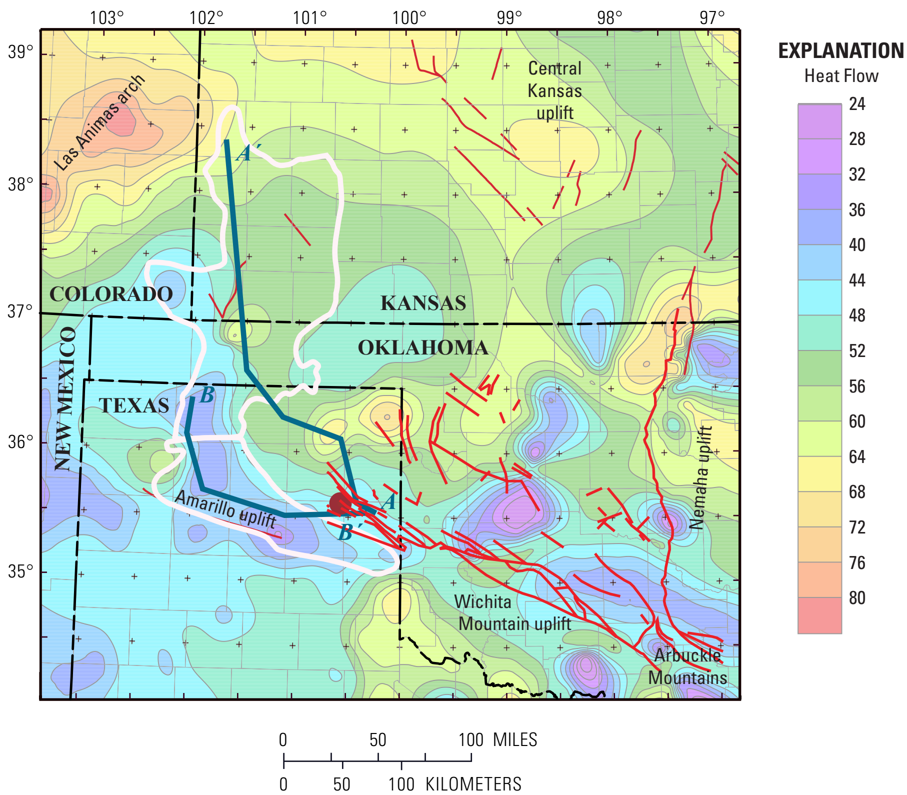


Figure 38. Map showing basement heat flow contours across the Anadarko Basin based on data from Carter and others (1998), Blackwell and Richards (2004), and data downloads from the Southern Methodist University Web site (*http://smu.edu/geothermal/*). Shown are the cross sections (blue lines) in figures 39 and 40, location of the one-dimensional burial history model (red dot), and Panhandle-Guymon-Hugoton field outlines (pink lines). Values are milliwatts per square meter (mW/m^2). The *A–A′* section crosses several zones of elevated heat flow and *B–B′* is mainly in areas of decreased heat flow. Basin areas north of the Wichita Mountain uplift and in the Amarillo uplift and northward exhibit generally lower heat flows than other basin areas. Highest measured heat flow is in the northwest, along the Las Animas arch. The northwest-trending Central Kansas uplift also exhibits elevated heat flow values. Red lines are faults on the top of the Hunton Group from Rottmann (2000a) that were used to contour Hunton and Woodford layers, and Precambrian faults (modified from Adler and others, 1971).

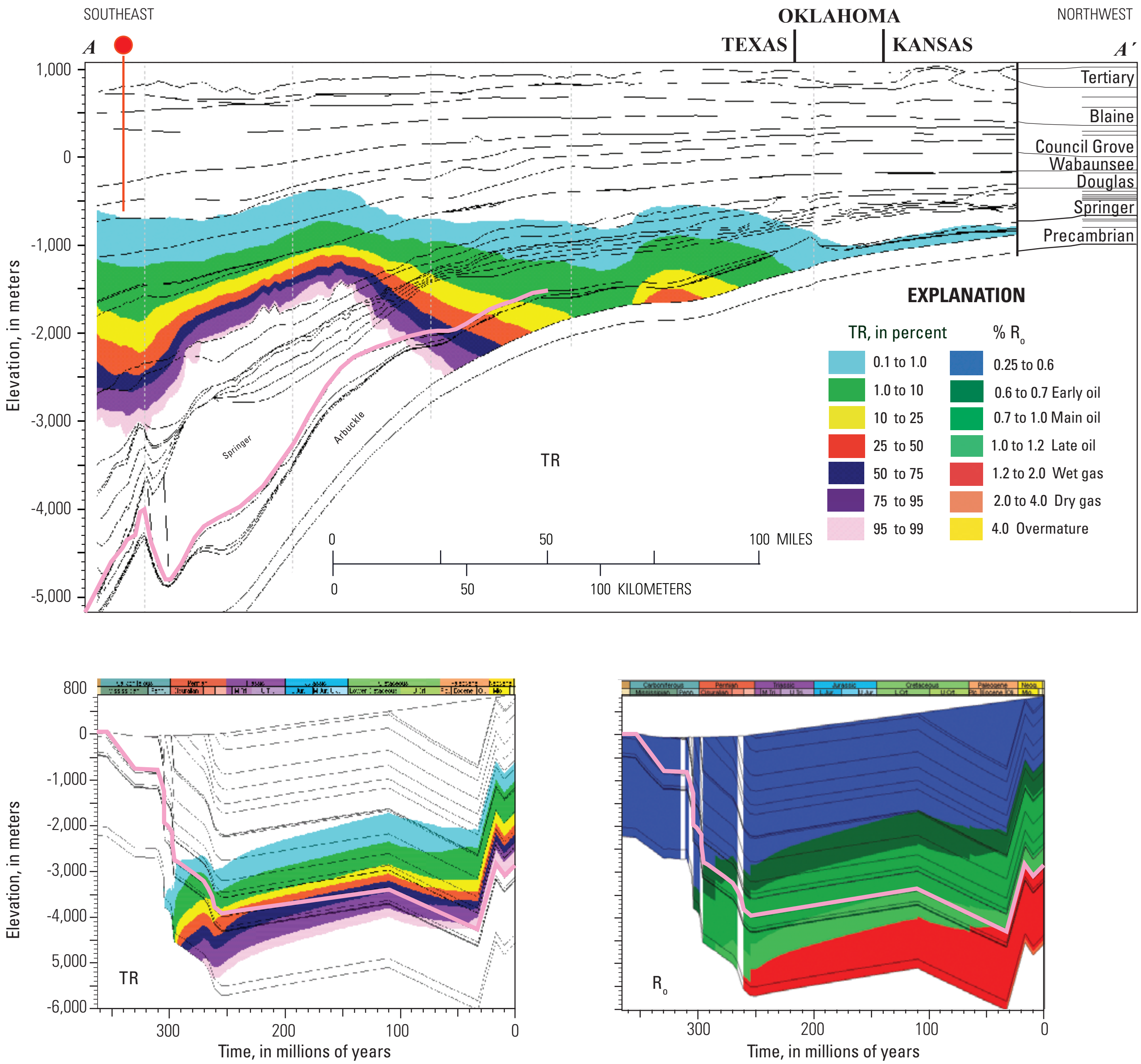
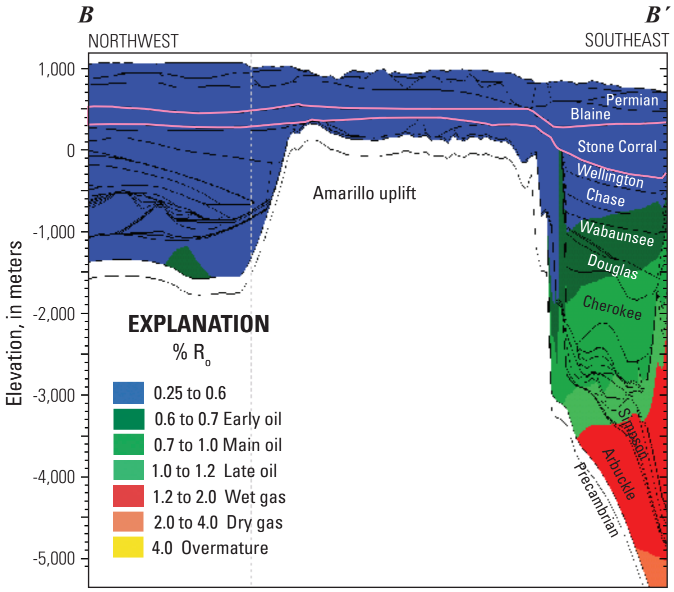


Figure 39. Southeast to northwest structural cross section with present-day transformation ratios (% TR). The burial history plot of TR and vitrinite reflectance (% R_o) is near the red dot on the cross section, and both locations are in figure 38. Pink lines are the general location of the Woodford Shale layer. The two “bumps” of increased thermal maturation on the cross section correspond to areas of increased heat flow in figure 38. Lithologic variation has minor effect on these increases because of the generalized lithofacies assignments in the model. If basement heat flow was one value across the basin, then the TR contours would be approximately horizontal because of the strong influence of burial depth. The burial history plots show the Council Grove layer as marginally mature for oil generation at 0.1 percent TR and 0.6% R_o, and the Woodford Shale layer is overmature for oil generation based on 100 percent TR and more than 1.2% R_o. The one-dimensional model is about 2 kilometers southwest of the Woodford Shale measurement of Cardott (1989, p. 45) for the 1 Miami Cattle well (1.56% mean R_o at -3,563 m elevation). These images are extractions from the four-dimensional petroleum system model, and are displayed in elevation relative to sea level.



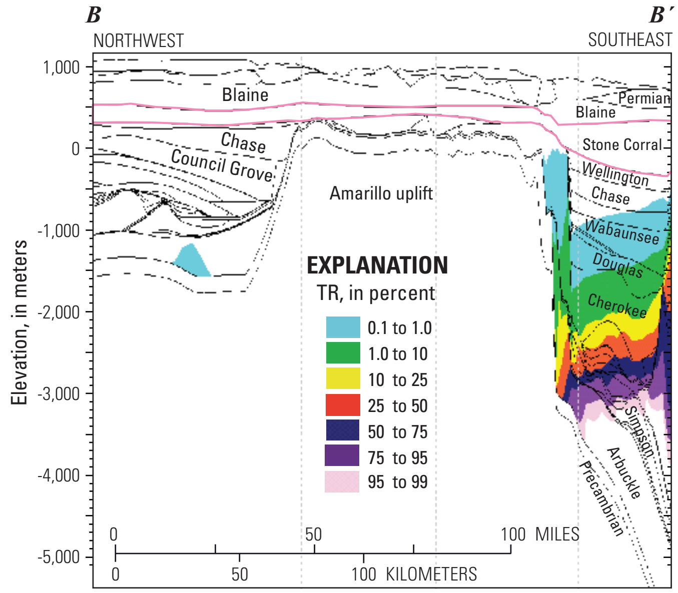


Figure 40. Cross section showing vitrinite reflectance (% R$_o$) and transformation ratio (% TR) is an extraction from the four-dimensional model across the Panhandle field. Location is in figure 38. The Panhandle field is located on the Amarillo uplift and oil and gas are produced from Wolfcampian and Leonardian strata. The Stone Corral model layer is bounded by pink lines and includes units from the top of the Leonardian Wellington to the base of the Guadalupian Blaine Formations (fig. 2). It is underlain by Wolfcampian strata. The Amarillo uplift and areas to the northwest are thermally immature for oil generation, and potential petroleum source rocks are absent because of erosion or nondeposition. Oil and gas migration flow paths appear west of the Panhandle field in figures 30 and 36; this indicates that hydrocarbons did flow through this field but were not trapped in this leaky model, and were most likely sourced from the east and northeast from Pennsylvanian and older source rocks and through open fault systems. Vertical exaggeration is 33 times.

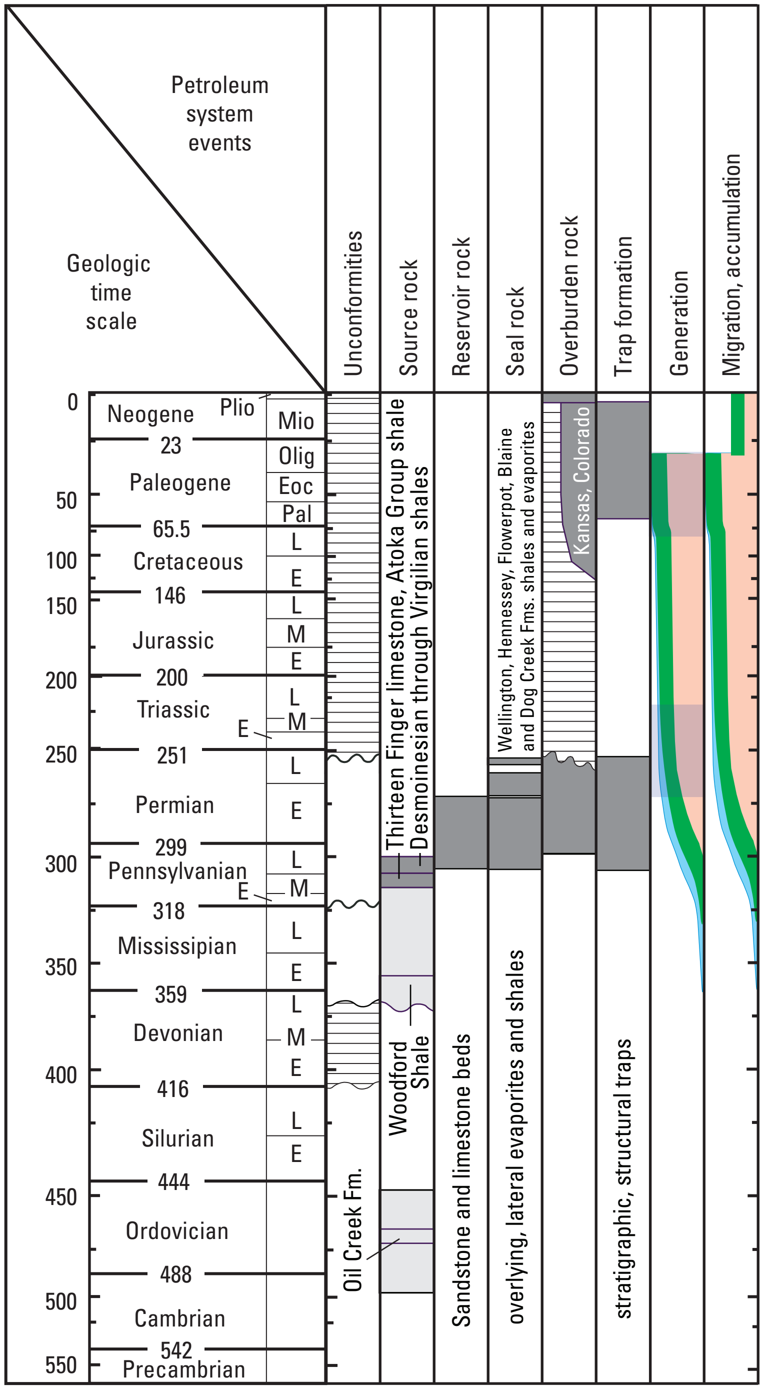


Figure 41. Petroleum system events chart for the Missourian-Permian AU of the Pennsylvanian Composite TPS. Primary hydrocarbon source rocks are dark gray rectangles, and age ranges of potential source rocks from Hatch and others (1986) (fig. 7) are light gray rectangles. Onset and peak petroleum generation (fig. 14) are shown for the Oil Creek (blue), Woodford (green), and Thirteen Finger limestone (tan) source rocks. Age ranges of peak hydrocarbon generation are indicated by blue rectangles. Paleogene trap formation, migration, and accumulation are based on Laramide generation and potential remigration associated with basin tilting. Unconformities, wavy and horizontal lines; Fm(s)., Formation(s); Plio, Pliocene; Mio, Miocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

Greater Granite Wash Composite Assessment Unit

The Greater Granite Wash Composite AU is defined as including Desmoinesian through Virgilian strata. The informally named granite wash strata consist mainly of arkosic shale to conglomerate. Every major stratigraphic unit from Morrow, and probably Springer, through Wolfcampian in the basin includes some granite wash facies near the mountains based on Dobervich and Parker (1958) and Edwards (1959).

The Wichita orogeny climaxed during the Atokan and slowed in Desmoinesian time; the orogeny was accompanied by uplift of tens of thousands of feet of the Wichita Mountain and Amarillo uplifts relative to the basin axis; associated erosion resulted in deposition of granite wash sediments in the subsiding basin north of the fault zones (Ball and others, 1991). Carbonate conglomerates were the first to form; these resulted from erosion of the thick sequence of early and middle Paleozoic carbonates that mantled the rising Wichita Mountain and Amarillo uplifts, subsequent deposition of conglomerates of arkosic lithofacies resulted from the exposure and erosion of granites and rhyolites in the core of the Wichita-Amarillo Mountains (Johnson, 1989; Gallardo and Blackwell, 1999). This heterogeneous mix of detritus in the granite wash became progressively finer northward of the source area.

The Anadarko Basin has been dormant since Early Permian time (Perry, 1989), as indicated by the relatively uniform thickness of Wolfcampian and Leonardian units across the basin, and that the Council Grove and Chase Groups, Hennessey Shale, and other strata can be correlated across the basin. Guadalupian and younger units exhibit more irregular distribution because of areas of nondeposition, and Laramide orogeny-associated uplift, tilting, and erosion but are present over much of the AU based on Adler and others (1971). The granite wash is generalized in figure 42 as the wedge-shaped

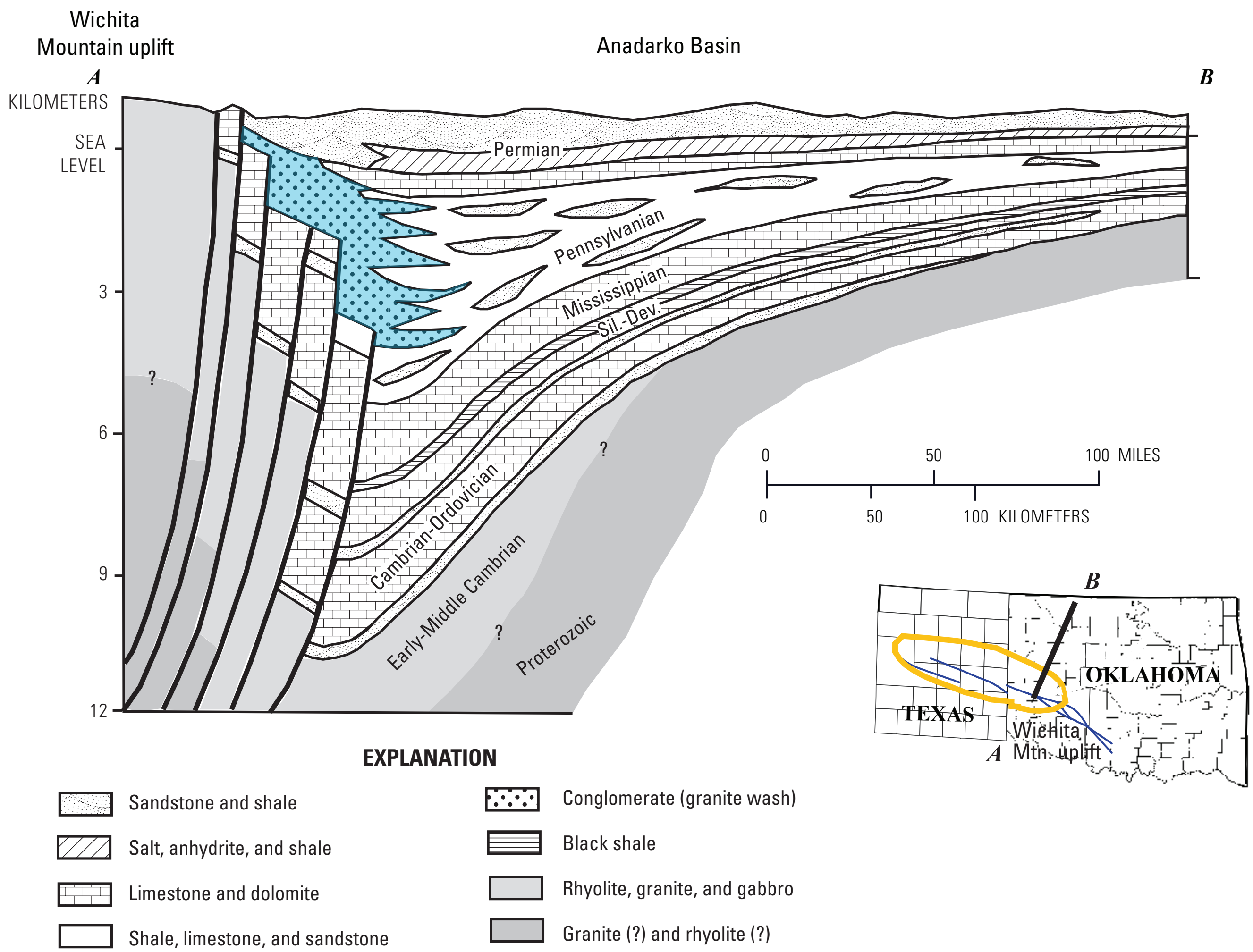


Figure 42. Simplified southwest to northeast structural cross section from the Oklahoma deep basin to the shelf shows interfingering of granite wash lithofacies (blue) with those basinward (modified from Johnson, 1989). Greater Granite Wash Composite Assessment Unit (AU) boundary is gold line and cross section location is red line on inset map. Datum is sea level. Sil.-Dev., Silurian-Devonian.

granite wash interval; lithofacies grade basinward into mostly marine strata. The granite wash sequence is as much as 5,000 ft thick and is located within about 30 miles north of the Wichita Mountain and Amarillo uplifts (Owen, 1975; Johnson, 1989). The extent of granite wash in Wolfcampian was less than 10 miles from the mountain front (Ball and others, 1991).

The greatest thickness of included strata in the AU is along the axis of the deep basin, with progressive northward and westward thinning. Thickness of the Morrowan through Wolfcampian section varies from 0 to more than 12,000 ft, and the Atoka Group to Stone Corral Formation interval has a similar thickness and distribution (fig. 43). Morrowan and Atokan strata, however, are absent over most of the Amarillo and Wichita Mountain uplifts. Determination of formation contacts from well logs south of the basin axis is complicated by interbedding of granite wash and marine lithofacies, and steeper dips proximal to the Wichita Mountain and Amarillo uplifts. Thicknesses in the figure 43 isopach map are not corrected to true stratigraphic thickness. More detailed descriptions and thickness maps of the various granite wash intervals are located in Mitchell (2011).

The Greater Granite Wash Composite AU has almost 20,000 wells, with cumulative production of about 1.6 BBO, 43.3 TCFG, and 1.1 BBW; about 11,000 of the wells are productive of oil and 19,000 have associated or nonassociated gas (IHS Energy, 2010a) (fig. 44). These totals include more than granite wash wells and production, mainly because the AU boundary includes strata that are not granite wash. This is because of the variable lateral extent and interfingering of these strata with other lithofacies, and some granite wash production is reported commingled with other units. Granite wash is listed as a producing interval from about 6,900 wells in the AU with cumulative production of about 1.44 BBO, 4.32 TCFG, and 1.03 BBW (IHS Energy, 2010b) (fig. 45). The Oklahoma Geological Survey (OGS, 2011b) Web site also includes information on granite wash and other plays, and reported granite wash production to 2008 as more than 61 MMBO and 1.88 TCFG from more than 4,200 wells. The apparent discrepancy between the IHS Energy and OGS numbers is partly the different reporting dates, but mainly because of the number and distribution of wells that were assigned to granite wash production (fig. 45). The OGS (2011b) included some wells just southeast of the TPS, and had fewer wells in the northwest Panhandle field area. Almost all wells in the western Panhandle field have completion dates after 2008, so the difference is likely how the OGS (2011b) evaluated the producing formations and associated production, compared to the reporting of IHS Energy (2011a, 2011b). Mitchell (2011) indicated that an average EUR from a vertical granite wash well is 1.5 BCFG and 21,000 BO. Many of the IHS Energy (2010a, 2010b) granite wash wells in the Panhandle field area correspond to oil wells in figure 44. Much of the Panhandle field gas production is identified as the informally named Wolfcampian Brown dolomite of the Chase Group and the Leonardian Red Cave of the Sumner Group, which are shallower than granite wash strata. The first Permian production

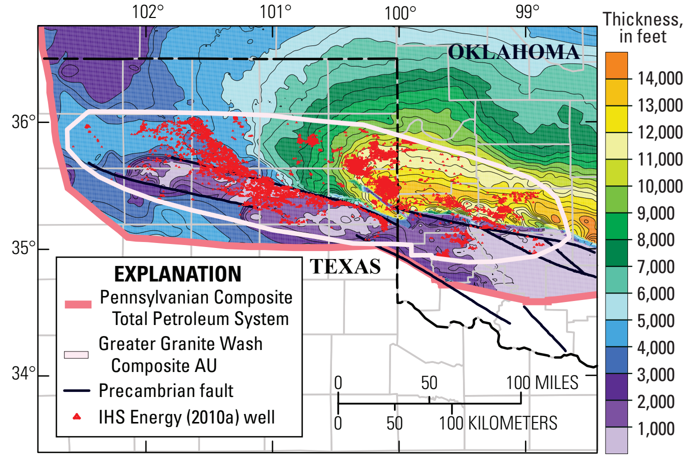


Figure 43. Map showing thickness of the top of the Atoka to the Stone Corral model layers in the Greater Granite Wash Composite Assessment Unit (AU) ranges from about 0 to more than 14,000 feet (ft). Areas of smooth contours have more limited data, such as the Wichita Mountain uplift and Panhandle field areas; actual thicknesses here are generally less than 1,000 ft (300 meters). Displayed wells produce oil and (or) gas from granite wash facies. Contour lines are 500-feet intervals. Precambrian faults (black) are from Adler and others (1971). Light gray lines are counties.

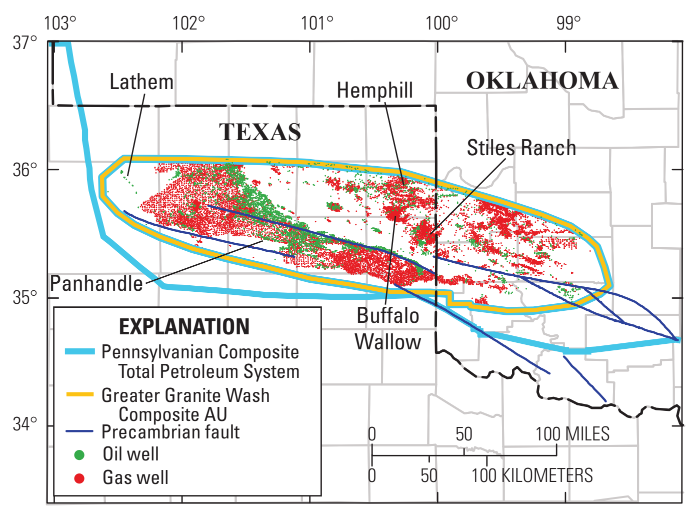


Figure 44. Map showing oil and gas wells that produce from the Greater Granite Wash Composite Assessment Unit (AU) in the Pennsylvanian Composite Total Petroleum System (TPS), Anadarko Basin Province (IHS Energy, 2010a, 2010b). Smaller scale views of oil and of gas wells are in the Desmoinesian and Missourian-Permian oil and gas figures 24 and 31. Generalized field locations are from IHS Energy (2010a), Nehring and Associates, Inc. (2009), and Bebout and others (1993). The largest field is Panhandle, which covers most of the Amarillo uplift and produces from granite wash and other lithofacies. Precambrian faults (blue) are from Adler and others (1971). Light gray lines are counties.

in the Greater Granite Wash Composite AU was from Red Cave interbedded redbeds and carbonates of the Panhandle field in 1919.

Cotner and Crum (1933) listed the range in GOR from 500 to 1,000,000 CFG/BO for the Panhandle field, which reflects that the Greater Granite Wash Composite AU includes oil and gas plays. Estimated gas/oil ratio (GOR) is 30,820 for the OGS (2011b) data. OGS (2011b) listed cumulative production of 99,400 BO, 1.0 BCFG, and more than 440,000 BW for a typical granite wash well. Smith and others (2001) indicated the average granite wash production for their 1,985 wells was 24 MBO and 1.15 BCFG; associated mean GOR is 48,000 CFG/BO.

Discovery halves for oil and thirds for gas accumulations are shown in figure 46. Discovery halves data for oil fields are too limited to form conclusions. The first and second thirds of gas accumulations have been stable through time, and a decrease in discovery thirds more than 20 BCFG for gas accumulations may reflect the shorter production time for these fields, as well as the largest accumulations generally being discovered early in exploration. The curves were not skewed by the Panhandle field, which is not included on these charts. Exploration histories of Greater Granite Wash Composite AU leases and of wells within the granite wash (fig. 47) follow similar trends with those of other AUs in the province, with the exception of later onset of drilling.

Drilling depths in the AU range from less than 100 ft to an estimated maximum of about 15,000 ft; petroleum production is as shallow as 300 ft, but most major reservoirs produce from depths of 4,700 to 16,500 feet based on Henry and Hester (1995) and Mitchell (2011). Permeability in the Pennsylvanian granite wash is variable, ranging from close to 0 to more than 300 mD, with about 20 percent average porosity (Mason, 1968) for these conglomeratic to arkosic strata. Published API gravity values of oil in the Panhandle field area range from 34 to 37^{o} (Owen, 1975). Mitchell (2011) listed API gravities of 45-60^{o} for oil and condensate, and natural gas liquid yields are as high as 190 barrels per million cubic feet of gas (B/MMCFG); Virgilian and Missourian granite wash reservoirs are shallower and more oil-prone with API gravities of 45–50^{o}.

Traps are structural and (or) stratigraphic. The northern fault of the Amarillo uplift brackets some oil wells, and wells north of the fault systems show a north-northwest trend that is oblique to Precambrian faults but fit well over Hunton fault systems of Rottman (2000a, 2000b) that are shown in figure 38. Panhandle field is located on the Amarillo uplift and is bracketed on the north and south by bounding faults (figs. 38 and 40). Seals include interbedded and overlying shales, change in updip and lateral facies, and fault offsets close to the Wichita and Amarillo uplifts. Differential compaction on the south side of the Amarillo uplift anticline also provided a seal (Mason, 1968). The Pennsylvanian in the Panhandle oil field area is underlain by up-tilted edges of older Paleozoic rocks (Mason, 1968), which probably resulted in contributions through time from multiple petroleum source rocks.

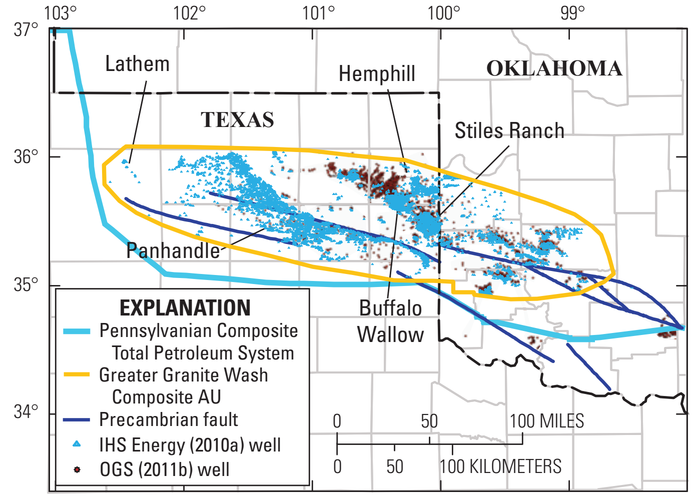


Figure 45. Map showing oil and (or) gas wells that produce from the granite wash within the Greater Granite Wash Composite Assessment Unit (AU). Some of the more than 3,600 Oklahoma Geological Survey (2011b) wells up to about 2008 are overlain by the more than 6,900 wells through September 2010 from IHS Energy (2010a, 2010b). Generalized field locations are from IHS Energy (2010a), Nehring and Associates, Inc. (2009), and Bebout and others (1993). Precambrian faults (blue) are from Adler and others (1971). Light gray lines are counties.

The western quarter of the AU, including most of the Amarillo and Wichita Mountain uplifts, are thermally immature for oil generation because of shallow burial depths and decreased basement heat flow (figs. 8 and 38–40). Thermal maturation of Pennsylvanian petroleum source and potential source rocks in the rest of the AU ranges from immature for oil generation to mature for dry gas generation, as indicated by a modeled R_o of less than 4 percent for the Thirteen Finger limestone layer (fig. 8). The Woodford Shale is absent over the western AU area, but deeper petroleum source rocks range in maturity from oil generation to overmature for gas generation. Hydrocarbon migration was primarily from the deep basin with flow to the west and northwest (fig. 30). The Greater Granite Wash Composite AU petroleum system events chart (fig. 48) shows the timing of hydrocarbon generation, migration, and accumulation based on petroleum system models (table 2) (Higley, 2014). Onset of oil generation from Pennsylvanian source rocks approximates the 300-Ma beginning of oil generation from Thirteen Finger limestone petroleum source rocks, based on petroleum system modeling. This onset preceded deposition of reservoir rocks from this AU, so the 270-Ma beginning of oil generation for this AU is based on the Higley (2012, table 3) modeled generation for potential Virgilian source rocks.

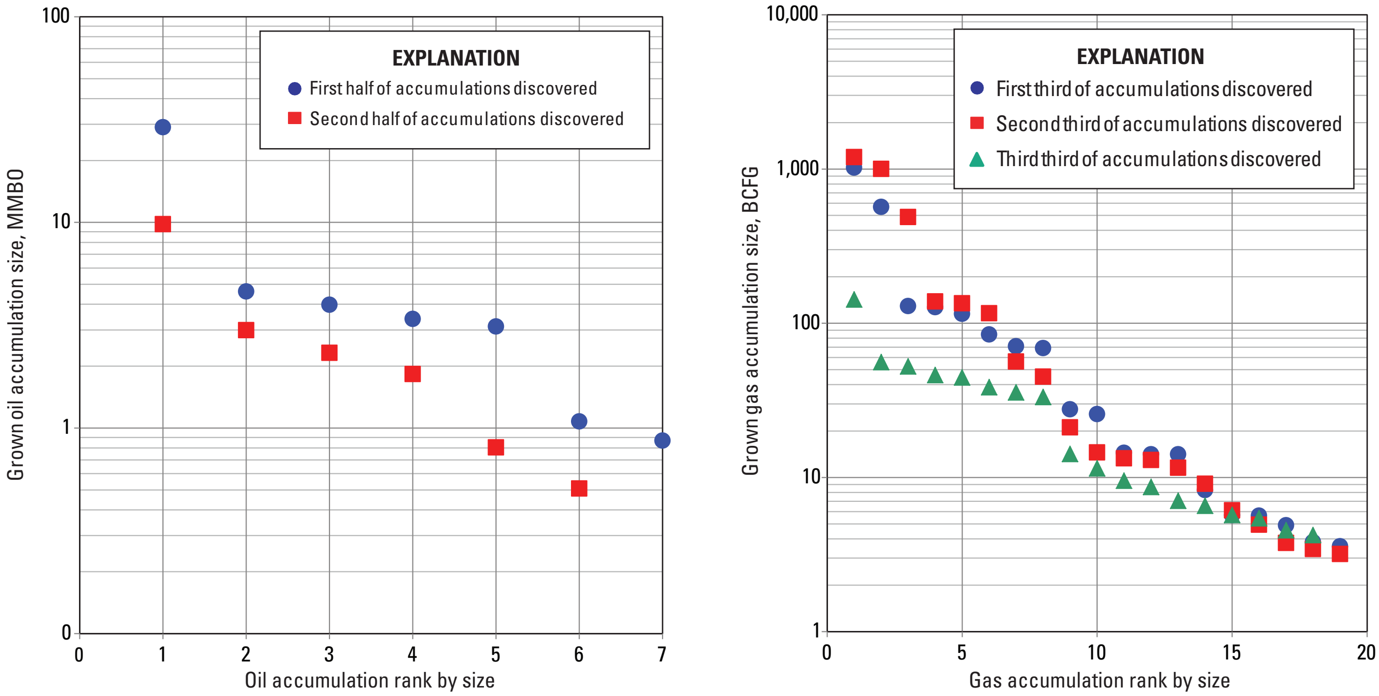


Figure 46. Discovery halves for oil and thirds for gas grown accumulations for the Greater Granite Wash Composite Assessment Unit (AU) in the Anadarko Basin Province. Only a fraction of the oil and gas fields that produce from this AU are shown, largely because most fields produce from multiple units with reported commingled volumes. These also include giant fields, such as Panhandle, which is not included in the discovery halves plot. Because these figures include some production from strata north of the granite wash lithofacies, the discovery plots are further compromised. The discovery halves of oil accumulations indicate that development has decreased through time. This "trend" probably reflects the paucity of data. The discovery thirds of gas accumulations indicates discovery has been fairly stable through time, although field sizes have decreased for larger fields as indicated by the third of accumulations greater than 20 billion cubic feet of gas (BCFG).

Mesozoic Strata

Post-Permian strata in the basin include scattered remnants of rocks ranging in age from Triassic to Quaternary. Mostly alluvial sediments of the Miocene to Pliocene Ogallala Formation were deposited on an erosional surface of mostly Permian strata in the western half of the basin (Seni, 1980; Johnson and others, 1988). Underlying Mesozoic units are present mostly in the Colorado and western Kansas portions of the province, with only scattered erosional remnants in Oklahoma and Texas.

Johnson and others (1988) estimated that 500–1,000 ft of Triassic and Jurassic strata were deposited in the Oklahoma and Texas portions of the basin but subsequent Early Cretaceous erosion removed all but the scattered 25–200 ft that remains in the far western part of the Anadarko Basin. Based on geologic maps of the States, outcrops of Mesozoic strata occur southeast of the province, in the Central Kansas uplift, along the western border in Colorado, Oklahoma, and Texas, the Amarillo uplift, and in scattered exposures along drainages in Kansas, New Mexico, and Oklahoma. The Lower Cretaceous Dakota Group sandstones and shales were deposited in the Colorado, western Kansas, and Oklahoma panhandle areas of the basin. Although the Muddy ("J") Sandstone of the Dakota Group is an important oil and gas reservoir in the Denver Basin, there is minimal potential for petroleum in the Anadarko Basin Province because of (1) thermally immature source rocks; (2) long vertical and lateral migration distances for Paleozoic source rocks; (3) depositional thinning and updip erosion of the strata; and (4) formation water in these porous and permeable sandstones. Other Mesozoic units have low potential for the same general reasons. An exception to this is the Upper Cretaceous Niobrara Shale in the northern Las Animas arch area of Colorado and western Kansas; however, this resource was included in the Denver Basin assessment (Higley and Cox, 2007; Higley and others, 2007) and will only be mentioned here. Because contained gas is biogenic, thermal maturity of source rocks and migration distances are not important considerations. Within the productive area, potential hydrocarbon source rocks are thermally immature for generation at about 0.3 to 0.4% R_o (Smagala and others, 1984, Tainter, 1984). Biogenic gas is located within shallow, underpressured, fractured, relatively clean chalks (Longman and others, 1998) in fields that have low-relief structural closures.

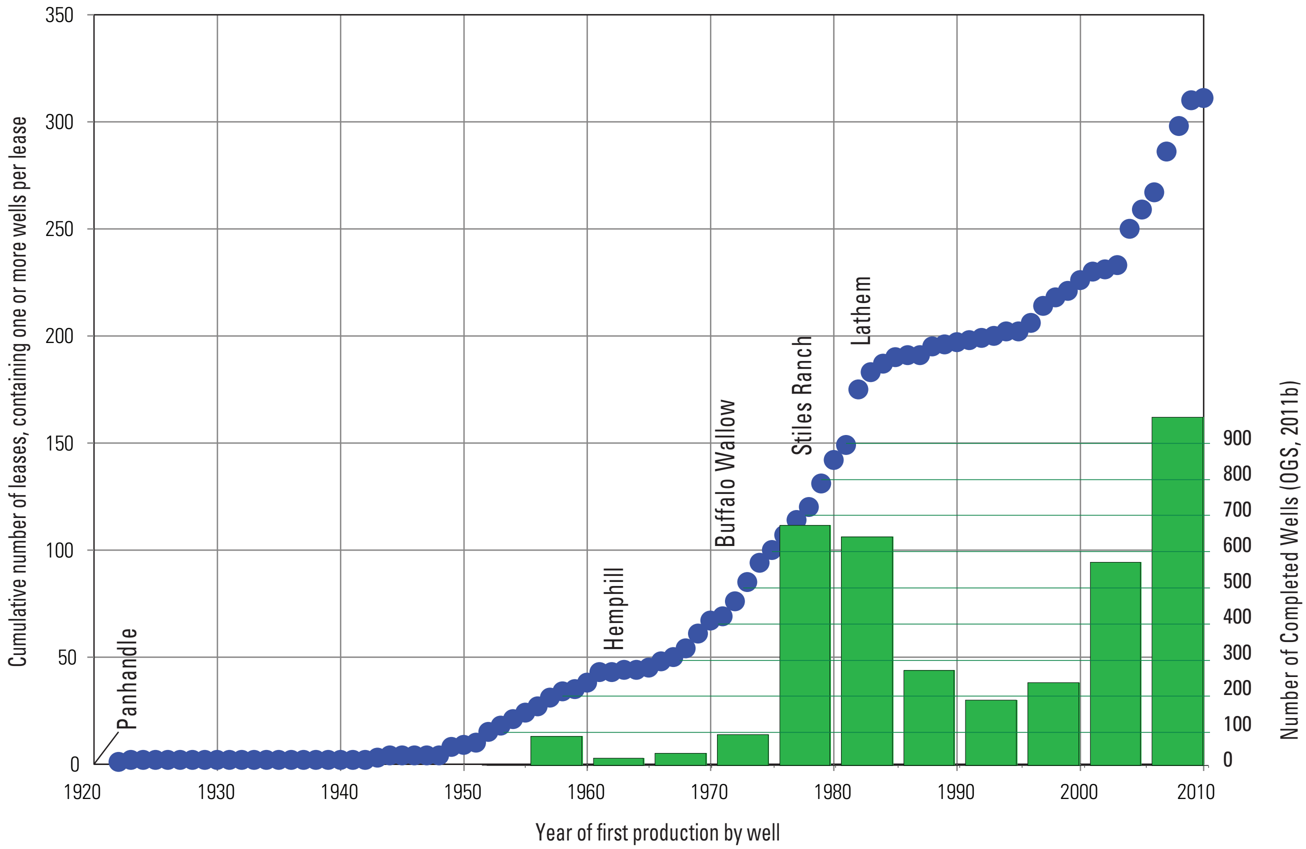


Figure 47. Production history of leases in the Greater Granite Wash Composite Assessment Unit in the Anadarko Basin Province is shown relative to the more than 3,700 completed wells for the same time increments from Oklahoma Geological Survey (OGS, 2011b). Granite wash development started about 1950 and the Oklahoma Geological Survey (2011b) bars follow industry boom and bust cycles with an increase in completions from 1976 to 1985, followed by a lull until about the 2002 increase in exploration. Shown are some of the major field discovery names and year (Nehring and Associates, Inc., 2009; IHS Energy, 2010a, 2010b).

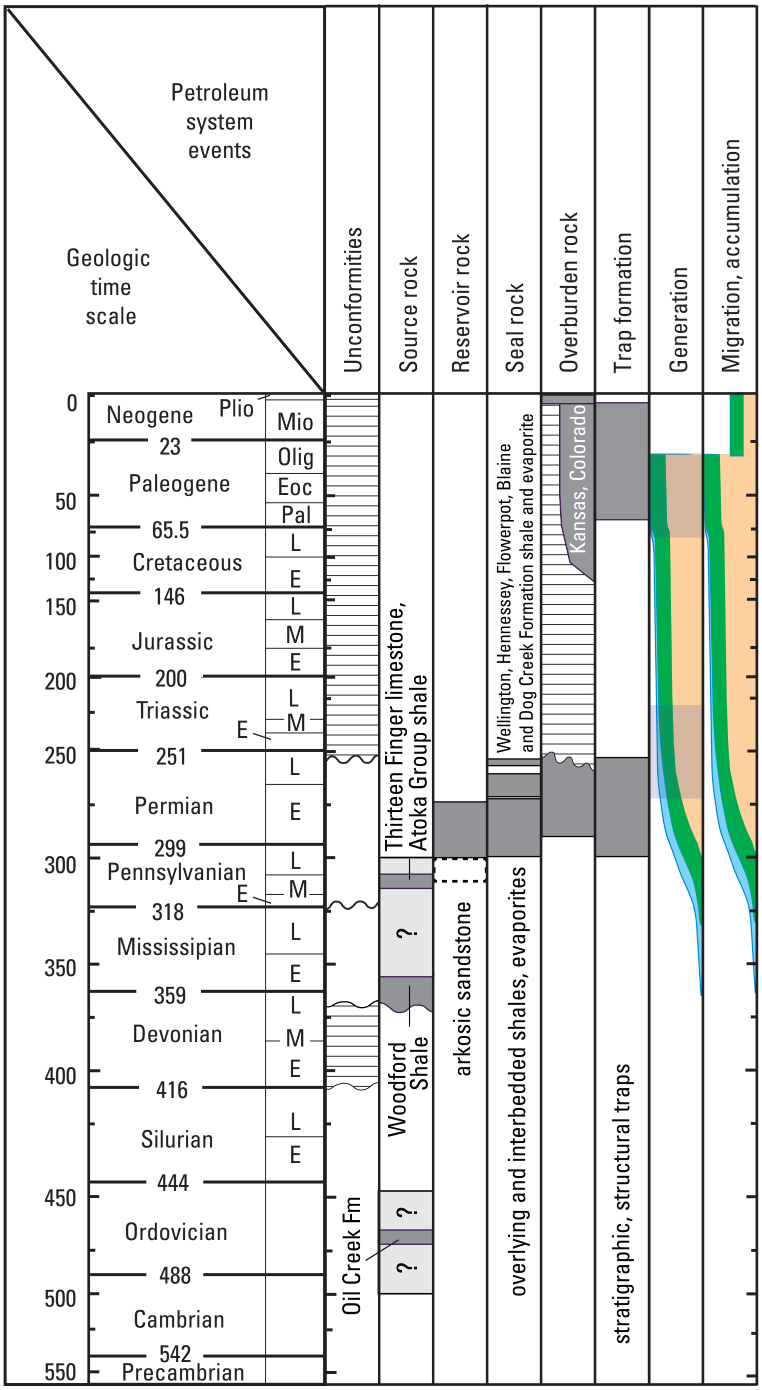


Figure 48. Petroleum system events chart for the Greater Granite Wash Composite Assessment Unit (AU) of the Pennsylvanian Composite Total Petroleum System (TPS). Dashed reservoir rock rectangle shows an interval of potential granite wash deposition that was included in the Morrowan-Atokan Assessment Unit (AU). Potential petroleum source rocks from Hatch and others (1986) (fig. 7) are light gray rectangles. Onset and peak petroleum generation (fig. 14) are shown for the Oil Creek Formation (blue), Woodford Shale (green), and Thirteen Finger limestone (tan) source rocks. Age ranges of peak generation are indicated by blue rectangles. Paleogene trap formation, migration, and accumulation are based on Laramide generation and potential remigration associated with basin tilting. Unconformities, wavy and horizontal lines; Fm., Formation; Plio, Pliocene; Mio, Miocene; Eoc, Eocene; Pal, Paleocene; L, Late; M, Middle; E, Early.

Reservoir quality is controlled by burial diagenesis (Scholle, 1977) and influenced by fracturing on low-relief structures. Fracturing may also be associated with dissolution of underlying Permian evaporites. The fractured Niobrara chalks commonly have porosities of 40 percent and greater (Lockridge and Scholle, 1978) but low matrix permeability. Burial temperatures do not exceed 75 ^{o}C in areas of active biogenic generation of gas (Rice and Claypool, 1981).

Conclusions

The Anadarko Basin Province is in a mature state of exploration and development, with more than 220,000 wells drilled. Oil and gas reserves and resources are distributed across the province and within Cambrian through Lower Permian strata. Much of the production is reported commingled from two or more formations, which complicates assigning oil and gas production and reserves to specific strata. This was a primary rationale for grouping assessment units (AU). The AUs discussed in this chapter of the report are conventional, with the exception of the continuous (unconventional) Thirteen Finger Limestone–Atoka Shale AU that has the same general extent as the vertically bounding Morrowan-Atokan AU.

The Mississippian AU extends across the province, with petroleum production from mostly Lower Mississippian carbonates through Upper Mississippian sandstones and carbonates. The Morrowan-Atokan AU outlines the extent of these strata. These Morrow and Atoka Group reservoirs are mostly marine and nonmarine sandstone and calcareous sandstone, with lesser limestone beds. The Thirteen Finger limestone and overlying Atoka shale intervals are the reservoir and petroleum source rocks for the Thirteen Finger Limestone–Atoka Shale AU. Cyclical thin limestone and shale beds are the potential reservoirs. The Greater Granite Wash Composite AU is located in the deep basin in Oklahoma and Texas. Informally named granite wash reservoirs consist mainly of Desmoinesian to Virgilian arkosic shale to conglomerate. Granite wash lithofacies grade northward and interfinger with mostly marine strata of other AUs. The surrounding Desmoinesian and Missourian-Permian AUs extend to the province boundaries. Desmoinesian, Missourian, and Virgilian strata were deposited in transgressive-regressive cycles that periodically inundated the province with alternating thin-bedded mainly marine sandstones, limestones, and shales that are stratigraphic packages of mostly sandstone or mostly limestone reservoirs. Desmoinesian AU reservoirs are clastic and carbonate beds of the Cherokee and Marmaton Groups, and their lateral equivalents. The Missourian-Permian AU includes Missourian, Virgilian, Wolfcampian, and Leonardian carbonate and clastic reservoirs.

Assignment of petroleum source rocks to AUs was based mainly on previous research, analysis of well history and production data from proprietary databases, and 1D and 4D petroleum system models that were constructed for this project. The Devonian-Mississippian Woodford Shale was the primary petroleum source rock for Mississippian and lower Morrow Formation units. Overlying Morrowan through Permian strata were mainly sourced from Pennsylvanian black shales, including the Atokan Thirteen Finger limestone.

The Anadarko Basin is the deepest basin in the onshore United States. It is markedly asymmetrical, with Precambrian basement ranging in depth from more than 40,000 ft at the basin axis in southern Oklahoma, to surface exposures on the broad shelf in the proximal Central Kansas uplift (CKU of Kansas). Ordovician through Pennsylvanian petroleum source rocks and potential source rocks in the shelf area are almost entirely thermally immature for oil generation. In the deep basin they range from marginally mature for oil generation to overmature for gas generation. Modeling indicates that oil generation began in the deep basin as early as 330 Ma in the Woodford Shale, 300 Ma in the Thirteen Finger limestone, and 270 Ma in Virgilian strata, which may contain the youngest petroleum source rock(s). Oil and gas were generated mostly in the deep basin and flowed radially northward. Flow in northern Oklahoma and in Kansas was directed toward the Las Animas arch, CKU, and Nemaha uplift. The Laramide orogeny may also have influenced petroleum migration through uplift and by imparting a subtle southeastern tilt to the basin, specifically resulting in redistribution of Panhandle field fluid columns with northward spilling of gas into the Hugoton embayment. Migration distances range from self-sourced for the Thirteen Finger Limestone–Atoka Shale AU, to long range from thermally mature source rocks in Oklahoma and Texas to reservoirs in Kansas and Colorado.

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References Cited

Abels, T.A., 1959, A subsurface study of the Morrowan Series in the northern Anadarko Basin: Oklahoma City Geological Society Shale Shaker, v. 9, p. 5–21.

Adams, W.L., 1964, Diagenetic aspects of lower Morrowan, Pennsylvanian, sandstones, northwestern Oklahoma: American Association of Petroleum Geologists Bulletin, v. 48, p. 1568–1580.

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, Jr., G., 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 Geologist Memoir 15, v. 2, p. 985–1120.

Al-Shaieb, Z., and Walker, P., 1986, Evolution of secondary porosity in Pennsylvanian Morrow sandstones, Anadarko Basin, Oklahoma, *in* Spencer, C.W., and Mast, R.F., eds., 1986, Geology of tight gas reservoirs: American Association of Petroleum Geologists Studies in Geology, no. 24, p. 45–67.

Al-Shaieb, Z., Shelton, J.W., and Puckette, J.O., 1989, Sandstone reservoirs of the mid-continent syllabus for short course, Mid-continent section of the American Association of Petroleum Geologists 1989 meeting: Oklahoma City Geological Society, 125 p.

Al-Shaieb, Zuhair, Puckett, J.O., Abdalla, A.A., and Ely, P.B., 1994, Megacompartment complex in the Anadarko Basin: A completely sealed overpressured phenomenon, *in* Ortoleva, P.J., ed., Basin compartments and seals: American Association of Petroleum Geologists Memoir 61, p. 55–68.

Anderson, C.J., 1991, Distribution of submarine fan facies of the Upper Red Fork interval in the Anadarko Basin, western Oklahoma: Oklahoma State University, Unpublished M.S. thesis, 127 p.

Andrews, R.D., 1999a, Map showing regional (sic) structure at the top of the Morrow Formation in the Anadarko Basin and shelf of Oklahoma: Oklahoma Geological Survey Special Publication 99–4, pl. 3.

Andrews, R.D., 1999b, Morrow gas play in the Anadarko Basin and shelf of Oklahoma: Oklahoma Geological Survey Special Publication 99–4, 133 p., 7 pls.

Andrews, R.D., 2001, Map showing regional structure at the top of the Springer Group in the Ardmore Basin, and the Anadarko Basin and shelf of Oklahoma: Oklahoma Geological Survey Special Publication 2001–1, pl. 5.

Andrews, R.D., Campbell, J.A., and Northcutt, R.A., 1996, Fluvial-dominated deltaic (FDD) oil reservoirs in Oklahoma: The Skinner and Prue plays, Oklahoma Geological Survey Special Publication 96–2, 106 p.

Ball, M.M., and Henry, M.E., 1995, Palo Duro Basin Province (043), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, Release 2, one CD-ROM, 5 p., available online at *http://pubs.usgs.gov/dds/dds-030/*.

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, 36 p.

Bebout, D.G., White, W.A., Hentz, T.F., and Grasmick, M.K., eds., 1993, Atlas of major mid-continent gas reservoirs: Bureau of Economic Geology, 85 p., 4 pls.

Blackwell, D.D., and Richards, M., 2004, Geothermal map of North America: American Association of Petroleum Geologists, 1 sheet, scale 1:6,500,000.

Boucher, Kurtis, 2009, Depositional setting, facies, and petroleum geology of the Cabaniss Group in portions of Washita, Custer, Blaine, Caddo, Canadian, and Grady Counties, OK, Part 2: Shale Shaker, the Journal of the Oklahoma City Geological Society, May–June 2009, p. 223–238.

Bowen, D.W., Weimer, Paul, 2003, Regional sequence stratigraphic setting and reservoir geology of Morrow incised-valley sandstones (lower Pennsylvanian), eastern Colorado and western Kansas: American Association of Petroleum Geologists Bulletin, v. 87, no. 5, p. 781–815.

Bowen, D.W., Weimer, Paul, 2004, Reservoir geology of Nicholas and Liverpool Cemetery fields (lower Pennsylvanian), Stanton County, Kansas, and their significance to the regional interpretation of the Morrow Formation incised-valley-fill systems in eastern Colorado and western Kansas: American Association of Petroleum Geologists Bulletin, v. 88, no. 1, p. 47–70.

Boyd, D.T., 2011, Oklahoma 2010 drilling highlights: Shale Shaker, Oklahoma City Geological Society, March/April 2011, no. 5, p. 293-306, accessed August 2011, at *http://www.ogs.ou.edu/OilGas/pdf/2010DrillingHighlights.pdf.*

Brewer, J.A., Good, R., Oliver, J.E., Brown, L.D., and Kaufman, S., 1983, COCORP profiling across the southern Oklahoma aulacogen: Overthrusting of the Wichita Mountains and compression within the Anadarko Basin: *Geology*, February 1983, v. 11, no. 2, p. 109–114.

Burke, K., 1977, Aulacogens and continental breakup: Annual Review of Earth and Planetary Sciences, v. 5, p. 371–396.

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, K.S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 53–64.

Carr, D.L., Hentz, Tucker F., 2009, Sequence stratigraphy and organic richness of the Lower Pennsylvanian Atoka series, northwest Anadarko Basin, Texas and Oklahoma Panhandle: American Association of Petroleum Geologists Annual Convention, June 7-10, 2009; Denver Colo., 1 p.

Carter, L.S., Kelly, S.A., Blackwell, D.D., and Naeser, N.D., 1998, Heat flow and thermal history of the Anadarko Basin, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 82, no. 2, p. 291–316.

Cederstrand, J.R., and Becker, M.F., 1998, Digital map of base of aquifer for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Open-File Report 98-393, digital data and metadata, accessed March 2011, at *http://cohyst.dnr.ne.gov/metadata/m001aqbs_99.html*.

Cotner, Victor, and Crum, H.E., 1933, Geology and occurrence of natural gas in Amarillo district, Texas: American Association of Petroleum Geologists Bulletin, v. 17, no. 8, p. 877–906.

Craig, L.C., and Conner, C.W., 1979, Paleotectonic investigations of the Mississippian system in the United States, *in* Craig, L.C., and Varnes, K.L., comps., History of the Mississippian System, an interpretive summary: U.S. Geological Survey Professional Paper 101, p. 371–406.

Davis, H.G., and Northcutt, R.A., 1989, The greater Anadarko Basin: An overview of petroleum exploration and development, *in* Johnson, K.S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 13–24.

Denison, R.E., Lidiak, E.G., Bickford, M.E., and Kisvarsanyi, E.B., 1984, Geology and geochronology of Precambrian rocks in the central interior region of the United States: U.S. Geological Survey Professional Paper 1241–C, 20 p.

Dobervich, George, and Parker, R.L., 1958, The Morrowan Series of the northern Texas Panhandle: Panhandle Geonews, v. 6, no. 1, p. 5–12.

Dubois, M.K., 2007, Chapter 3. Depositional model, in Dubois, M.K., Byrnes, A.P., Bhattacharya, Saibal, Bohline, G.C., Doveton, J.H., and Barba, R.E., comps., Hugoton asset management project (HAMP): Hugoton geomodel final report: Kansas Geological Survey Open-File Report 2007-06, 22 p., accessed August 2011, at *http://www.kgs.ku.edu/PRS/publication/2007/OFR07_06/KGS_2007-06-3_Chapter03_DepoModels.pdf*.

Dubois, M.K., Byrnes, A.P., Bhattacharya, Saibal, Bohline, G.C., Doveton, J.H., and Barba, R.E., 2006, Hugoton asset management project (HAMP): Hugoton geomodel final report: Kansas Geological Survey Open-File Report 2007-6, 2 p., accessed August 2011, at *http://www.kgs.ku.edu/PRS/publication/2007/OFR07_06/*.

Edwards, A.R., 1959, Facies changes in Pennsylvanian rocks along north flank of Wichita Mountains, *in* Petroleum geology of southern Oklahoma: American Association of Petroleum Geologists, v. 2, p. 142–153.

Fay, R.O., 1964, The Blaine and related formations of northwestern Oklahoma and southern Kansas: Oklahoma Geological Survey Bulletin B98, 238 p., 24 pls.

Feinstein, Shimon, 1981, Subsidence and thermal history of southern Oklahoma aulacogen: Implications for petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 65, v. 12, p. 2521–2533.

Frezon, S.E., and Jordan, Louise, 1979, Oklahoma, *in* Craig, L.C., and Connor, C.W., coordinators, Paleotectonic investigations of the Mississippian Systems in the United States: U.S. Geological Survey Professional Paper 1010, p. 147–159.

Gallardo, Jaquidon, and Blackwell, D.D., 1999, Thermal structure of the Anadarko Basin: Association of Petroleum Geologists Bulletin, v. 83, no. 2, p. 333–361.

Galloway, W.E., Ewing, T.E., Garrett, C.M., Tyler, N., and Bebout, D.G., 1983, Panhandle granite wash/dolomite, *in* Atlas of major Texas oil reservoirs: Bureau of Economic Geology, Austin, Tex., University of Texas, p. 135–136.

Galloway, W.E., Yancey, M.S., and Whipple, A.P., 1977, Seismic stratigraphic model of depositional platform margin, eastern Anadarko Basin, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1437–1447.

Gilbert, M.C., 1983, Timing and chemistry of igneous events associated with the southern Oklahoma aulacogen, *in* Morgan, P., and Baker, B.H., eds., Processes of continental rifting: Tectonophysics, v. 94, p. 439–455.

Gaswirth, S.B., and Higley, D.K., 2014, Geologic assessment of undiscovered oil and gas resources in the Cambrian-Devonian stratigraphy of the Anadarko Basin, Oklahoma, Kansas, Texas, and Colorado, chap. 5, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58: U.S. Geological Survey Digital Data Series 69–EE, 42 p.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Bleeker, Wouter, Lourens, L.J., 2004, A new geologic time scale with special reference to Precambrian and Neogene: Episodes, June 2004, v. 27, no. 2, p. 83–100.

Grammer, G.M., Eberli, G.P., Van Buchem, F.S.P., Stevenson, G.M., and Homewood, Peter, 1996, Application of high-resolution sequence stratigraphy to evaluate lateral variability in outcrop and subsurface—Desert Creek and Ismay intervals, *in* Longman, M.W., and Sonnenfeld, M.D., eds., Paradox Basin: Paleozoic Systems of the Rocky Mountain Region: Rocky Mountain Section of the Society for Sedimentary Geology (SEPM), p. 235–266.

Ham, W.E., 1973, Regional geology of the Arbuckle Mountains, Oklahoma: Oklahoma Geological Survey Special Publication 73-3, 56 p.

Ham, W.E., and Wilson, J.L., 1967, Paleozoic epiorogeny and orogeny in the central United States: American Journal of Science, v. 265, p. 332–407.

Haq, B.U., and Van Eysinga, F.W.B., 1998, Geological time table: Amsterdam, New York, Elsevier Science, 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 research on energy resources—1986, program and abstracts: U.S. Geological Survey Circular 974, p. 21–23.

Henry, M.E., and Hester, T.C., 1995, Anadarko Basin Province (058), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, Release 2, one CD-ROM, accessed June 2011, at *http://certmapper.cr.usgs.gov/data/noga95/prov58/text/prov58.pdf*.

Higley, D.K., 2014, Thermal maturation of petroleum source rocks in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas, chap. 3, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58: U.S. Geological Survey Digital Data Series 69–EE, 53 p.

Higley, D.K., Charpentier, R.R., Cook, T.A., Klett, T.R., Pollastro, R.M., and Schmoker, J.W., 2007, Executive summary—2002 Assessment of undiscovered oil and gas in the Denver Basin Province, Colorado, Kansas, Nebraska, South Dakota, and Wyoming, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Denver Basin Province, Colorado, Kansas, Nebraska, South Dakota, and Wyoming—USGS Province 39: U.S. Geological Survey Digital Data Series 69–P, chap. 1, 4 p.

Higley, D.K., and Cox, D.O., 2007, Oil and gas exploration and development along the Front Range in the Denver Basin of Colorado, Nebraska, and Wyoming, chap. 2, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Denver Basin Province, Colorado, Kansas, Nebraska, South Dakota, and Wyoming—USGS Province 39: U.S. Geological Survey Digital Data Series DDS–69–P, 40 p., accessed June 2011, at *http://pubs.usgs.gov/dds/dds-069/dds-069-p/REPORTS/69_p_CHAP_LIST.pdf*.

Higley, D.K., Cook, T.A., and Pawlewicz, M.J., 2014a, Petroleum systems and assessment of undiscovered oil and Gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—Woodford Shale Assessment Units, chap. 6, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58: U.S. Geological Survey Digital Data Series DDS–69–EE, 24 p.

Higley, D.K., Gaswirth, S.B., Abbott, M.M., Charpentier, R.R., Cook, T.A., Ellis, G.S., Gianoutsos, N.J., Hatch, J.R., Klett, T.R., Nelson, Philip, 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, 2010: U.S. Geological Survey Fact Sheet 2011–3003, 2 p., accessed February 2011, at *http://pubs.usgs.gov/fs/2011/3003/*.

Higley, D.K., Gianoutsos, N.J., Pantea, M.P., and Strickland, S.M., 2014b, Precambrian to ground surface grid cell maps and 3D model of the Anadarko Basin Province, chap. 13, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58: U.S. Geological Survey Digital Data Series DDS–69–EE, 7 p.

IHS Energy, 2009, GDS database: Unpublished geological data services database available from IHS Energy, 15 Inverness Way East, Englewood, CO 80112.

IHS Energy, 2010a, IHS energy well database: Unpublished database available from IHS Energy, 15 Inverness Way East, Englewood, CO 80112.

IHS Energy, 2010b, IHS energy production data on CD-ROM: Unpublished database available from IHS Energy, 15 Inverness Way East, Englewood, CO 80112.

IHS Energy, 2012, IHS energy production data on CD-ROM: Unpublished database available from IHS Energy, 15 Inverness Way East, Englewood, CO 80112.

Johnson, K.S., 1989, Geologic evolution of the Anadarko Basin, *in* Johnson, K.S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 3–12.

Johnson, K.S., Amsden, T.W., Denison, R.E., Dutton, S.P., Goldstein, A.G., Rascoe, B., Jr., Sutherland, P.K., and Thompson, D.M., 1988, Southern midcontinent region, *in* Sloss, L.L., ed., Sedimentary cover—North American craton, U.S., The Geology of North America: Boulder, Colo., Geological Society of America, v. D–2, p. 307–359.

Jorgensen, D.G., 1989, Paleohydrology of the Anadarko Basin, central United States, *in* Johnson, K.S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 176–193.

Kansas Geological Survey, 2010, downloadable formations tops and LAS well data: accessed February 2011, at *http://www.kgs.ku.edu/PRS/petroDB.html*.

Keighin, C.W., 1995, Las Animas Arch Province (40), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, Release 2, one CD-ROM, 7 p. accessed August 2011, at *http://pubs.usgs.gov/dds/dds-030/*.

Keighin, C.W., and Flores, R.M., 1989, Depositional facies, petrofacies, and diagenesis of siliclastics of Morrow and Springer rocks, Anadarko Basin, Oklahoma, *in* Johnson, K.S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 147–159.

Keller, G.R., Lidiak, E.G., Hinze, W J., and Braile, L.W., 1983, The role of rifting in the tectonic development of the midcontinent, U.S.A., *in* Morgan, P., and Baker, B.H., eds., Processes of continental rifting: Tectonophysics, v. 95, p. 391–412.

Kluth, C.F., 1986, Plate tectonics of the Ancestral Rocky Mountains: *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountains region, United States: American Association of Petroleum Geologist Memoir 41, p. 353–369.

Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10–15.

Krumme, G.W., 1981, Stratigraphic significance of limestones of the Marmaton Group (Pennsylvanian, Desmoinesian) in eastern Oklahoma: Oklahoma Geological survey Bulletin 131, 67 p.

Lewan, M.D., and Ruble, T.E., 2002, Comparison of petroleum generation kinetics by isothermal hydrous and nonisothermal open-system pyrolysis: Organic Geochemistry, v. 33, no. 12, p. 1457–1475.

Lockridge, J.P., and Scholle, P.A., 1978, Niobrara gas in eastern Colorado and northwestern Kansas, *in* Pruit, J.D., and Coffin, P.E., eds., Energy resources of the Denver Basin: Rocky Mountain Association of Geologists, p. 35–49.

Longman, M.W., Luneau, B.A., and Landon, S.M., 1998, Nature and distribution of Niobrara lithologies in the Cretaceous Western Interior Seaway of the Rocky Mountain region: The Mountain Geologist, v. 35, no. 4, p. 137–170.

Ludvigson, G.A., Sawin, R.S., Franseen, E.K., Watney, W.L., West, R.R., and Smith, J.J., 2009, A review of the stratigraphy of the Ogallala Formation and revision of Neogene ("Tertiary") nomenclature in Kansas: Kansas Geological Survey, Current Research in Earth Sciences, Bulletin 256, pt 2, 9 p., accessed February 2011, at *http://www.kgs.ku.edu/Current/2009/Ludvigson/index.html*.

Maher, John C., 1953, Paleozoic history of southeastern Colorado: American Association of Petroleum Geologists Bulletin, v. 37, no. 11, p. 2475–2489.

Mapel, W.J., Johnson, R.B., Backman, G.O., and Varnes, K.L., 1979, Southern midcontinent and southern Rocky Mountains region, *in* Craig, L.C., Connor, C.W., coordinators, and Varnes, K.L., Mast, C.A., and Kitely, L.W., assistant coordinators, Introduction and regional analysis of the Mississippian System, part 1 of Paleotectonic investigations of the Mississippian Systems in the United States: U.S. Geological Survey Professional Paper 1010–J, p. 161–187.

Mason, J.W., 1968, Hugoton Panhandle field, Kansas, Oklahoma and Texas, *in* M 9: Natural gases of North America, volume two: American Association of Petroleum Geologists Volume A008, p. 1539–1547.

McCrone, A.W., 1964, Water depth and mid-continent cyclothems: Kansas Geological Survey Bulletin 169, v. 1, p. 275–281.

Mitchell, John, 2011, Horizontal drilling of deep granite wash reservoirs, Anadarko Basin, Oklahoma and Texas: Oklahoma City Geological Society Shale Shaker, September—Oklahoma, 2011, p. 118–167.

Moore, G.E., 1979, Pennsylvanian paleogeography of the southern mid-continent, *in* Hyne, N.J., ed., Pennsylvanian sandstones of the mid-continent: Tulsa Geological Society Special Publication 1, p. 2–12.

Morse, N.R., 1963, Northeast Waynoka, T25N, R's 15 and 16W, Woods County, *in* Cramer, R.D., Gatlin, Leroy, and Wessman, H.G., eds., Oil and gas fields of Oklahoma: Oklahoma City Geological Society Reference Report, v. 1, p. 118A–121A.

National Geologic Map Database, 2011: U.S. Geological Survey, accessed September 2011, at *http://ngmdb.usgs.gov/Geolex/*.

Nehring and Associates, Inc. (NRG), 2009, Significant oil and gas fields database: Colorado Springs, Colorado, NRG Associates, Inc. (Database available from NRG Associates, Inc., P.O. Box 1655, Colorado Springs, CO 80901).

Nicholas, R.L., and Rozendal, R.A., 1975, Subsurface positive features within Wichita foldbelt in Texas and their relation to Paleozoic cratonic margin: American Association of Petroleum Geologists Bulletin, v. 59, no. 2, p. 193–216.

Oklahoma Geological Survey (OGS), 2011a, Databases: accessed September 2011, at *http://www.ogs.ou.edu/level3-databases.php.*

Oklahoma Geological Survey (OGS) 2011b, Granite wash overview: accessed September 2011, at *http://www.ogs.ou.edu/MEETINGS/.../GraniteWash08/GWOverview.ppt.*

Owen, E.W., 1975, Part II. Panhandle-Hugoton gas and oil field, *in* Owen, E.W., ed., Trek of the oil finders: A history of exploration for petroleum: American Association of Petroleum Geologists Memoir 6, p. 939–959.

Perry, W.J., Jr., 1989, Tectonic evolution of the Anadarko Basin region, Oklahoma: U.S. Geological Survey Bulletin 1866-A, p. A1–A19.

Pippin, Lloyd, 1970, Panhandle-Hugoton field, Texas-Oklahoma-Kansas—The first fifty years, *in* Halbouty, M.T., ed., Geology of giant petroleum fields: American Association of Petroleum Geologists Memoir 14, p. 24–222.

Rascoe, B., Jr., 1978, Sedimentary cycles in the Virgilian Stage (Upper Pennsylvanian) of the Anadarko Basin, parts 1 and 2: Oklahoma City Geological Society Shale Shaker, v. 28, p. 123–131, p. 144–149.

Rascoe, B., Jr., and Adler, F.J., 1983, Permo-Carboniferous hydrocarbon accumulations, mid-continent USA: American Association of Petroleum Geologists Bulletin, v. 67, no. 6, p. 979–1001.

Rascoe, B., Jr., and Hyne, N.J., 1987, Petroleum geology of the midcontinent: Tulsa Geological Society Special Publication 3, 162 p.

Rice, D.D., and Claypool, G.E., 1981, Generation, accumulation, and resource potential of biogenic gas: American Association of Petroleum Geologists Bulletin, v. 65, p. 5–25.

Rice, D.D., Threlkeld, C.N., and Vuletich, A.K., 1988a, Character, origin and occurrence of natural gases in the Anadarko Basin, western Kansas, western Oklahoma and Texas Panhandle, U.S.A.: Chemical Geology, v. 71, p. 149–157.

Rice, D.D., Threlkeld, C.N., and Vuletich, A.K., 1988b, Analysis of natural gases from the Anadarko Basin, southwestern Kansas, western Oklahoma and Texas Panhandle: U.S. Geological Survey Open-File Report 88–391, 6 p.

Rice, D.D., Threlkeld, C.N., and Vuletich, A.K 1989, Characterization and origin of natural gases of the Anadarko Basin, *in* Johnson, K.S., ed., Anadarko Basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 47–52.

Robbins, S.L., and Keller, G.R., 1992, Complete Bouguer and isostatic residual gravity maps of the Anadarko Basin, Wichita Mountains, and surrounding areas, Oklahoma, Kansas, Texas, and Colorado: U.S. Geological Survey Bulletin 1866–G, 11 p., 2 pls.

Roth, R.I., 1955, Paleogeology of Panhandle of Texas: American Association of Petroleum Geologists Bulletin, v. 39, no. 4, p. 422–443.

Rottmann, Kurt, 2000a, Structure map of Hunton Group in Oklahoma and Texas Panhandle: Oklahoma Geological Survey Special Publication 2000-2, pl. 3.

Rottmann, Kurt, 2000b, Isopach map of Woodford Shale in Oklahoma and Texas Panhandle: Oklahoma Geological Survey Special Publication 2000-2, pl. 2.

Schatski, N.S., 1946, The great Donets Basin and the Wichita system; comparative tectonics of ancient platforms: Akademiya Nauk SSSR Izvestiya, Seriya Geologicheskaya, v. 6, p. 57–90.

Schlumberger, 2011, PetroMod Basin and Petroleum Systems Modeling Software: IES GmbH, Ritterstrasser, 23, 52072 Aachen, Germany.

Scholle, P.A., 1977, Chalk diagenesis and its relation to petroleum exploration—Oil from chalks, a modern miracle: American Association of Petroleum Geologists Bulletin, v. 61, p. 982–1009.

Seni, S.J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: Texas Bureau of Economic Geology Report of Investigations 105, 36 p.

Smagala, T.M., Brown, C.A., and Nydegger, G.L., 1984, Log-derived indicator of thermal maturity, Niobrara Formation, Denver Basin, Colorado, Nebraska, Wyoming, *in* Woodward, J., Meissner, F.F., and Clayton, J.C., eds., Hydrocarbon source rocks of the Greater Rocky Mountain area: Rocky Mountain Association of Geologists Guidebook, p. 355–363.

Smith, P.W., Hendrickson, W.J., and Woods, R.J., 2001, Comparison of production and reservoir characteristics in "granite-wash" fields in the Anadarko Basin: Oklahoma Geological Survey Circular 106, p. 19–27.

Sorenson, R.P., 2005, A dynamic model for the Permian Panhandle and Hugoton fields, western Anadarko Basin: American Association of Petroleum Geologists Bulletin, v. 89, no. 7, p. 921–938.

Swanson, D.C., 1979, Deltaic deposits in the Pennsylvanian upper Morrow Formation of the Anadarko Basin, *in* Hyne, N.J., ed., Pennsylvanian sandstone of the mid-continent: Tulsa Geological Society Special Publication 1, p. 115–168.

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. 1559–1570.

Tainter, P.A., 1984, Stratigraphic and paleostructural controls on hydrocarbon migration in Cretaceous D and J sandstone of the Denver Basin, *in* Woodward, J.F., Meissner, F., and Clayton, J., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 339–354.

Wang, H.D., and Philp, R.P., 1997, Geochemical study of potential source rocks and crude oils in the Anadarko Basin, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 81, no. 2, p. 249–274.