

The Woodford Shale in southeastern New Mexico: distribution and source rock characteristics

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Abstract

The Woodford Shale (Upper Devonian) is 0–300 ft thick in southeastern New Mexico. Maximum thickness is in south-central Lea County where it lies at depths of 18,000 ft. The Woodford pinches out to the north and northwest in Roosevelt and Chaves Counties where it is present at depths of less than 7,000 ft as it rises out of the Permian Basin. The Woodford Shale is absent from the highest parts of the Central Basin Platform in southeastern Lea County. The Woodford consists predominantly of black, organic-rich shales and minor black cherts, siltstones, sandstones, and greenish-colored shales. The Woodford unconformably overlies Wristen (Silurian) and Thirtyone (Lower Devonian) carbonates as well as scattered remnants of the pre-Woodford shale (Middle to Upper Devonian). The Woodford is unconformably overlain by the lower Mississippian limestone.

The black organic-rich shales are a hydrocarbon source facies. Present-day total organic carbon (TOC) ranges from 1.7 to 4.9 wt. %. Original, pre-maturation TOC ranged from 1.8 to 6.8%. Both original and present-day TOC are greatest in southern Lea County and decrease to the north and west. The kerogen fraction of the black Woodford shales is dominated by amorphous and herbaceous types. Woody and inertinitic types are prevalent to the north, closer to the Woodford pinchout.

Thermal maturity is greatest in southwestern Lea and southeastern Eddy Counties where the Woodford is within the thermogenic gas and condensate window. Thermal maturity is lower to the north and west where the Woodford is within the oil window. The volume of hydrocarbons generated within the Woodford increased to the southeast along with increasing TOC, thickness, and thermal maturity.

The Gladiola Woodford oil pool is the only reservoir productive from the Woodford Shale in southeastern New Mexico. This reservoir is located in northern Lea County where the Woodford is within the oil maturation window. Produced hydrocarbons are oil and associated gas, in agreement with the thermal maturity of the Woodford in the area.

The Woodford has been long considered as the source rock for hydrocarbons within carbonate reservoirs of the underlying Wristen Group and Thirtyone Formation. Gas-oil ratios from Wristen reservoirs reflect thermal maturity levels of the Woodford and possibly the geographic distribution of Woodford kerogen types. The composition of Wristen oils also may reflect the distribution of kerogen types.

Introduction

The Woodford Shale (Upper Devonian) is present throughout most of southeastern

New Mexico (Fig. 1), where it consists predominantly of black, organic-rich marine shales with minor siltstones, sandstones, black cherts, and lighter-colored greenish shales. Depth to the Woodford ranges from less than 7,000 ft in Chaves and

Roosevelt Counties to more than 18,000 ft in south-central Lea County. Thickness is a maximum of approximately 300 ft in southern Lea County. From there, the Woodford thins to a pinchout to the north and west. The Woodford is absent from

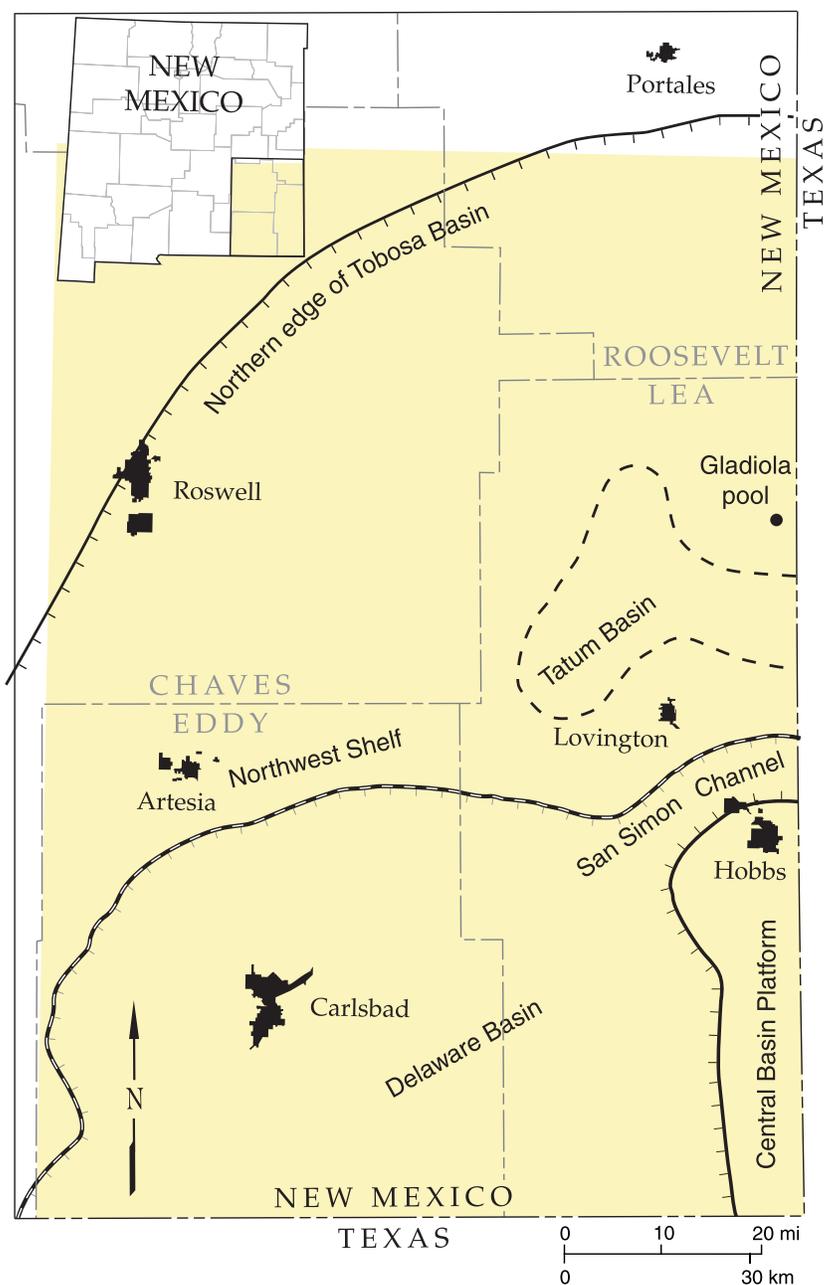


FIGURE 1—Outlines of the late Paleozoic Permian Basin (Delaware Basin, Central Basin Platform and Northwest Shelf) and Tatum Basin and the middle Paleozoic Tobosa Basin in southeastern New Mexico. Project area shown in yellow. Outlines of Permian Basin from Hills (1984) and Dutton et al. (2005). Outline of Tobosa Basin from Adams (1965).

TABLE 1—Petroleum source rock data used on maps presented in this paper. Analytical values are averages for wells with more than one sample. Complete source rock data available in Broadhead (2005). *Thickness is corrected to account for structural dip; NC, not calculated.

Well	Location (S-T-R)	Depth to Woodford (ft)	Woodford thickness (ft)	TOC present day (wt%)	TOC original (wt%)	PI	R _o (mean)	TAI
Ohio Oil No. 1 Federal McGrail	20-08S-37E	11,983	95	1.70	1.77	0.21		
Pan American No. 1 Federal White	13-9S-30E	10,590	108	2.20	NC	0.25		
Amerada Petroleum No. 1 State BTA	2-12S-33E	10,704	30	1.73	1.88	0.22		
E. P. Operating No. 1 Federal 9	9-13S-29E	9,450	17	1.79	2.03	0.26		
Pan American Petroleum No. 1 East Saunders	12-14S-34E	14,760	52	2.41	2.85	0.44		
T. P. Coal & Oil No. 1 Simmons-Schenck	12-14S-37E	12,947	143	2.03	2.44	0.21		
Standard of Texas No. 1 Lillian Coll 10 (2 samples)	10-16S-31E	13,055	63	3.63	4.42	0.26		2.7
Stanolind No. 1 State AB	29-17S-28E	11,040	10	1.99	2.71	0.39	1.64	3.2
Phillips Petroleum No. 6 Leamex (3 samples)	23-17S-33E	14,954	146	2.94	3.94	0.39		2.9
Ralph Lowe No. 1 Yates Federal 69	24-18S-32E	14,596	116	2.55	3.12	0.35	1.18; 1.69	3.3
T. P. Coal & Pure Oil No. 1 State W	28-18S-36E	11,967	167	4.16	5.68	0.22		2.8
Maralo No. 1 Hanson Federal	34-20S-27E	11,764	37	2.19	2.53	0.36		
Richardson & Bass No. 1 Legg	27-22S-30E	15,381	165	3.44	4.14	0.45		
Shell No. 1 Federal GR 4	4-22S-34E	14,262	152	2.73	NC	0.29		
Delta Drilling No. 1 Jurnegan Point	5-24S-25E	11,568	92	4.03	NC	0.37		
Pure Oil No. 1 Red Hills	32-25S-33E	17,266	160	3.09	4.23	0.38		3.2
Southland Royalty No. 1 Gulf Federal	20-25S-35E	18,220	213	4.36	6.79	0.48		3.5
Continental No. 3 Wells B1	1-25S-36E	9,806	275*	4.93	6.61	0.16		
Yates Petroleum No. 1 Welch ABV Federal	21-26S-27E	13,478	136	3.49	4.25	0.44		

the highest points of the Central Basin Platform of eastern Lea County where it was removed by erosion before deposition of Permian strata.

Several studies have long recognized the Woodford Shale as a major petroleum source rock in the Permian Basin (Galley 1958; Jones and Smith 1965; Wright 1979; Hills 1984; Horak 1985; Comer 1991). However, published maps of Woodford thickness (Wright 1979; Comer 1991) are generalized and have used relatively few wells within New Mexico because these studies covered both the Texas and New Mexico parts of the Permian Basin. Published analytical data and assessments are also generalized and concentrated in the Texas part of the basin. This paper presents detailed maps of Woodford thickness and source rock characteristics in the New Mexico part of the Permian Basin and also discusses the relevance of mapped parameters to hydrocarbon accumulations within the Woodford as well as in the carbonate reservoirs in the underlying Wristen Group (Middle to Upper Silurian) and the Thirtyone Formation (Lower Devonian).

Maps presented in this report were contoured digitally with *Surfer 8* (*Surfer 8* is a registered trademark of Golden Software, Inc.) using a kriging algorithm. Structural elevation and thickness data were obtained by correlating well logs from 537 petroleum exploration and development wells that penetrated the pre-Woodford Wristen and Thirtyone carbonates. Petroleum source rock analyses were made on 22 samples of drill cuttings from 19 exploration wells

(Table 1). The drill cuttings are stored in the cuttings collection of the New Mexico Bureau of Geology and Mineral Resources.

Definition, extent, and thickness

Taff (1902) first applied the term Woodford chert to a stratal unit of thinly interbedded cherts and black shales, 500–700 ft thick, that crops out in the Arbuckle Mountains of south-central Oklahoma (Jicha and Lochman-Balk 1958, pp. 129–130; Kerohar et al. 1966, pp. 4292–4293). Equivalent strata, mostly dominated by organic-rich black shale, have been correlated throughout large portions of the southern midcontinent and into western Texas and southeastern New Mexico (Ellison 1950) as well as into southwestern New Mexico (Laudon and Bowsher 1949; Kottowski 1963; Raatz 2005), and the Illinois, Appalachian, and Michigan Basins (see Roen and Kepferle 1993). The terms Woodford Chert, Woodford Shale, and Woodford Formation have variously been applied to these strata in the southern midcontinent and southeastern New Mexico because they contain a wide variety of rock types, including black shales, black cherts, sandstones, siltstones, and lighter-colored shales (Comer 1991). Black shale is dominant in most places, including southeastern New Mexico, where black to dark-gray siltstone, very fine grained silty sandstones, cherts, greenish-colored shales, and minor black glauconitic sandstones are also present. (For a correlation chart of Devonian strata across south-central and southwestern New Mexico, turn to page 96.)

The Woodford Shale of the Permian Basin is Late Devonian in age (Fig. 2; Ellison 1950; Meyer and Barrick 2000). Recent work (Meyer and Barrick 2000) places the Woodford in the upper part of the Upper Devonian on the basis of conodont assemblages. In the Permian Basin, the Woodford unconformably overlies Silurian and Lower Devonian carbonate strata of the Wristen Group and the Thirtyone Formation and, in places, an upper Middle Devonian to lowermost Upper Devonian pre-Woodford shale unit. In south-central and southwestern Lea County, a sequence of cherty dolostones and bedded chert composing the Thirtyone Formation is truncated to the north and northwest under a regional angular unconformity that pre-dated deposition of the overlying Upper Devonian shales (Ruppel and Barnaby 2001). North and west of the Thirtyone erosional limit, the dolomitic carbonates of the Wristen Group (Middle to Upper Silurian) form the subcrop under the Devonian shales.

Meyer and Barrick (2000) used conodont biostratigraphic zonation to identify two separate units within the Devonian shale sequence. Most of the Devonian shale section belongs in the upper part of the Upper Devonian and was assigned to the Woodford Shale. The Woodford, as identified by Meyer and Barrick (2000), consists predominantly of organic-rich black shale and subordinate black to dark-gray siltstone and fine-grained sandstone with minor, locally present black glauconitic sandstone.

Underlying the Woodford, but overlying the Silurian and Lower Devonian carbonate and chert units, is an upper Middle

System	Series	Stage	Lithostratigraphic unit
Mississippian	Upper	Chesterian	Chester
		Meramecian	Meramec
	Lower	Osagian	lower Mississippian limestone
		Kinderhookian	
Devonian	Upper	Famennian	Woodford Shale
		Frasnian	
	Middle	Givetian	pre-Woodford shale
		Eifelian	
	Lower	Emsian	Thirtyone Fm.
		Pragian	
		Lochkovian	
Silurian	Pridolian	Wristen Group	
	Ludlovian		
	Wenlockian		
	Llandoveryan		Fusselman Formation

FIGURE 2—Stratigraphic chart of the Woodford Shale and associated strata in southeastern New Mexico.

Devonian to lower Upper Devonian unit referred to as the pre-Woodford shale by Meyer and Barrick (Figs. 2, 3a). The pre-Woodford shale consists of green and gray clay shales that rest unconformably on the underlying Silurian–Devonian carbonates and cherts. This unit infills karst cavities within the underlying carbonates and is present as erosional remnants above the carbonates but below the Woodford Shale. On well logs, the pre-Woodford shale appears to be associated with a transitional zone that is more radioactive than the underlying Silurian–Devonian carbonates but is less radioactive than the overlying Woodford (Fig. 3a). The contact between the pre-Woodford shale and the Woodford Shale appears sharp on well logs. On the basis of this log signature, examination of well logs indicates the distribution of the pre-Woodford shale is spotty and that the unit is absent in most areas in southeastern New Mexico (Fig. 3b).

Ellison (1950) and Comer (1991) stratigraphically subdivided the Woodford Shale into three units (Fig. 3c) using gamma-ray well logs and lithology. The lower unit has a relatively low radioactivity response on gamma-ray logs and consists of dark-

gray shale with interbedded limestones. The middle unit consists almost entirely of black shale and has the highest radioactivity response on gamma-ray logs. The upper unit also consists of black shale but is less radioactive than the middle unit. Wright (1979) assigned the upper unit an Early Mississippian age on the basis of lithostratigraphic correlation with strata in the Llano uplift of central Texas. Meyer and Barrick (2000), however, found no Mississippian conodonts in the Woodford and also concluded that the latest part of the Devonian section is absent from the Woodford, indicating that the upper part of the Woodford is Devonian rather than Mississippian.

For this project, the Woodford was mapped as a single stratigraphic unit. The pre-Woodford shale was not included. Thickness data uncorrected for structural dip were obtained from correlating the Woodford on well logs and indicate that the Woodford is 0–728 ft thick in southeastern New Mexico (Fig. 4). However, the logs depict the Woodford (and other stratigraphic units) as it intersects a borehole that is essentially vertical. If the Woodford has no dip within the borehole (i.e., it is horizontal) then the thickness as

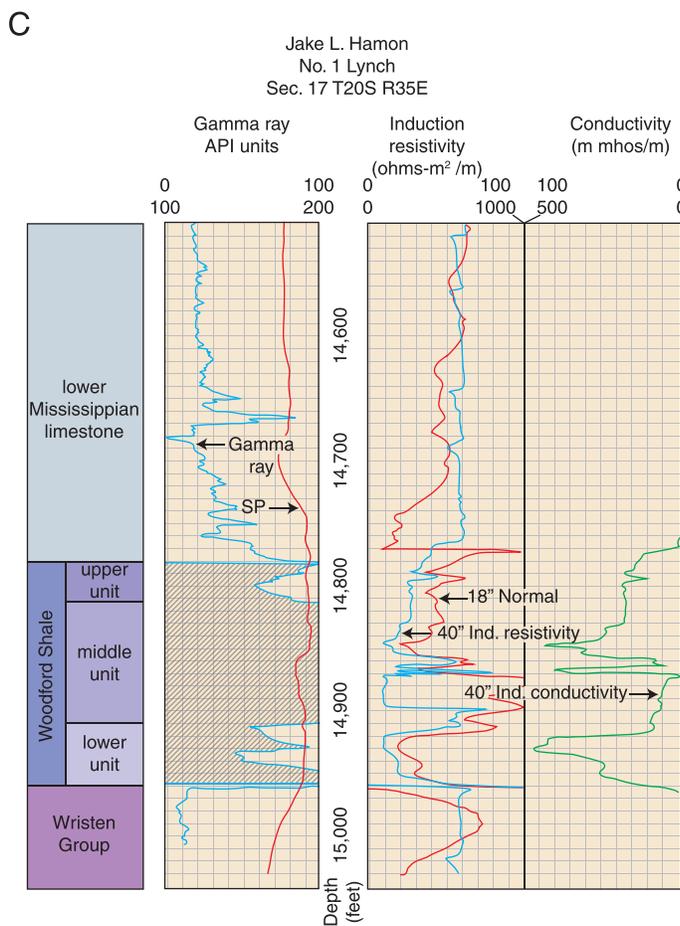
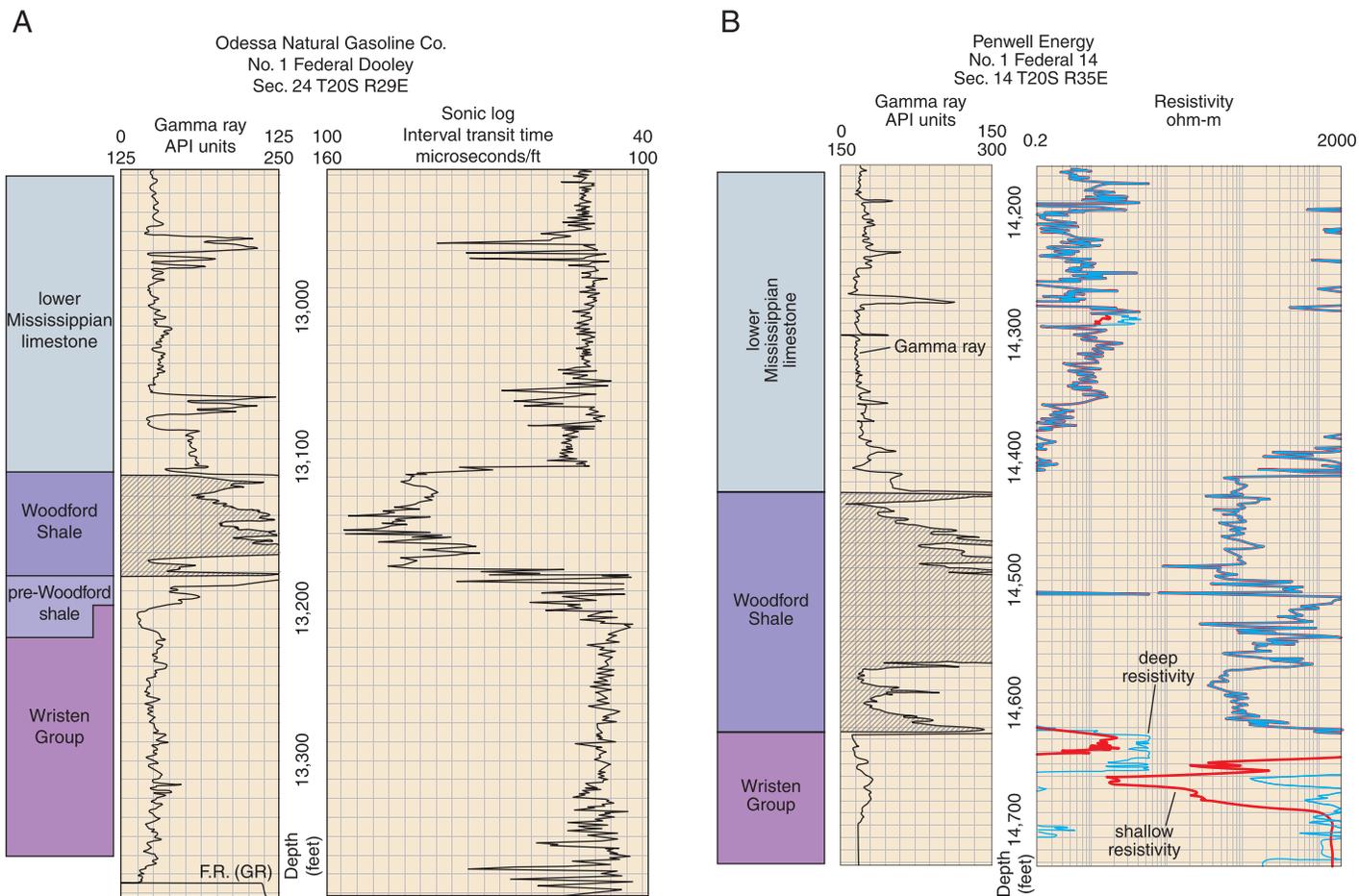
measured in the borehole is true stratigraphic thickness. However, if the Woodford has structural dip, the apparent thickness will be more than true thickness. If structural dip is less than approximately 30°, apparent thickness does not significantly exceed true thickness (Fig. 5). However, at dips more than 30°, apparent thickness significantly exceeds true thickness. At a 60° dip apparent thickness is twice true thickness. This has significance for the Woodford isopach map (Fig. 4).

Many, if not most, of the wells that were drilled to a sufficient depth to penetrate the base of the Woodford were targeting reservoirs in the underlying Wristen Group. The Wristen is productive mainly from trap-forming fault blocks that were uplifted during the Pennsylvanian (see, for example, Speer 1993; Speer and Hanagan 1995; Hanagan 2002). After uplift, the fault blocks were buried by Late Pennsylvanian and Permian sediments. Steep dips are present on the flanks of many of these paleostructures. Therefore the uncorrected isopach map of the Woodford (Fig. 4) indicates apparent thickness where strata have steep dips and true thickness (or a value close to true thickness) where strata are either horizontal or dip is relatively gentle.

An example of the effect of steep dips on apparent thickness can be seen in the Arco No. 1 Custer Wells, located in sec. 6 T25S R37E. The apparent thickness of the Woodford, as correlated on the gamma-ray log, is 406 ft. The well has a dipmeter log that indicates an east dip of 46° for strata beneath the Pennsylvanian. True thickness is calculated as 282 ft. Therefore, apparent thickness is 144% of true thickness. Although this indicates a substantial difference between true thickness and apparent thickness, it also indicates that the Woodford has a true thickness of at least 282 ft in some areas of southeastern New Mexico.

Apparent thickness of the Woodford will exceed true thickness by significant amounts where structural dips are steep on the flanks of some of the Pennsylvanian-age paleostructures. This is thought to be a complication only where there is a large amount of variation in apparent Woodford thickness over a small geographic area, perhaps one township. Dipmeter logs are rarely run and were available for less than 1% of the wells used in this project. Because dipmeter logs are necessary to calculate true thickness, the latter could not be calculated for most wells. Therefore, another method had to be used to construct an isopach map of true Woodford thickness.

An isopach map of true Woodford thickness (Fig. 6) was prepared by eliminating wells where apparent Woodford thickness is more than 300 ft. The 300-ft value was chosen because the Woodford is known to be almost 300 ft thick in one well (Arco No. 1 Custer Wells) and because wells with apparent Woodford thickness significantly in excess of 300 ft are geographically juxtaposed with wells with less than 300-ft thickness over a



small area, an indication of the presence of Pennsylvanian-age paleostructures. Also eliminated were the thickest data points with apparent thickness less than 300 ft in local areas characterized by large variations of apparent thickness. The resulting isopach map (Fig. 6) approximates or estimates true Woodford thickness. Although interpretative, it is a better approximation of true Woodford thickness than the map contoured from uncorrected apparent thickness data (Fig. 4).

The true-thickness isopach map indicates that the Woodford is absent from large parts of the Central Basin Platform in eastern Lea County. The platform was not formed until the Pennsylvanian. Strata on this structure, including the Woodford, were exposed and eroded during the Pennsylvanian through Early Permian (Adams 1965; Meyer 1966; Hills 1984). The thickest Woodford is aligned along an axis west of the Central Basin Platform. From there, the Woodford thins gradually to the north and west to an irregular pinchout in Chaves and Roosevelt Counties. A second axis of thick Woodford trends west-northwest across

FIGURE 3—Geophysical well logs of the Woodford Shale in southeastern New Mexico. **A** is from a well with the pre-Woodford shale, **B** is from a well where the pre-Woodford shale is not present, and **C** indicates Ellison's (1950) three subdivisions of the Woodford Shale in the Permian Basin.

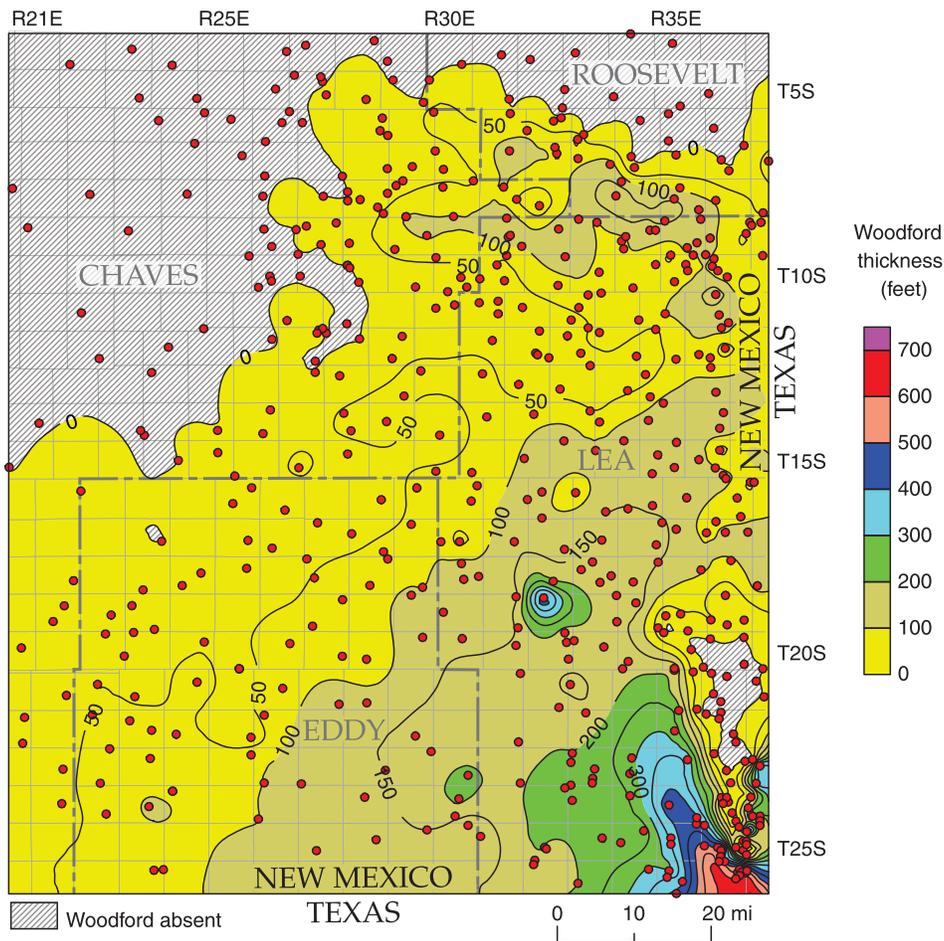


FIGURE 4—Isopach map of the Woodford Shale, uncorrected for structural dip.

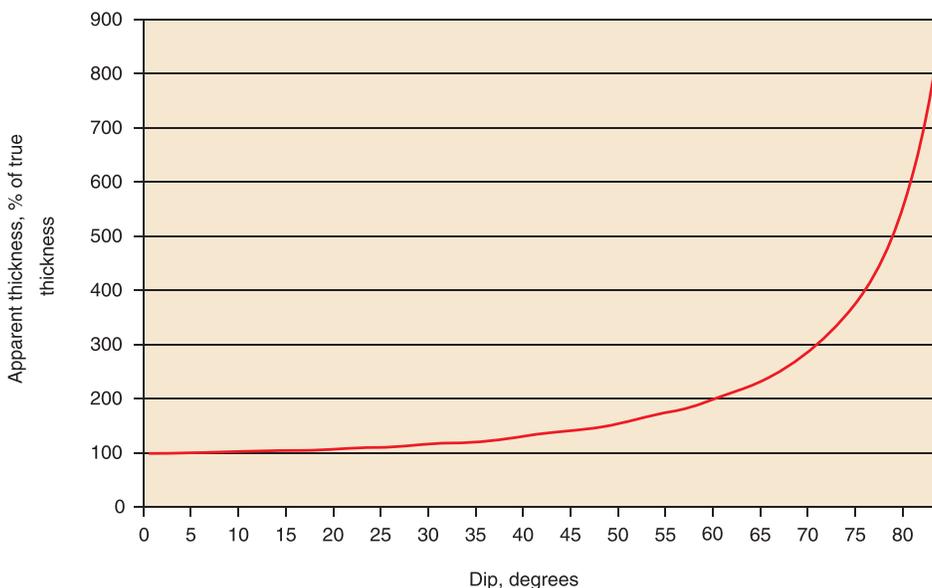


FIGURE 5—Graph showing apparent thickness of a stratal unit in a vertical wellbore as a function of structural dip.

southern Roosevelt County. This axis is well defined by several wells, indicating that it is real and not the result of apparent, dip-related structural thickening. Perhaps this thick axis represents deposition or preferred preservation of strata in a Late

Devonian paleostructural low, or perhaps it represents a relict latest Devonian to earliest Mississippian paleogeomorphic highland that was formed by erosion before deposition of the lower Mississippian limestone. The thick west-northwest axis

lies north of the Tatum Basin (see Fig. 1), which suggests that the Tatum Basin was not present during the Late Devonian. However, the Tatum Basin does appear to have been a structurally low area during the Early Mississippian (Broadhead 2009), so the isopach map of the Woodford acts to constrain the onset of subsidence that formed this tectonic feature.

Woodford source rock character

The Woodford Shale has long been recognized as a major petroleum source rock in southeastern New Mexico (Galley 1958; Jones and Smith 1965; Wright 1979; Hills 1984; Horak 1985; Comer 1991). It is thought that the black Woodford shales have served as the primary source rocks for many oil and gas accumulations in the Permian Basin, especially in the underlying Silurian and Lower Devonian carbonates and cherts (Hills 1984; Comer 1991).

For this project, petroleum source rock analyses were run on 22 samples of drill cuttings of Woodford Shale from 19 exploration wells in southeastern New Mexico (Table 1; Fig. 7). Analyzed samples are composites of cuttings from several 10-ft drilled intervals. In most cases, there is one composite sample per well that covers the entire thickness of the Woodford, but in wells where the Woodford is relatively thick there is more than one composite sample. Cuttings were carefully selected (“picked”) to exclude non-Woodford lithologies (cavings from shallower stratigraphic units). Only the dark shale source facies from the Woodford were analyzed; siltstones and greenish-colored shales were omitted from the samples by the selection process.

Several types of analyses were made on the samples:

1. total organic carbon (TOC) in weight percent of the rock, analyzed by the Leco method,
2. Rock-Eval pyrolysis,
3. determination of kerogen type by optical petrography,
4. Thermal Alteration Index (TAI), an indicator of thermal maturity.

In addition, it was attempted to assess thermal maturity by analyzing vitrinite reflectance (R_o), but vitrinite was not present in sufficient quantities in most samples. R_o measurements are therefore available on only two samples (Table 1). Optical petrographic analysis of kerogen types and determination of TAI were run on 10 samples from seven wells. Leco TOC and Rock-Eval pyrolysis were run on all 22 samples.

Analyses of TOC made on the samples are the present day (TOC_{pd}), and not the original pre-maturation TOC (TOC_o). Woodford TOC_{pd} ranges from 1.7 wt. % to 4.9% (Fig. 7; Table 1). Because the TOC measurements were made on composite samples

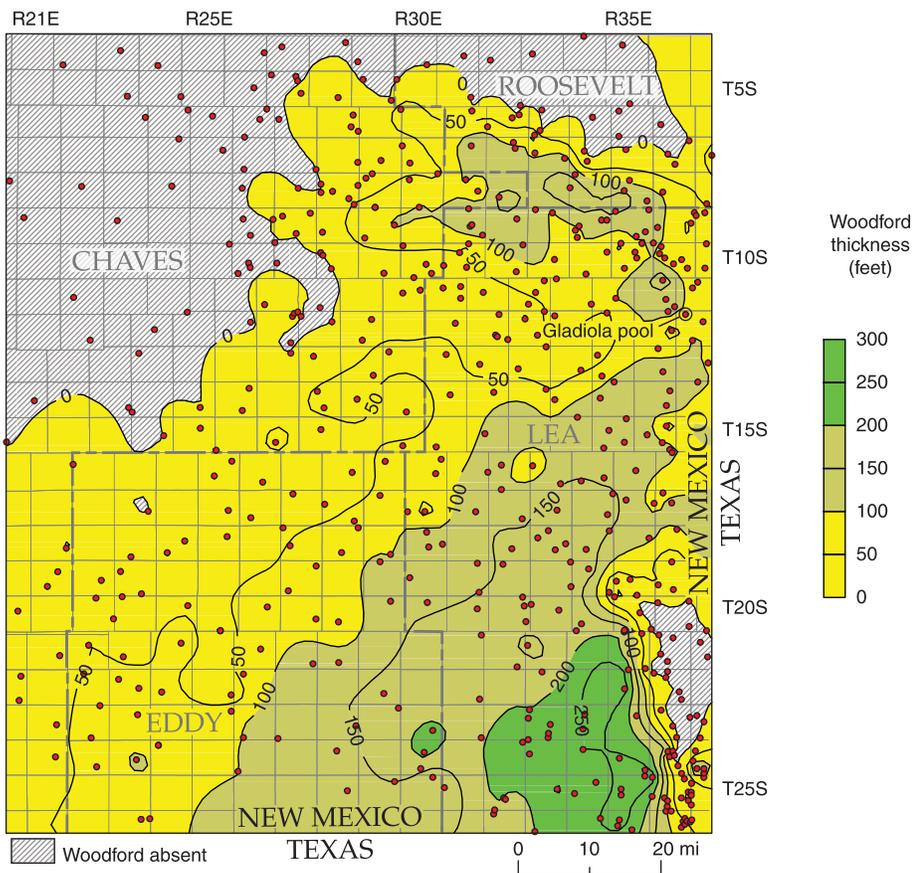


FIGURE 6—Isopach map of true thickness of the Woodford Shale.

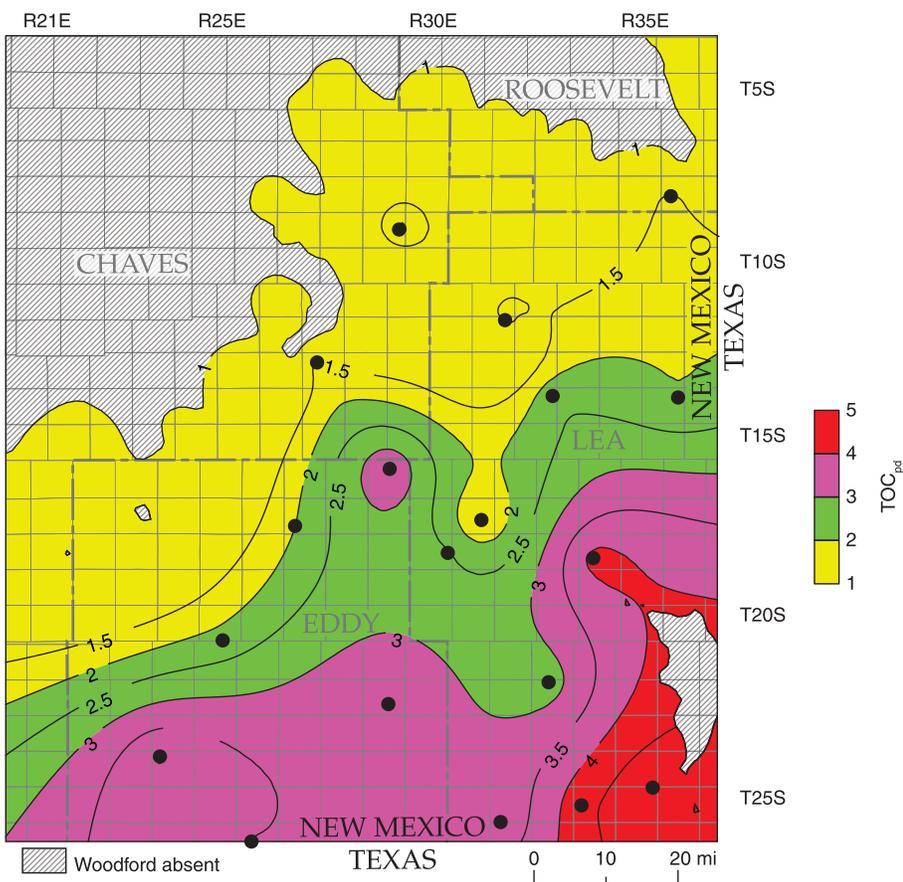


FIGURE 7—Contours of present-day total organic carbon (TOC_{pd}) of the Woodford Shale, in wt. %.

from the entire thickness of the Woodford in each well, these percentages represent an average TOC for the Woodford in each well. Within each well there undoubtedly will be shale beds with more TOC than the average value and other shale beds with less TOC than the average value. The contour map of TOC content indicates a gradual increase in organic content from the northwest to the southeast. On the basis of TOC content, the Woodford can everywhere be classified as a good to very good source rock in southeastern New Mexico. Organic content increases to the southeast along with thickness, which indicates total generative capacity increases to the southeast.

The determination of kerogen types by optical petrography indicates that amorphous and herbaceous kerogens (Type I and Type II kerogens) dominate the Woodford kerogens. These kerogen types constitute more than 70% of the kerogen population in most samples. In most cases, these kerogen types will have produced oil and associated gas upon maturation with amorphous kerogens generally producing more oil and gas than herbaceous kerogens (Hunt 1996). Gas-prone woody kerogens are generally less than 20% of the kerogen population. Inertinite, which is either non-generative multi-cycle kerogen or generative kerogen that is post-mature and no longer capable of generating oil or gas, is less than 10% of the kerogen population in most samples. Figure 8 indicates the geographic distribution of kerogen types within the Woodford. In general, amorphous and herbaceous kerogens dominate throughout the central and southern areas. Woody kerogens, as well as inertinites, are prevalent only in the north, closer to the Woodford paleoshoreline. The kerogen-type map was constructed from the optical determination of kerogen types, supplemented by plotting the Rock-Eval Hydrogen Index and Oxygen Index on a pseudo Van Krevelen diagram (Fig. 9; see Peters 1986; Hunt 1996; Dembicki 2009).

Thermal maturity of the Woodford can be evaluated by three methods with the available analytical data. The first method uses the Thermal Alteration Index (TAI), a parameter derived from petrographic examination of kerogen. The other two methods of maturity evaluation use data obtained from Rock-Eval pyrolysis. The Rock-Eval TMAX value is the maximum temperature obtained by the Rock-Eval S₂ peak and generally increases with thermal maturity. The Rock-Eval Productivity Index (PI) is the ratio of the amount of hydrocarbons that have been generated by natural means from kerogen in the source rock (and are unmigrated, i.e., remain in the source rock) to the total amount of hydrocarbons that could be generated if the rock was eventually matured to its maximum generative capacity. PI is calculated by the following equation:

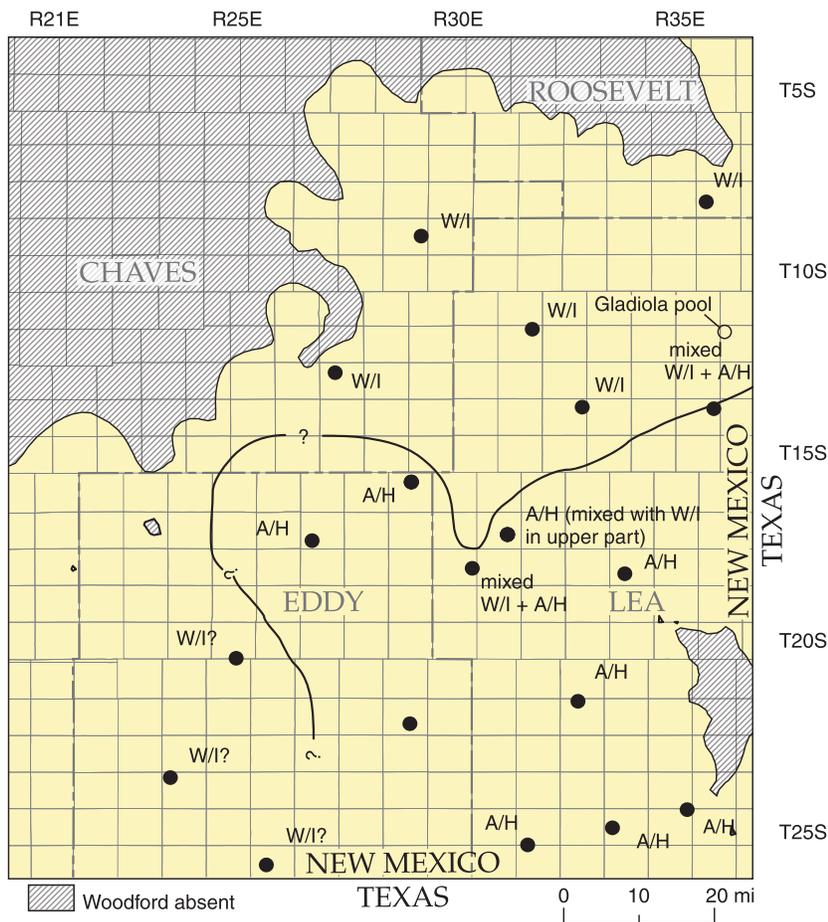


FIGURE 8—Kerogen facies in the Woodford Shale.

$$PI = \frac{S_1}{S_1 + S_2}$$

Where: S_1 = amount of free hydrocarbons in the source rock, in mg hydrocarbons per gram of source rock

S_2 = amount of hydrocarbons generated by the pyrolytic degradation of the remaining kerogen in the rock, in mg hydrocarbons per gram of source rock.

Peters (1986) and Dembicki (2009) presented thorough analyses of the limitations of Rock-Eval pyrolysis in the evaluation of the thermal maturity of a source rock. Both TMAX and PI are sensitive to a number of factors that can result in erroneous indications of thermal maturity. However, Rock-Eval analyses are often preferred to TAI or R_o as indicators of thermal maturity because of lower cost and faster turnaround times. Peters (1986) recommended that the Rock-Eval maturity indicators be confirmed by other, more stable, analytical measurements such as TAI or R_o .

For the Woodford Shale, Rock-Eval TMAX and PI were plotted against TAI (Figs. 10a, 10b) and against each other (Fig. 10c) in order to assess the validity of the Rock-Eval parameters in determining

thermal maturity. Both parameters should increase with increasing TAI, and PI should have a positive correlation with TMAX. For the Woodford samples, TMAX exhibits a negative relationship with both TAI and PI (Figs. 10a, 10c). However, PI exhibits a positive correlation with TAI (Fig. 10b), as it should. These relationships indicate that PI, rather than TMAX, is the valid Rock-Eval maturation parameter for the Woodford Shale of southeastern New Mexico. Deviations from a straight-line relationship between PI and TAI may be caused by variations in kerogen types, the presence of migrated oil within the source rock, and indigenous heavy bitumens in the sample (see Peters 1986; Hunt 1996).

PI indicates that the thermal maturity of the Woodford is highest in the Delaware Basin (Figs. 11, 12). Maturity is lowest on the Central Basin Platform and also decreases to the north as the Woodford rises out of the basin. Throughout most of southeastern New Mexico, PI is between 0.2 and 0.4, indicating that the Woodford is within the oil generation window. In the south, PI is greater than 0.4, indicating that the Woodford is within the thermogenic gas and condensate window. TAI values are highest in this area as well (Fig. 13). The location of the Woodford gas and condensate window

is offset to the west from the current structural center of the basin and is not strictly depth dependent (Fig. 12).

Original TOC

As hydrocarbons are generated from a maturing source rock, the TOC content will decrease over time as a result of the conversion of a portion of the kerogen to oil and natural gas and expulsion of the oil and natural gas from the source rock. Therefore, TOC before the onset of thermal maturation (original TOC = TOC_o) will have been more than the present-day TOC (TOC_{pd} ; mapped in Fig. 7). Jarvie et al. (2007), based upon techniques set forth by Claypool (*in* Peters et al. 2006), developed a methodology to calculate TOC_o from TOC_{pd} , the Rock-Eval present-day Hydrogen Index (HI_{pd}), and the Rock-Eval PI. The calculation also involves estimating the original pre-maturation HI (HI_o) from petrographic determination of kerogen types. The HI is the ratio of the mass of hydrocarbons that are emitted from a source rock during pyrolytic degradation to the TOC of the source rock. HI_{pd} of the samples is calculated from the Rock-Eval S_2 parameter and TOC ($HI_{pd} = (S_2/TOC) \times 100$; see Peters 1986; Hunt 1996). HI_o is calculated from the petrographic determination of kerogen types present in the source rock. The different kerogen types (I, II, III, and IV) contribute differentially to the HI_o with Type I contributing more than Type II, which contributes more than Type III. Type IV kerogens contribute the least to the HI_o value.

For this project, petrographic analyses of kerogen types were available for 10 samples from seven wells. HI_o was calculated assuming that petrographically determined amorphous and herbaceous kerogens are predominantly Type II; if a portion or all of the amorphous kerogen is derived from marine algal matter (a distinct possibility in the Woodford Shale), then HI_o will be higher than estimated for this project, and calculated TOC_o will subsequently be underestimated. For samples without organic petrography, kerogen types were estimated from the pseudo Van Krevelen diagram (Fig. 9) for samples where the position on the plot made interpretation of kerogen types unambiguous. Differentiation of kerogen types using a pseudo Van Krevelen diagram can be misleading if kerogen petrography is not considered (see Dembicki 2009). This technique also requires relatively low thermal maturity because samples consisting of Type I and Type II kerogens that are very mature will plot in the same position as samples with Type III and Type IV kerogens that are also mature.

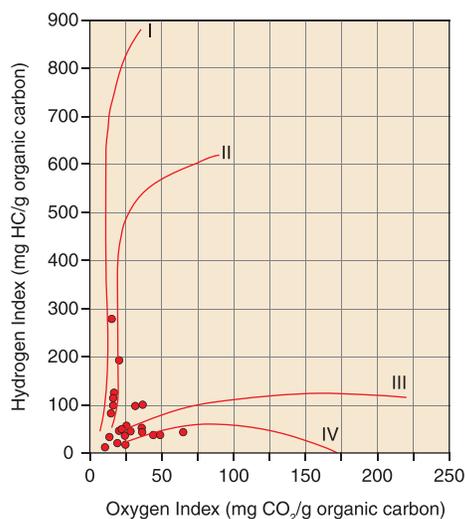


FIGURE 9—Rock-Eval Hydrogen Index (HI) and Oxygen Index (OI) values from Woodford source rock analyses plotted on a pseudo-Van Krevelen diagram. Curves of Type I, II, III, and IV kerogens from Peters (1986).

TOC_o (Fig. 14) increases to the southeast, similar to TOC_{pd} (Fig. 7). As expected from a thermally mature source rock, TOC_o will be substantially greater than TOC_{pd}. The difference between TOC_o and TOC_{pd} will increase with increasing thermal maturity as larger percentages of kerogen have been transformed into oil and gas. The difference between TOC_o and TOC_{pd} will also vary with kerogen composition because convertible carbon decreases from Type I to Type II to Type III and is least in Type IV (Jarvie 1991; Hunt 1996). The difference between TOC_o and TOC_{pd} multiplied by thickness of the Woodford (Fig. 15) will be an indication of the relative volumes of hydrocarbons generated from the Woodford. This value increases to the southeast along with TOC (Figs. 7 and 14), Woodford thickness (Fig. 6), thermal maturation (Fig. 11), and the change in kerogen facies (Fig. 8). In spite of the large increase of (TOC_o - TOC_{pd}) × thickness to the southeast, most of the hydrocarbon accumulations in the Wristen are in the north (see Fig. 16) where this value is less than 100,

indicating that the Woodford is either adequate to have generated substantial commercial volumes of hydrocarbons in this region, or that the hydrocarbons were generated in the Woodford in the deeper parts of the basin and migrated laterally updip to traps in the Wristen.

Gladiola Woodford oil pool

The Gladiola Woodford oil pool is the only oil or gas pool productive from the Woodford Shale in southeastern New Mexico. The Gladiola Woodford pool is a one-well oil pool located in sec. 5 T12S R38E, Lea County (Figs. 1 and 6). The discovery well was the Platinum Exploration No. 2 Angel, which was originally drilled in 1957 as the Ralph Lowe No. 2 Aztec Adamson. The original well was completed as an oil well in the Wristen (Silurian) carbonates over an open-hole interval from 11,992 to 12,030 ft. In 1977 the Wristen reservoir was abandoned, and the well was plugged back to a depth of 9,640 ft and completed in Wolfcamp (Lower Permian) carbonates through perforations from 9,475 to 9,561 ft. In 2004 the Wolfcamp zone was abandoned, and the perforations were squeezed off. The well was subsequently recompleted in the uppermost 10 ft of the Woodford Shale through perforations from 11,920 to 11,930 ft (Fig. 17). Initial production was 150 BOPD, 25 MCFGD, and 4,000 BWPD. Production commenced in December 2004 and continued until November 2006. Cumulative production from the Woodford was 9,322 BO, 3,062 MCFG, and 435,625 BW. This is the only well that was completed in the Gladiola Woodford oil pool.

The perforated interval is in the upper 10 ft of the Woodford. The Woodford is unconformably overlain by the lime mudstones, wackestones, and dark-gray shales of the lower Mississippian limestone. Samples and sample logs from nearby wells indicate the presence of fine-grained silty sandstones in the upper part of the Woodford. The large initial daily flow rates from the well indicate high permeability that is unlikely to be associated with the matrix properties of the sandstones and indicate

the presence of natural fractures. If so, then the Woodford becomes an exploration target. Frenzel (1960) reported that a sandstone present between the Woodford Shale and the lower Mississippian limestone is oil stained in the Gladiola field. More recent correlations (Fig. 17; see Comer 1991) appear to place the sandstone within the upper part of the Woodford Shale. Frenzel's oil-stained sandstone may be the productive reservoir in the Gladiola Woodford pool.

Thermal maturity of the Woodford is related to hydrocarbon type. PI is approximately 0.25 in the area around the Woodford Gladiola oil pool (Fig. 11). At a PI of 0.25, an oil-prone source rock such as the Woodford will have been matured to the stage of oil generation, with burial not yet sufficient to have cracked the oil to gas. The hydrocarbons produced from the Gladiola pool were dominantly oil with relatively little gas (gas-oil ratio, GOR, at cumulative production = 0.328 BCF/MMBO).

Relationship of Woodford source rock character to Wristen gas-oil ratios

As discussed previously, the Woodford Shale is thought to be the main source rock for the oil and gas that has been trapped in the underlying Wristen reservoirs. Wristen reservoirs in the deepest part of the Delaware Basin have the highest GOR values (Fig. 16). In the deep Delaware Basin, the Rock-Eval PI is more than 0.4, indicating that the Woodford and underlying Wristen carbonates are in the thermogenic gas and condensate window. The expected reservoir fluids are therefore gas and condensates with perhaps some light oils at this level of maturity. GOR decreases to the east onto the Central Basin Platform where the PI is between 0.1 and 0.2, indicating that the Woodford Shale is within the upper part of the oil window and reservoir hydrocarbons in the underlying Wristen expected to be mostly oil with subsidiary gas. From the deep Delaware Basin, GOR values also decrease to the north and northwest as the Wristen carbonates gradually rise out of the Delaware Basin and Woodford maturity decreases. Yet farther to the

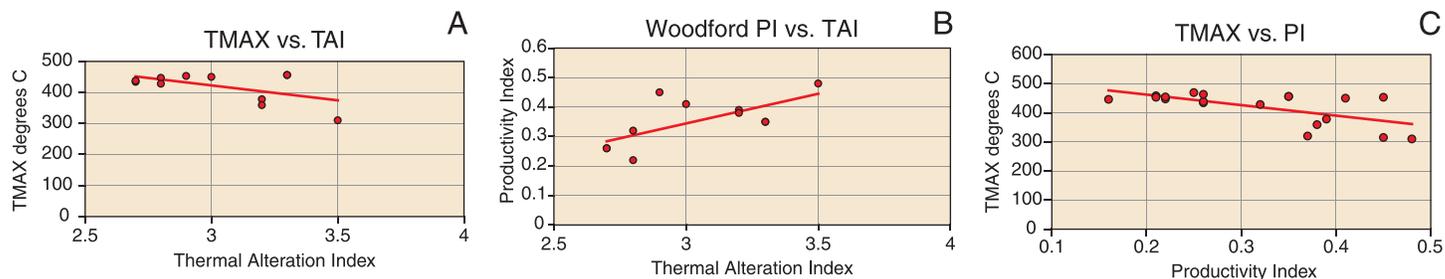


FIGURE 10—Crossplots of maturation parameters for the Woodford Shale in southeastern New Mexico. **A**—Rock-Eval TMAX versus TAI, **B**—Rock-Eval PI versus TAI, and **C**—Rock-Eval TMAX versus Rock-Eval PI.

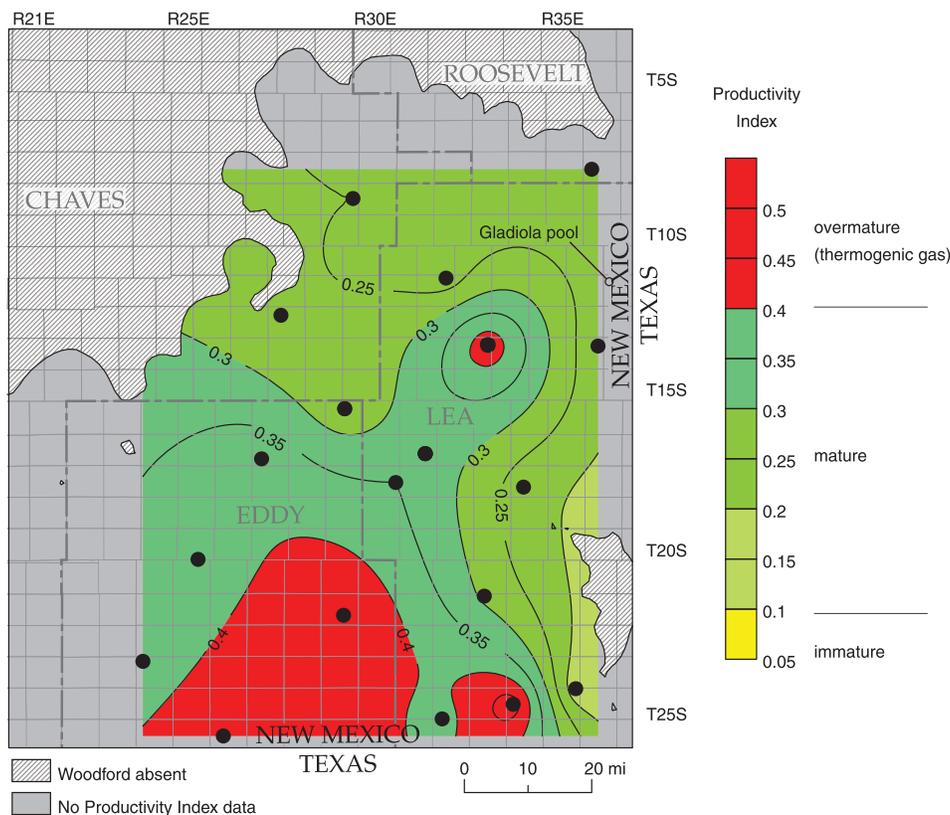


FIGURE 11—Contours of the Rock-Eval Productivity Index for the Woodford Shale.

north and northwest, the trend reverses, and GOR increases. This coincides with the increased presence of gas-prone woody kerogens in the northern part of the Woodford (Fig. 8) and supports the conclusion that Wristen oils in this area were generated locally within the Woodford rather than in the deeper parts of the basin to the south. Therefore, lateral migration distances are relatively short. North of the Woodford pinchout, hydrocarbons trapped in the Wristen were either generated from the Woodford and subsequently migrated laterally updip into traps within the Wristen

or the hydrocarbons were generated from other source rocks such as the micritic limestones and dark-gray shales of the overlying lower Mississippian limestone, which rests unconformably on the Wristen north of the Woodford pinchout.

Wristen oils are dominantly paraffinic. In northern Lea County, Wristen oils have lower concentrations of aromatic hydrocarbons than Wristen oils in reservoirs to the south (Jones and Smith 1965). Jones and Smith attributed this distribution of aromatic hydrocarbons to water washing in the reservoir. However, the presence of

enhanced concentrations of aromatics in oils can also result from enhanced concentrations of marine organic matter in the source rock. Nonmarine organic matter produces oils with lower concentrations of aromatics (Tissot and Welte 1984). The distribution of kerogen facies (Fig. 8) explains the decreased concentrations of aromatics in Wristen oils in the north, where Woodford kerogens are dominated by nonmarine types.

Summary

The Woodford Shale (Upper Devonian) is 0–300 ft thick in the New Mexico part of the Permian Basin. The Woodford consists predominantly of black marine shales with minor black cherts, siltstones, sandstones, and greenish shales. Maximum thickness in southeastern New Mexico is 300 ft in south-central Lea County where depth to the Woodford is 18,000 ft. From there, the Woodford rises to the north and west out of the Permian Basin and is present at depths of less than 7,000 ft in Roosevelt and Chaves Counties where it pinches out along an irregular erosional boundary.

The Woodford is considered to be the source rock for oil and gas accumulations in the underlying Wristen and Thirtyone carbonates as well as a single discovered oil accumulation within the Woodford. Maximum present-day TOC is 4.9% in southern Lea County. From there, TOC decreases to the north and west to less than 2% near its pinchout. Original, pre-maturation TOC attained values in excess of 6% in southern Lea County and decreased northward to values less than 2% near the Woodford pinchout. Woodford kerogens are dominantly amorphous and herbaceous types that generated oil and associated gas upon maturation. Woody and inertinitic types are prevalent in the north near the pinchout.

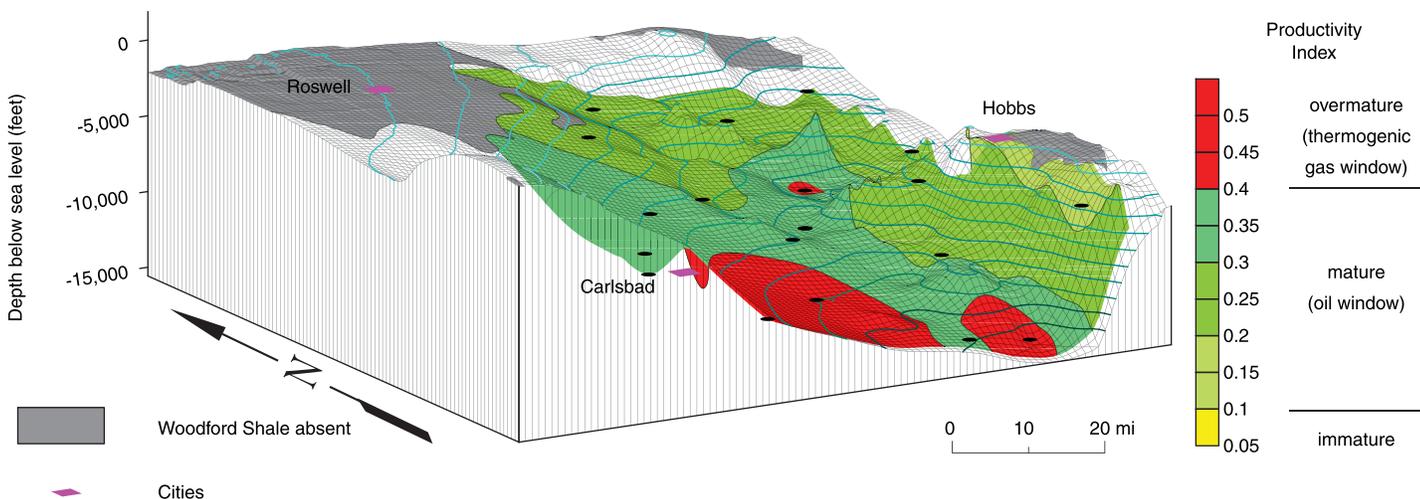


FIGURE 12—Contours of the Woodford Rock-Eval Productivity Index superimposed on a wireframe diagram of the structural elevation of the top of the pre-Woodford (Wristen and Thirtyone) carbonates.

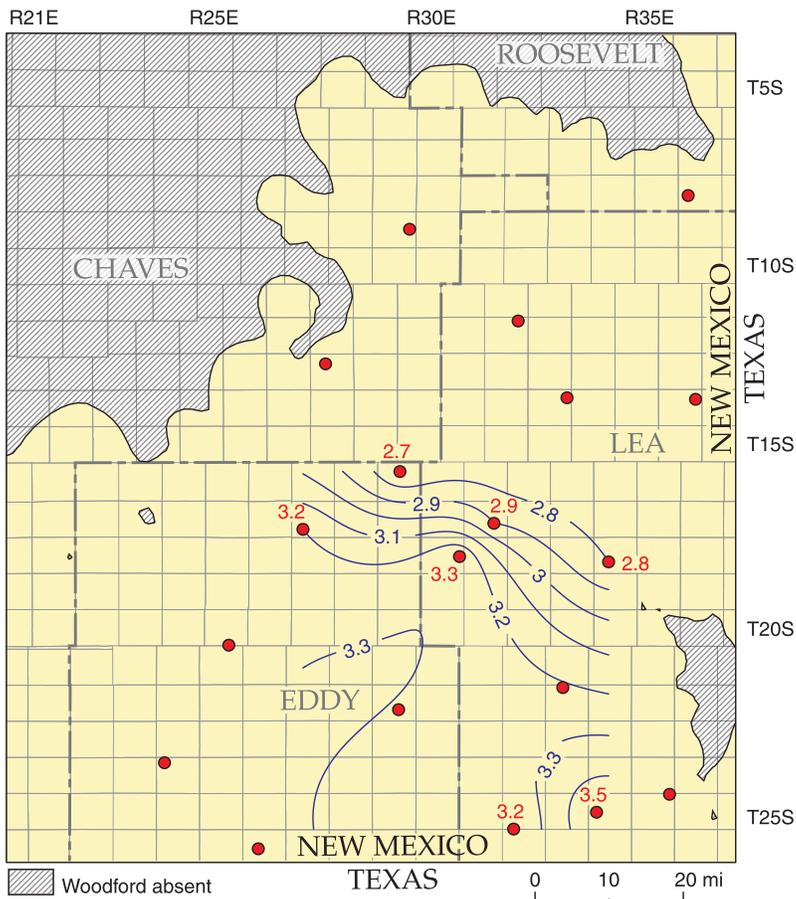


FIGURE 13—Contours of TAI for the Woodford Shale.

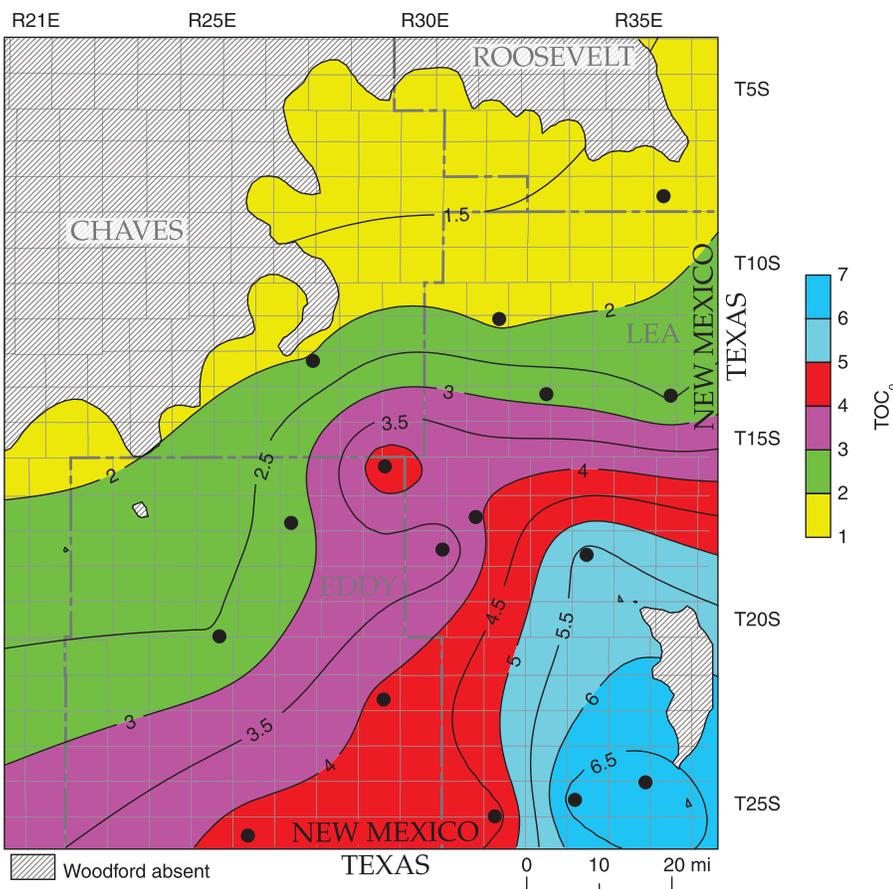


FIGURE 14—Contours of original TOC (TOC_0) for the Woodford Shale.

The Woodford is within the gas and condensate window to the south in the deeper parts of the Permian Basin. It is less mature to the north and west where it is within the oil window. Areas of maximum thermal maturity are offset to the west of the current structural center of the basin. Gas-oil ratios from Wristen reservoirs reflect thermal maturity levels of the Woodford and possibly the geographic distribution of Woodford kerogen types. The composition of Wristen oils may also reflect the distribution of kerogen types.

The Gladiola Woodford oil pool is the only reservoir productive from the Woodford Shale in southeastern New Mexico. This reservoir is located in northern Lea County where the Woodford is within the oil maturation window. Produced hydrocarbons are oil and associated gas, as expected from the thermal maturity of the Woodford in the area.

Acronyms used in the paper

- BCF/MMBO, billion cubic feet/million barrels of oil
- BO, barrels of oil
- BOPD, barrels of oil per day
- BW, barrels of water
- BWPD, barrels of water per day
- GOR, gas-oil ratio
- HI, Rock-Eval Hydrogen Index
- Leco, measuring TOC by the analytical method of the Lincoln Electric Holdings, Inc.
- MCFG, thousand cubic feet of gas
- MCFGD, thousand cubic feet of gas per day
- OI, Rock-Eval Oxygen Index
- PI, Rock-Eval Productivity Index
- R, vitrinite reflectance
- TAI, Thermal Alteration Index
- TMAX, Rock-Eval maximum temperature that accompanies pyrolytic degradation of kerogen
- TOC, total organic carbon

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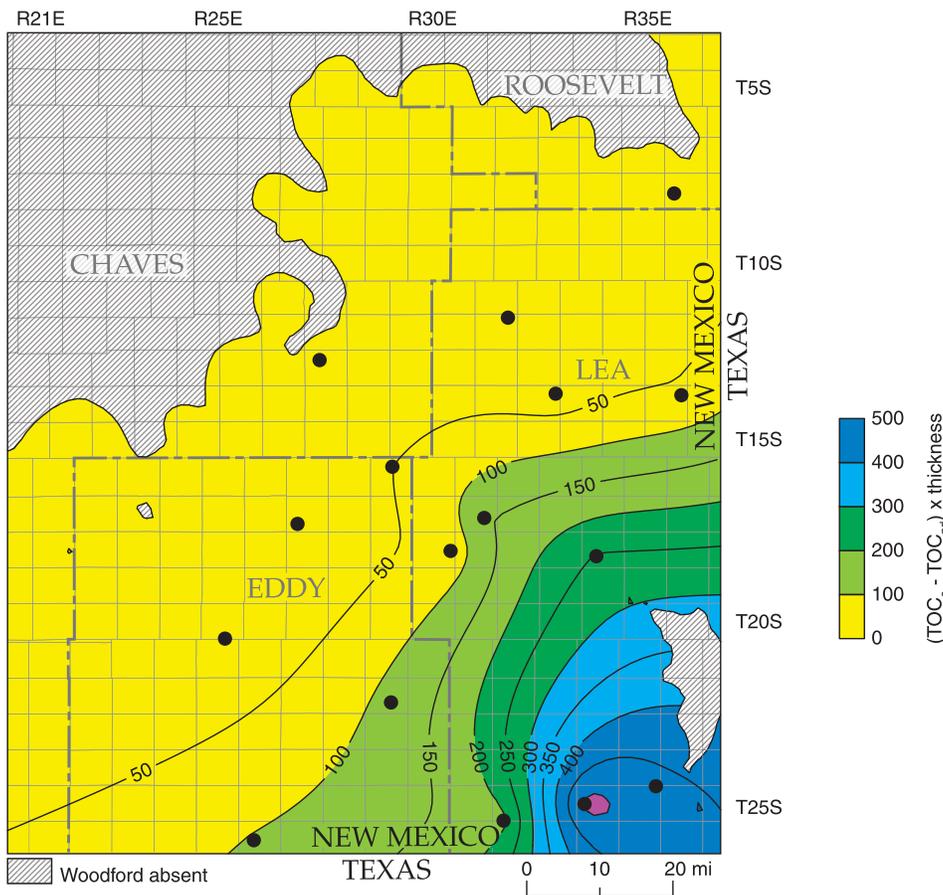


FIGURE 15—Contours of TOC_0 minus TOC_{pd} multiplied by the Woodford true thickness.

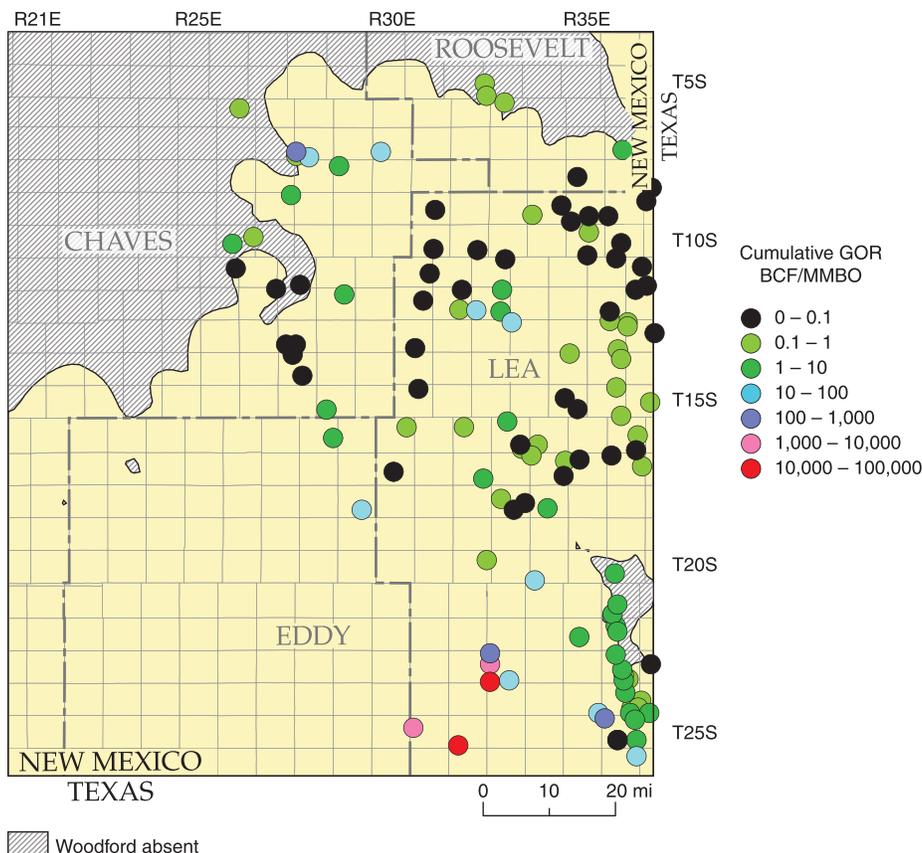


FIGURE 16—Gas-oil ratios at cumulative production from reservoirs productive from the Wristen carbonates (Silurian), southeastern New Mexico.

maturation) and provided helpful advice concerning the types of analyses that were run. Ash Hall, a matriculated student in the Earth and Environmental Science Department at New Mexico Tech calculated the latitude and longitude of wells used in constructing the isopach maps portrayed in this paper. Bill Raatz of OXY Petroleum and Brent May of Marbob Energy reviewed the manuscript and provided many thoughtful suggestions. Phil Miller drafted the illustrations.

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Platinum Exploration
 No. 2 Angel
 Sec. 5 T12S R38E
 Gladiola Woodford oil pool (discovery well)

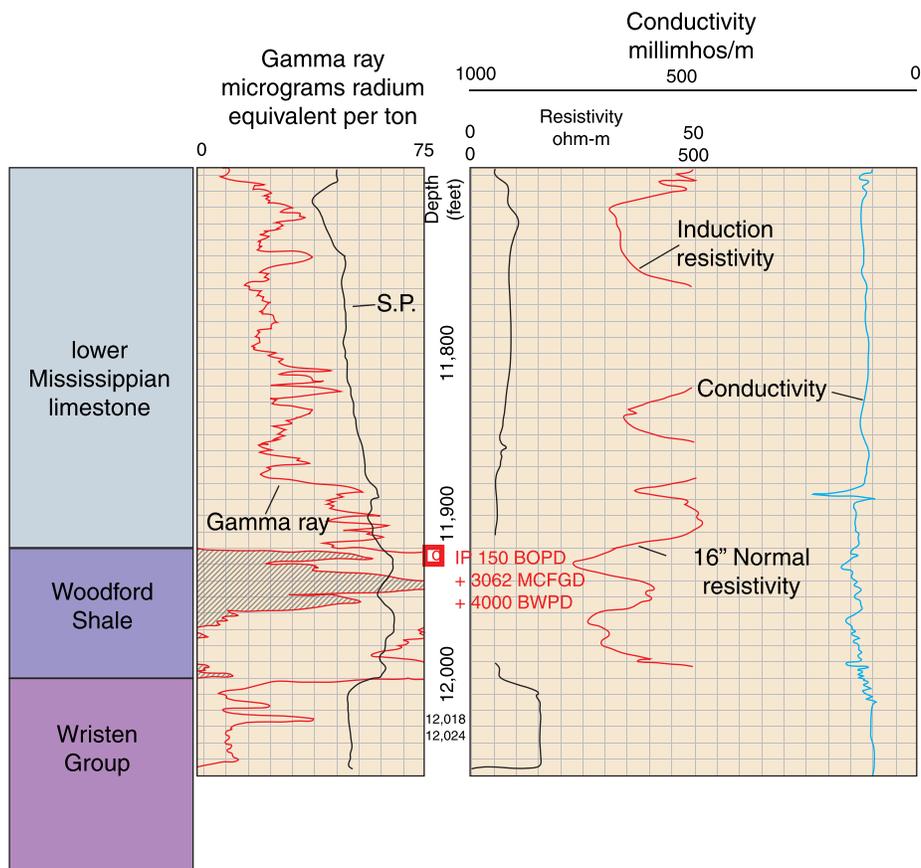


FIGURE 17—Log of the productive well in the Gladiola Woodford oil pool, indicating casing perforations within the Woodford.

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