Regional aspects of the Wristen petroleum system, southeastern New Mexico

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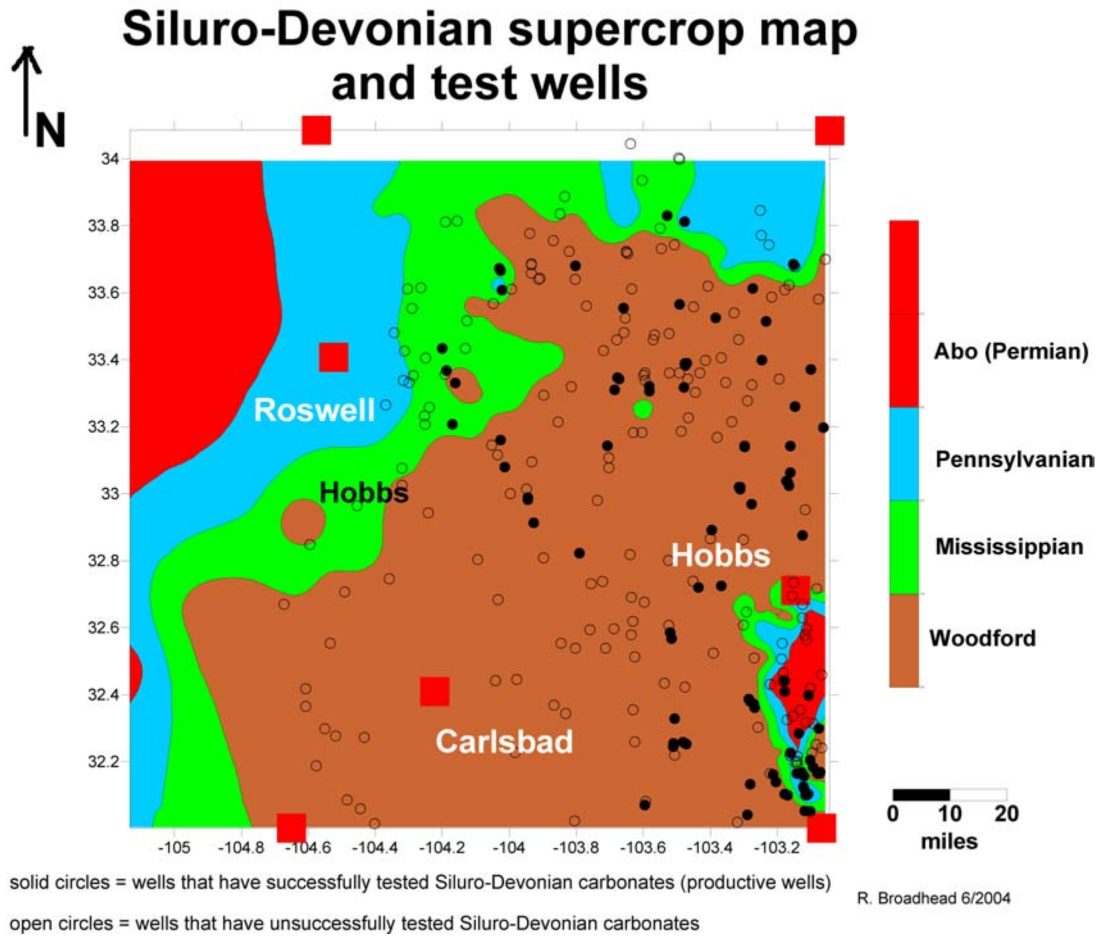

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Abstract

Carbonate reservoirs of Siluro-Devonian age have produced more than 440 MMBO in southeastern New Mexico, or 9.9 percent of the oil produced in southeastern New Mexico. Of the 48 reservoirs that have produced at least 1 MMBO from Siluro-Devonian strata, 47 are productive from strata and only one is productive from the Devonian. The Wristen Formation (Silurian), which covers a large part of southeastern New Mexico, has yielded 84 percent of the Siluro-Devonian oil.

Productive reservoirs are located on the Northwest Shelf, the Central Basin Platform, and in the Delaware Basin. Traps are formed primarily by anticlines bounded by high-angle faults of Late Paleozoic age. Paleostructure maps of the Northwest Shelf indicate major structural trends.

Reservoirs within the deep Delaware Basin produce primarily gas from depths of more than 17,000 ft. Most reservoirs on the Northwest Shelf and Central Basin Platform produce oil with associated gas from reservoirs shallower than 13,000 ft.

The vertical seal for most traps is provided by the Woodford Shale (Devonian). True thickness of the Woodford exceeds 250 ft in southern Lea County and thins to the north and west to a regional pinchout in southern Chaves and Roosevelt Counties. The Woodford is absent from large portions of the Central Basin Platform where it has been removed by erosion following Late Paleozoic uplift.

The Woodford has good source character throughout its extent in southeastern New Mexico. TOC exceeds 1.5 percent in all places it was measured. TOC is highest is highest in southern Lea County and gradually decreases to less than 2 percent along the northwestern regional Woodford pinchout. Oil and gas accumulations have been discovered in Silurian strata northwest of the regional Woodford pinchout where the Silurian carbonates are overlain by Mississippian, and in places Pennsylvanian strata.

The Woodford Shale is thermally mature over its entire extent in the Delaware Basin. It is in the thermogenic gas and condensate window in the deeper parts of the

Delaware Basin and is in the oil window on the Northwest Shelf and where present on the Central Basin Platform. Thermal maturity is not completely correlative with depth; maturity is high in the western, shallower portions of the Delaware Basin.

Introduction

This open-file report summarizes work performed as part of a larger multidisciplinary research project at New Mexico Tech that is funded by the U.S. Department of Energy (DOE Contract No. DE-AC-26-99BC15218: Risk Reduction with a Fuzzy Expert Exploration Tool). The purpose of the project is to apply modern artificial intelligence and fuzzy logic techniques to develop a computerized tool that reduces risk in oil and gas prospecting. This fuzzy expert tool that is currently under development relies on an extensive computerized database of geologic data and utilizes a complex system of neural networks to mathematically analyze imprecise and nonexplicit parameters and values related to the accumulation of oil and gas. The purpose is to integrate diverse sets of geologic, geophysical, and geochemical data in order to emulate geologic and geophysical experts in prospect evaluation and the assessment of prospect risk.

The portion of the project summarized in this report involves the acquisition, synthesis, and analysis of structural, stratigraphic, production, reservoir, and source-rock data from Wristen (Silurian) reservoirs and associated strata in the New Mexico part of the Permian Basin. The data are collected from wells drilled on all three tectonic parts of the Permian Basin in southeastern New Mexico, the deep Delaware basin, the Northwest Shelf, and the Central Basin Platform (Figure 1). Wherever possible, data were collected so that data from productive wells in Wristen reservoirs were offset by nonproductive wells adjacent to those reservoirs as well as nonproductive wells that are distant from known, discovered reservoirs. In this way, geologic contrasts between productive areas and immediately adjacent nonproductive areas are reflected in the dataset and its derivative maps. Maps presented in this report were plotted and contoured using Surfer 8.0 (Surfer 8.0 is a product and registered trademark of Golden Software, Inc.). The data presented in this report will be combined with gravity and aeromagnetic data and will be integrated into the fuzzy logic system. Data synthesis and analysis performed as this part of the project will be used to help devise and structure the neural network/fuzzy logic system.

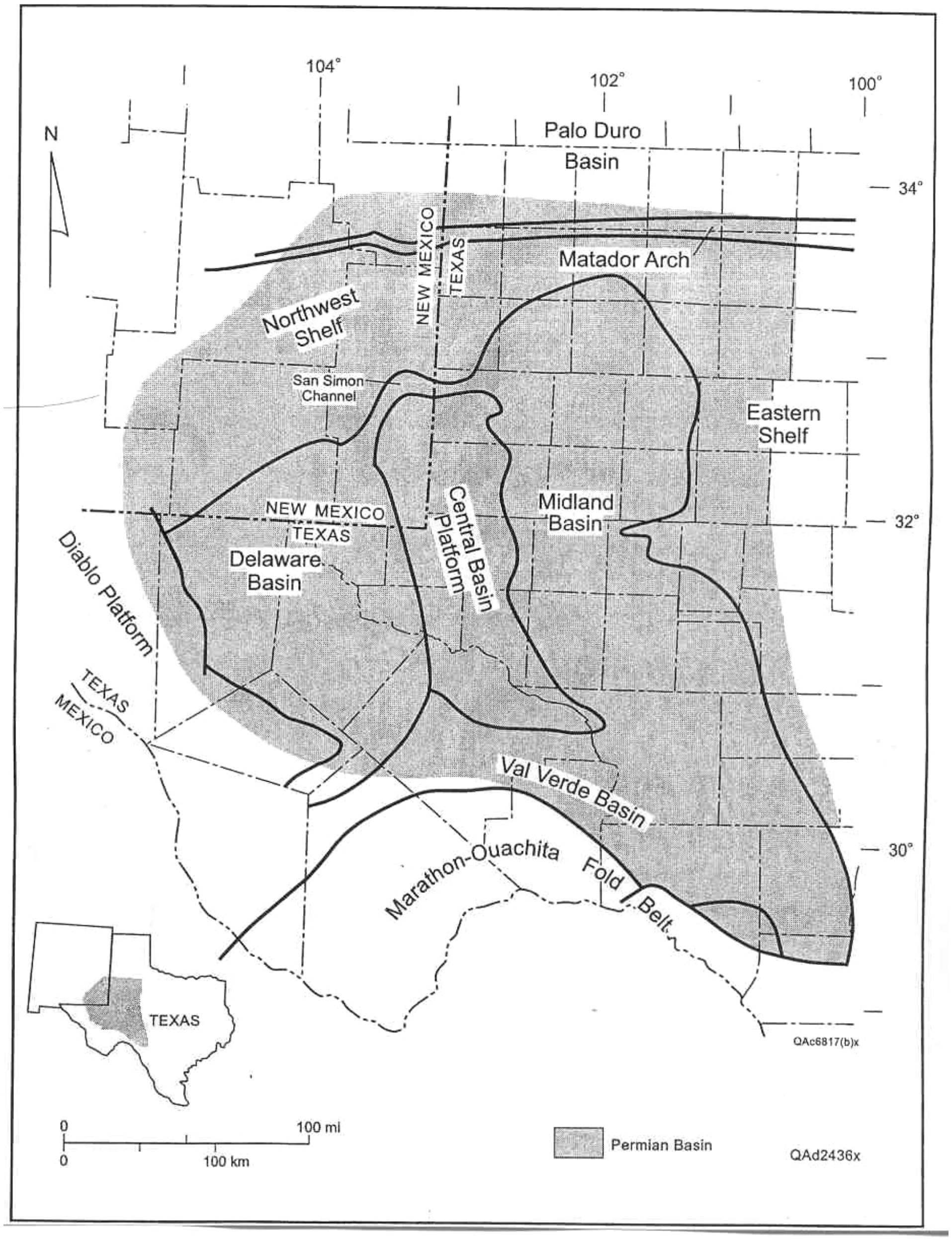

Figure 1. Major boundaries and subdivisions of the Permian Basin in west Texas and southeastern New Mexico (from Dutton et al., 2003, as modified from Hills, 1984 and Frenzel et al., 1988). The Permian Basin is subdivided into the Northwest Shelf Delaware Basin, Central Basin Platform, Midland Basin, Val Verde Basin, and Eastern Shelf.

Acknowledgments

A number of people contributed ideas, discussions, or time to the project that resulted in this report. Lynsey Rutherford, a now-graduated student in the Earth and Environmental Sciences Department at New Mexico Tech prepared well cuttings for analyses by picking Woodford Shales in sample intervals that sometimes had substantial cavings from overlying strata and also calculated the longitude and latitude of many of the wells used in this project. Ash Hall, also a former student at the Earth and Environmental Sciences Department at New Mexico Tech, helped gather data from well records for the Abo-Mississippian isopach map and calculated the latitude and longitude of the wells used in making that map. I would also like to thank my partners at the Petroleum Recovery Research Center at New Mexico Tech, Bob Balch, Sue Schrader, and Tongjun (Roger) Ruan, who have used the data presented in this report to construct the artificial intelligence/fuzzy logic system to assess exploratory risk in the Wristen petroleum system. Geoffrey Bayliss of Geochem Laboratories, Inc. in Houston, Texas analyzed the Woodford samples for source rock characteristics and also provided much information discussion and help into which analytical techniques could best be applied to assess Woodford source character. Bill Raatz, formerly of the New Mexico Bureau of Geology and Mineral Resources and now with Oxy Permian provided much informative discussion into the stratigraphy and petroleum geology of the Wristen Group in southeastern New Mexico and adjacent areas of West Texas. And last but certainly not least, appreciation goes to the U.S. Department of Energy for funding this work and to Jim Barnes, our contract manager at DOE, for providing guidance and commentary throughout the course of the project.

The Wristen play – stratigraphy and extent

Strata of Siluro-Devonian age in southeastern New Mexico are assigned to four lithostratigraphic units (ascending; Figure 2): Fusselman Formation (Ordovician-Silurian), Wristen Group (Silurian), Thirtyone Formation (Devonian), and Woodford Shale (Devonian). Significant volumes of oil and natural gas have been produced from Fusselman, Wristen, and Thirtyone reservoirs, with most production obtained from Wristen reservoirs (Table 1). In the New Mexico part of the Permian Basin, 36 reservoirs have produced more than 1 million bbls oil (MMBO) from the Wristen (Figure 3, Table 2). Cumulative production from these 36 reservoirs was 369 MMBO as of 2000.

System	Series	Lithostratigraphic unit		
Mississippian	Chesterian	undivided		
	Meramecian			
	Osagian			
	Kinderhookian			
Devonian	Upper	Woodford Shale		
	Middle			
	Lower	Thirtyone Fm.		
Silurian	Pridolian	Wristen Gp.	Fasken Fm.	Frame Fm.
	Ludlovian			
	Wenlockian			Wink Fm.
	Llandoverian	Fusselman Fm.		
Ordovician	Upper	Montoya Fm.		
	Middle	Simpson Gp.		
	Lower	Ellenburger Fm.		

Figure 2. Stratigraphic chart of Silurian and Devonian strata and overlying and underlying strata in southeastern New Mexico. Silurian and Ordovician stratigraphy from Ruppel and Holtz (1994). Ordovician and Mississippian stratigraphy from Stewart (1983a, 1983b).

Wristen Buildups and Platform Carbonate Play

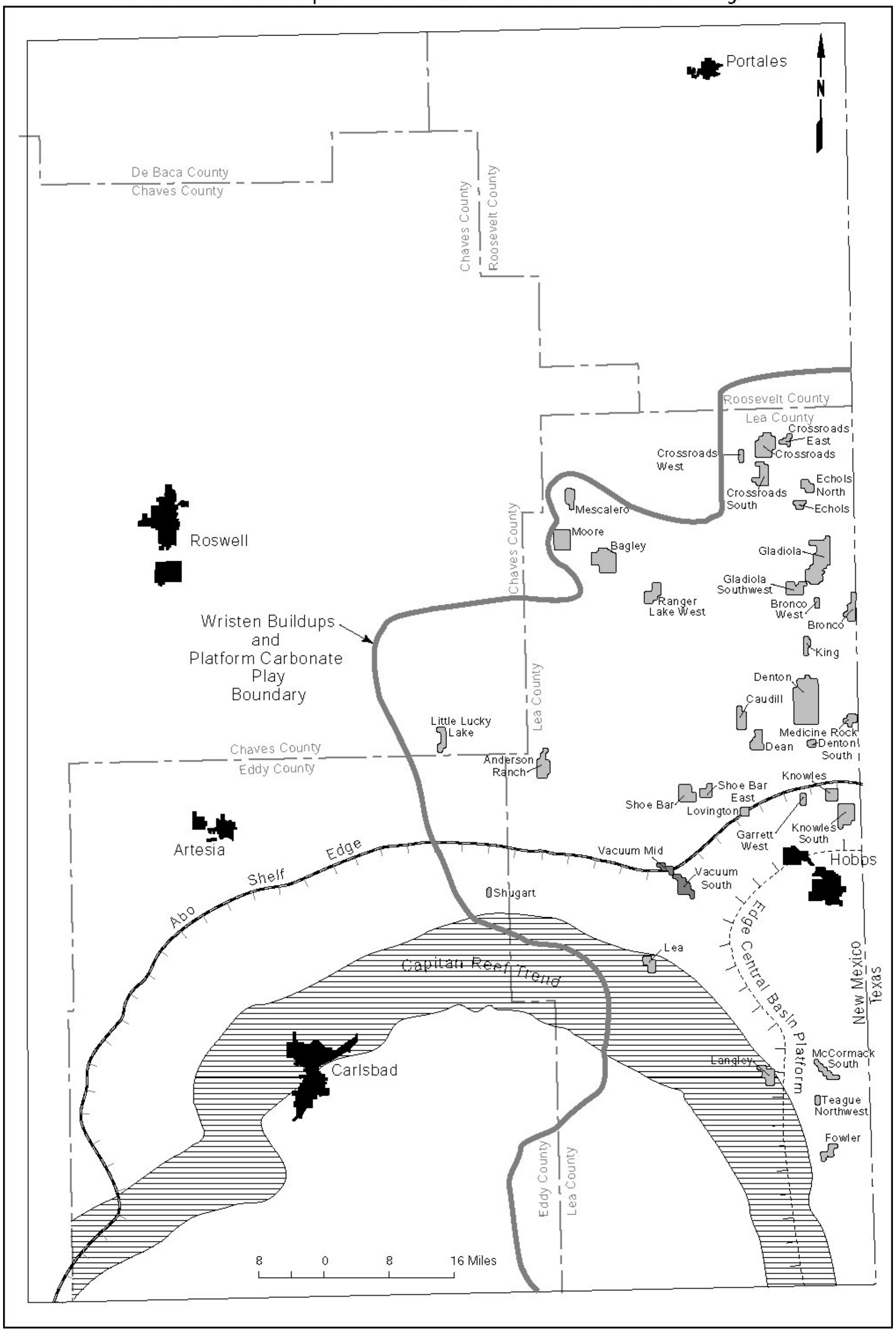

Figure 3. Wristen reservoirs that have produced more than 1 MMBO in southeastern New Mexico. From Broadhead et al. (2004).

Table 1. Silurian and Devonian stratigraphic units in southeastern New Mexico that have produced oil and gas and data pertaining to reservoirs that have produced at least 1 MMBO from these stratigraphic units. Modified from Broadhead et al. (2004).

Stratigraphic unit	**Age**	**Primary reservoir lithology**	**Number reservoirs with > 1 MMBO production**	**2000 production MMBO**	**Cumulative production MMBO**
Devonian Thirtyone Deep Water Chert	Devonian	chert	1	0.07	9.18
Wristen Buildups and Platform Carbonate	Silurian	carbonate	36	1.08	368.82
Fusselman Shallow Platform Carbonate	Silurian	carbonate	11	0.25	62.01

Production obtained from Wristen reservoirs has been assigned historically to stratal units described as “Devonian”, “Silurian”, of “Siluro-Devonian”. Recent research and stratigraphic analyses have indicated that most carbonate strata previously thought to be Devonian are actually Silurian in age (Barrick, et al., 1993; Barrick, 1995; Ruppel and Holtz, 1994). The only pre-Woodford strata that are Devonian in age belong to the Thirtyone Formation; strata of the Thirtyone Formation are widespread in the Texas part of the Permian Basin but in New Mexico are limited to the southern part of Lea County.

In Texas, the Wristen Group has been subdivided into a lower unit of gray lime mudstones and wackestones of the Wink Formation and an upper unit of shaley lime mudstones and wackestones of the Frame Formation (Hills and Hoenig, 1979). The Wink and Frame Formations are largely basinal deposits. In New Mexico, however, the Wristen the Wristen is a shelf deposit in all but the southernmost portions of Lea and Eddy Counties and the Frame and Wink Formations are not correlatable northward onto the New Mexico shelf (Ruppel and Holtz, 1994). North of the shelf margin, the Wristen is comprised of interbedded limestones and dolostones with a variety of depositional textures ranging from mudstones to grainstones to boundstones (Ruppel and Holtz, 1994). The Wristen has not been regionally subdivided throughout its extent in New Mexico and its entire extent north of the shelf margin is correlated as the Fasken Formation (Ruppel and Holtz, 1994). Fasken facies have not been mapped within New Mexico. Productive Fasken facies appear to be characterized generally by vugular dissolution porosity and by solution-enlarged fractures, but the relationship of porosity fairways to depositional facies has not been established.

Table 2. Reservoirs that produce from the Wristen Group in southeastern New Mexico that had produced 1 MMBO as of the end of 2000. Cumulative production is through the end of 2000. Data from Broadhead et al. (2004). Does not include major Wristen gas reservoirs in the deep Delaware Basin.

Reservoir Name	County	Discovery Year	Depth (feet)	2000 oil production (MMBO)	Cumulative production (MMBO)
Anderson Ranch	Lea	1953	13374	0.01	8.73
Bagley	Lea	1949	10950	0.12	28.46
Bronco	Lea	1955	11700	0.05	16.05
Bronco West	Lea	1965	12170	0.01	1.42
Caudill	Lea	1954	13585	0.02	5.71
Crossroads	Lea	1948	12115	0.06	43.44
Crossroads East	Lea	1956	12173	0.05	2.54
Crossroads South	Lea	1954	12250	0.03	3.27
Crossroads West	Lea	1959	12000	0.00	2.06
Dean	Lea	1955	13600	0.00	3.03
Denton	Lea	1949	12200	0.27	101.23
Denton South	Lea	1955	13110	0.00	3.75
Echols	Lea	1951	11500	0.00	4.62
Echols North	Lea	1952	12057	0.02	1.42
Fowler	Lea	1955	7587	0.01	1.33
Garrett West	Lea	1970	12850	0.01	3.12
Gladiola	Lea	1950	11859	0.04	52.84
Gladiola Southwest	Lea	1960	12304	0.01	4.44
King	Lea	1956	12439	0.01	6.24
Knowles	Lea	1949	12570	0.02	4.94
Knowles South	Lea	1954	12140	0.10	9.71
Langley	Lea	1979	12150	0.00	1.37
Lea	Lea	1960	14400	0.02	7.80
Little Lucky Lake	Chaves	1958	11050	0.01	1.83
Lovington	Lea	1969	11570	0.01	1.74
McCormack South	Lea	1967	7100	0.06	1.02
Medicine Rock	Lea	1961	12630	0.00	1.64
Mescalero	Lea	1952	9850	0.02	5.83
Moore	Lea	1952	10100	0.01	22.22
Ranger Lake West	Lea	1966	12850	0.01	1.19
Shoe Bar	Lea	1953	12480	0.00	1.08
Shoe Bar East	Lea	1968	13013	0.01	1.94
Shugart	Eddy	1957	12362	0.00	1.11
Teague Northwest	Lea	1992	7450	0.05	1.00
Vacuum Mid	Lea	1963	11644	0.01	1.77
Vacuum South	Lea	1958	11546	0.02	8.93
TOTALS				**1.08**	**368.82**

Wristen strata have a maximum thickness of approximately 1400 ft in Andrews County, Texas and in southeastern Lea County, New Mexico (Figure 4). From there, Wristen strata thin to an erosional pinchout underneath the Woodford Shale in southeastern Chaves, northern Lea, and northwestern Eddy Counties. It is generally thought that successively older strata are truncated unconformably northerly and northwesterly underneath the Woodford Shale (Canter et al., 1992). It is possible that in places the Woodford Shale was completely removed by erosion prior to deposition of

Mississippian strata; the Mississippian may unconformably overlie Wristen in these areas.

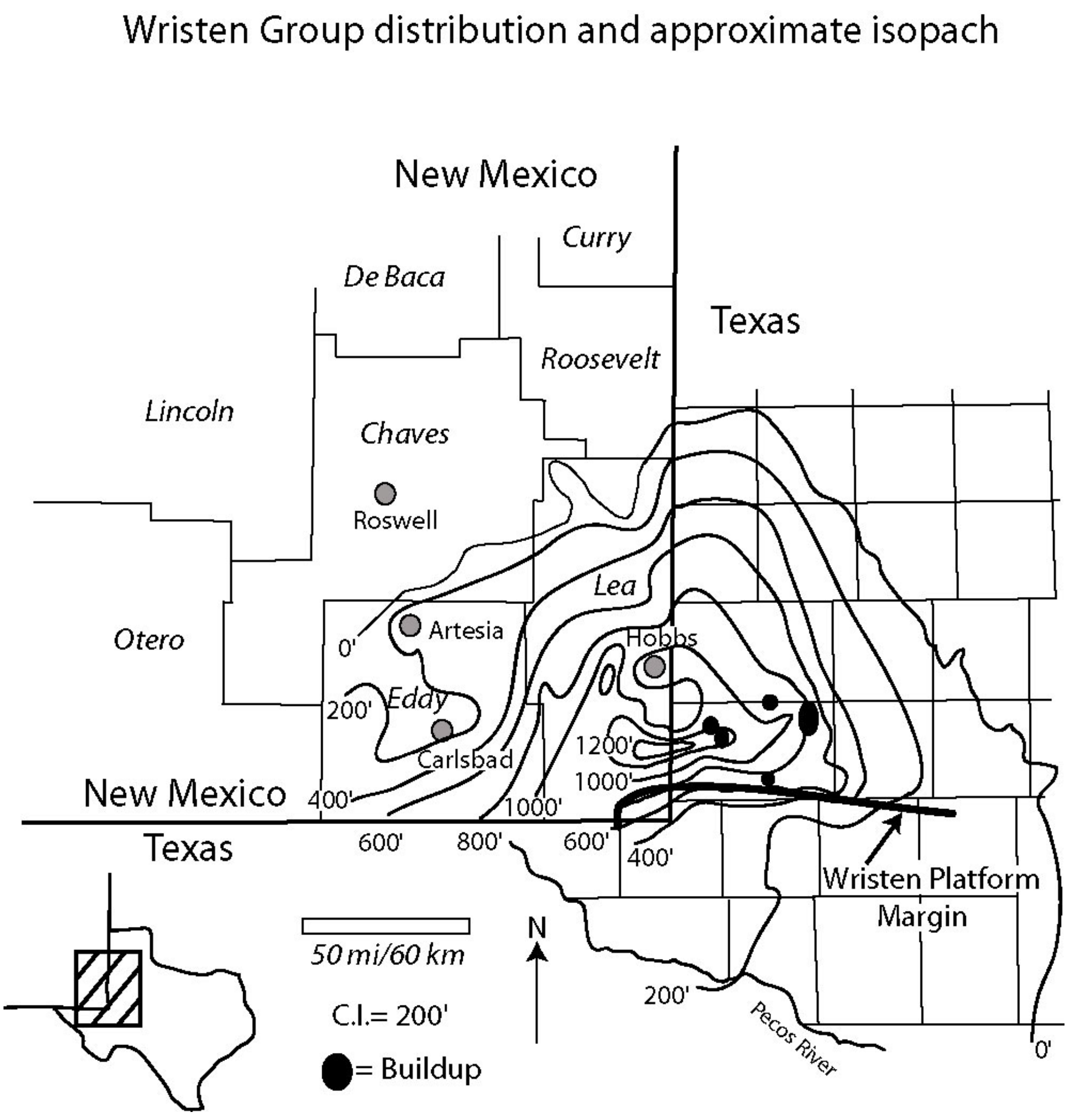

Figure 4. Isopach map of the Wristen Group in New Mexico and west Texas. From work by W.D. Raatz in Broadhead et al. (2004).

The Wristen play – reservoirs and hydrocarbon traps

The dominant trapping mechanisms for most known Wristen reservoirs are narrow anticlines bounded on one or more sides by high-angle, basement-involved faults (Figure 5). They are the "bending-fold" traps of North (1985). The faults that bound the anticlines die out upward within Pennsylvanian strata (Figure 6). A few may possibly penetrate strata as young as Wolfcampian (Early Permian). This relationship of strata for the faults dates their primary movement as Pennsylvanian in age. The faults appear to have been active primarily from the Middle Pennsylvanian ("Strawn") through the early Permian ("Wolfcamp") as a result of regional tectonism that formed the Ancestral Rocky Mountains. As a result, strata of Middle Pennsylvanian through Wolfcampian age thin over the trap-forming structures (Figure 6; Speer and Hanagan, 1995; Hanagan, 2002). The trap-forming structures and the thinning of Pennsylvanian and Lower Permian strata are identifiable on reflection seismic sections (Figure 7; Hanagan, 2002). Because trap-forming structures generally have maximum aerial extent of only a few square miles, 3-D seismic surveys have been very helpful in their location and delineation (Speer and Hanagan, 1995). Hanagan (2002) recommended isochron mapping the interval in seismic sections between the top of the Abo Formation (Lower Permian) and the top of the Mississippian as an important exploration tool. Thin areas on the isochron maps denote Ancestral Rocky Mountain paleostructures that may form traps.

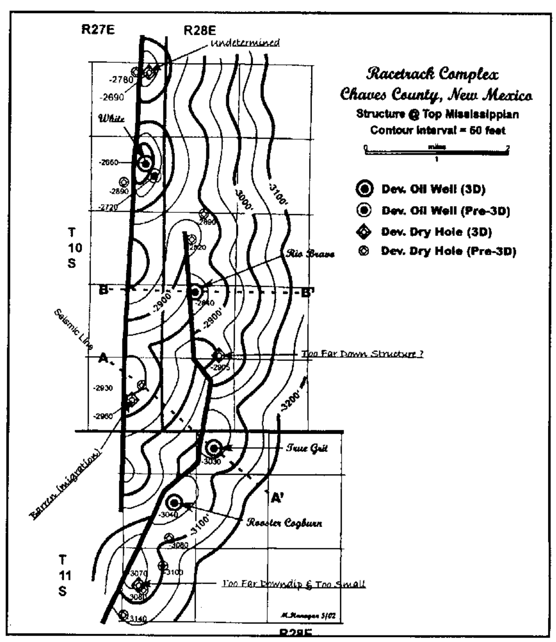

Figure 5. Structure contours on the upper surface of Mississippian strata at the Racetrack Wristen reservoir, Chaves County, New Mexico. From Hanagan (2002).

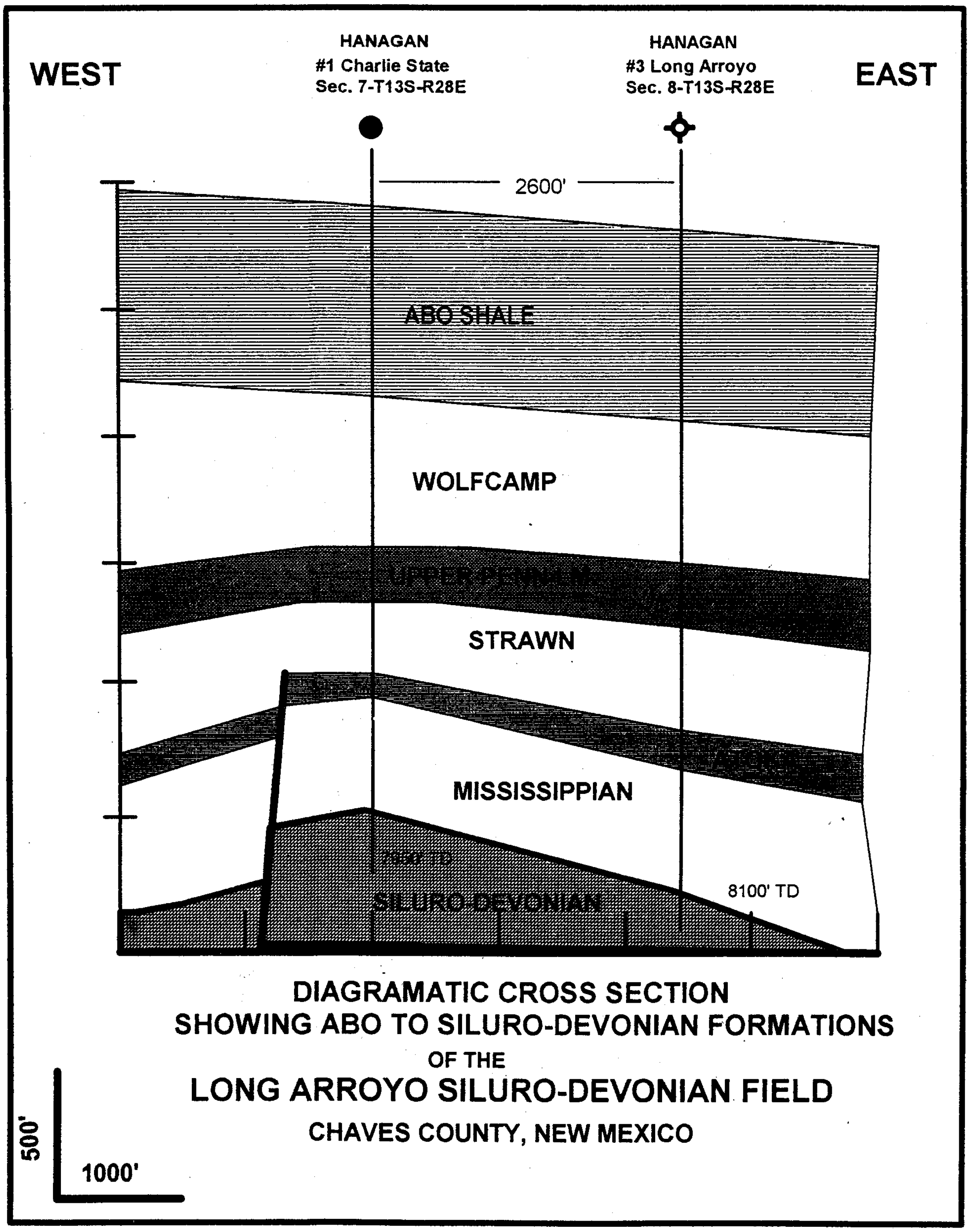

Figure 6. The faults that form the traps in the Wristen reservoirs die out upward in the section and were active from the Middle Pennsylvanian through the early Permian as a result of regional tectonism that formed the Ancestral rocky mountains. This cross section through the Long Arroyo Wristen reservoir of Chaves County is from Speer and Hanagan (1995).

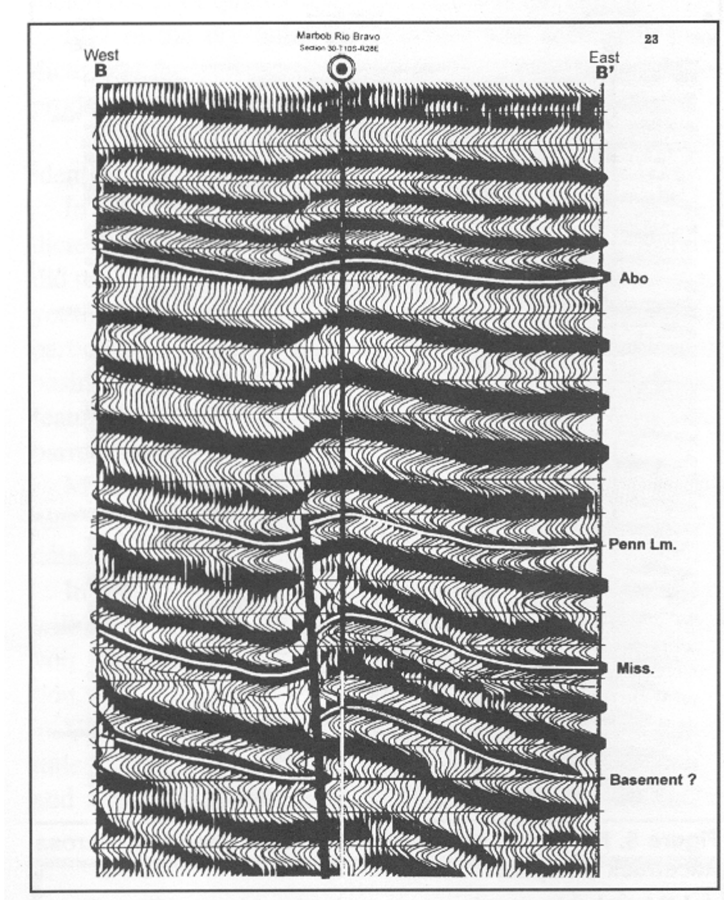

Figure 7. The relatively small structures that form traps in Wristen reservoirs are identifiable on seismic sections where bounding faults, the anticlinal form of the trap, and the thinning of overlying Pennsylvanian and Lower Permian strata are apparent. This seismic section across the Racetrack reservoir of Chaves County (Figure 5) is from Hanagan (2002).

Wristen structure and paleostructure

The structure on top of the Siluro-Devonian carbonates clearly indicates the major tectonic components of the Permian Basin within New Mexico: the deep Delaware Basin, the Northwest Shelf, and the Central Basin Platform (Figures 8, 9). The top of the Siluro-Devonian section is the erosional top of the Wristen Group throughout most of southeastern New Mexico. In southern Lea County, it is the erosional top of the Thirtyone Formation. North and west of the Wristen pinchout (Figure 4), the erosional top of the Fusselman Formation marks the top of the Siluro-Devonian carbonate section. The top of the Siluro-Devonian carbonate section varies from approximately 15,000 ft below sea level in the deeper parts of the Delaware Basin to 4000 to 500 ft below sea level over most of the Central Basin Platform (Figures 8, 9). The top of the Siluro-Devonian carbonate section is 4000 to 7000 ft below sea level over most of the Northwest Shelf. Particularly noticeable is the steep slope that forms the western edge of the Central Basin Platform. This tectonic boundary is formed by high-angle, near-vertical faults that were formed during the Pennsylvanian and Early Permian (Hills, 1984). The boundary between the Delaware Basin and the Northwest Shelf is gradational and is the product of both late Paleozoic Ancestral Rocky Mountain tectonism and a gentle tectonic down warping of early Paleozoic age, the latter resulting in the formation of the Tobosa Basin (Wright, 1979; Hills, 1984). Superimposed on both the gentle structures of early Paleozoic age and the more pronounced structures of late Paleozoic age was the eastward tilting of the entire basin that occurred during Laramide (Late Cretaceous - Early Tertiary) tectonism (Hills, 1963, 1984). The structures that form traps in the Wristen carbonate reservoirs are the smallest ones portrayed on the structure maps in this report.

Following the suggestions of Hanagan (2002), a regional isopach map of the interval between the top of the Abo Formation (Lower Permian) and the top of the Mississippian section was prepared (Figure 10). Local thin areas delineate paleostructures that may form traps. These thin areas define northerly and northwesterly trending trains of paleostructures that were probably formed along regional faults or fault zones during the Pennsylvanian and earliest Permian.

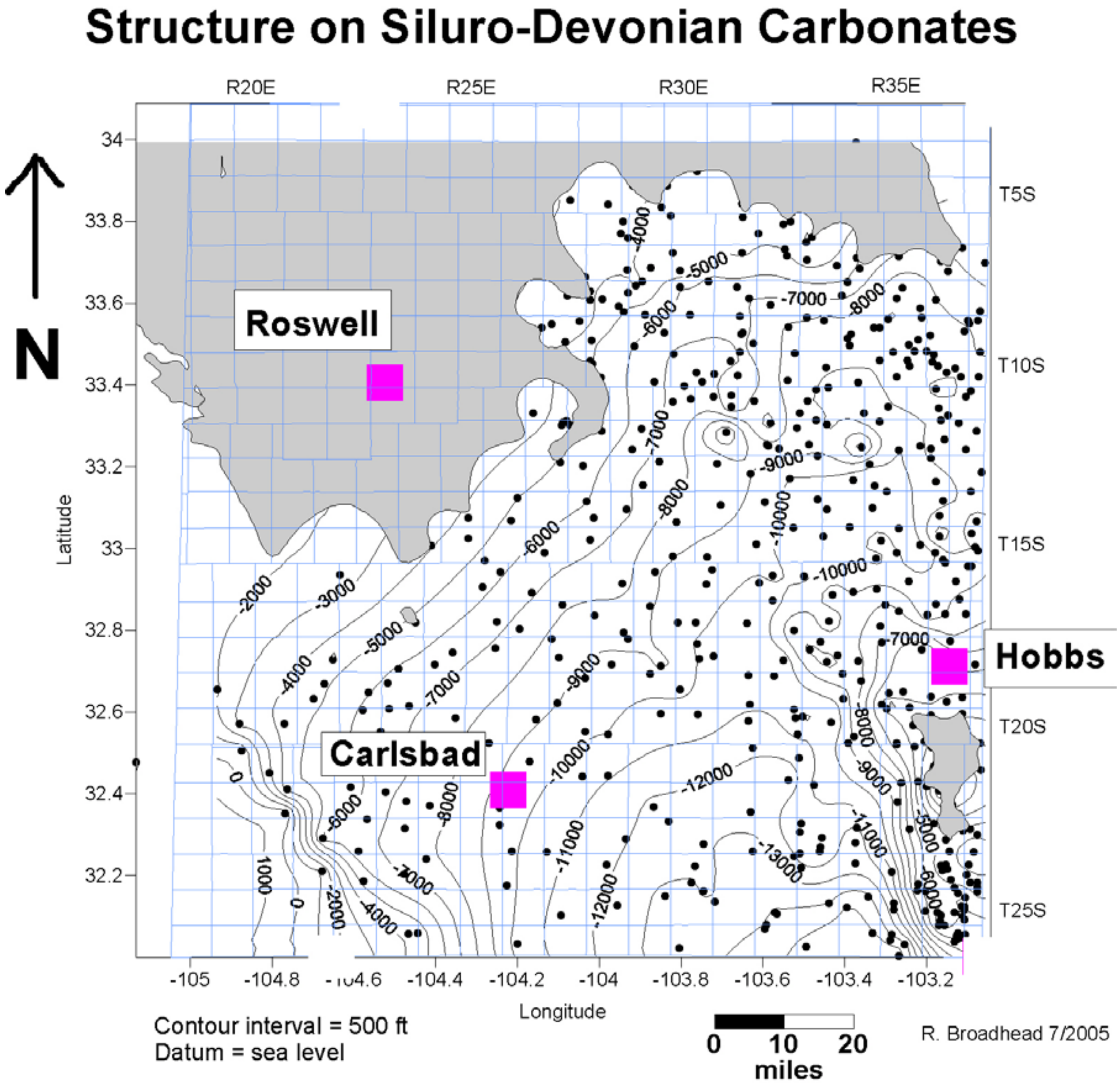

Figure 8. Structure contours on Siluro-Devonian carbonate strata (Wristen Group and Thirtyone Formation) in southeastern New Mexico. The Wristen and Thirtyone are absent from the gray area south of Hobbs, where they have been removed by erosion on high paleostructures prior to deposition of Lower Permian strata. The northerly limit of contours coincides with the northern extent of the Woodford Shale.

Structure Top Siluro-Devonian Carbonates

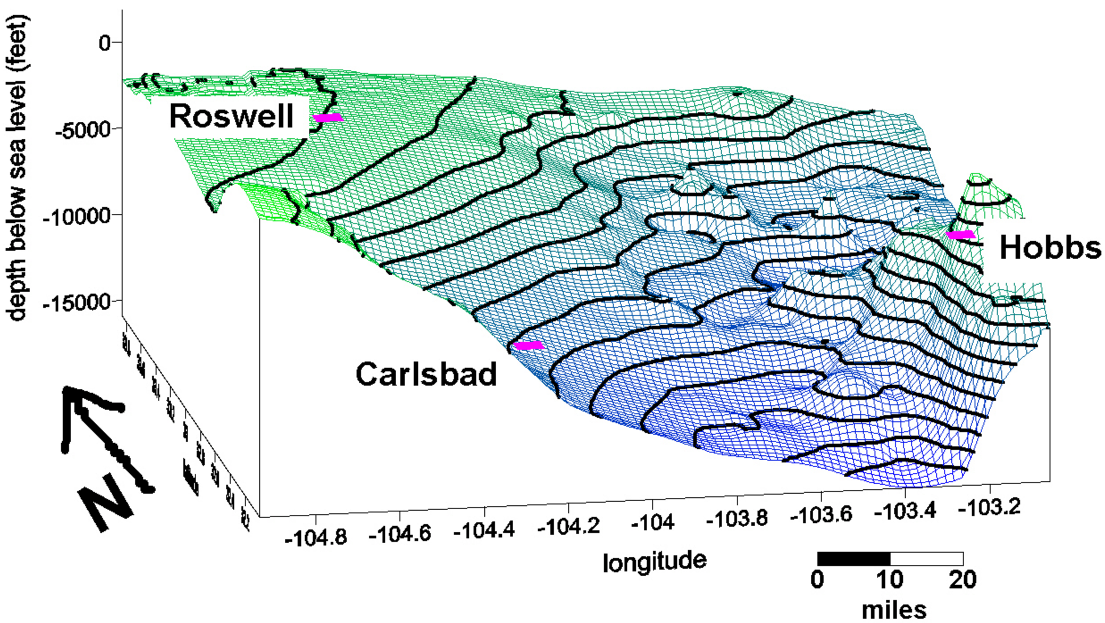

Figure 9. Three-dimensional wireframe diagram showing structure on top of the Siluro-Devonian carbonates in southeastern New Mexico.

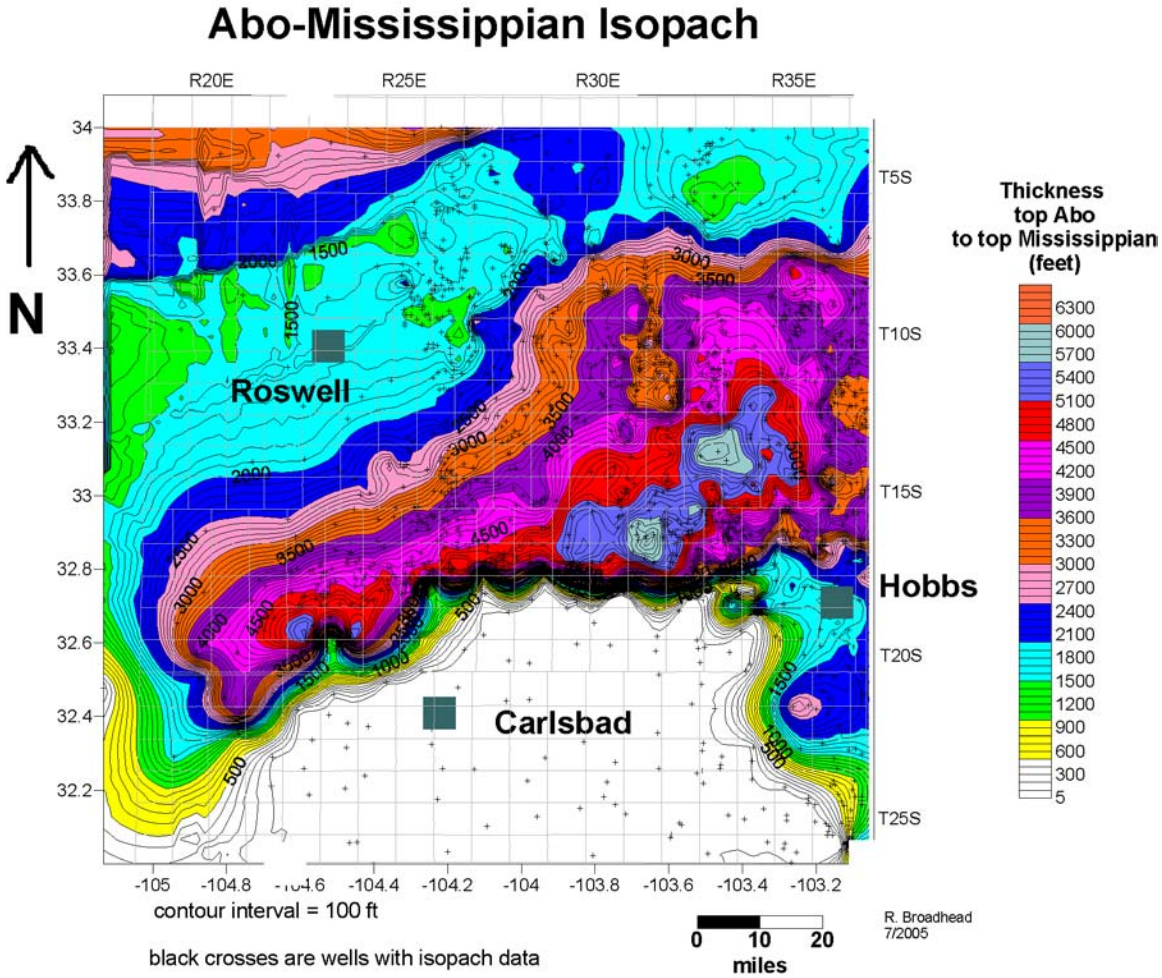

Figure 10. Isopach map of the stratigraphic interval between the top of the Abo Formation (Lower Permian) and the top of the Mississippian section in southeastern New Mexico. Local thin areas denote paleostructures of Pennsylvanian to Early Permian age.

The Woodford Shale – source rock and seal

The Woodford Shale (Upper Devonian) overlies the Siluro-Devonian carbonate section throughout most of southeastern New Mexico (Figure 11). Over the most pronounced paleostructures on the Central Basin Platform, the Woodford has been removed by post-Mississippian erosion and pre-Woodford rocks are overlain either by Mississippian strata, Pennsylvanian strata, or Lower Permian strata. To the north and northwest, the Woodford zero isopach (Figure 12) may be depositional in some areas and erosional in other places, the latter being the result of the formation of the unconformity between the Woodford and overlying Mississippian strata. The presence of outliers of Woodford north of the regional zero isopach line in the area south and east of Roswell suggests that the Woodford zero isopach is an erosional limit defined by the unconformity that separates the Woodford from overlying Mississippian shales and limestones. Further to the northwest, the Mississippian is overstepped by Middle to upper Pennsylvanian carbonates and shales that rest unconformably on Silurian carbonates, and even Ordovician carbonates in places. Most of the production from the Wristen is obtained from reservoirs that overlain by the Woodford. The Woodford forms the hydrocarbon seal for most Wristen oil and gas accumulations.

The Woodford Shale appears to be the major source rock for oil and gas accumulations within Wristen carbonates. It is the major pre-Mississippian stratigraphic unit in southeastern New Mexico that contains significant kerogen-rich strata. The Silurian section is comprised almost entirely of carbonates that are too organically lean to be considered major source rocks.

For this project, two isopach maps of the Woodford Shale were prepared (Figures 12, 13). The first is a “raw” isopach map of the Woodford. This map contains Woodford thickness data from 537 well logs correlated in southeastern New Mexico. The map is based on apparent thickness data and true thickness data. Apparent thickness will exceed true thickness in vertical wells that penetrate strata that have a structural dip greater than 0 degrees (Figure 14). When structural dip of strata exceeds 30 degrees, apparent thickness exceeds true thickness by a significant amount; when structural dip is 45 degrees, apparent thickness is more than 140 percent of true thickness. Steep dips are common on the flanks of paleostructures that form traps in Wristen carbonates in southeastern New Mexico. Therefore, the raw isopach map of the Woodford Shale (Figure 12) portrays apparent thickness of the Woodford in places where wells were drilled on the flanks of these structures. As such, apparent thickness may exceed true thickness by 200 percent or more where dips are steep. This is thought to be a complication only in places where there is a large amount of variation in apparent Woodford thickness over a small geographic area.

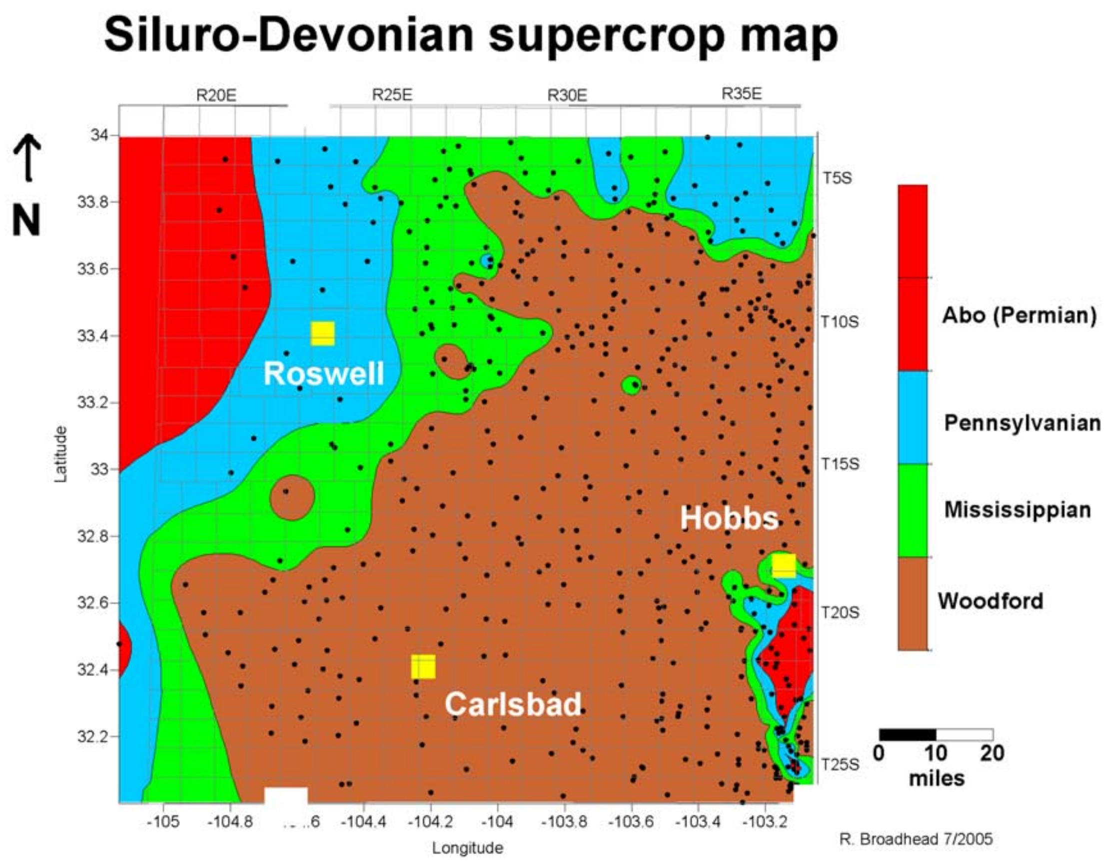

Figure 11. Supercrop map of the Siluro-Devonian carbonate section, indicating the stratigraphic units that rest on the Siluro-Devonian carbonates.

A few dipmeter logs were available for analysis and calculation of true Woodford thickness. Dipmeter logs have not been run in the vast majority (significantly greater than 99 percent) of wells drilled in the study area. Analysis of one dipmeter log from a well drilled in the southeastern most part of the project area revealed an apparent thickness of 406 ft and a true thickness of 282. This indicates that the Woodford has a true thickness of at least 300 ft in at least some wells.

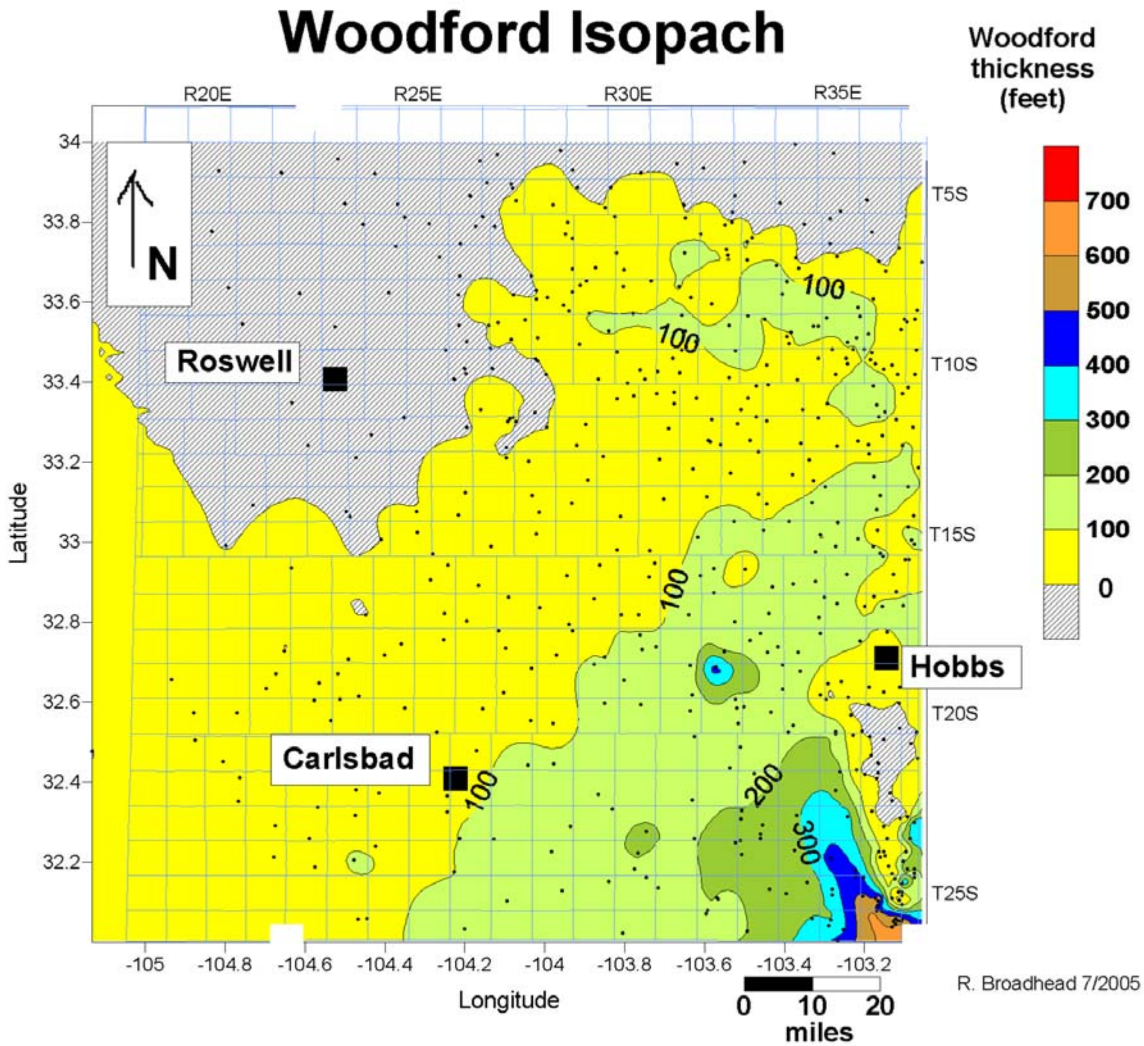

Figure 12. Isopach of the Woodford Formation. This is a map of apparent thickness of the Woodford using wells where apparent thickness is significantly greater than true thickness due to steep structural dips.

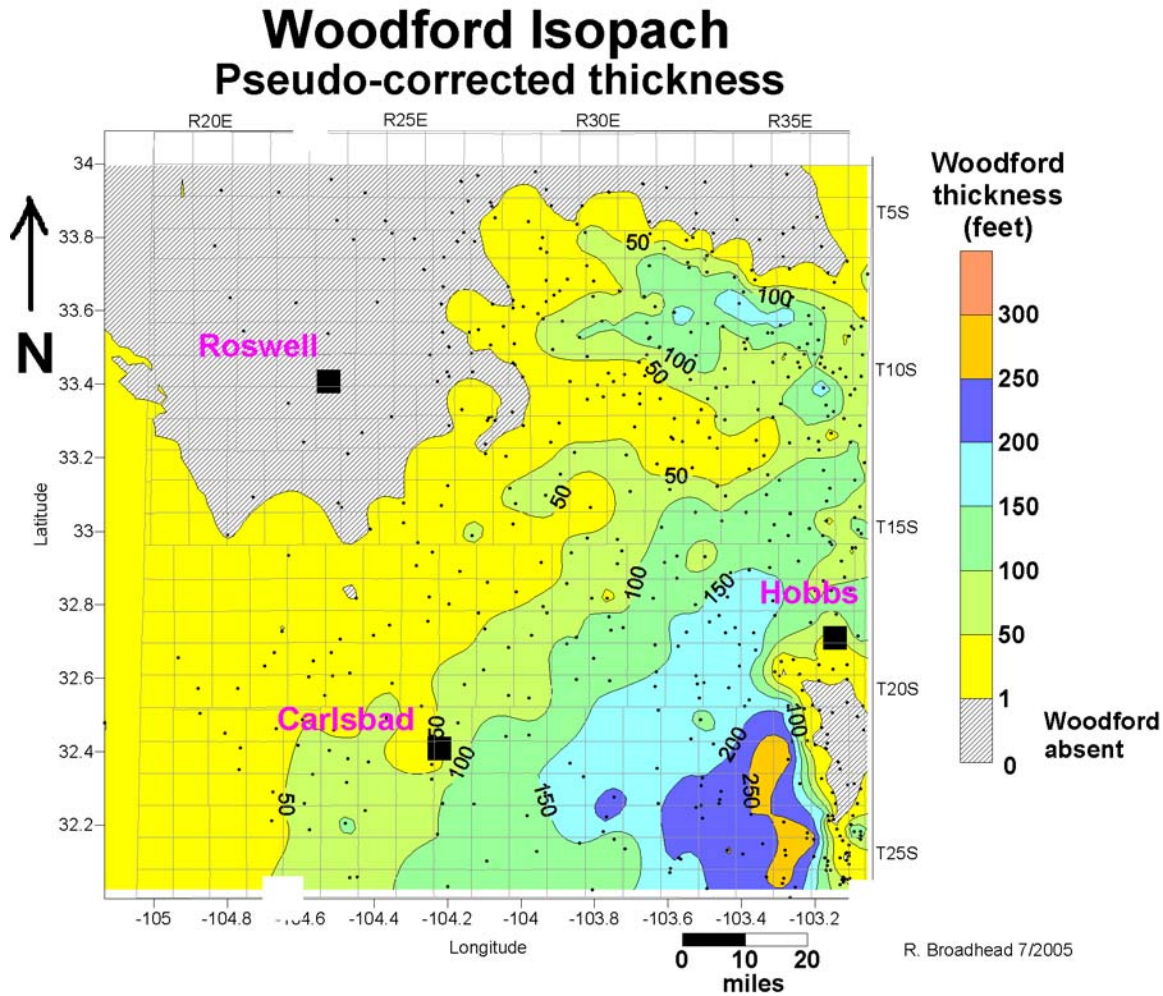

Figure 13. Isopach map of the Woodford Shale, constructed by correcting apparent thickness to true thickness in wells with dipmeter logs and by omitting wells with local anomalous and overly thick Woodford.

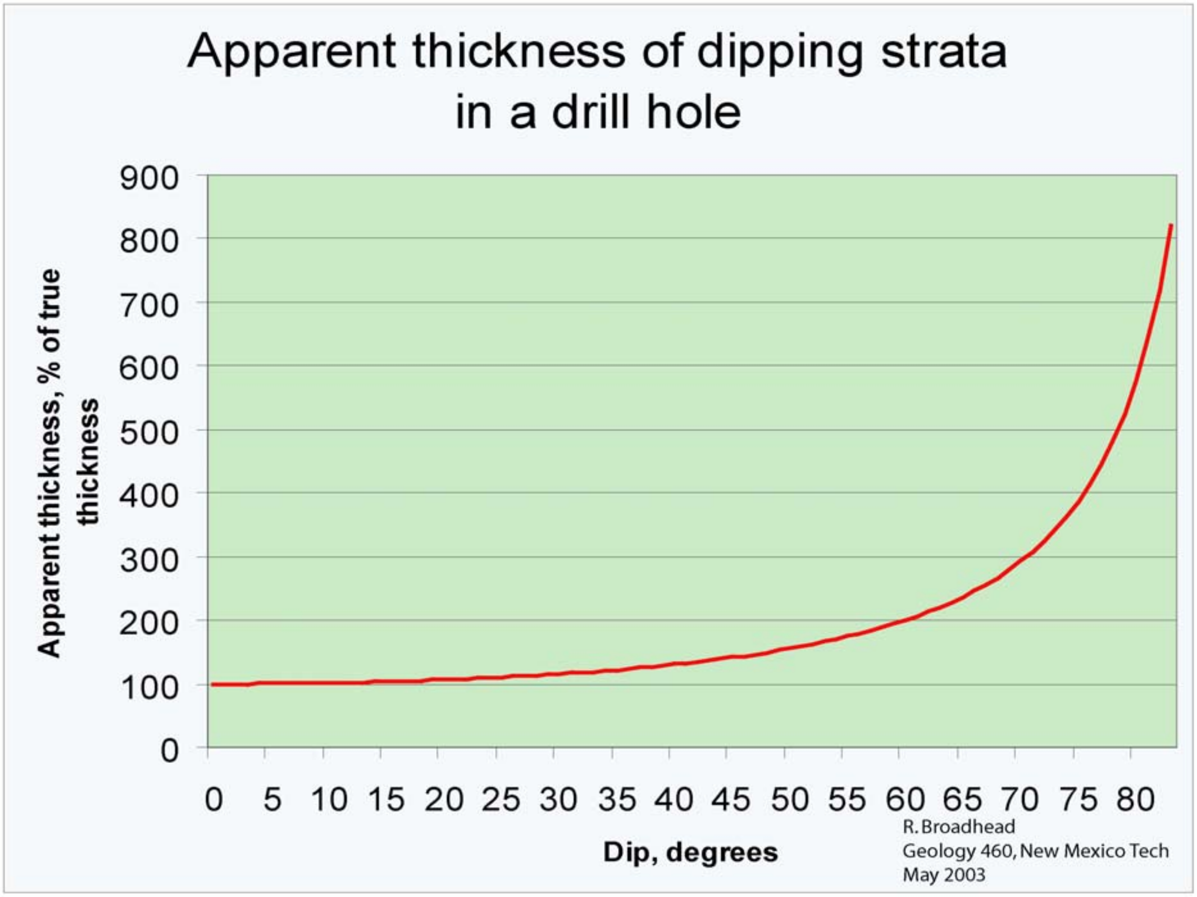

Figure 14. Apparent thickness of dipping strata in a vertical borehole (as a percentage of true thickness) as a function of structural dip.

The isopach map of true Woodford thickness (Figure 13) was prepared by eliminating data points where apparent thickness is greater than 300 ft. Also eliminated were the thickest data points in local areas with large variations in Woodford thickness because it is thought that local, large thickness variations are caused by steep dips on the flanks of structures. Given that a large percentage of wells that penetrate pre-Woodford strata targeted the types of structures that form traps in Wristen carbonates, the occasional location of these wells on the flanks of paleostructures (as opposed to the tops where strata dip more gently) is expected. The resulting map (Figure 13) is thought to be a reasonable approximation of true Woodford thickness. Because dipmeter logs were only available for a few wells, true thickness cannot be calculated for more than 99 percent of the wells. As such, this map is referred to as a “pseudo-corrected isopach” (or thickness) map.

Introduction to source rocks and source rock evaluation

A *petroleum source rock* can be defined as any unit of rock that has generated and expelled oil and/or gas in commercial quantities (Hunt, 1996). When assessing source-rock potential, four questions must be answered (Dow, 1978; Barker, 1980; Brooks et al., 1987; Hunt, 1996). First, does the rock have sufficient organic matter? Second, is the organic matter capable of generating petroleum and, if so, is it oil prone or gas prone? Third, is the organic matter thermally mature? Fourth, have generated hydrocarbons been expelled from the rock?

The question of whether or not the rock has sufficient organic matter to be a source rock can be answered on the basis of total organic carbon (TOC) measurements. Rocks that have insufficient TOC content can be rule out as possible source rocks. Jarvie (1991) has summarized TOC ratings systems for screening potential source rocks (Table 3). The TOC content needed for petroleum generation is thought to be greater in siliciclastic shales than in carbonate source rocks.

The second question asks what type of organic matter is present within the rock. The type of organic matter, if present in sufficient quantity, will determine if a source rock will produce principally oil or principally gas upon maturation (Table 4). For this project, identification of organic-matter type was based mainly on petrographic analyses of kerogen concentrate. Algal, herbaceous, and much amorphous kerogen (kerogen types I and II) will generate oil and associated gas upon maturation (Hunt, 1996; Brooks et al., 1987; Tyson, 1987). Woody kerogen (kerogen type III) and some amorphous kerogen will generate gas and possibly a minor amount of oil or condensate upon maturation. Inertinites are type IV kerogens that have extremely low hydrogen contents and are incapable of generating significant amounts of hydrocarbons. Although it is possible to differentiate kerogen types I, II, and III using Rock-Eval pyrolysis (e.g. Tissot and Welte, 1978; Peters, 1986), some type III kerogens may be confused with other types of kerogens and result in misleading characterization of kerogen types when using pyrolysis (Tyson, 1987). Oxidation of kerogen may also alter its Rock-Eval character. Also, pyrolysis cannot discern the different varieties of kerogens present in samples with mixed kerogen assemblages. For these reasons, Rock-Eval pyrolysis was used only as reinforcement for petrographically determined kerogen identification.

The level of thermal maturity can be evaluated using visual kerogen analyses. Kerogen color in transmitted light changes from yellow to orange to brown to black with increasing maturation (Staplin, 1969). Based on calibrated color charts, the sample is assigned a numerical value (Thermal Alteration Index or TAI) that ranges from 1.0 (immature) to 5.0 (metamorphosed; Table 5).

Vitrinite reflectance (Ro) is a measure of the percentage of incident light that is reflected from the surface of vitrain, a type of woody kerogen. It can be used to assess thermal maturity of a source rock and is a standard measurement of maturity. Essentially, at vitrinite reflectance increases with thermal maturity

Table 3. Generation potential of petroleum source rocks based on TOC content. From Jarvie (1991).

Generation potential	**TOC in shales (weight percent)**	**TOC in carbonates (weight percent)**
Poor	0.0 - 0.5	0.0 - 0.2
Fair	0.5 - 1.0	0.2 - 0.5
Good	1.0 - 2.0	0.5 - 1.0
Very good	2.0 - 5.0	1.0 - 2.0
Excellent	> 5.0	> 2.0

and can be used to assess whether or not a source rock has attained a sufficient level of maturation for petroleum generation. For this project, the only vitrinite reflectance data available were for donated analyses; these data were converted to TAI using published tables (Hunt, 1996; Merrill, 1991; Geochem Laboratories, Inc., 1980) and the converted data were used in maturity evaluation.

Rock-Eval pyrolysis can also be used to evaluate thermal maturity. The temperature at which the maximum amount of hydrocarbons is generated from the S_2 peak (TMAX, ^{o} C) has been correlated to the thermal maturity of the source rock (Peters, 1986; Table 5). This method, although rigorously quantitative, does not give as complete an evaluation of maturity as TAI and only places a sample as being within, above, or below the oil window. Also, the measured value of TMAX is partially dependent upon the type of organic matter present as well as numerous other factors (Peters, 1986). Therefore, for this project, thermal maturity was determined primarily from TAI values and R_o values converted to TAI values. Rock-Eval TMAX values were used to support TAI data or were used in wells for which no TAI or R_o data were available.

Table 4. Kerogen types and petroleum products produced upon thermal maturation. Based on summary works of Merrill (1991) and Tyson (1987).

General kerogen type	Kerogen type	Petrographic form	Coal maceral group	Hydrocarbons generated
sapropelic (oil prone)	I	algal	exinite or liptinite	oil, gas
		amorphous		
	II	herbaceous		
humic (gas prone)	III	woody	vitrinite or huminite	gas, possibly minor oil
	IV	coaly (inertinite)	inertinite	none

The Rock Eval Productivity Index (PI) is a measure of thermal maturity. PI is defined as the ratio of the S_1 value to the sum of the S_1 and S_2 values:

$$PI = S_1/(S_1 + S_2)$$

The S_1 value is a function of the volume of hydrocarbons already generated by the source rock in its present state of thermal maturity. The S_2 value is a function of the remaining oil and gas that could be generated by the source rock if it was allowed to reach ultimate maturity and hydrocarbon generation.

The fourth question concerns the expulsion of generated hydrocarbons from the source rock. This question is more difficult to answer than the other three questions. For the most part, studies of thermal maturity of a source rock are empirically correlated with the presence of oil in associated reservoirs. It is generally assumed that once a sufficient volume of hydrocarbons have been generated in a source rock,
they will be expelled and migrate into reservoirs. Reservoirs that are thinly interbedded with reservoirs will expel hydrocarbons at lower levels of thermal maturity than thick source rocks that contain few or no interbedded reservoirs (Leythauser et al., 1980; Cornford et al., 1983; Lewan, 1987).

Table 5. Correlation of maturation parameters with zones of hydrocarbon production. Based on Geochem Laboratories, Inc. (1980), Sentfle and Landis (1991), Peters (1986), and Hunt (1996).

Maturation level (products generated)	**Visual kerogen Thermal Alteration Index (TAI)**	**Vitrinite reflectance R_o**	**Rock-Eval Productivity Index**	**Rock-Eval TMAX (^oC)**
Immature (biogenic gas)	1.0 - 1.7	< 0.45		
Moderately immature (biogenic gas and immature oil)	1.8 - 2.1	0.45 - 0.5		<435
Moderately mature (immature heavy oil)	2.2 - 2.5	0.6 - 0.8	<0.1	
Mature (mature oil, wet gas)	2.6 - 3.5	0.9 - 1.6	0.1 – 0.4	435 - 470
Very mature (condensate, wet gas, thermogenic dry gas)	3.6 - 4.1	1.7 - 2.4	>0.4	
Severely altered (thermogenic dry gas)	4.2 - 4.9	> 2.5		>470
Metamorphose d	5.0			

Source rock assessment of the Woodford Shale

As discussed above, the Woodford Shale is the only stratal unit in southeastern New Mexico that is identified as having significant volumes of kerogen-rich strata. The Woodford consists dominantly of black to brown shale; fine-grained sandstones and siltstone are present in areas close to the regional zero isopach line on the north and northwest. Therefore hydrocarbon source rock analyses were run on 25 Woodford samples from 19 exploration wells drilled in southeastern New Mexico (Figure 15; see database *Wdfdsrc.xls*). Analyzed samples were drill cuttings from the collections at the

New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. Analyzed samples are composites of several 10 ft drill intervals that in most cases were selected to represent the entire thickness of Woodford in each well. Cuttings were carefully selected to exclude on-Woodford lithologies, that is, cavings from shallower stratigraphic units. Only dark-shale source facies from the Woodford were analyzed. Samples were analyzed at Geochem Laboratories, Inc. of Houston, Texas.

Several types of analyses were performed on each sample, including:

1. Total organic carbon (TOC);
2. Rock-Eval pyrolysis;
3. Visual kerogen assessment of kerogen type;
4. Thermal Alteration Index (TAI), an indicator of source rock maturity using the color of the kerogen in transmitted light compared to a standardized color scale.

In addition, it was attempted to assess thermal maturity by analyzing Vitrinite reflectance (R_o), but it was found that vitrinite was not present in a large percentage of Woodford samples. Therefore, vitrinite reflectance could not be measured.

Woodford Total Organic Carbon (TOC) varies from 1.7 percent to 4.93 percent (Figure 15). TOC content increases in a gradual, consistent manner to the southeast toward the center of the Tobosa Basin. In most places, Woodford TOC exceeds 2 percent. On the basis of TOC, the Woodford can everywhere be classified as a good to very good source rock.

Visual analysis of Woodford kerogen types revealed that amorphous and herbaceous kerogens dominate the Woodford. In most samples, the sum of the amorphous and herbaceous kerogens exceeds 70 percent of the kerogen population. Gas-prone woody types are generally less than 20 percent of the kerogen population. Inertinite (non-generative kerogen) is less than 20 percent of the kerogen population in most samples. Therefore, the Woodford in southeastern New Mexico is in general dominated by oil-prone kerogens that will have generated oil and associated gas upon maturation.

Thermal maturity of the Woodford can be assessed by three techniques with the analytical data obtained for this project: (1) the Rock-Eval TMAX value; (2) the Rock-Eval Productivity Index (PI), and (3) the Thermal Alteration Index (PI). Because Rock-Eval analyses are substantially less costly than TAI analyses, the Rock-Eval analyses were performed on all analyzed samples. TAI was performed on only a selected subset of

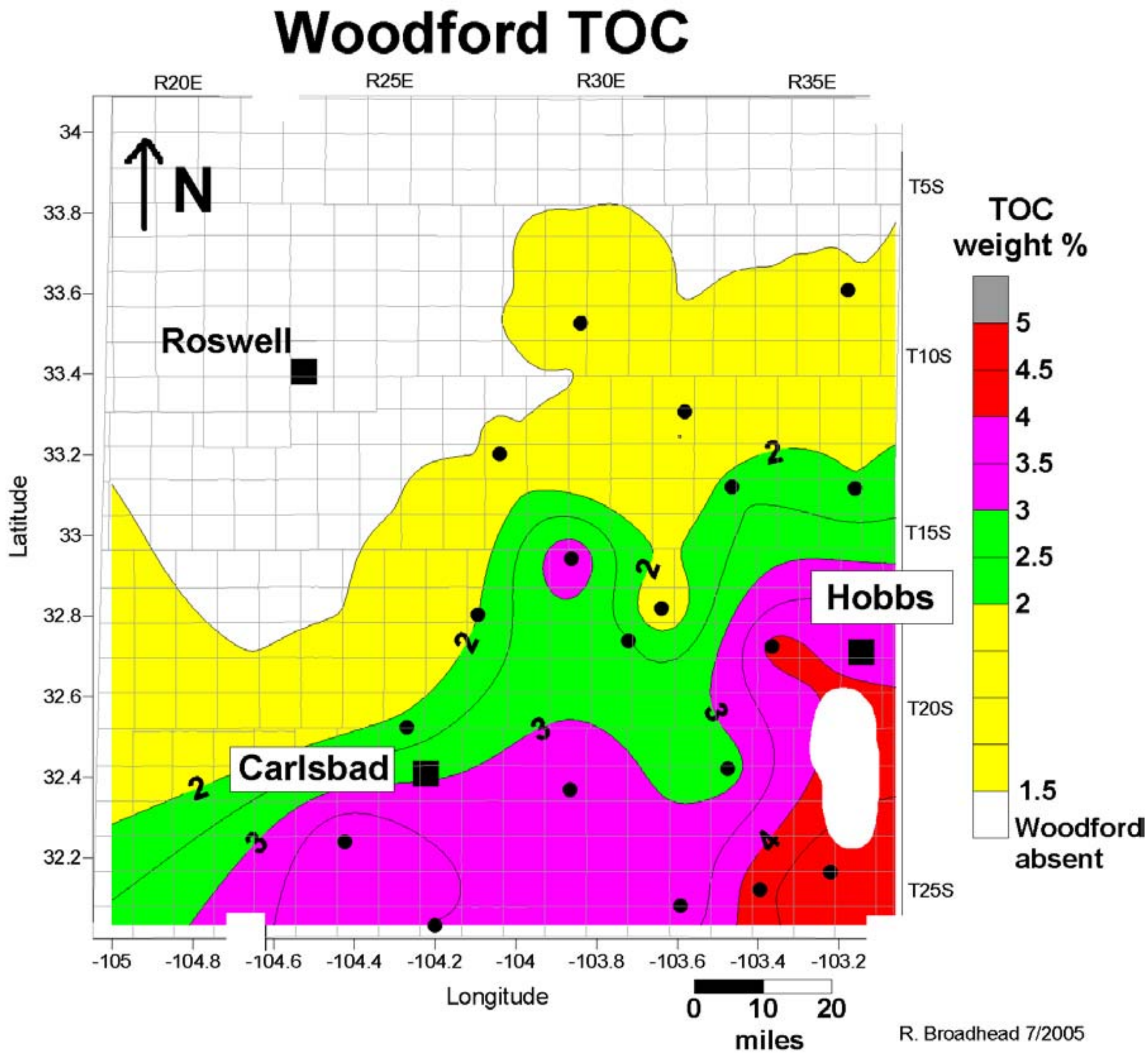

Figure 15. Average Total organic carbon (TOC) content of the Woodford Shale in weight percent in southeastern New Mexico.

Woodford samples. Peters (1996) and Hunt (1996) emphasized that thermal maturity assessments made from TMAX measurements should be confirmed with other standard measurements of thermal maturity, either R_o or TAI, because of inherent inaccuracies associated with TMAX in many source rocks. Because vitrinite is not present in a large percentage of Woodford samples, it was decided to use TAI to conform TMAX because TAI can be determined from all translucent kerogens, which make up the majority of kerogens in the Woodford.

TMAX values were plotted against both the Thermal Alteration Index (TAI; Figure 16) and the Rock-Eval Productivity Index (PI; Figure 17). For the Woodford samples, TMAX exhibits a negative relationship with both TAI and PI. The relationship with both parameters should be positive. However, PI exhibits a positive relationship with TAI (Figure 18), as it should. This relationship indicates that PI, rather than TMAX, is the Rock-Eval maturity indicator that is valid for the Woodford Shale in 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 (Peters, 1986; Hunt, 1996).

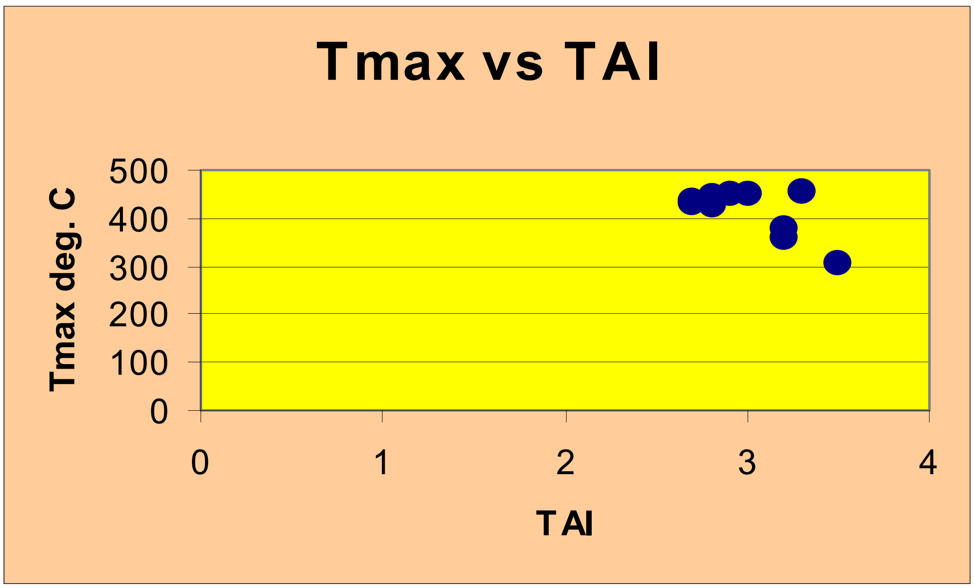

Figure 16. Rock-Eval TMAX plotted as a function of the Thermal Alteration Index (TAI) for Woodford Shale samples in southeastern New Mexico.

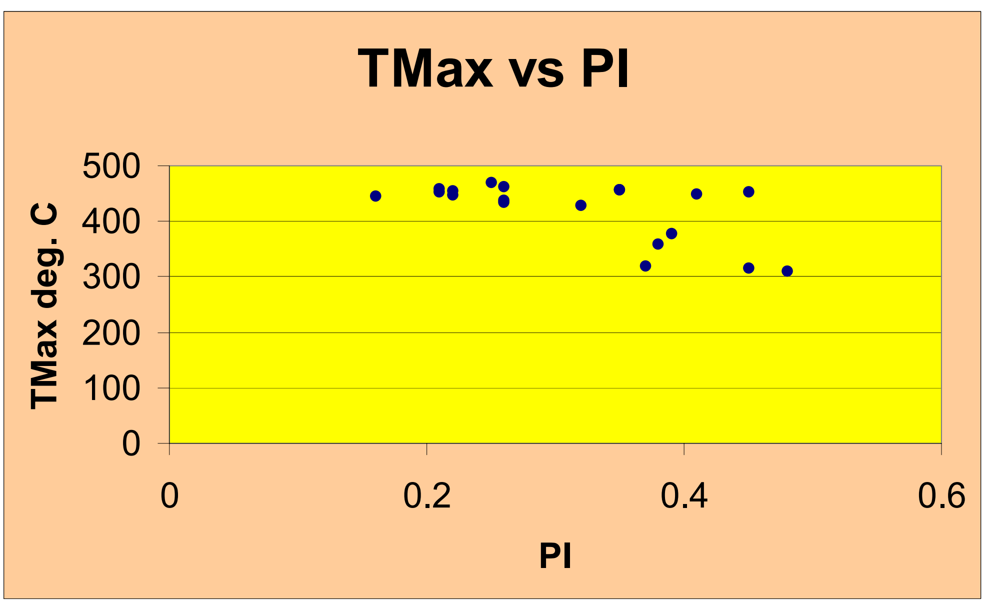

Figure 17. Rock-Eval TMAX plotted as a function of the Rock-Eval Productivity Index (PI) for Woodford Shale samples in southeastern New Mexico.

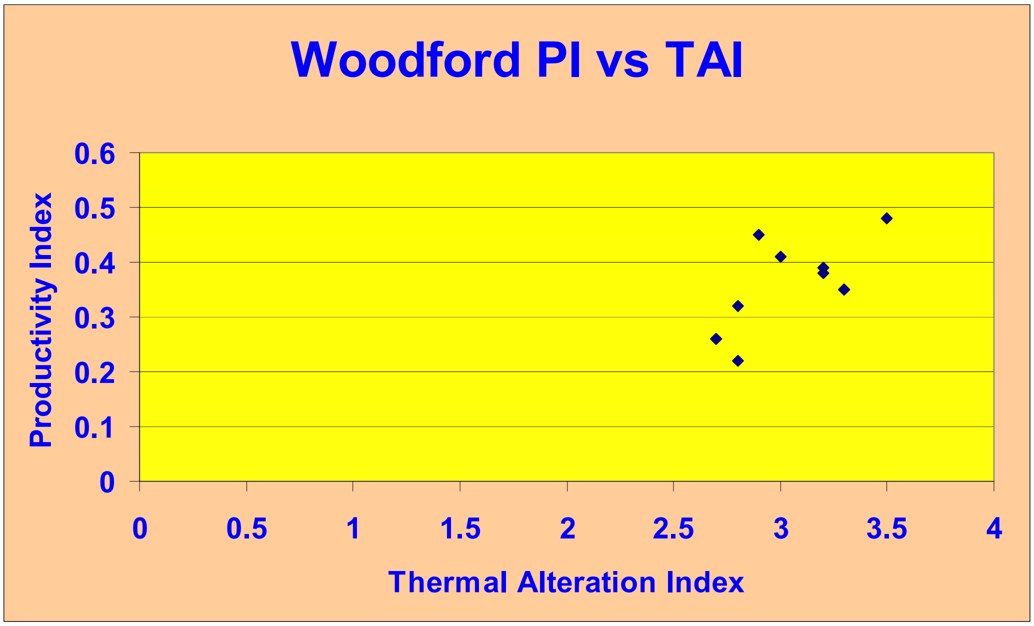

Figure 18. Rock-Eval Productivity Index (PI) plotted as a function of the Thermal Alteration Index (TAI) for Woodford Shale samples in southeastern New Mexico.

The Productivity Index indicates that thermal maturity of the Woodford increases generally southward with increasing depth (Figure 19). Thermal maturity is lowest on the Central Basin Platform and also decreases to the north as the Woodford Shale rises onto the Northwest Shelf. Over most of the project area, PI is between 0.2 and 0.4, indicating that the Woodford is within the oil generation window.

The Woodford PI is greater than 0.4 in the south-central part of the project area. This indicates that the Woodford is within the thermogenic gas window in this area. Oil generated from the Woodford and subsequently trapped in reservoirs in this area would have been converted to gas and gas condensate. PI is dependent on depth and the Woodford is within the thermogenic gas window where the base of the Woodford (top of the Siluro-Devonian carbonate section; Figure 20) is more than 10,000 ft below sea level (approximately 13,000 to 14,000 ft below the land surface).

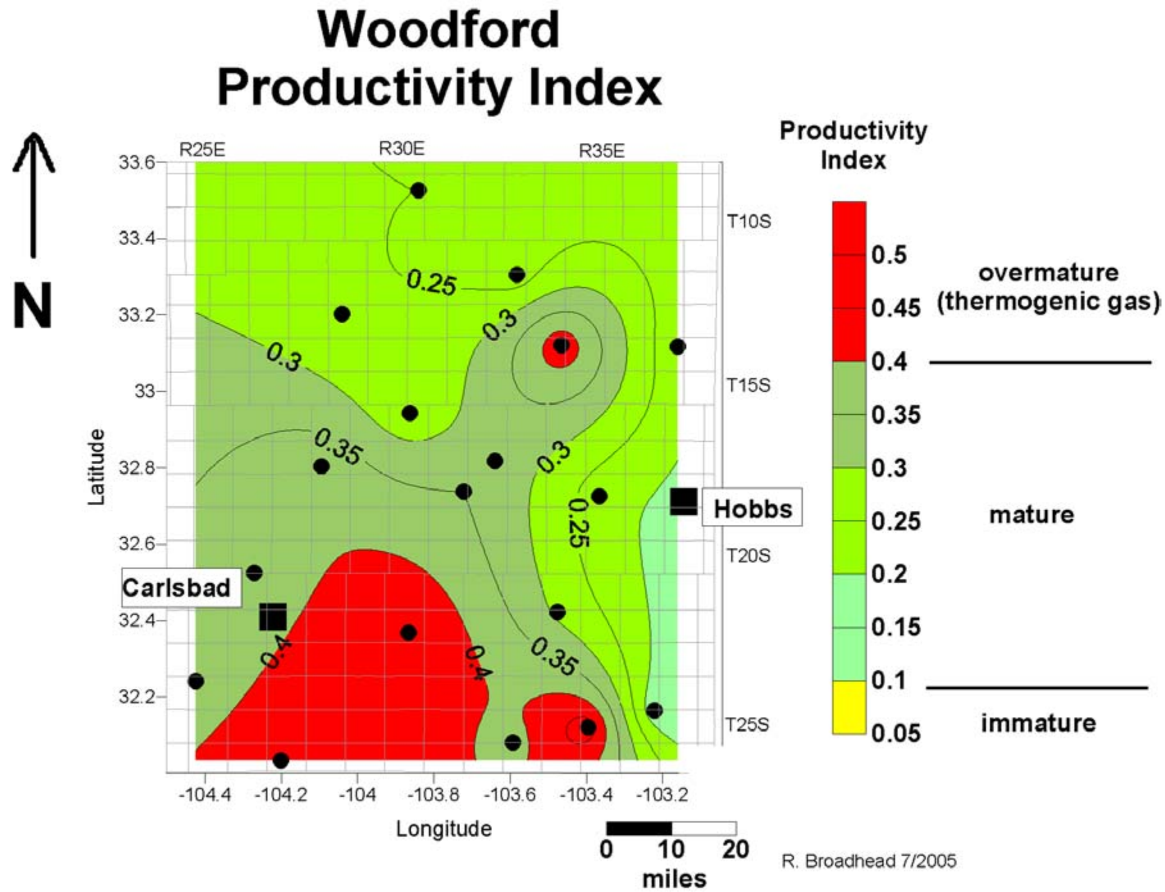

Figure 19. Rock-Eval Productivity Index (PI) of the Woodford Shale in southeastern New Mexico.

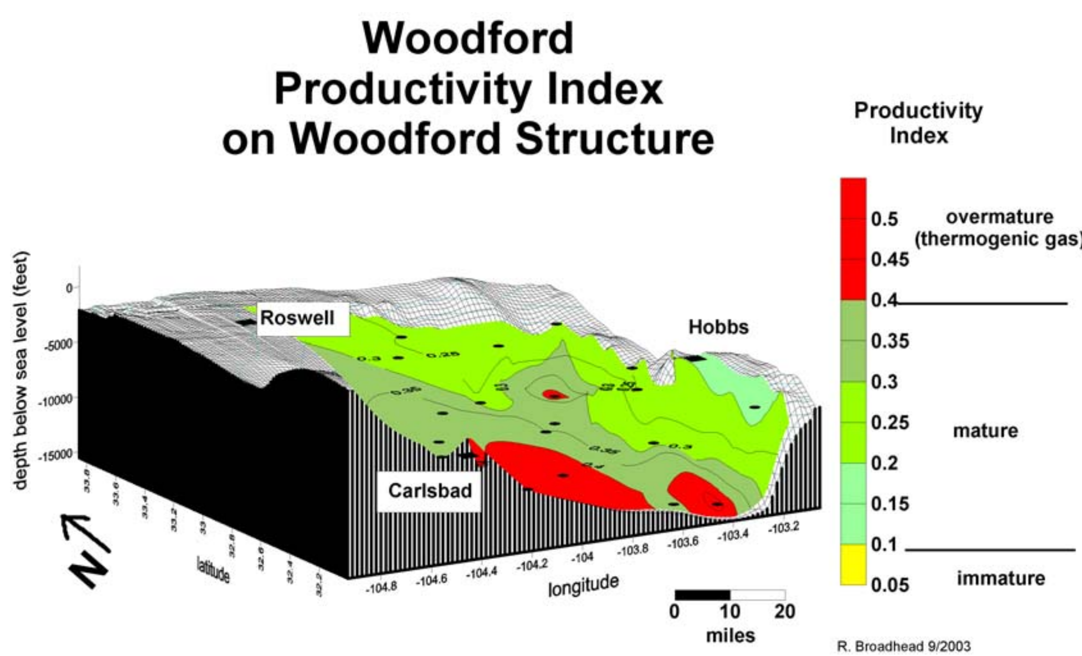

Figure 20. Rock-Eval Productivity Index of the Woodford Shale plotted on a wireframe structural relief diagram of the Woodford.

Woodford thickness data and Rock Eval parameters were used to calculate the Source Potential Index (SPI) of Demaison and Huizinga (1991; Figure 21). The SPI is the maximum amount of hydrocarbons (in kg hydrocarbons per ton of source rock) that were generated under any 1 m^2 of surface area of the source rock. It is dependent upon:
1) thickness of the source rock in meters; 2) the density of the source rock in metric tons per m^3; and 3) the average genetic potential or amount of hydrocarbons that could be generated from a source rock per ton of source rock. Following the lead of Demaison and Huizinga (1991), a value of 2.5 g/cm^3 was assigned to all Woodford source rocks in order to simplify calculations; refined values of density could be obtained by contouring Woodford density from formation density logs. The average genetic potential (or amount of hydrocarbons that could be generated per metric ton of source rock) is obtained by adding the S_1 and S_2 Rock-Eval parameters. SPI is then calculated by the following equation (Demaison and Huizinga (1991):

$$SPI = h\ (S_1 + S_2)\ p/1000$$

where:

h = thickness of the source rock in meters

p = source rock density in tons/m^3

S_1 = Rock-Eval S_1 peak in kg hydrocarbons per metric ton of rock

S_2 = Rock-Eval S_2 peak in kg hydrocarbons per metric ton of rock.

The Woodford SPI varies from 0.01 tons hydrocarbons/m^2 to 5.3 tons hydrocarbons/m^2. SPI increases from minimum values in the northwest and northeast to maximum values in the southeast. This southeastward increase is controlled by both southeastward thickening of the Woodford (Figure 13) and the southeastward increase in total organic carbon (Figure 15). Over most of the project area, the Woodford has an SPI of less than 0.5 tons hydrocarbons/m^2.

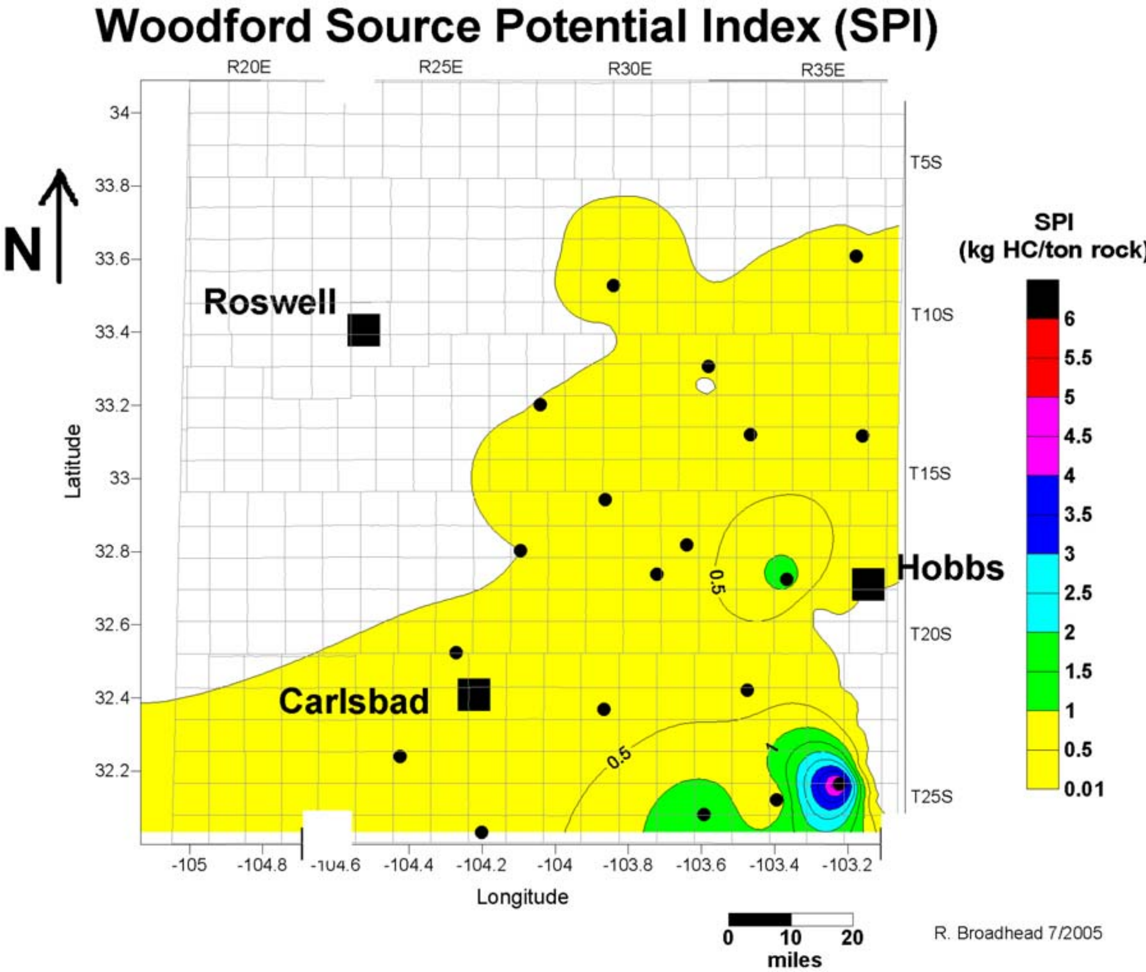

Figure 21. Source Potential Index (SPI) for the Woodford Shale in southeastern New Mexico.

Regional geologic aspects of Wristen production

The gas-oil ratio (GOR) of Wristen reservoirs, as calculated in BCF gas per MMBO, ranges from less than 0.1 to more than 10,000 (Figure 22). When GOR is superimposed on Wristen structure (Figure 23), it is readily apparent that higher GOR's dominate the deeper parts of the Delaware Basin. This is where the Woodford Productivity Index indicates the Woodford is more mature (Figure 24). In areas where Woodford PI exceeds 0.4, the Woodford is in the thermogenic gas window and Wristen reservoirs produce the most gas relative to produced oil volumes. As depth of the Wristen becomes shallower to the north, northwest and east, the GOR at cumulative production decreases to less than 10 BCF per MMBO in most reservoirs (Figures 22, 23). This decrease in GOR is attributed to decreasing thermal maturity of the Woodford and placement of the Woodford (as well as the underlying Wristen reservoirs) in the oil window. The geographic association of Wristen reservoirs with high GOR values with Woodford source rocks in the thermogenic gas window is suggestive of, but not proof of, short lateral migration distances of hydrocarbons generated within the Woodford.

Toward the northernmost and northwestern most limits of Wristen production, the GOR at cumulative production increases to values of 10 BCF per MMBO (Figure 23). In this area, the Wristen is present at shallow depths compared to the rest of the project area and the Woodford is the least mature. In this region the Woodford pinches out to the north and the Wristen is overlain by Mississippian strata (Figure 11). Most Wristen production is limited to areas where it is overlain by the Woodford, but in a few places the Wristen is productive where it is north and west of the Woodford pinchout (Figure 25). Superposition of the Wristen GOR map over the Siluro-Devonian supercrop map (Figure 26) reveals that the increase in gassiness of the Wristen reservoirs in the north coincides approximately with the Woodford pinchout. Perhaps the gas in the Wristen in this area is derived from the basal Mississippian shales that overlie the Wristen or perhaps Woodford kerogens are more gas prone along its northernmost extent.

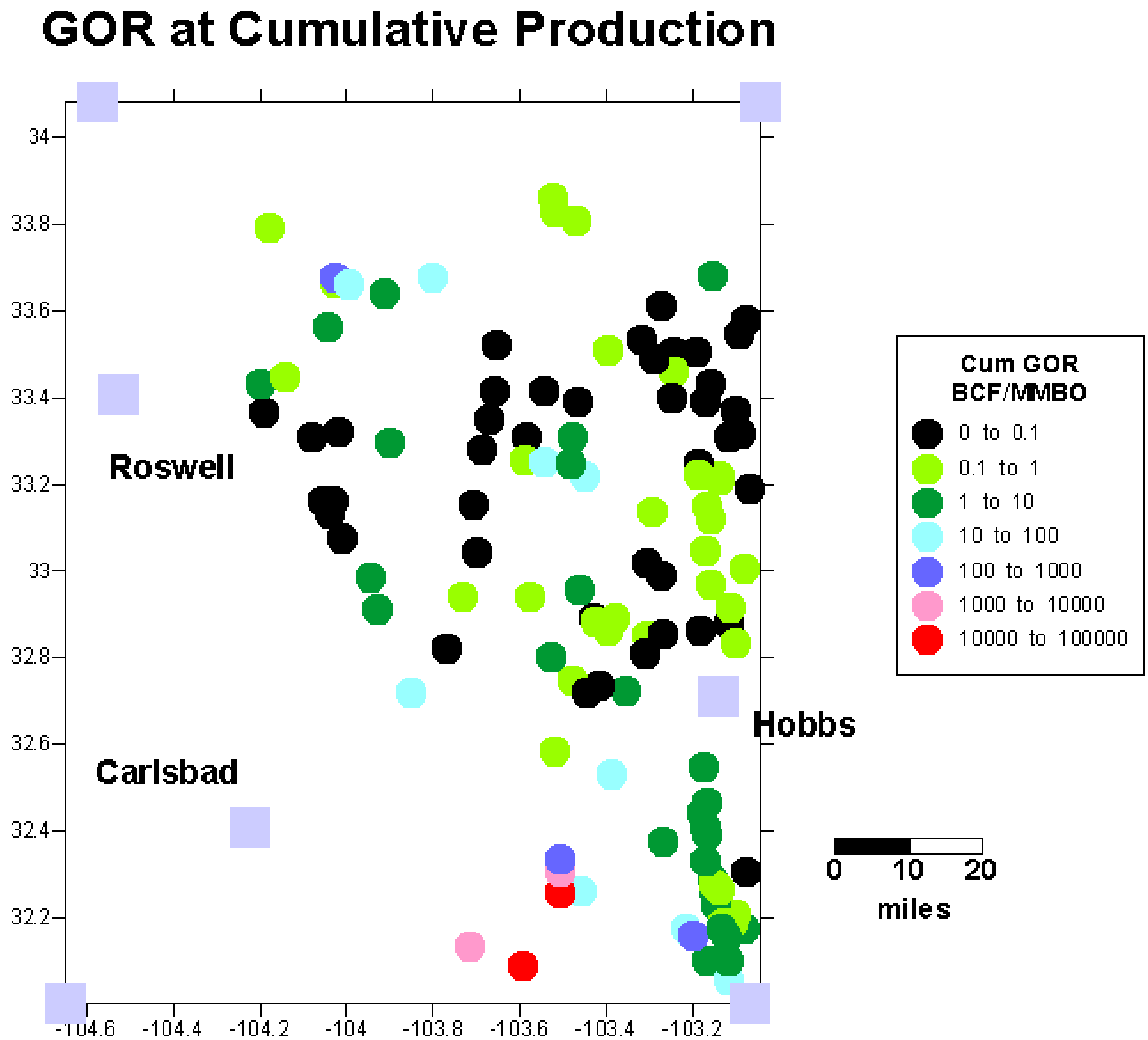

Figure 22. The gas-oil ratio (GOR) of Wristen oil and gas reservoirs at cumulative production (as of 2000).

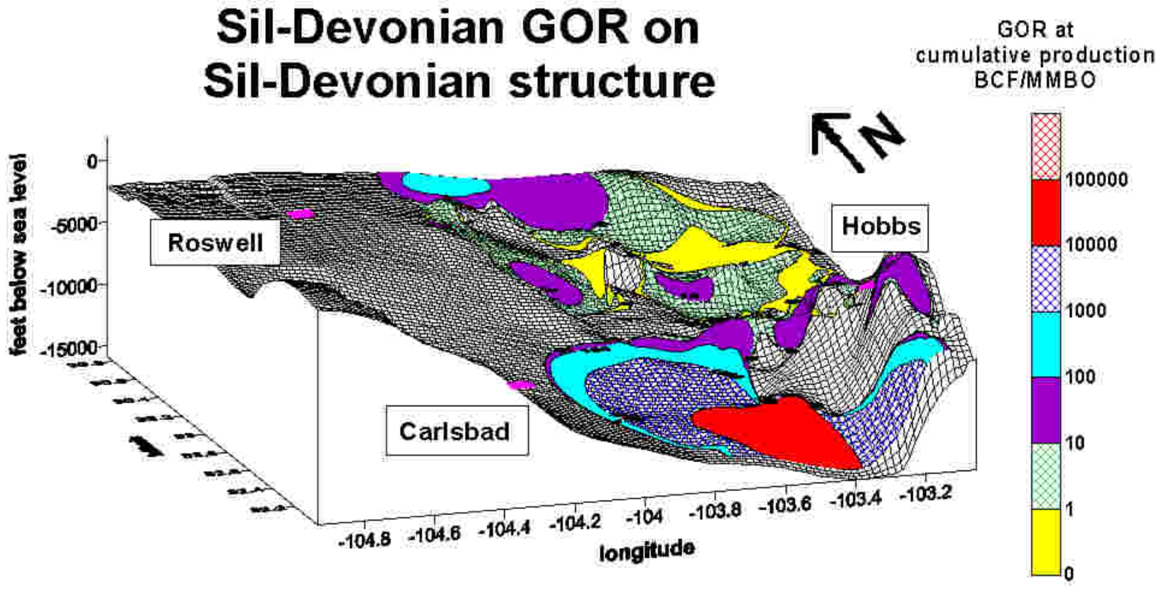

Figure 23. The GOR of Wristen oil and gas reservoirs at cumulative production plotted on a wireframe structural relief diagram of the Siluro-Devonian carbonates.

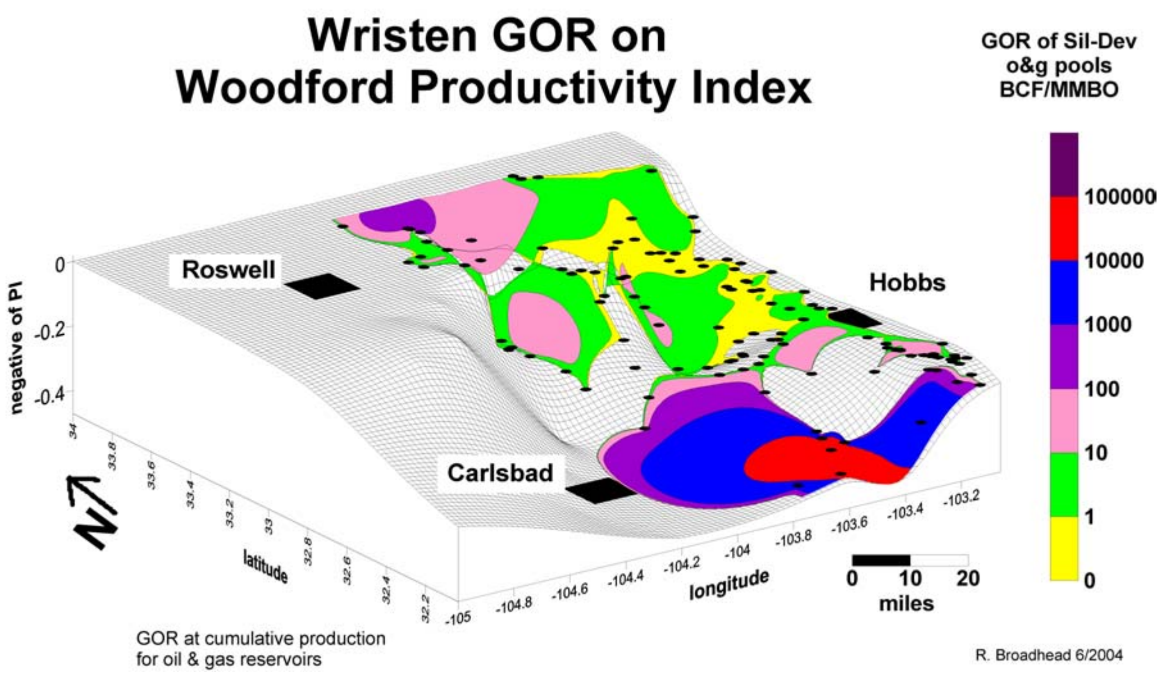

Figure 24.Wristen GOR at cumulative production superimposed on the negative of the Woodford Productivity Index. By inverting the Woodford PI, more mature source rocks appear lower, or deeper, on the diagram.

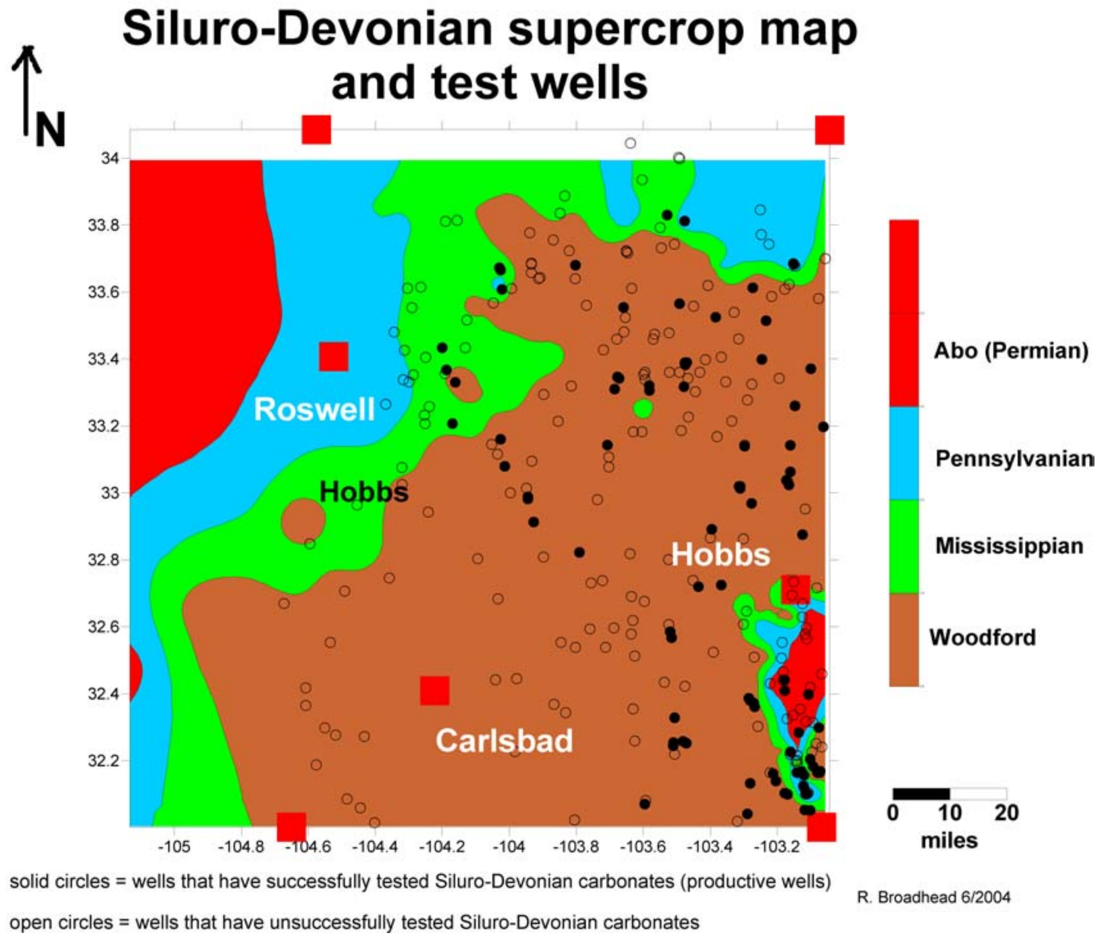

Figure 25. A random set of Wristen test wells, subdivided into those that established Wristen production and those that failed to establish production from the Wristen, plotted on the supercrop map of the Siluro-Devonian carbonate section.

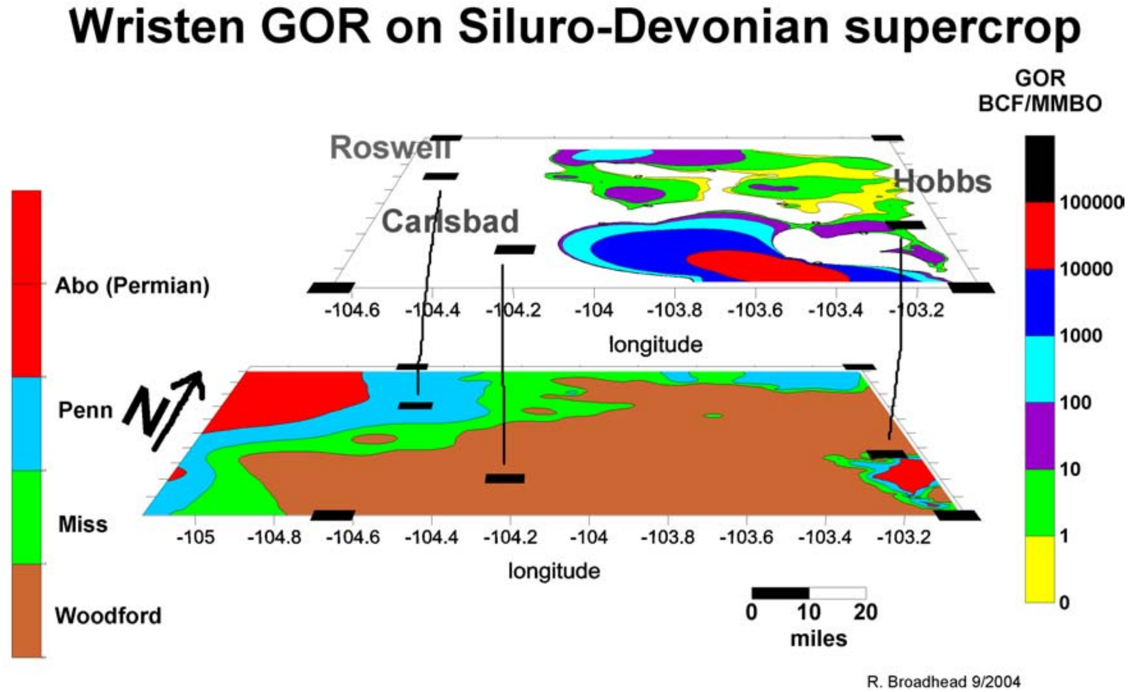

Figure 26. Map of GOR at cumulative production from Wristen reservoirs (above) superimposed on the supercrop map of the Siluro-Devonian carbonate section**.**

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Appendix – The Woodford source rock database

This database (see file *Wdfdsrc.xls* on this CD) contains the petroleum source rock analyses that were used to determine and map the source character of the Woodford Shale. Analyses were run on 25 Woodford samples from 19 exploration wells drilled in southeastern New Mexico (Figure 15; see database *Wdfdsrc.xls*). Analyzed samples were drill cuttings from the collections at the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. Analyzed samples are composites of several 10 ft drill intervals that in most cases were selected to represent the entire thickness of Woodford in each well. Cuttings were carefully selected to exclude on-Woodford lithologies, that is, cavings from shallower stratigraphic units. Only dark-shale source facies from the Woodford were analyzed. Samples were analyzed at Geochem Laboratories, Inc. of Houston, Texas.

Several attributes are given for each sample, including:

API number of the well, if on file at the New Mexico Bureau of Geology and Mineral Resources.

Operator – the company that drilled the well.

Lease name – the lease name of the well.

Well number – the number of the well in the lease.

Location - given as section-township-range.

Latitude - calculated from the section-township-range location.

Longitude - calculated from the section-township-range location.

Sampled interval - as depth in well, in feet.

Formation sampled - Woodford in all cases.

TOC - total organic carbon (weight percent).

TMAX - the temperature, in degrees centigrade, of the S_2 peak derived from Rock-Eval pyrolysis. A measure of thermal maturity.

S_1 - Rock Eval S_1 peak, measured in milligrams evolved hydrocarbons per gram of rock.

S_2 - Rock Eval S_2 peak, measured in milligrams evolved hydrocarbons per gram of rock.

S_3 - Rock Eval S_3 peak, measured in milligrams evolved carbon dioxide per gram of rock.

PI – the Rock-Eval Productivity Index

OI – the Rock-Eval Oxygen Index

HI – the Rock-Eval Hydrogen Index

R_o (mean) – mean vitrinite reflectance, a measure of thermal maturity.

TAI – the Thermal Alteration Index, a measure of thermal maturity.

Algal % - the percentage of the kerogen that is algal material, as determined by visual kerogen analysis.

Amorphous % - the percentage of the kerogen that is amorphous material, as determined by visual kerogen analysis.

Herbaceous % - the percentage of the kerogen that is herbaceous material, as determined by visual kerogen analysis.

Woody % - the percentage of the kerogen that is woody material, as determined by visual kerogen analysis.

Inertinite % - the percentage of the kerogen that is inertinite, as determined by visual kerogen analysis.

Elevation – the elevation of the well in feet above sea level.

Datum – the datum at which the elevation of the well was determined; KB – Kelly bushing; DF – derrick floor.

Top Woodford – depth to the top of the Woodford in the well, in feet.

Base Woodford – depth to the top of the Woodford in the well, in feet.

Woodford thickness – thickness of the Woodford in the well I feet, not corrected for structural dip.

SPI – the Source Potential Index, as calculated for the Woodford Shale in the well.