

The Barnett Shale in southeastern New Mexico:
Distribution, thickness, and source rock characterization

By

Ronald F. Broadhead and Lewis Gillard

New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech
Socorro, New Mexico 87801

Open-file Report 502

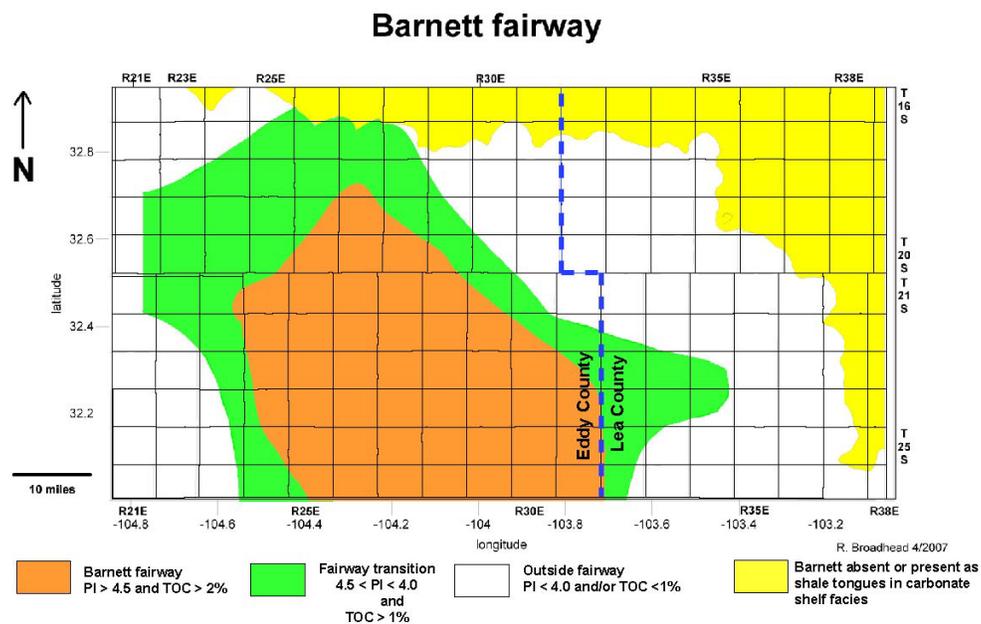
May 2007

The Barnett Shale in southeastern New Mexico: Distribution, thickness, and source rock characterization

By

Ronald F. Broadhead and Lewis Gillard

New Mexico Bureau of Geology and Mineral Resources
A division of New Mexico Tech



Open File Report No. 502

New Mexico Bureau of Geology and Mineral Resources
A Division of New Mexico Tech
Socorro, NM 87801
Dr. Peter A. Scholle, Director

May 2007

*Work performed in cooperation with the New Mexico State Land Office
The Honorable Patrick H. Lyons, Commissioner of Public Lands*

Abstract

Basinal dark-gray to black marine shales in the New Mexico part of the Permian Basin that have been traditionally correlated as the Barnett Shale (Upper Mississippian) are late Mississippian to Morrowan (Early Pennsylvanian) in age. The Upper Mississippian Barnett Shale in the south correlates northward with Chesterian and Meramecian strata on the Mississippian shelf. The shelf strata in the north are dominated by marine limestones; tongues of Barnett shales extend northward onto the shelf where they intertongue with the shelf limestones. The overlying Morrowan (Lower Pennsylvanian) shales grade northward into a sandy facies consisting of interbedded dark-gray to black shales and lenticular sandstones.

That part of the Upper Mississippian – Lower Pennsylvanian shale sequence that is correlated as the Barnett Shale consists of 200 to 350 ft of dark-gray to black shale with minor thin sandstones and minor thin limestones throughout most of its extent in the New Mexico part of the Permian Basin. The overlying Morrowan (Lower Pennsylvanian) shales are subdivided into two stratal units, the lower Morrow shale and the upper Morrow shale. The lower Morrow shale consists of 200 to 350 ft of dark-gray to black marine shales and minor thin sandstones. The upper Morrow shale consists of 100 to 800 ft dark-gray to black marine shales and minor thin sandstones.

The Barnett Shale contains mature, organic-rich petroleum source rocks. Total Organic Carbon (TOC) content ranges from 0.85 to 4.9 percent in the New Mexico part of the Permian Basin. The kerogen population is dominantly gas prone but also appears to contain oil-prone types. The Barnett Shale is thermally mature throughout its extent in the New Mexico part of the Permian Basin. A northwest-southeast trending fairway for Barnett shale gas exploration extends throughout the western portion of the New Mexico part of the Permian Basin. This fairway is defined by the most thermally mature source rocks with TOC contents greater than 2 percent. Exploratory drilling for shale gas has not yet taken place in the New Mexico part of the Permian Basin.

The lower and upper Morrow shales contain sufficient TOC to be considered source rocks in southeastern New Mexico and are thermally mature. The Morrow shales are less thermally mature than the deeper, underlying Barnett Shale.

Introduction

This report presents stratigraphic and structure contour maps and contour maps of petroleum source rock parameters for the Barnett Shale (Upper Mississippian) in the Permian Basin of southeastern New Mexico (Figure 1). The Permian Basin is typically portrayed as being subdivided into several tectonic and bathymetric elements including the Northwest Shelf, the deep Delaware and Midland Basins, and the Central Basin Platform (Figure 2). However, those geologic elements did not appear until the advent of Ancestral Rocky Mountain deformation during the Pennsylvanian. During the Late Mississippian, the area was subdivided into a northern shelf dominated by deposition of limestones and a southern basin dominated by deposition of the Barnett Shale (Figure 3; Hamilton and Asquith, 2000; Broadhead, 2006a, 2006b).

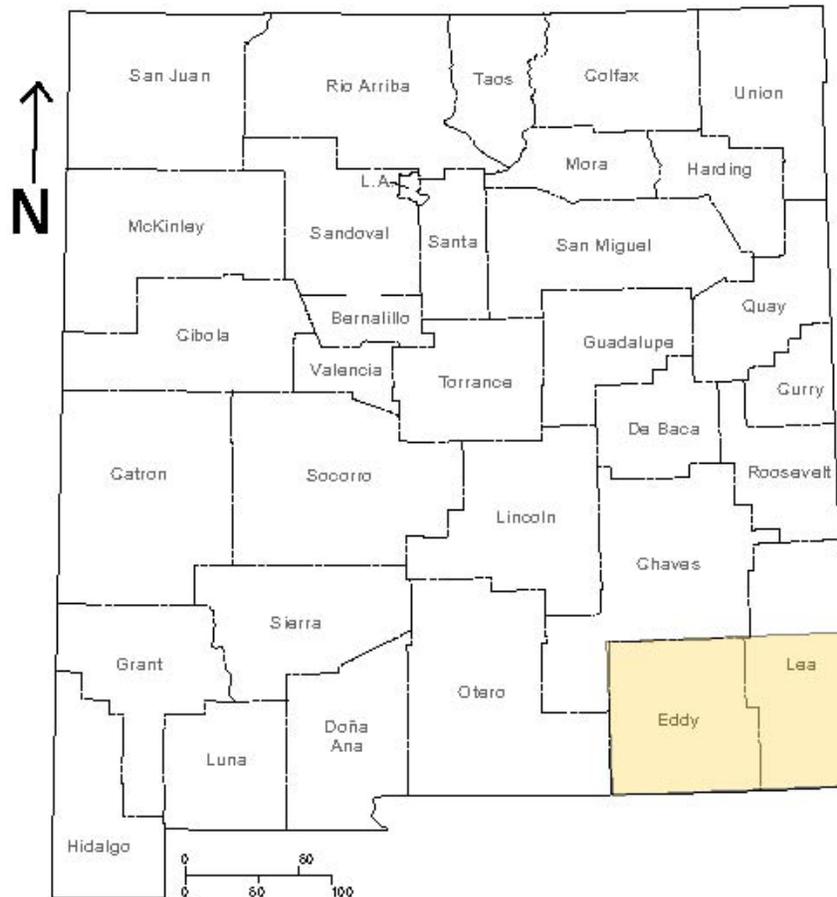


Figure 1. Location of project area within New Mexico.

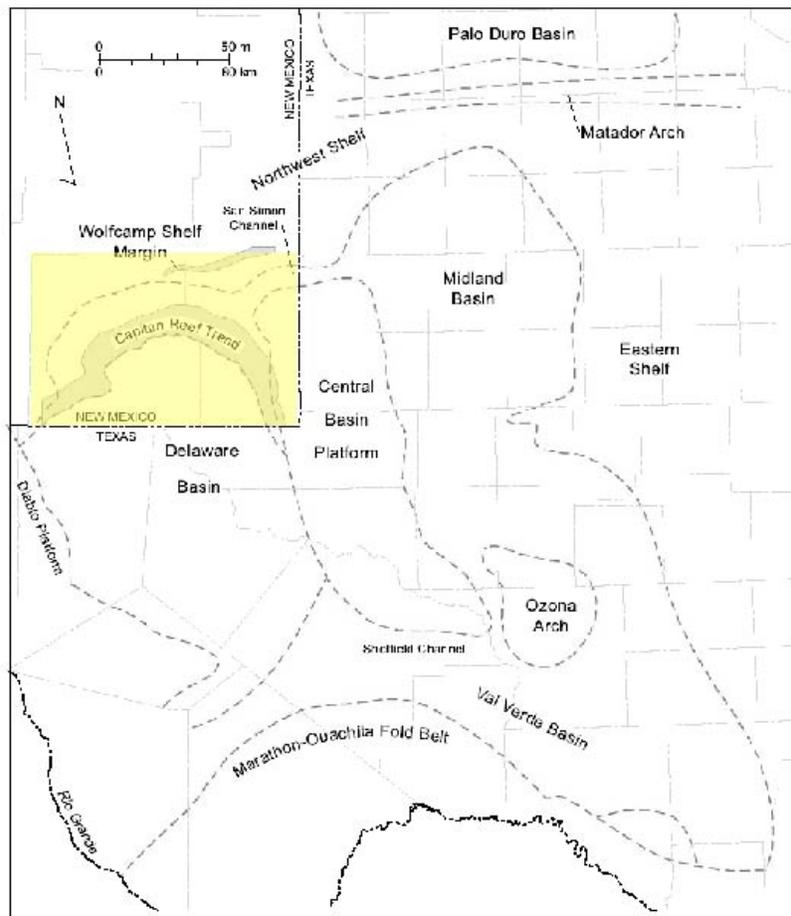


Figure 2. Project area (in yellow) and major subdivisions of the Permian basin in southeastern New Mexico and west Texas. From Dutton and others (2005 as modified from Silver and Todd (1969), Hills (1984), Frenzel and others (1988), Kisters and others (1989), Ewing (1990), Tyler and others (1991) and Kerans and Fitchen (1995).

This report contains several sections. The main body of the report constitutes a description of the stratigraphy, structure and petroleum source rock character of the Barnett Shale and presents several maps that describe the Barnett and its stratigraphy, structure and source rock character. Except as otherwise noted, the contour maps in this report were constructed using *Surfer 8* (*Surfer 8* is a product of Golden Software, Inc.); data were gridded and contoured using the kriging method employed by *Surfer 8*. Appendix A contains four cross sections that were constructed and prepared digitally for this report. Appendix B presents several of the maps constructed for this report as large

format pdf files; these maps are suitable for printout on a large format plotter. Appendix C includes the databases of well data (*Barnett wells database*) and petroleum source rock data (*Barnett source rock database*) in Microsoft Excel format. Appendix D contains GIS projects of maps prepared for this report. The GIS projects are in both *ArcInfo* and *ArcReader* formats. *ArcReader* and *ArcInfo* are products of ESRI Corp. *ArcReader* is a free viewer that allows the user to view and superimpose the maps on the computer. A copy of the *ArcReader* is included with this report in Appendix D. Instructions for installing *ArcReader* on your computer are included on the section on Appendix D at the end of this document.

The senior author of this report prepared the database, the maps, and the written text. The junior author incorporated the maps into the Arc GIS projects presented in Appendix D. The data and ideas expressed in this report are the responsibility of the senior author.

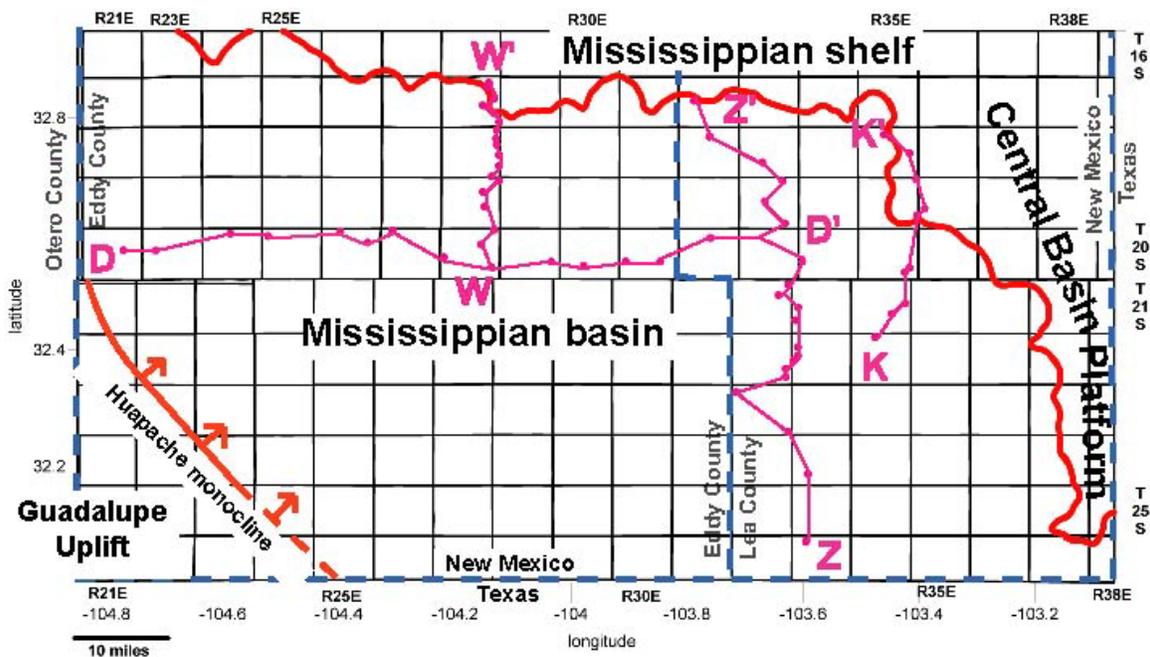


Figure 3. Location of the Mississippiian shelf-to-basin transition, the Central Basin Platform, the Huapache monocline and the Guadalupe Uplift in southeastern New Mexico. Also shown are the locations of the four cross sections included in Appendix A.

Purpose and Scope

The main purpose of this work was to provide the New Mexico State Land Office with information and data relevant to the possibility of establishing commercial gas production from the Barnett Shale in southeastern New Mexico. Interest in the Barnett Shale and stratigraphically equivalent shales has risen in recent years as the Barnett has become a major productive gas reservoir in the Fort Worth Basin of north-central Texas. More than 1 million trillion ft³ (TCF) gas have been produced from the Barnett in the Fort Worth Basin. The Fort Worth Barnett currently provides more than one-half of the shale gas produced in the United States and contains an estimated 26 TCF of recoverable undiscovered hydrocarbon gas (Durham, 2005; Martineau, 2007; Pollastro 2007; Pollastro et al., 2007). Exploratory interest in the Barnett Shale has extended into west Texas and into stratigraphically equivalent shales in Oklahoma (Caney Shale) and Arkansas (Fayetteville Shale; Brown, 2006). Although several wells have reportedly been drilled to test the gas potential of the Barnett in the Texas portion of the Permian Basin, results of those wells were not available at the time this report was written.

During the course of this project, the top and base of the Barnett Shale were correlated in 388 wells in Lea and Eddy Counties, New Mexico. Correlations were tied to a network of 15 cross sections that were constructed in hardcopy format in order to assure consistency of correlation. The cross sections were also constructed to determine the stratigraphic relationships between strata on the Mississippian shelf in the north and the Mississippian basin in the south. This was essential in order to distinguish between Upper Mississippian basinal shales (Barnett) and the overlying Lower Pennsylvanian basinal shales (Morrow). Four of the 15 cross sections (see Figure 3 for cross section locations) were prepared in digital format and are presented in Appendix A.

Source rock analyses were obtained from 35 samples of well cuttings from 19 petroleum exploration wells in southeastern New Mexico (see *Barnett source rock database*) in Appendix C. Source rock analyses on nine samples were obtained from the New Mexico Petroleum Source Rock Database (Broadhead et al., 1998). Those analyses were the work of Geoffrey Bayless and colleagues of Geochem Laboratories, Inc. and include Leco Total Organic Carbon, Rock-Eval pyrolysis and optical determination of kerogen type and thermal maturity (Thermal Alteration Index). For this project, analyses

of 26 additional samples were obtained specifically with the intent of evaluating the Barnett Shale (Upper Mississippian) and very similar marine shales in overlying Morrowan (Lower Pennsylvanian) strata. These 26 analyses were made by Dan Jarvie and staff at Humble Geochemical Services, Inc. and include Leco Total Organic Carbon and Rock-Eval pyrolysis. These additional analyses rendered it possible to map the organic richness and thermal maturity of the Barnett Shale, lower Morrow shale, and upper Morrow shale with a fair degree of confidence. All cuttings samples used in both sets of analyses were obtained from drill cuttings archived in the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources.

Acknowledgments

The work that resulted in this report was funded in part by the New Mexico State Land Office (The Honorable Patrick H. Lyons, Commissioner of Public Lands) through Professional Services Contract No. 07-539-P615-2114 to the New Mexico Institute of Mining and Technology. John Bemis, Jami Bailey, Joe Mraz, and Eleanore Nestlerode of the New Mexico State Land Office were most helpful in the initiation of this project.

My appreciation extends to Mr. Dan Jarvie, President of Humble Geochemical Services, Inc. for expediting the petroleum source rock analyses. Dr. Tim Ruble of Humble Geochemical Services provided helpful and thoughtful suggestions concerning the analyses. Dr. Robert Cluff provided valuable discussion concerning the stratigraphic relationships between the Barnett Shale and time-equivalent shelf strata to the north. As always, gratitude is extended to Annabelle Lopez and Amy Kracke of the New Mexico Bureau of Geology and Mineral Resources for their meticulous efforts in maintaining the archives in the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. Peter Scholle, Director of the New Mexico Bureau of Geology and Mineral Resources, supported the production of this report.

Stratigraphy

The Mississippian System in southeastern New Mexico is 0 ft to more than 1200 ft thick (Wright, 1979; Broadhead, 2006a, b; this report). The Mississippian section is stratigraphically subdivided into the Lower Mississippian Series of Kinderhookian to Osagian age and the Upper Mississippian Series of Meramecian to Chesterian age (Figure 4). The Lower Mississippian section consists of the Lower Mississippian limestone. The Upper Mississippian section exhibits a transition from a limestone-dominated shelf facies in the north to a shale-dominated basinal facies in the south. The shelf facies consists of two informal lithostratigraphic units, the Meramec and the Chester (see Hamilton and Asquith, 2000; Broadhead, 2006a). The Meramec and Chester are comprised primarily of shallow-water limestones. Tongues of basinal (Barnett) shale extend northward onto the shelf where they are intercalated with the shelf limestones.

SYSTEM	SERIES	STAGE	Sacramento Mountains (Pray, 1961)	Southeastern New Mexico (subsurface)				
				Northern Lea County (Hamilton and Asquith, 2000)		Lea, Eddy & Chaves Counties (this study)		"Traditional" correlations
				basin (south)	shelf (north)	basin (south)	shelf (north)	basin (south)
Pennsylvanian	Lower		Atokan	Atokan	Atoka	Atoka	Atoka	Atoka
		Morrowan ?	Morrow	Morrow	Morrow	Morrow	Morrow	Morrow
Mississippian	Upper	Chesterian	Helms Fm.	Barnett Shale	upper Chester Barnett tongue lower Chester Barnett tongue	Upper Mississippian Barnett Shale	Upper Mississippian Chester	"Barnett" Shale
		Meramecian	Rancheria Fm.	Meramec	Meramec	Upper Mississippian Meramec	Meramec	
	Lower	Osagian	Lake Valley Fm.	Osage	Osage	lower Mississippian limestone	lower Mississippian limestone	lower Mississippian limestone
		Kinderhookian	Caballero Fm.	Not described				
Devonian	Upper		Sly Gap and Percha (?) Fms.	Not described		Woodford Shale	Woodford Shale	Woodford Shale

Figure 4. Stratigraphic column of Mississippian strata in southeastern New Mexico.

The Barnett Shale constitutes the basinal shale facies of the Upper Mississippian. In southeastern New Mexico, the Barnett consists of 0 to 350 ft of dark-gray to black marine shales and minor fine-grained sandstones and limestones. In the northern part of the basin, thin tongues of Meramec and Chester limestones extend southward into the basin where they are intercalated with the Barnett shales. The limestones pinchout southward.

The placement of the upper boundary of the Barnett Shale has not been well documented. Most workers have traditionally placed the upper boundary at the base of the lowest sandstone in the Mississippian-Pennsylvanian sequence and this functions as an operational definition that is useful for most purposes. However, this criterion for correlation places the top of the Barnett within the lower Morrow (Lower Pennsylvanian) section because there is a transition within the lower Morrow from a facies of dark-gray to black shales and lenticular sandstones in the northern part of the area covered by this report to a dark-gray to black shale facies with only minor thin sandstones in the south. The type locality of the Barnett Shale is on the Llano Uplift of central Texas (Moore and Plummer, 1922; Hass, 1953). Insufficient information is available to reliably correlate the Barnett from its type locality into southeastern New Mexico, a distance of 300 miles and such correlations have not been demonstrated conclusively in the literature. Published cross sections (Matchus and Jones, 1984; Vertrees et al, 1964; Hamilton et al, 1991) provide very general data or present well logs with the term Barnett expressed in quotation marks and apparently utilizing an operational definition of the Barnett similar to that described above.

For this report, the upper boundary of the Barnett was determined by constructing a series of cross sections (Plates I-IV in Appendix A are selected cross sections digitally prepared for this report) that extend from the Mississippian shelf in the north into the Mississippian basin in the south. North of the shelf-to-basin transition, the Chester (Upper Mississippian) carbonates are unconformably overlain by Morrowan (Lower Pennsylvanian) nonmarine to perhaps marginal-marine and shallow-marine lenticular sandstones and interbedded shales. The boundary between the Mississippian System and the Pennsylvanian System is reasonably well documented on the shelf (see Hamilton and Asquith, 2000; Broadhead, 2006a, b). To the south, however, the lower Morrowan

sandstone facies grades laterally into a shale facies dominated by dark-gray to black shales that are difficult, if not impossible, to differentiate from the Barnett shales based on macroscopic description or well-log signatures. In addition, the Morrowan sandstone facies prograded south so that a wedge of sandstone-bearing strata of Morrowan age overlies a wedge of Morrowan shales. Placing the top of the Barnett at the base of the lowest Morrowan sandstone therefore results in placing the top of the Barnett at a time-transgressive facies boundary that occurs within the Lower Pennsylvanian section. As the Barnett is a Mississippian unit (Hass, 1953), this is an incorrect correlation.

Construction of cross sections with closely spaced wells (see Plates I-IV in Appendix A) allows for correlation of the top of the Mississippian from where it is well defined on the shelf to the basin where it is poorly defined. In addition, these cross sections have allowed the subdivision of the Morrowan shale section into two informal stratal units, the lower Morrow shale and the upper Morrow shale (Figure 4; Plates I, IV). Minor thin sandstones are locally present within the lower and upper Morrow shales. The top of the Morrow, as determined by fusulinid biostratigraphic determinations made by the late R.V. Hollingsworth is approximately coincident with a log marker that is 250 to 350 ft above the top of the upper Morrow shale (see Plate IV). Because the two Morrow shale units have traditionally been considered to be part of the Barnett by many workers, the basinal Mississippian section as defined in previous reports (e.g. Wright, 1979; Broadhead, 2006a, b) includes the Morrowan shale section as well as the real Barnett (Upper Mississippian).

Thickness of the Barnett, as correlated for this project, ranges from approximately 0 ft to more than 350 ft (Figure 5). Regionally, the Barnett thins northward from more than 350 ft in the deepest part of the Delaware Basin to approximately 200 ft in T17-18S. Further north, the Barnett intertongues with the limestone shelfal facies of the Upper Mississippian Meramec and Chester units and is not correlated as a separate stratal unit. On the shelf, tongues of Barnett black shale are intercalated with shelf limestones. In general, the Barnett is thickest in the southeastern and south-central parts of the Delaware Basin where it is 200 to 350 ft thick in most places. To the east in T21-25S R37-38E, it is absent due to Pennsylvanian-age erosion on the Central Basin Platform. On the Central Basin Platform, Upper Pennsylvanian and Permian strata rest unconformably on Lower

Mississippian or pre-Mississippian units. To the west, the Barnett thins to less than 200 ft. In the west, the isopach contours follow a northwest-southeast oriented trend that is

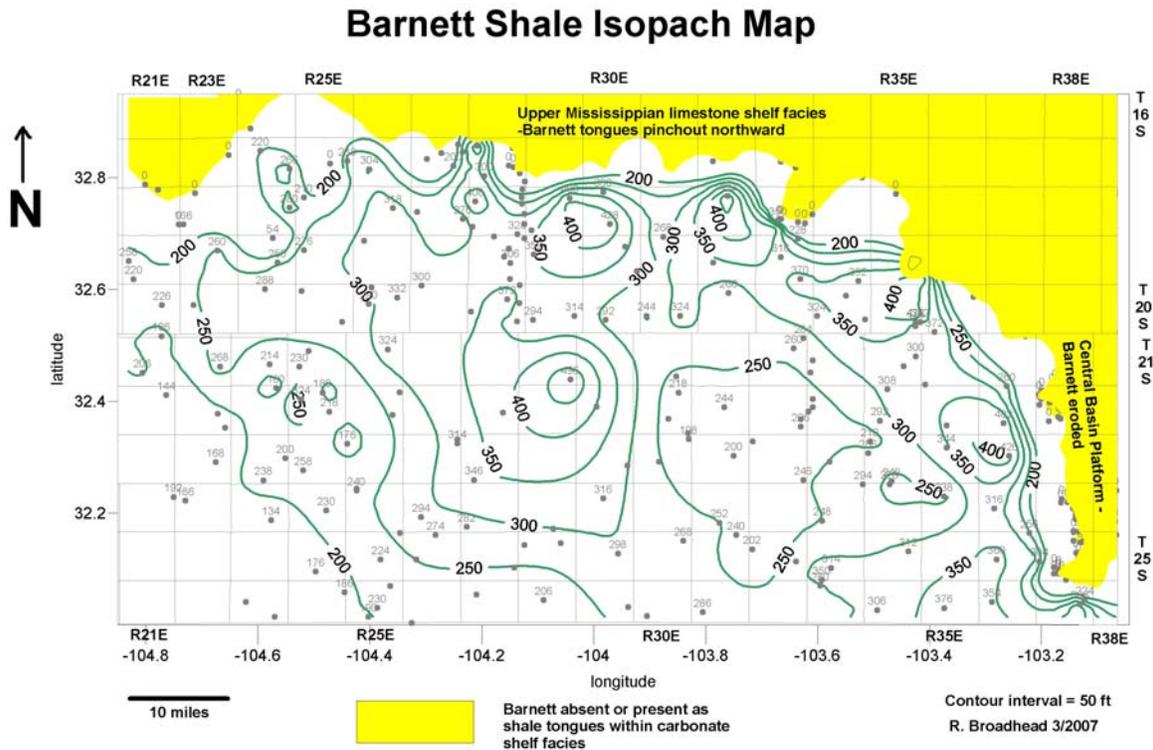


Figure 5. Isopach map of the Barnett Shale.

parallel to the Huapache monocline; the southwest thinning occurs over a distance of approximately 15 miles, indicating that it is not associated solely with the Huapache monocline.

Local thick areas, defined by single data points (wells), may have one of two origins. In some cases, the thick areas are located in downdropped fault blocks between structurally higher areas; the upper part of the Barnett was preserved in these low areas but was removed from the adjacent high areas by Early Pennsylvanian erosion. In other cases, the localized thick areas may result from apparent thickness as measured in a vertical well bore that has penetrated steeply dipping strata on the flanks of an Ancestral Rocky Mountain structure; in these cases, true thickness of the Barnett will be similar to that observed in offsetting wells where the Barnett is either horizontal or has only a shallow dip.

The lower Morrow shale is 0 to 350 ft thick (Figure 6). In the northern part of the project area, the lower Morrow shale has not been correlated or mapped because it is represented by the northern sandy facies of the Morrow. Examination of cross section Z-Z' (Plate IV in Appendix A) suggests that a part of the lower Morrow shale may be a stratigraphic wedge that pinches out to the north and is represented on the shelf by an unconformity that is perhaps the unconformity that separates Chesterian strata from Morrowan strata on the Mississippian shelf. The lower Morrow shale is not present on the Central Basin Platform where it was either never deposited or deposited and subsequently removed by erosion on this Ancestral Rocky Mountain uplift.

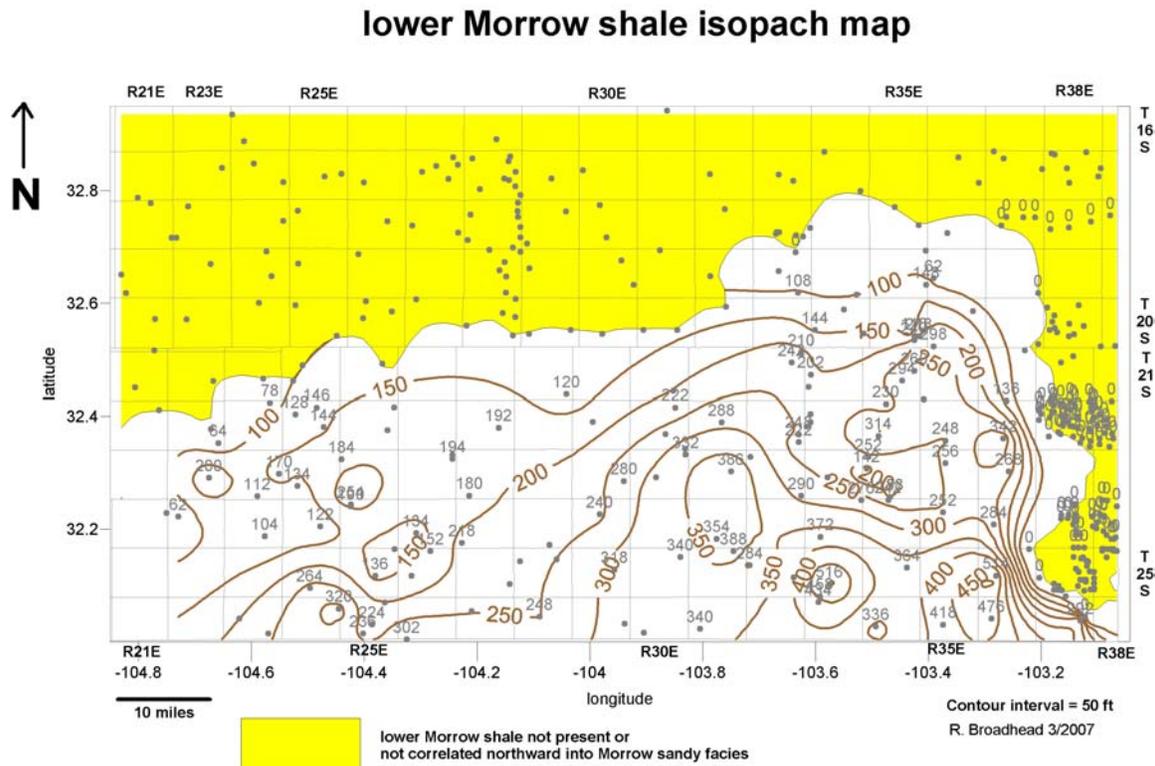


Figure 6. Isopach map of the lower Morrow shale.

The upper Morrow shale is 0 to 800 ft thick (Figure 7). Similar to the lower Morrow shale and the Barnett Shale, it is absent from the Central Basin Platform. The upper Morrow thins to the north and west of the deepest part of the Delaware Basin where it is more than 800 ft thick. Further north, the upper Morrow grades laterally into the sandy facies of the Morrow. Local thin areas are associated with upthrown fault

blocks of Ancestral Rocky Mountain age; a thinner section of upper Morrow shale was deposited over the tops of the faults blocks and thicker sections of shale were deposited off the flanks of these structures.

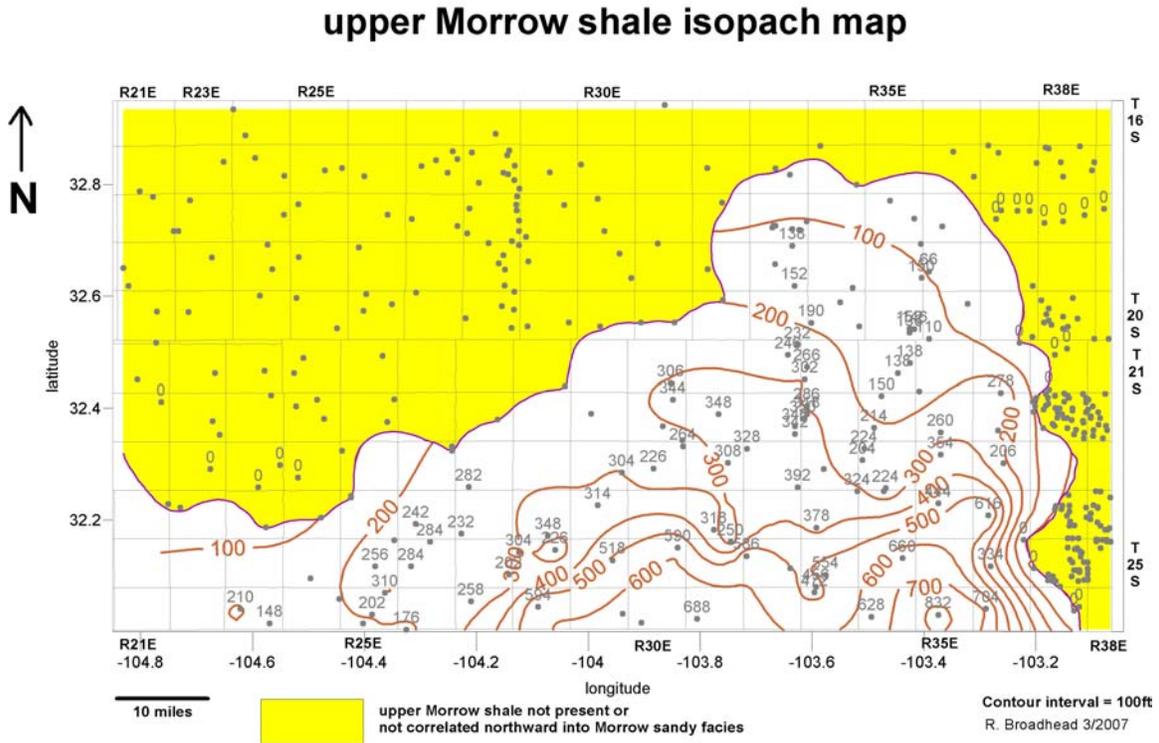


Figure 7. Isopach map of the upper Morrow shale.

Structure

Structure contours on top of the Barnett Shale and the upper Morrow shale reveal the present-day geometry of the New Mexico part of the Permian Basin (Figures 8, 9): the deep Delaware Basin, the Central Basin Platform, the Guadalupe Uplift and Huapache monocline, and the Northwest Shelf. The southeastward dip into the Delaware Basin from the Northwest Shelf dominates the structure in the northern and central parts of the maps. Neither structure map indicates a sharp boundary between the Northwest Shelf and the Delaware Basin, which is largely an Upper Pennsylvanian and Permian depositional boundary caused by localization and upward growth of Pennsylvanian and Lower Permian (Abo) shelf-margin reef complexes, possibly over pre-existing structural flexures. The Huapache monocline is clearly delineated by structure contours in the southwest part of the map. Although this structure is defined by a reverse fault zone at the Mississippian level (see Casavant, 1999), the computer-generated contour map depicts the fault zone as closely spaced contours. The Central Basin Platform, formed by high-angle faults (Hills, 1984; Haigler and Cunningham, 1972) is also clearly defined by the structure contour map on top of the Mississippian System. Again, the closely spaced contours define the fault zones that bound this uplifted tectonic block. On higher parts of the Central Basin Platform, Mississippian strata were removed by erosion during Pennsylvanian time and therefore no structure contours are present in these areas.

Depth to the Barnett and Morrow shales

Depth to the Barnett Shale and Morrow shales is an important variable to consider when contemplating exploration for shale gas. Depth not only affects geologically related properties such as thermal maturity and fracture behavior, but also affects drilling economics. For these reasons, contour maps of the depth to the Barnett Shale and the upper Morrow shale were prepared (Figures 10,11).

The depth to the Barnett and upper Morrow shales reflects the structure of the Permian Basin in southeastern New Mexico. Depth to the upper Morrow shale varies from 8200 to 16,500 ft. Depth to the Barnett Shale varies from 6000 to 18,000 ft. The Delaware Basin is clearly defined in the south-central part of the region. To the east, the Central Basin Platform is defined by the absence of the upper Morrow and Barnett shales.

Depth to both units is distinctly less west of the Huapache monocline than it is to the east of this structure. Depth to the Barnett and upper Morrow shales decreases gradually to the northwest and north as these strata gradually rise out of the Permian Basin.

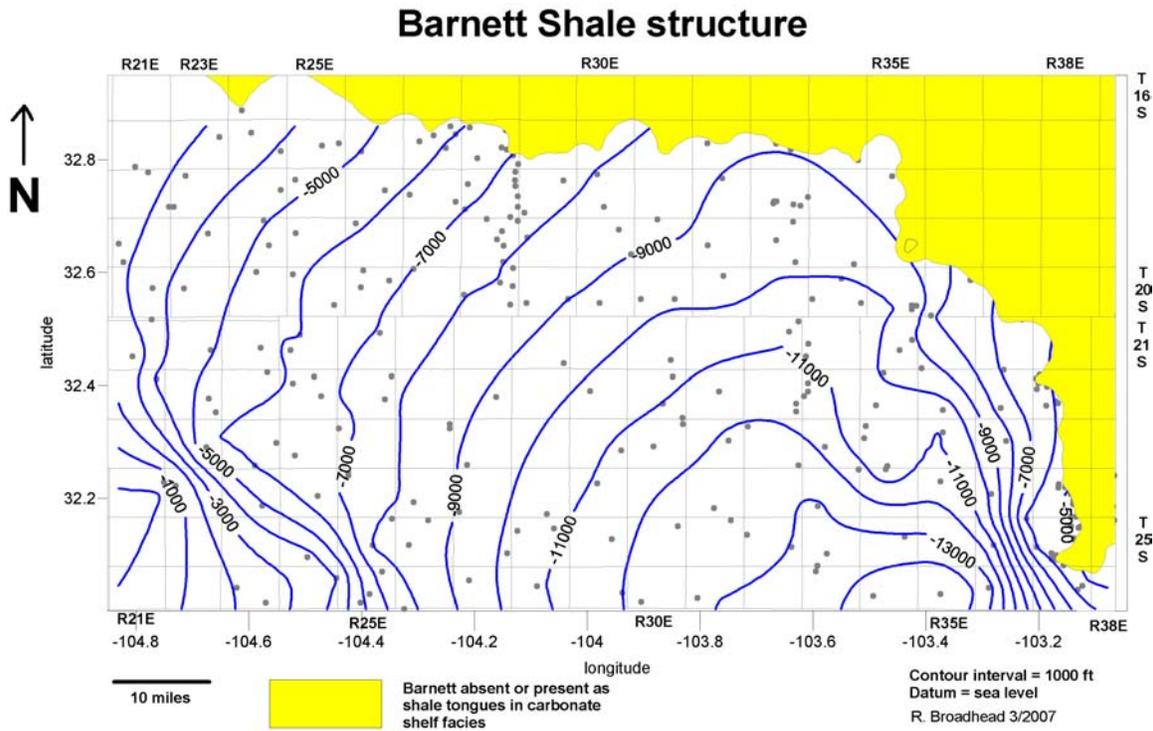


Figure 8. Structure contours on top of the Barnett Shale.

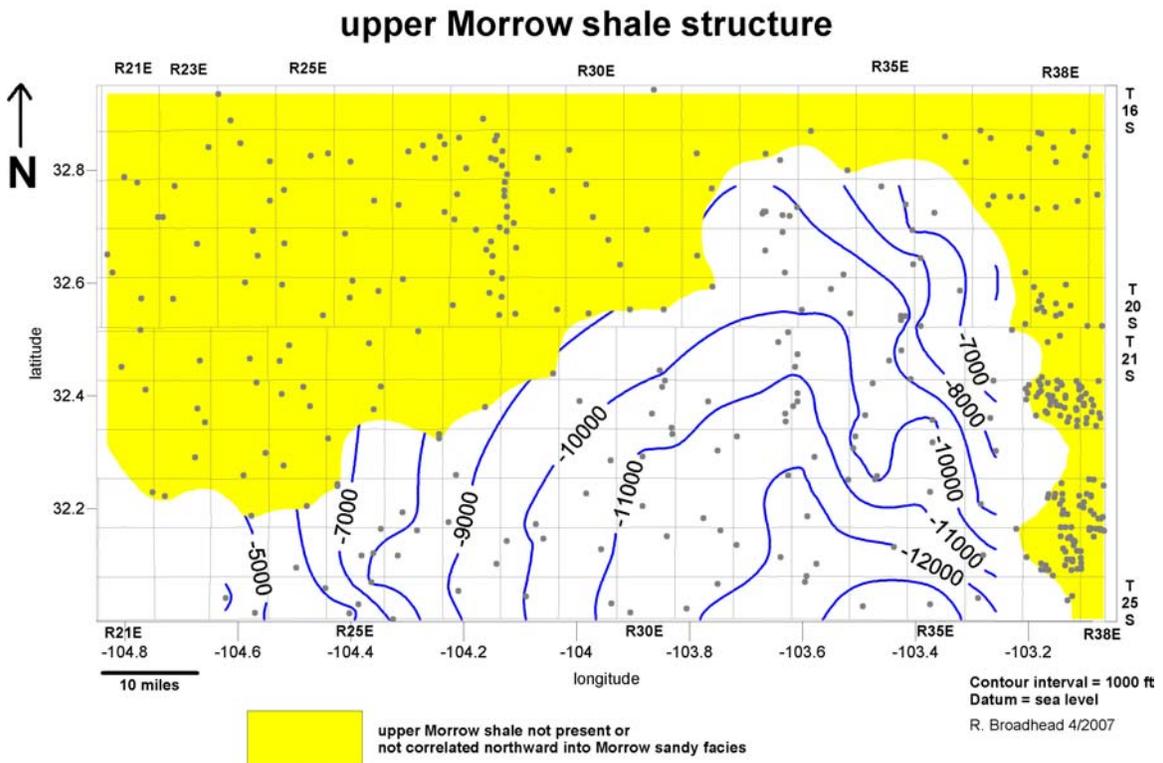


Figure 9. Structure contours on top of the upper Morrow shale.

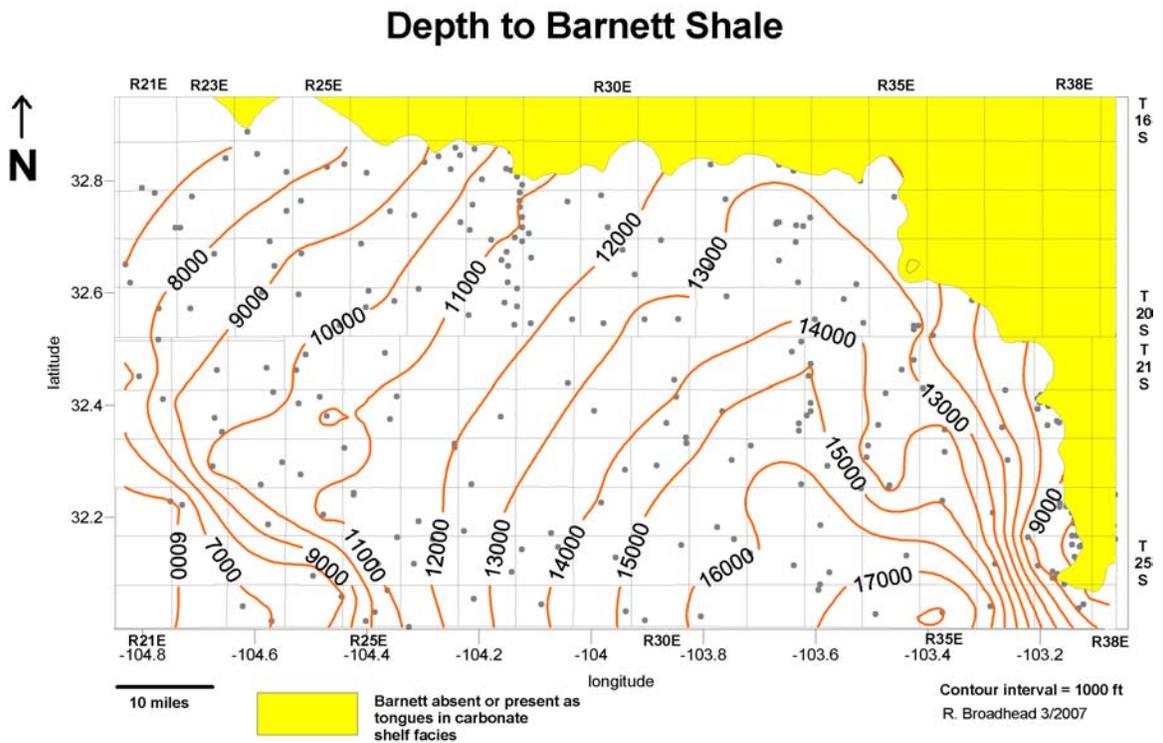


Figure 10. Depth to the Barnett Shale.

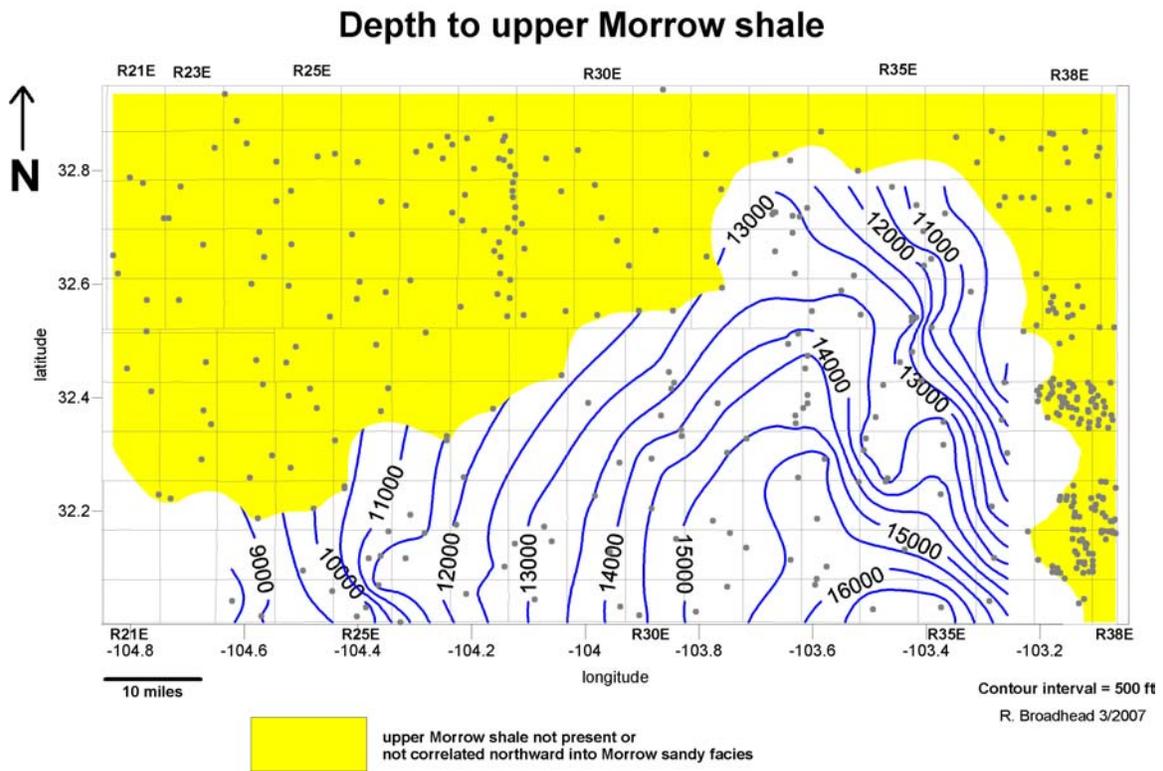


Figure 11. Depth to the upper Morrow shale.

Petroleum Source Rocks and Exploration Fairways

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 considered 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 1). 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 2). For this project, identification of organic-matter type was based mainly on petrographic analyses of kerogen concentrate as well as Rock-Eval pyrolysis parameters. 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. Furthermore, pyrolysis cannot discern the different varieties of kerogens present in samples with mixed kerogen assemblages. For these reasons, Rock-

Eval pyrolysis should be used only as reinforcement for petrographically determined kerogen identification.

The level of thermal maturity can be evaluated using visual kerogen analyses. Kerogen color 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), which ranges from 1.0 (immature) to 5.0 (metamorphosed; Table 3). This is a standard method of determining thermal maturity that can be used to confirm measurements made with other techniques (see Hunt, 1996; Peters, 1986). For this study, TAI determinations were available for relatively few samples. As such, they provided baseline measurements of thermal maturity that could be used to confirm thermal maturity determinations derived from less expensive Rock-Eval pyrolysis techniques.

Vitrinite reflectance (R_o) 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. Vitrinite reflectance increases with thermal maturity of a source rock. It is considered by many to be one of the most reliable techniques for determining thermal maturity of source rocks. Vitrinite reflectance measurements were not available for this study, so the Thermal Alteration Index was used for baseline measurements instead.

Table 1. 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

Table 2. 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

Rock-Eval pyrolysis can also be used to evaluate thermal maturity. The temperature at which the maximum amount of hydrocarbons is generated from the S₂ peak (TMAX, ° C) has been correlated to the thermal maturity of the source rock (Peters, 1986; Table 3). This method, although quantitative, does not give as complete an evaluation of maturity as TAI. Also, the measured value of TMAX is partially dependent upon the type of organic matter present as well as numerous other factors and can be erroneous if the S₂ peak is bimodal or flat (see Peters, 1986; Hunt, 1996).

The Rock-Eval Productivity Index is also a measure of the thermal maturity of a source rock. The Productivity Index is a calculated value based on the S₁ and S₂ peaks of the Rock-Eval analysis and is calculated by the following equation:

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

Where: PI = Productivity Index

S₁ = the amount of free hydrocarbons present in the sample, as determined through pyrolysis, in mg HC/g sample,

S_2 = the amount of hydrocarbons formed by the thermal breakdown of the kerogen in the sample when the kerogen is heated during the analytical process.

The Productivity Index is essentially a measure of the amount of hydrocarbons that have actually been generated compared to the total amount of hydrocarbons that could be generated from a sample given complete maturation to the stage where no more oil and gas is capable of being generated. The Productivity Index is sensitive to a number of factors, especially the presence of hydrocarbons that contaminate the sample during the drilling process or the presence of hydrocarbons that have migrated into the sample from elsewhere by natural processes. The presence of hydrocarbons derived from contamination or migration will lead to an artificially large S_1 value that will result in an artificially high estimate of thermal maturity. Analyses with unreasonably high S_1 values should be examined carefully and not used if it is determined that the high S_1 value is a result of the presence of contaminant hydrocarbons or migrated oil. One sample analysis was rejected for this reason; on the advice of Dr. Tim Ruble of Humble Laboratories, the sample was re-analyzed after solvent extraction that removed contaminant hydrocarbons. Use of the Productivity Index as a maturation parameter should be confirmed with another standard method of estimating thermal maturity. As discussed below, determinations of Thermal Alteration Index confirm the use of the Productivity Index as a maturation parameter for samples analyzed from the Barnett Shale. Therefore, contour maps of maturity were constructed using the Productivity Index because it was possible to obtain several times more analyses using the Rock-Eval technique than would have been possible if TAI or R_o were used as a maturation parameter.

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). For the Barnett, this question may be largely irrelevant because the dominant interest, at least for the present, is exploring for natural gas in a source rock that also functions as a reservoir, that is, the interest is in the hydrocarbon fraction that has been generated but not expelled from the source rock and is measured by the Rock-Eval S₁ peak.

Table 3. Correlation of maturation parameters with zones of hydrocarbon production. Based on Geochem Laboratories, Inc. (1980), Sentfle and Landis (1991), Peters (1986), Mukhopadhyay (1994), Peters and Cassa (1994), and Hunt (1996).

Maturation level (products generated)	Thermal Alteration Index (TAI)	Vitrinite Reflectance R_o	Rock-Eval Productivity Index (PI)	Rock-Eval TMAX (°C)
Immature (biogenic gas)	1.0 – 1.7	< 0.45		
Moderately immature (biogenic gas and immature oil)	1.8 – 2.3	0.45 – 0.5		< 435
Moderately mature (immature heavy oil)	2.3 - 2.5	0.5 – 0.7	< 0.1	425-435
Mature (mature oil, wet gas)	2.5 - 3.3	0.7 - 1.3	0.1 – 0.4	435 - 470
Very mature (condensate, wet gas, petrogenic dry gas)	3.3 – 3.8	1.3 - 2.0	> 0.4	> 470
Severely altered (petrogenic dry gas)	3.8 - 4.9	> 2.0		
Metamorphosed	5.0			

Sampling methods

Source rock analyses for this project were obtained from samples of drill cuttings. Because of the limited volumes of samples available, cuttings were analyzed from several

10 ft intervals that were combined in order to increase the volume of sample available. Cuttings from non-source lithologies such as sandstone or cavings from shallower strata were excluded from the sample prior to analysis as was extraneous material present in the samples such as material added to the drilling fluid to prevent lost circulation. Most analyses were performed on composite cuttings over a 100 ft depth interval. Because of the sampling methodology, TOC analyses can be considered to be an average of the shales over the 100 ft composite interval; because TOC will not be distributed evenly over the entire 100 ft interval, some of the shales in the 100 ft in the interval will undoubtedly have a TOC less than what the analysis yielded and other shales within the 100 ft interval will have a TOC greater than what the analysis yielded.

As previously mentioned, analyses on nine samples used in this study were obtained from the New Mexico Petroleum Source Rock Project (Broadhead et al, 1998). Those analyses were performed by Geochem Laboratories, Inc. as part of the New Mexico Petroleum Source Rock project and include petrographic determination of kerogen type and Thermal Alteration Index in addition to Total Organic Carbon and Rock-Eval pyrolysis. For this project, Total Organic Carbon and Rock-Eval analyses were performed on 26 additional samples by Humble Laboratories, Inc. of Humble, Texas. These additional analyses rendered it possible to map the organic richness and thermal maturity of the Barnett Shale, lower Morrow shale, and upper Morrow shale with a fair degree of confidence.

Barnett Shale

Organic content: The Barnett Shale is an organically rich, thermally mature source rock throughout a large part of its extent in southeastern New Mexico. Total organic carbon (TOC) ranges from 0.85 to 4.9 percent, more than sufficient for generation of hydrocarbons. Thermal maturity is within the oil window over large parts of southeastern New Mexico. The analyses indicate the Barnett has been matured past the stage of oil and generation along a northwest-southeast trending fairway, where it is within the condensate or thermogenic gas windows. This fairway defines an area of maximum interest regarding exploration for shale gas within the Barnett.

Total organic carbon ranges from 1.2 to 4.9 percent (Figure 12). Maximum values of more than 4 percent TOC occur in the central and southeastern parts of the project area. TOC decreases to the north, south and west of the maximum-value areas. The decrease in TOC is most pronounced to the north and northwest where Barnett shales have TOC contents less than 2 percent in the northern part of the Mississippian basin and in the Barnett tongues that extend northward onto the shelf.

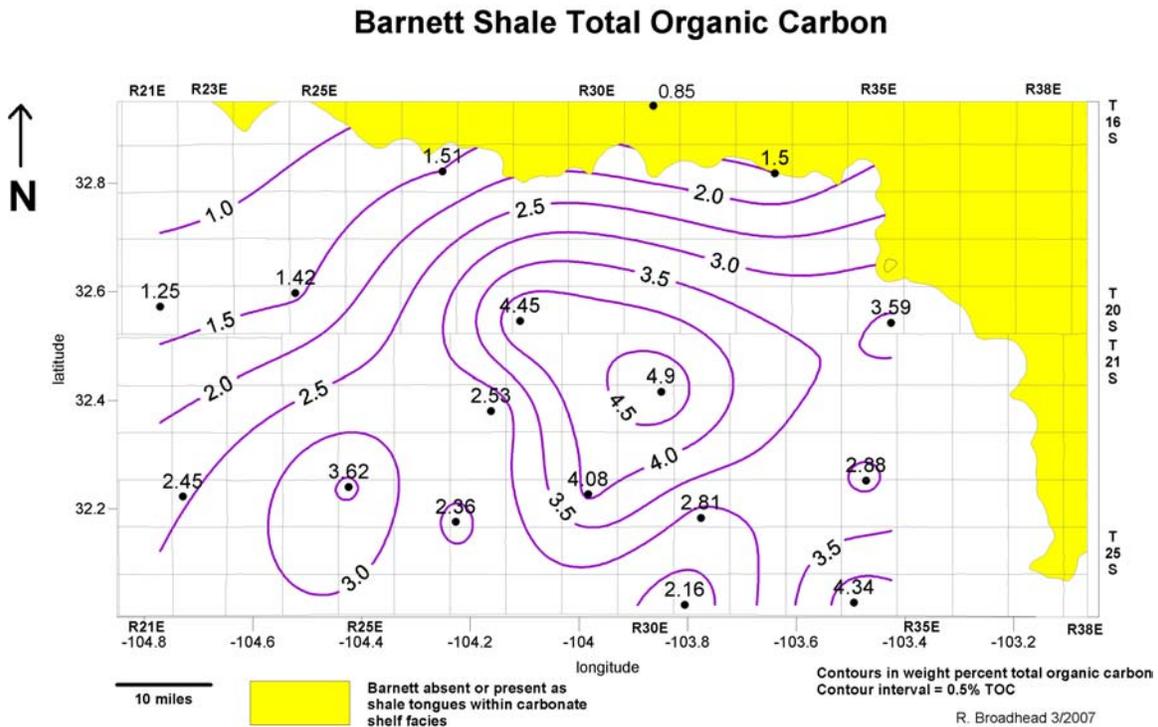


Figure 12. Contours of Total Organic Carbon (TOC) content of the Barnett Shale in weight percent.

Kerogens in Barnett shales are a mixture of woody, herbaceous, amorphous and inertinitic types. Organic petrographic analyses indicate that Barnett kerogens are comprised of 9 to 33 percent amorphous material, 17 to 36 percent herbaceous material, 17 to 36 percent woody material, and 17 to 33 percent inertinite (Figure 13). Amorphous types are generally less than 20 percent of the kerogen population. The composition of kerogens indicates that the Barnett is a dominantly gas-prone source rock but that some oils may have been generated upon maturation from the amorphous and herbaceous

populations. A plot of the Rock-Eval Hydrogen Index (HI) vs. the Oxygen Index (OI; Figure 14) indicates that the Barnett samples are characteristic of Type III kerogen rather than Type I or Type II kerogen. The location of the samples on the HI-OI plot is no doubt due to the large percentages of woody and inertinitic materials within the kerogen population. However, the relatively high degree of thermal maturity of the Barnett, as discussed below, may influence the location of samples on the HI-OI plot, with the mature amorphous and herbaceous population contributing less to the Hydrogen Index than would be the case if the Barnett was substantially less mature.

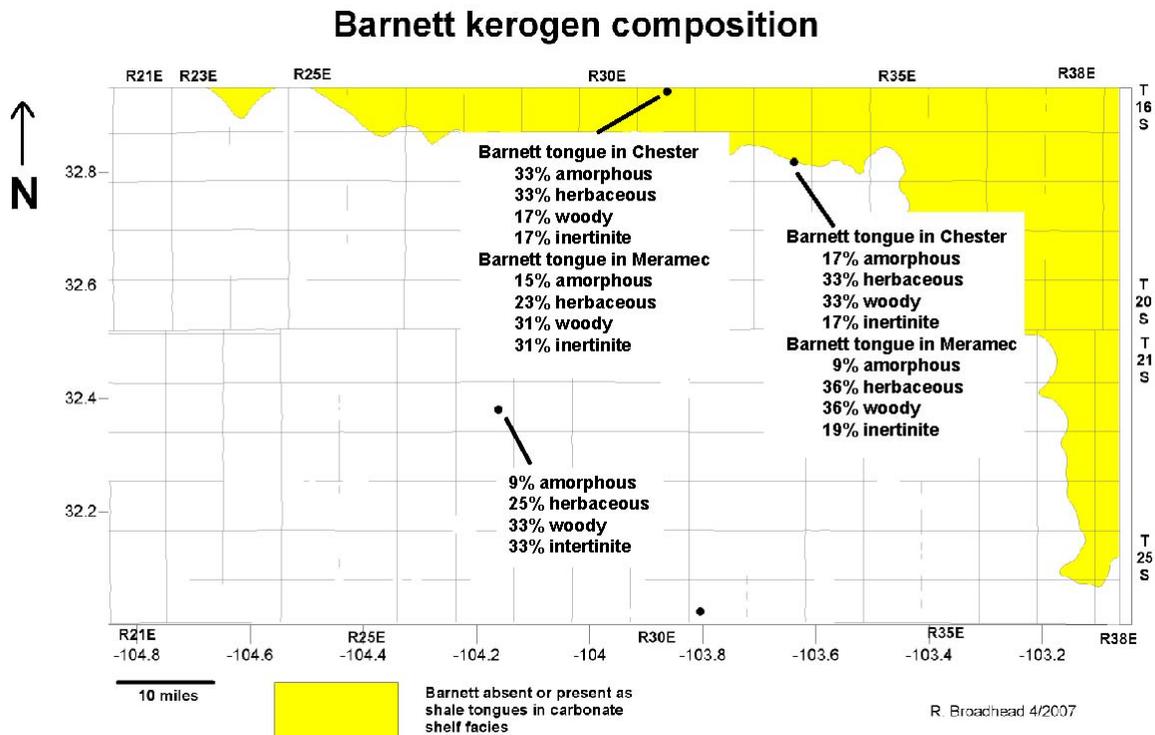


Figure 13. Types of kerogens present in the Barnett Shale.

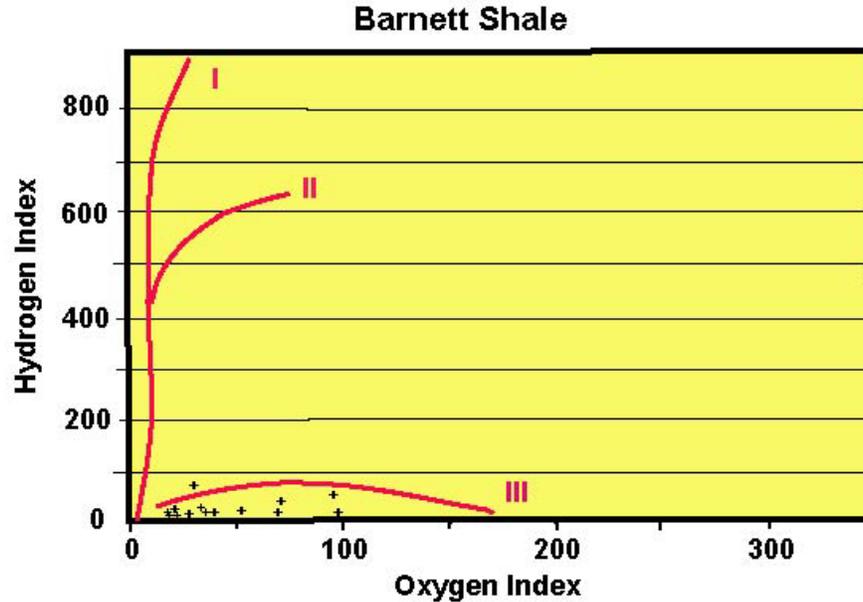


Figure 14. HI–OI plot derived from Rock-Eval analyses of samples of the Barnett Shale. Maturation path lines of Type I, II, and III kerogens from Peters (1986).

Inertinite is generally considered to be non-generative kerogen (Jacobson, 1991). It is derived from other kerogen types either through high levels of thermal maturity that leaves a carbon-rich, hydrogen-poor polymeric ring structure capable of generating additional hydrocarbons or through the recycling of kerogens eroded from pre-existing sedimentary rocks. The petrographic analyses of Barnett shales indicate inertinite constitutes 17 to 33 percent of the kerogen population in the Barnett Shale. It is unknown what percentage of the inertinite is recycled organic matter and what percentage is thermally overmature kerogen that has yielded hydrocarbons, but the relatively high levels of thermal maturation in the Barnett suggest that some of the inertinite may have been generative kerogen that now is post-mature and incapable of generating additional hydrocarbons. If this is the case, then the determination of 17 to 33 percent inertinite is misleading in terms of the overall generative potential of the Barnett. However, even if all of the inertinite in the Barnett is recycled organic matter that was never capable of generating hydrocarbons, sufficient generative types are still present to qualify the Barnett as a good source rock on the basis of TOC content.

Thermal maturity: The Barnett Shale is thermally mature throughout its extent in southeastern New Mexico. Levels of thermal maturity are indicated by the Thermal Alteration Index (TAI) and measurements and parameters derived from Rock-Eval pyrolysis. TAI was available for Barnett samples from three wells (Figure 15). For a fourth well, TAI analyses were available for the overlying lower Morrow shale and the underlying Woodford Shale (Devonian); in this well, the lower Morrow and Woodford values (3.1 and 3.2 respectively) were averaged to give a mappable TAI value of 3.15 for the Barnett. When mapped and contoured, the TAI values (Figure 15) indicate that the Barnett is within the oil window in the northeastern part of the project area and that maturity increases to the southwest. The highest values as portrayed on the contour map indicate the Barnett is fully mature and within the condensate or thermogenic gas windows in the southwestern part of the project area.

The Productivity Index was also contoured (Figure 16). When contours of the Productivity Index are superimposed on the contours of TAI (Figure 17), the contours of the two parameters are roughly parallel, indicating that the Productivity Index is supported by TAI. The Productivity Index attains a maximum along a northwest-southeast oriented trend in the western and south-central parts of the project area. This is a region of maximum thermal maturity. Maturity as determined by PI can only be partially related to depth (Figure 18) or structure (Figure 19). There is a general decrease in thermal maturity to the northeast that is oblique to structure and depth contours. There is a decrease in thermal maturity to the southwest associated with shallower areas of the Guadalupe Uplift west of the Huapache monocline. Although the isolated high PI value of 0.67 in T24S R29E may be a suspect for contamination of the cuttings by migrated hydrocarbons (an hypothesis not supported by the relatively low Hydrogen Index of 0.22), the concentration of samples with PI values uniformly greater than 0.45 indicates that the trend of maximum maturity is real.

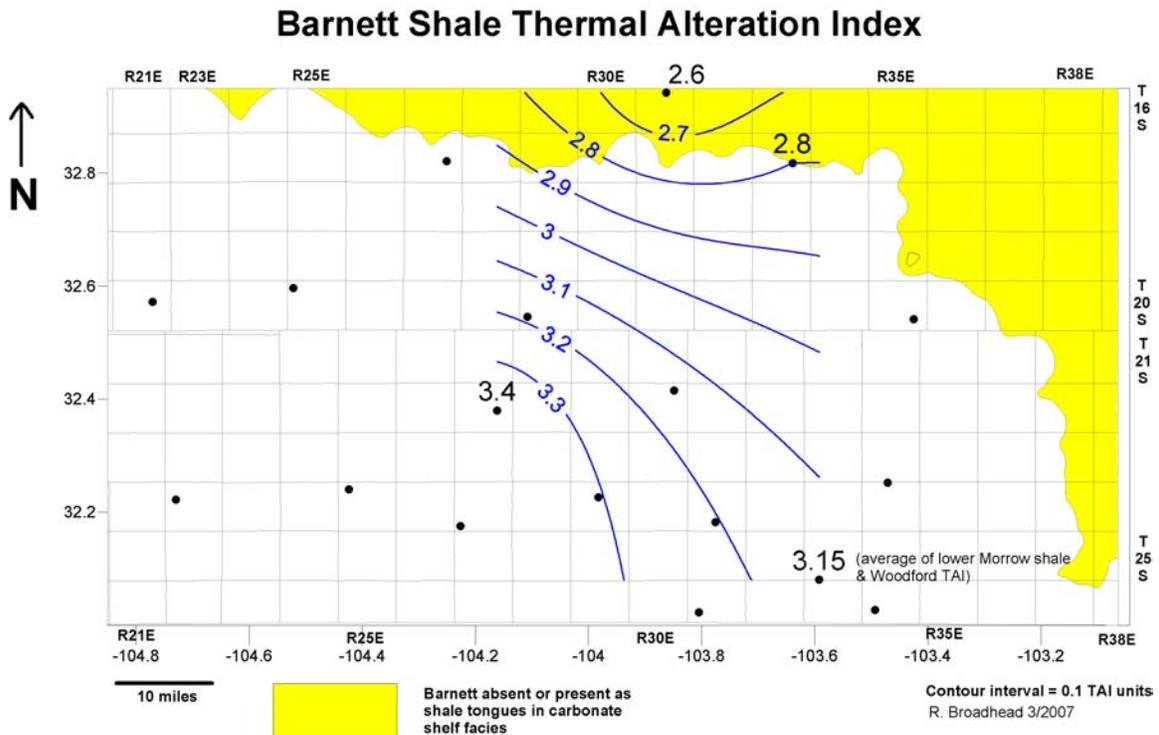


Figure 15. Contours of Thermal Alteration Index (TAI) of the Barnett Shale, including tongues of Barnett Shale that are interbedded with Upper Mississippian limestones on the Mississippian shelf.

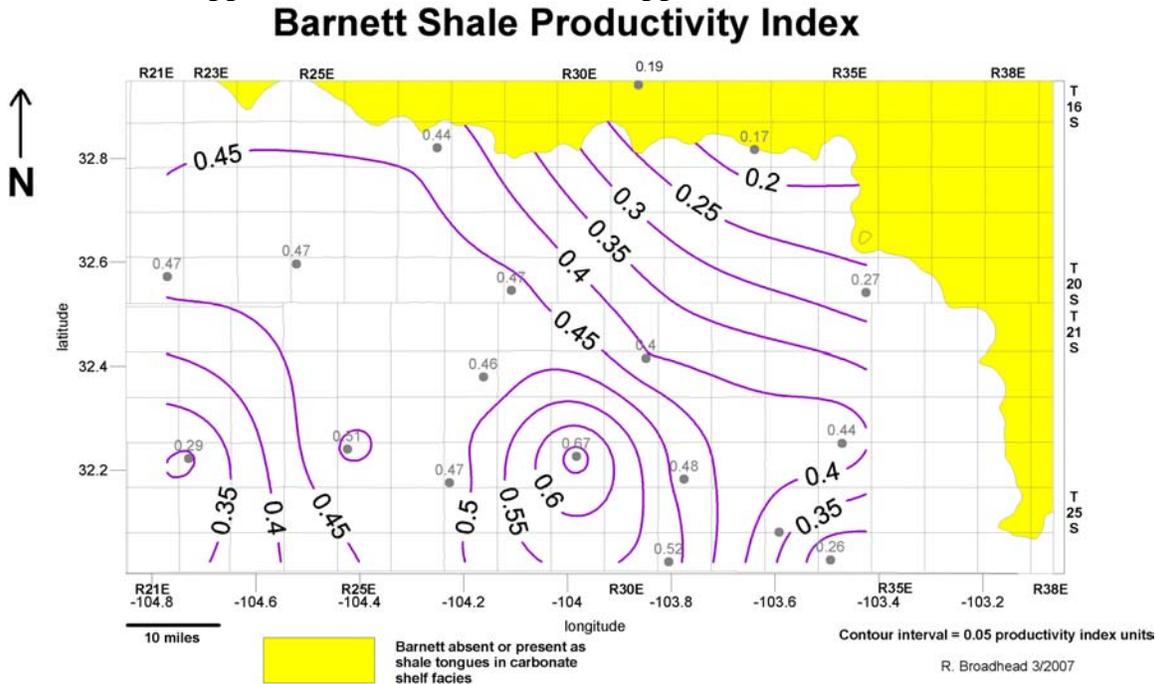


Figure 16. Contours of Rock-Eval Productivity Index (PI) of Barnett Shale.

Barnett Shale Productivity Index and Thermal Alteration Index

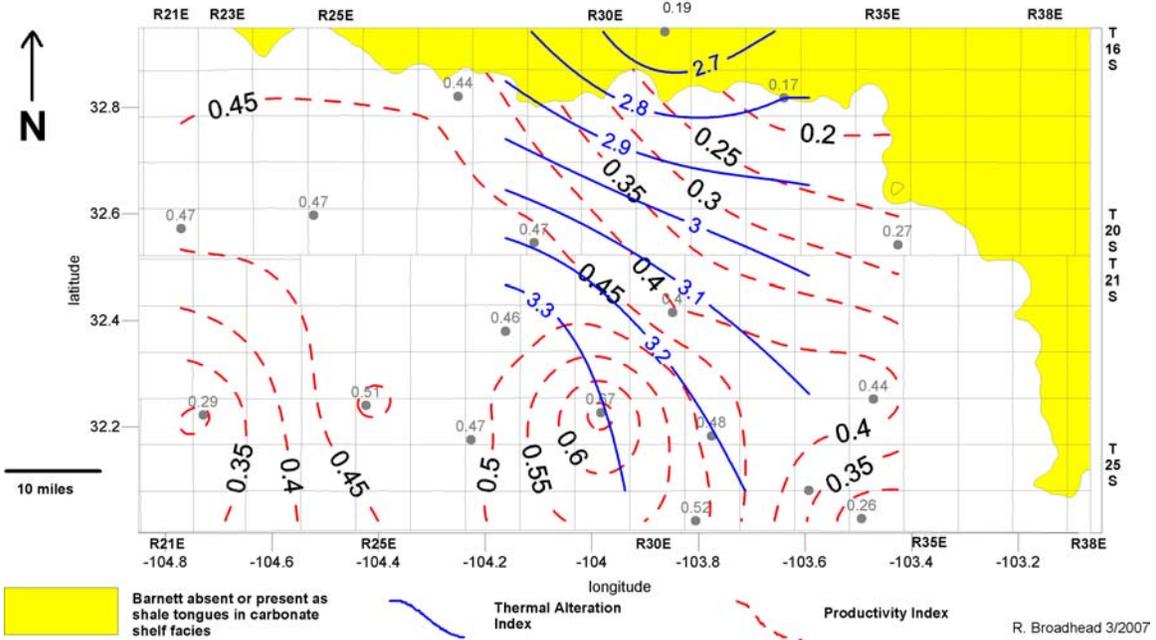


Figure 17. Contours of PI superimposed on contours of TAI for Barnett Shale.

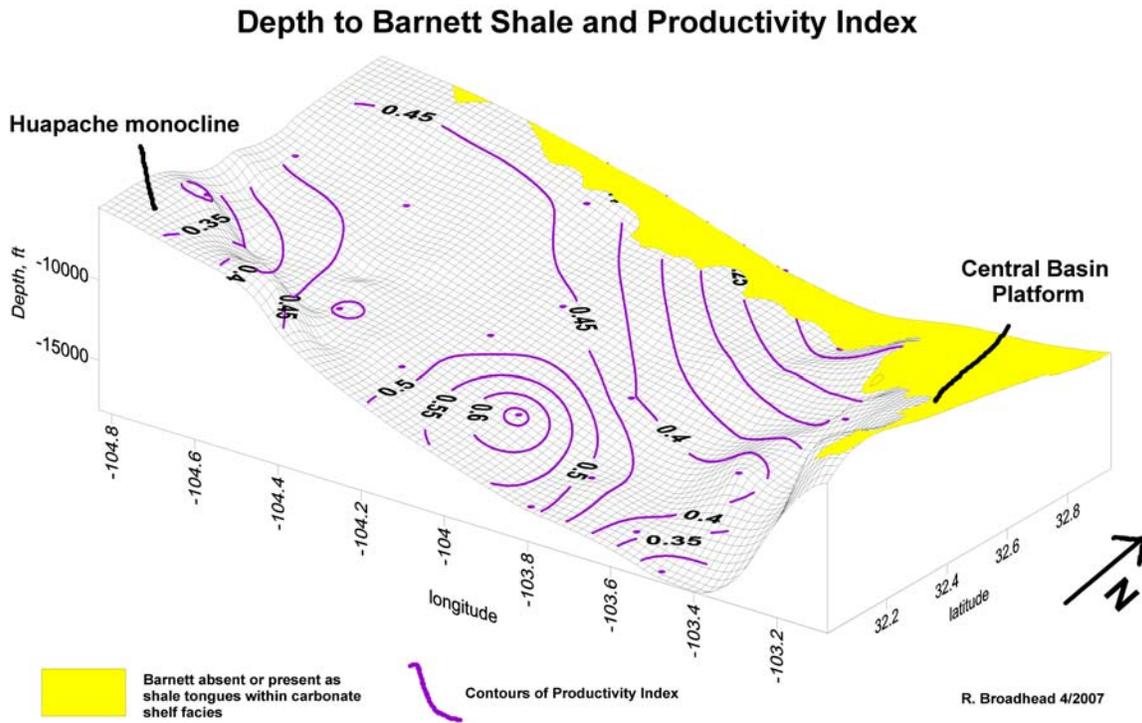


Figure 18. Barnett Shale Productivity Index superimposed on depth to top of Barnett Shale.

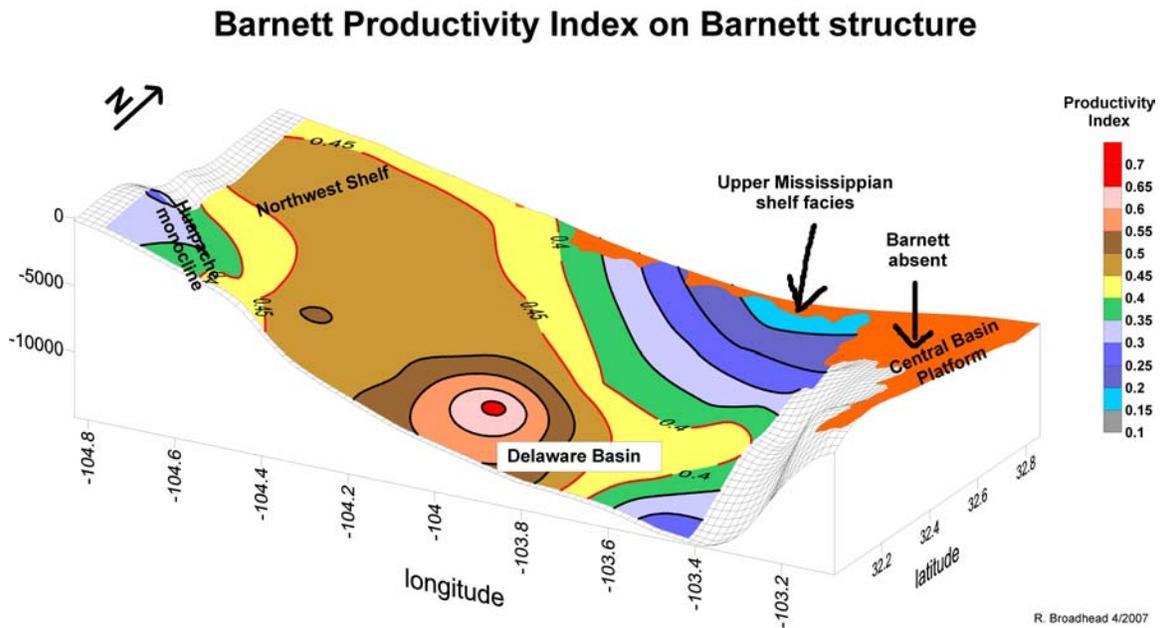


Figure 19. Barnett Shale Productivity Index superimposed on wireframe diagram of Barnett structure.

Barnett exploration fairway: A map of areas favorable for gas exploration in the Barnett was constructed utilizing the thermal maturity maps and the TOC map (Figure 20). Thermal maturity is used to define areas that are beneath the oil window and therefore optimum for gas generation. TOC is used to define areas of optimum organic richness. A combination of the two parameters allows for the delineation of a fairway of maximum interest for gas exploration.

As described above, there is a northwest-southeast trending area of maximum thermal maturity that extends through the west-central and south-central parts of the project area. Although the base of the oil-window/top of the thermogenic gas and condensate window is placed at a PI value of 0.4 by most workers (e.g. Geochem Laboratories, Inc, 1980; Peters and Cassa, 1994; Hunt, 1996), for this report a more conservative PI value of 0.45 was chosen to delineate the area of maximum thermal maturity and was used to define the fairway of maximum interest for gas exploration. The region of the map with PI values between 0.4 and 0.45 is considered a transitional zone between the fairway of maximum interest and those areas where the Barnett is within the oil window, but not within the thermogenic gas/condensate window. Within the fairway, values of PI range from 0.46 to 0.67 with three wells having PI values greater than 0.5.

The fairway is delineated on the northwest by the 2 percent TOC contour. Northwest of this contour, TOC is less than 2 percent. Although these values are sufficient for hydrocarbon generation, they fall beneath the more optimal values in excess of 2 percent (see Table 1). If the inertinite present within the Barnett kerogens was not derived by maturation but instead was recycled kerogen, then regions with less than 2 percent TOC may be somewhat marginal for oil and gas generation, even if thermally mature.

The area of most interest for gas exploration in the Barnett Shale therefore trends northwest-southeast through the western and south-central parts of the project area. It is defined by the 0.45 contour line of the Rock-Eval Productivity Index as well as the 2 percent contour of Total Organic Carbon. While this is of most interest for gas exploration, areas to the north and east of the fairway have sufficient organic content for hydrocarbon generation. The eastern and northern areas are within the oil window and the Barnett in these areas is a source of both gas and oil.

Barnett fairway

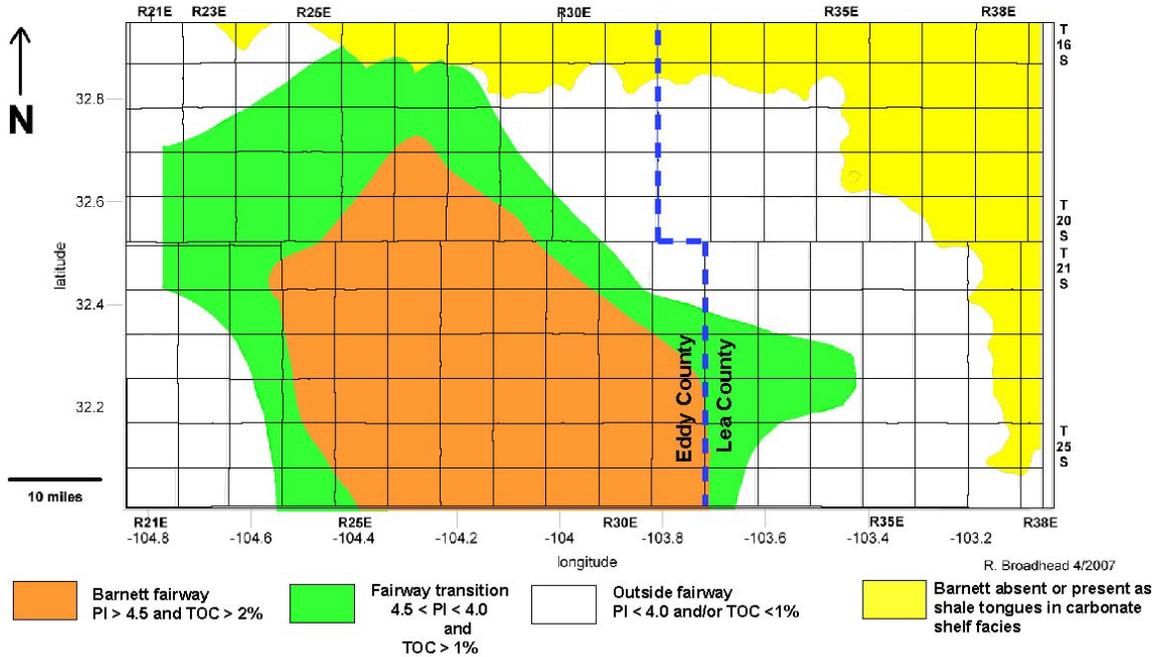


Figure 20. Areas of favorable interest (exploration fairway) for Barnett Shale.

Lower Morrow shale

Organic content: The lower Morrow shale contains a sufficient amount of organic matter for hydrocarbon generation. Total Organic Carbon (TOC) content ranges from 2.1 to 2.65 percent (Figure 21). Petrographic analysis of kerogen types was available for one sample, located in T22S R37E (Figure 22). The kerogen population in that sample contained 36 percent woody types, 36 percent inertinite, 28 percent herbaceous types, and 0 percent amorphous types. This indicates a predominantly gas-prone source rock. On the HI-OI plot for the lower Morrow shale (Figure 23), the samples plot along the Type III kerogen path. The HI-OI plot and the petrographic analysis indicate that kerogens in the lower Morrow shale are dominantly gas prone.

lower Morrow shale TOC

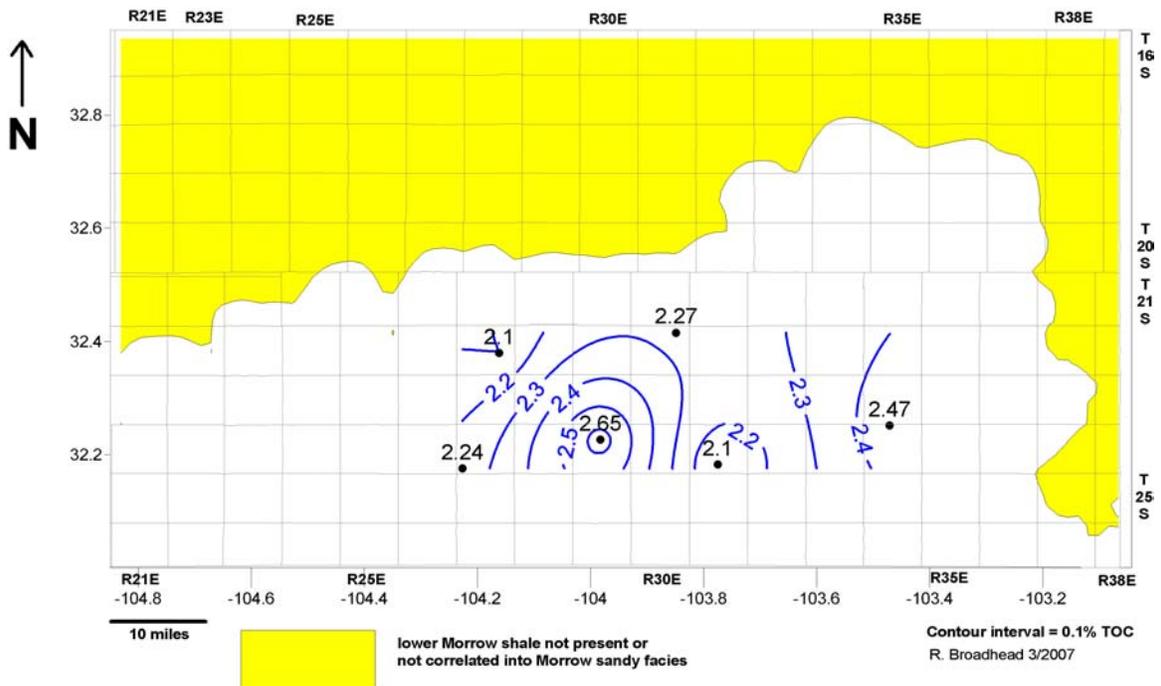


Figure 21. Contours of Total organic carbon (TOC) content of lower Morrow shale, in weight percent.

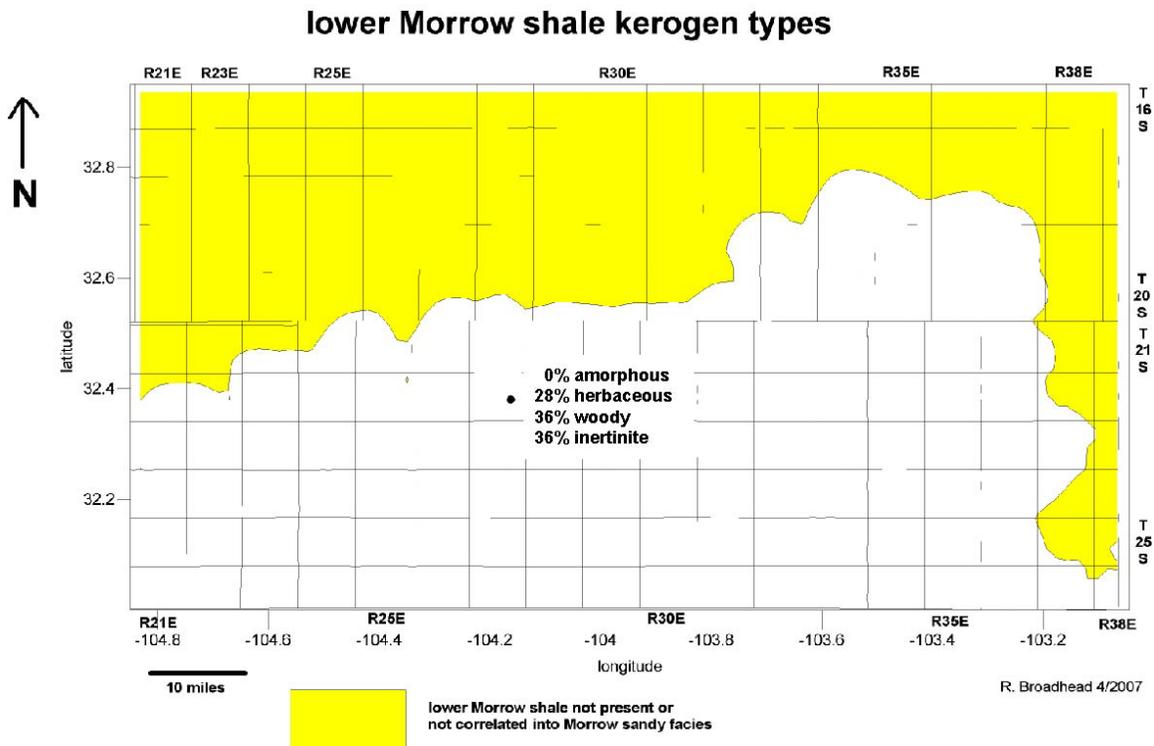


Figure 22. Types of kerogens present in lower Morrow shale.

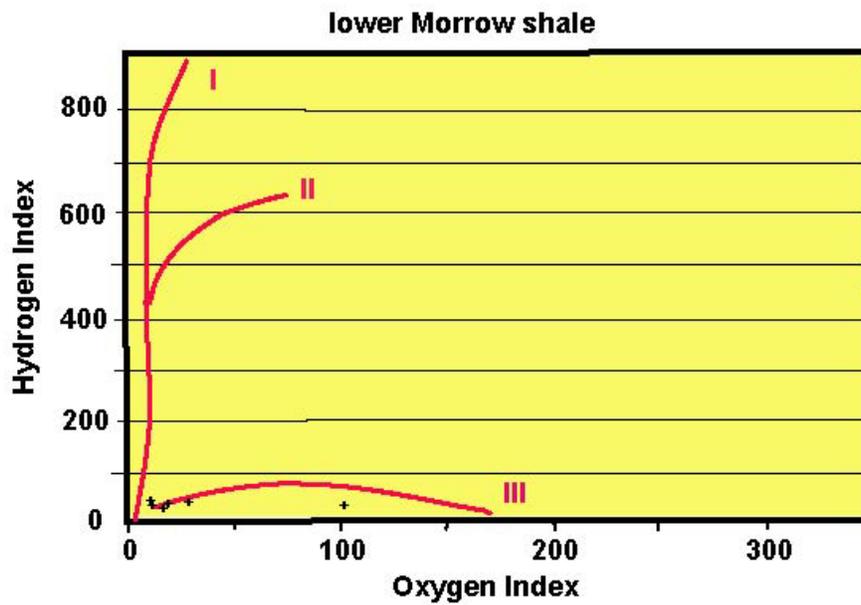


Figure 23. HI–OI plot derived from Rock-Eval analyses of samples of the lower Morrow shale. Maturation path lines of Type I, II, and III kerogens from Peters (1986).

Thermal maturity: Thermal maturity of the lower Morrow shale appears to be somewhat lower than the thermal maturity of the underlying Barnett Shale. The Rock-Eval Productivity Index varies from 0.24 to 0.35 (Figure 24), indicating that the lower Morrow shale is within the oil window. The values suggest that the lower Morrow is mostly within the lower part of the oil window. The single TAI measurement available (TAI = 3.4; Figure 25) indicates that the lower Morrow shale is very mature and at least locally may be at the top of the condensate/gas window or at the boundary between the oil window and the condensate/gas window.

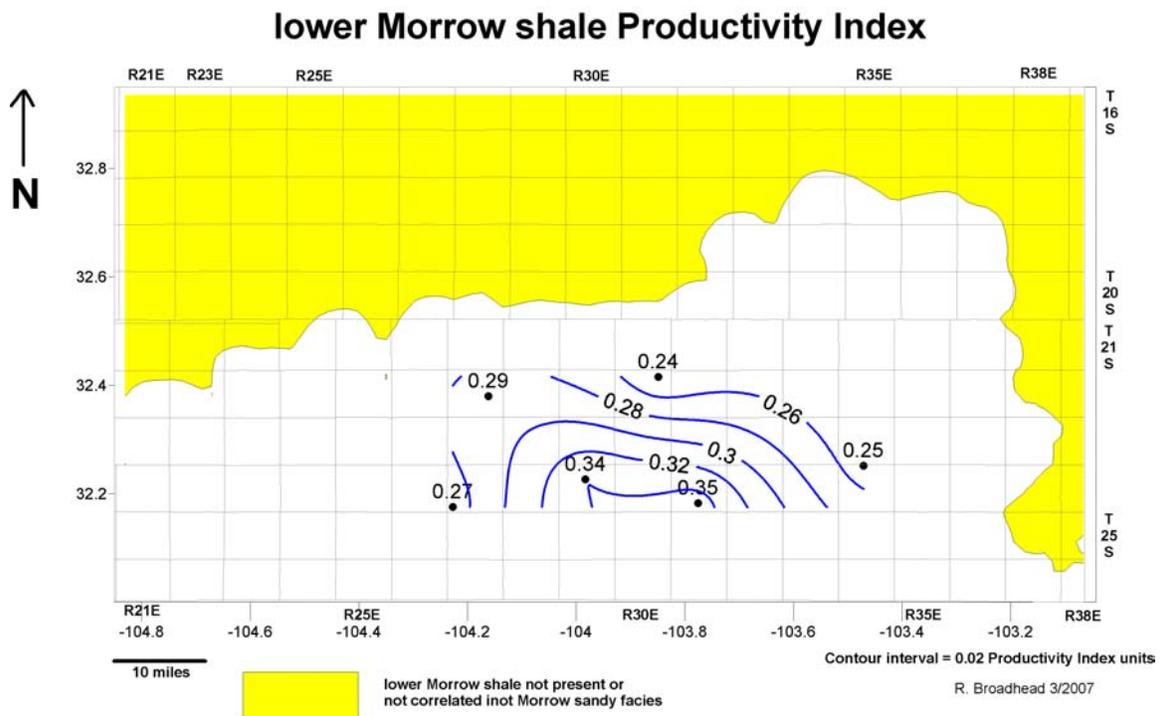


Figure 24. Contours of Rock-Eval Productivity Index (PI) of lower Morrow shale.

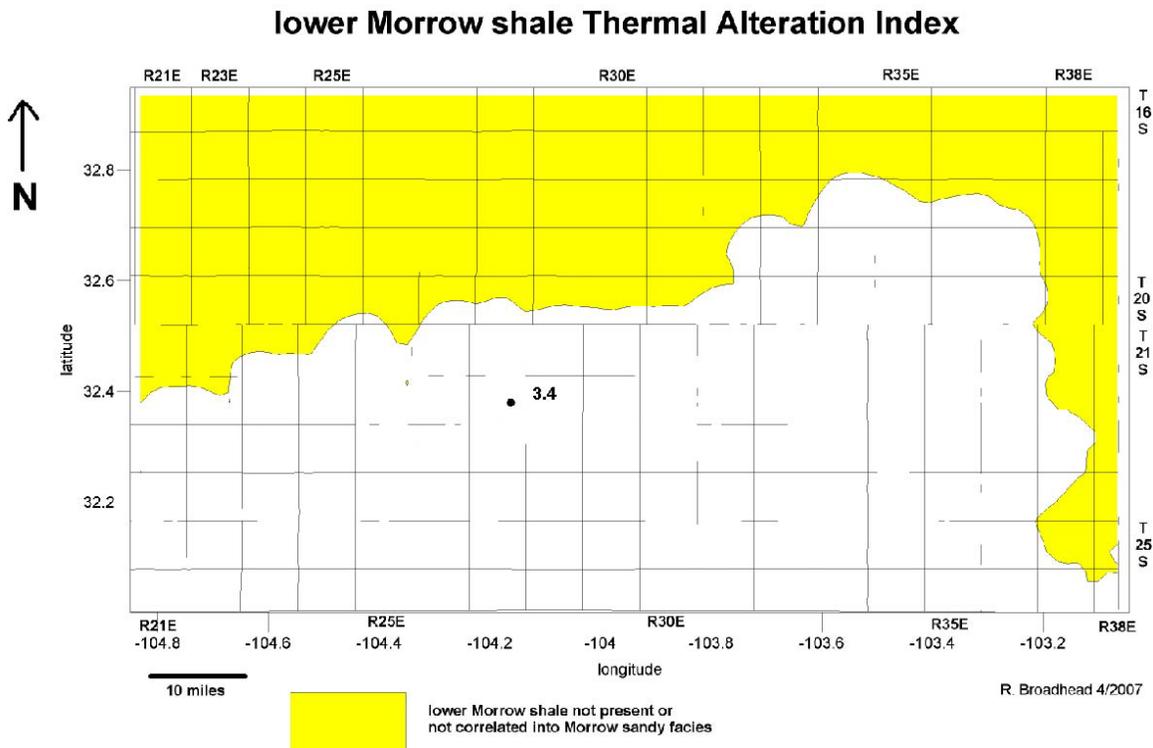


Figure 25. Values of Thermal Alteration Index (TAI) of lower Morrow shale.

Lower Morrow shale exploration: Insufficient data area available to delineate an exploration fairway in the lower Morrow shale. Thermal maturity parameters indicate the lower shale is mostly within the lower part of the oil window or at the oil window – condensate/gas window transition. Combined with the gas-prone nature of the kerogen population, the lower Morrow should have generated gas throughout a large part of the project area. This is not surprising given that the Morrow is one of the principal gas-producing stratal units in southeastern New Mexico (see Speer, 1993; Broadhead and Speer, 1995).

Upper Morrow shale

Organic content: The upper Morrow shale contains a sufficient quantity of organic matter for hydrocarbon generation. Total organic carbon (TOC) content ranges from 1.3 to almost 2.4 percent (Figure 26). Petrographic analyses of kerogen types were available from three samples from one well in T25S R33E (Figure 27). Vertical variability of kerogen types within the upper Morrow shale in this well is minimal with amorphous types ranging from 25 to 31 percent of the kerogen population, herbaceous types ranging from 31 to 33 percent, woody types ranging from 23 to 25 percent, and inertinites ranging from 15 to 17 percent. When plotted on the Hydrogen Index – Oxygen Index (HI-OI) diagram (Figure 28), the upper Morrow shale samples fall either on the Type III kerogen path or in an area between the Type II and Type III kerogen paths. The samples that plot between the Type II and Type III paths are those for which petrographic analyses of kerogen types are available and the location of these samples on the HI-OI plot is consistent with a mixed kerogen population of both gas-prone and oil-prone types. From the distribution of sample points on the HI-OI plot, it is evident that kerogens in the upper Morrow shale range from gas-prone types to a mixture of gas-prone and oil-prone types.

Thermal maturity: The Thermal Alteration Index (TAI) of the three samples of upper Morrow shale from the well in T25S R33E is 3.1 (Figure 29). This places the upper Morrow shale within the lower part of the oil window. Values of the Rock-Eval productivity Index (PI) range from 0.29 to 0.56 (Figure 30). The well in T25S R33E has PI values for three samples of 0.55, 0.39, and 0.34 in order of increasing depth. Given that the TAI for all three samples is 3.1, it was decided to average the two lower values to 0.36 for purposes of contouring, a value in agreement with the TAI value of 3.1. Although there are insufficient data to regionally contour thermal maturity parameters for the upper Morrow shales, Figures and indicate that they are within the lower part of the oil window. Therefore, the upper Morrow shale generated gas and associated oil upon maturation in the part of the basin for which samples have been analyzed.

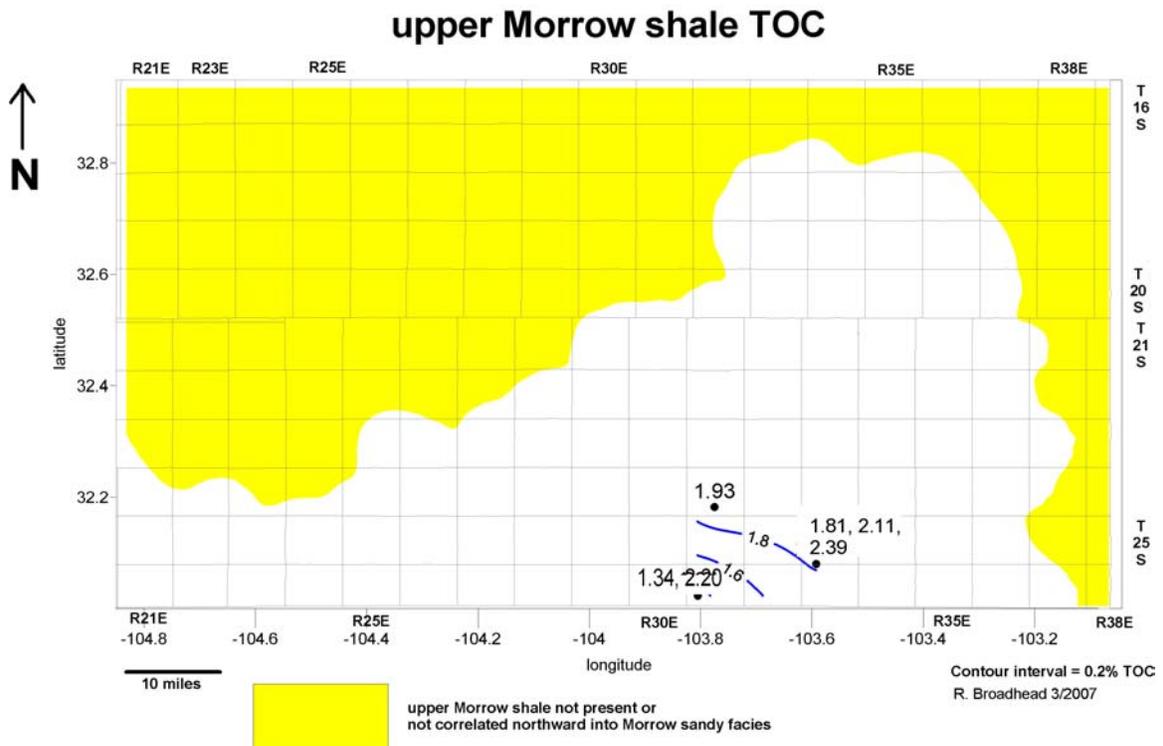


Figure 26. Contours of Total Organic Carbon (TOC) content of upper Morrow shale, in weight percent.

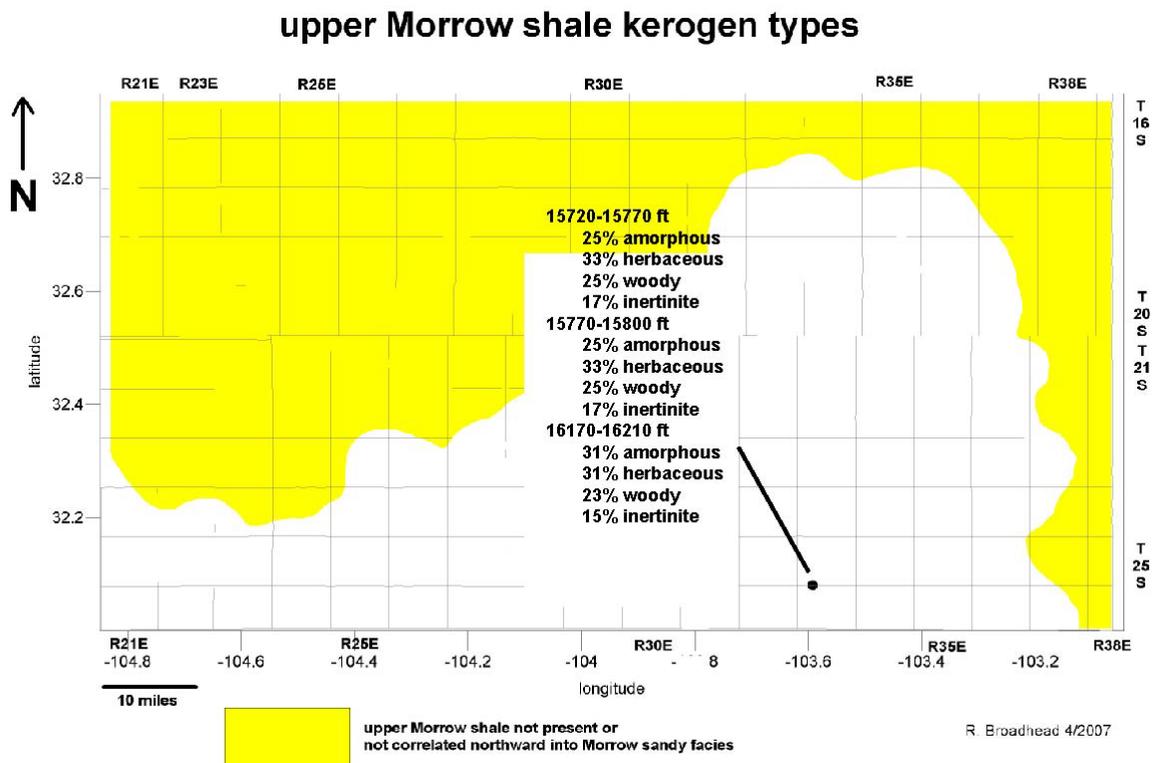


Figure 27. Types of kerogens present in upper Morrow shale.

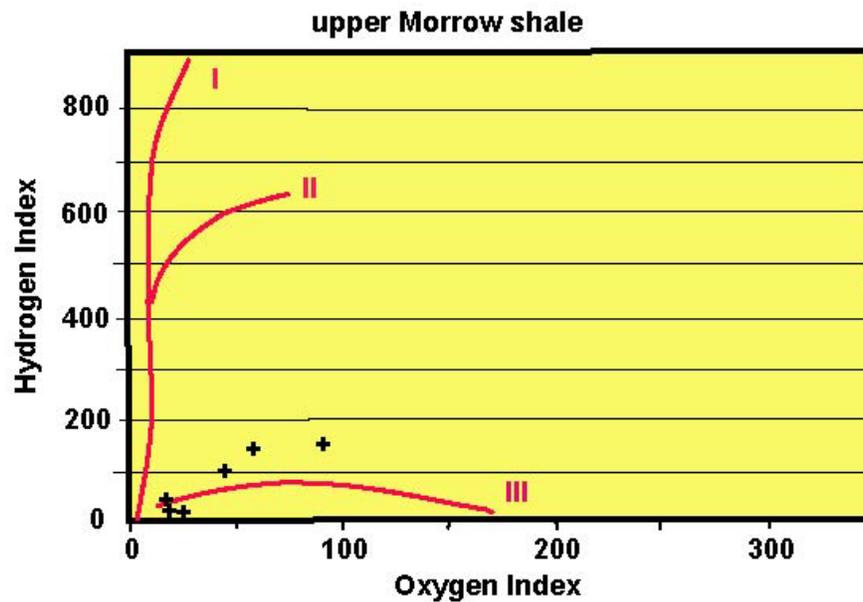


Figure 28. HI–OI plot derived from Rock-Eval analyses of samples of the upper Morrow shale. Maturation path lines of Type I, II, and III kerogens from Peters (1986).

upper Morrow shale Thermal Alteration Index

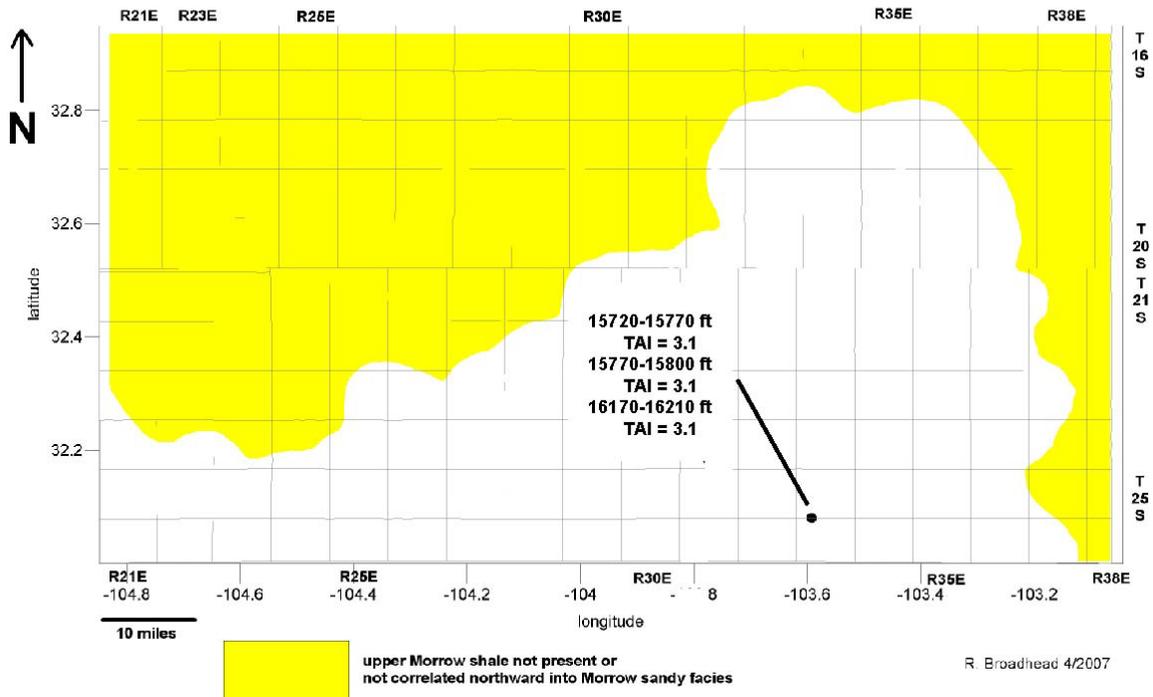


Figure 29. Values of Thermal Alteration Index (TAI) of upper Morrow shale.

upper Morrow shale Productivity Index

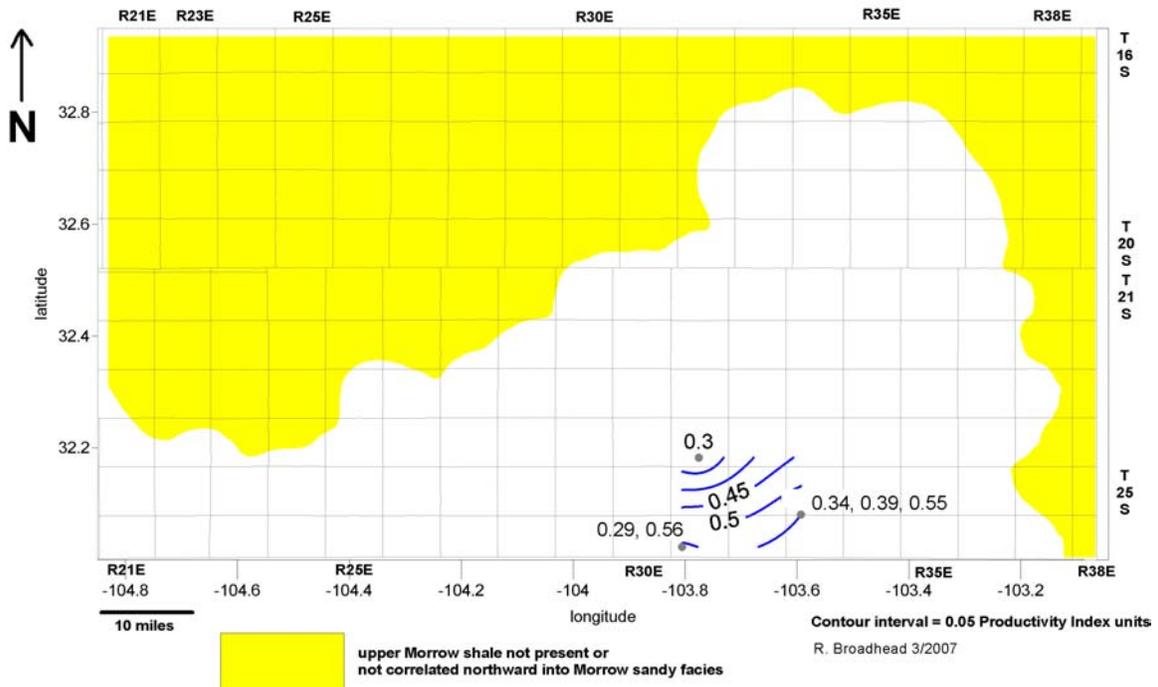


Figure 30. Contours of Rock-Eval Productivity Index (PI) of upper Morrow shale.

Upper Morrow shale exploration: Insufficient data area available to delineate an exploration fairway in the upper Morrow shale. Thermal maturity parameters indicate the upper shale is mostly within the lower part of the oil window. Combined with the mixed gas-prone and oil-prone nature of the kerogen population, the lower Morrow should have generated gas or gas with oil throughout a large part of the project area. This is not surprising given that the Morrow is one of the principal gas-producing stratal units in southeastern New Mexico.

Hydrocarbon shows in Barnett Shale

Mudlogs archived in the log library of the New Mexico Bureau of Geology and Mineral Resources were examined for indications of hydrocarbon shows in the Barnett Shale. The mudlogs were examined for indications of mud gas or cuttings gas detected within the Barnett Shale. Determinations of shows, or absence of shows, on the mudlogs are presented in the Barnett wells database attached to this report in Appendix D. Shows were described in terms of whether the show was confined to a discrete stratigraphic interval or was a more diffuse, unconfined show. If the shows were confined, information about the thickness of the show interval was recorded. Also recorded was information concerning the composition of hydrocarbons in the shows. Specifically, the composition in terms of C₁ (methane), C₂ (ethane), C₃ (propane), or C₄ (butane or isobutane) hydrocarbons were recorded into the database. Some mudlogs have chromatographic analyses that portray curves for shows with hydrocarbons with C₁, C₂, C₃, and C₄. Other mudlogs only have curves that distinguish the presence of hydrocarbons with a composition of C₁ and those hydrocarbons with composition of C₂ or longer chains; in the latter case, the shows were recorded in the database as C₂₊ as it is not possible to distinguish the presence of hydrocarbons heavier than C₂ in these shows.

Most available mudlogs indicate gas shows within the Barnett. Figure 31 is a map that indicates the composition of the shows by hydrocarbon type (C₁, C₂, C₃, or C₄). Although determinations of molecular composition of hydrocarbon type from mudlogs is imprecise, Figure 31 indicates that the Barnett in the northern and northeastern portion of

the project area is characterized by heavier hydrocarbons in the C₃₊ (propane and heavier) range in addition to C₁ and C₂ (methane and ethane) hydrocarbons. The Barnett in the southern and southwestern parts of the project area is characterized by C₁ and C₂ hydrocarbons (methane and ethane); heavier hydrocarbons were generally not detected by the mudlogs in this area. This distribution of Barnett hydrocarbon composition is in agreement with the Thermal Alteration and Productivity Index maps (Figures 15, 16) that indicate that the Barnett is more mature in the south and southwest and is within the gas and condensate window in these areas.

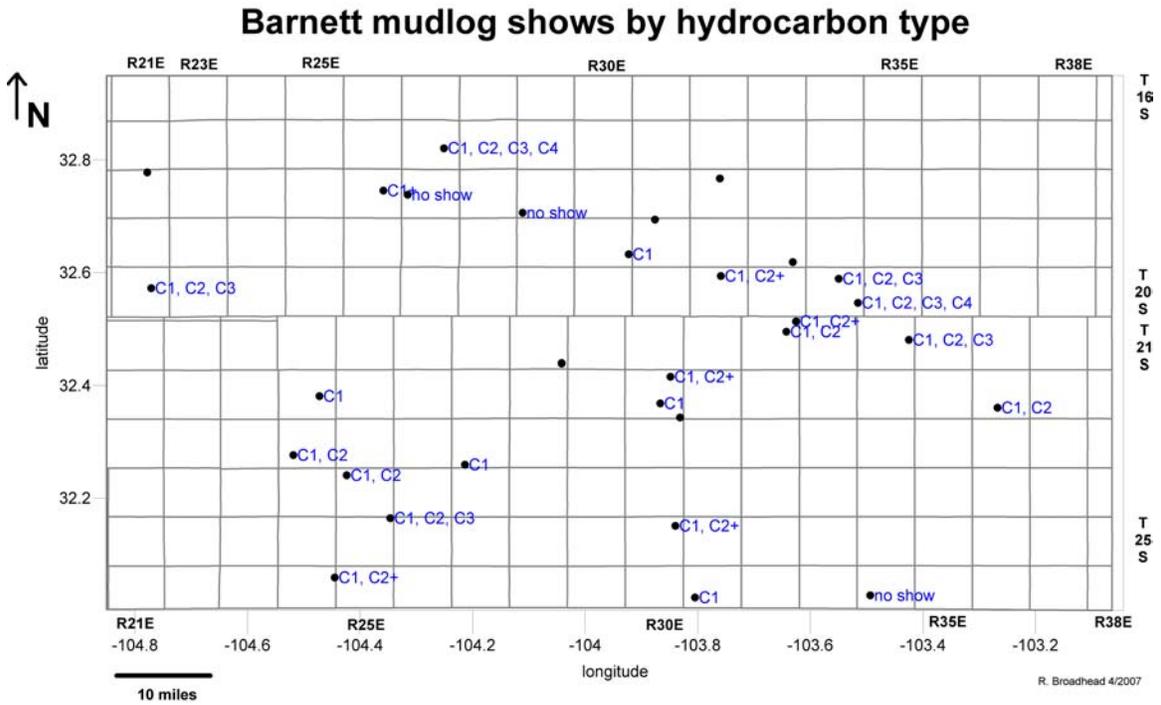


Figure 31. Hydrocarbon shows from mudlogs of wells that penetrated Barnett Shale, classified by hydrocarbon type (C₁, C₂, C₃, or C₄).

New Mexico State Trust Lands

Several thousand acres of New Mexico State Trust lands are present within the project area (Figure 32). Large blocks of State Trust Land occur within the Barnett fairway (Figure 33), which is that part of the Barnett characterized by shales that are thermally mature (Rock-Eval productivity Index greater than 4.5) and organically rich (TOC > 2%). Large blocks of State Trust Land are also present within the fairway transition. The fairway delineates the area of high potential for shale gas in the Barnett Shale.

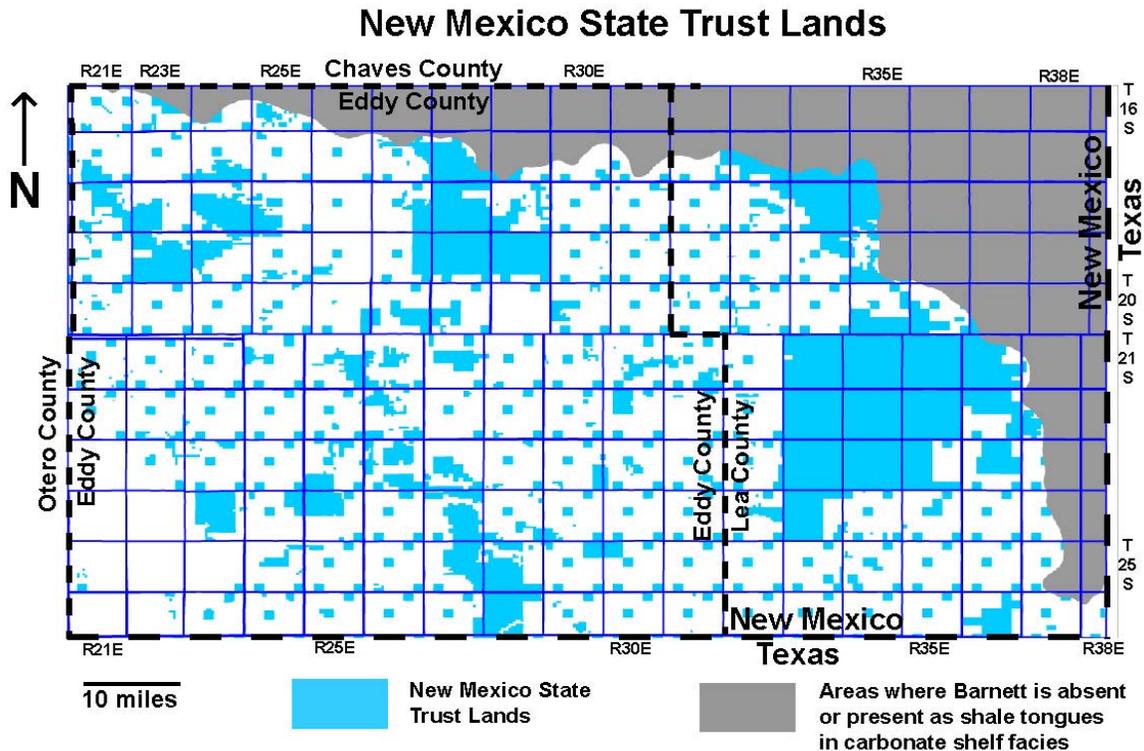


Figure 32. New Mexico State Trust Lands in the area underlain by the Barnett Shale in southeastern New Mexico.

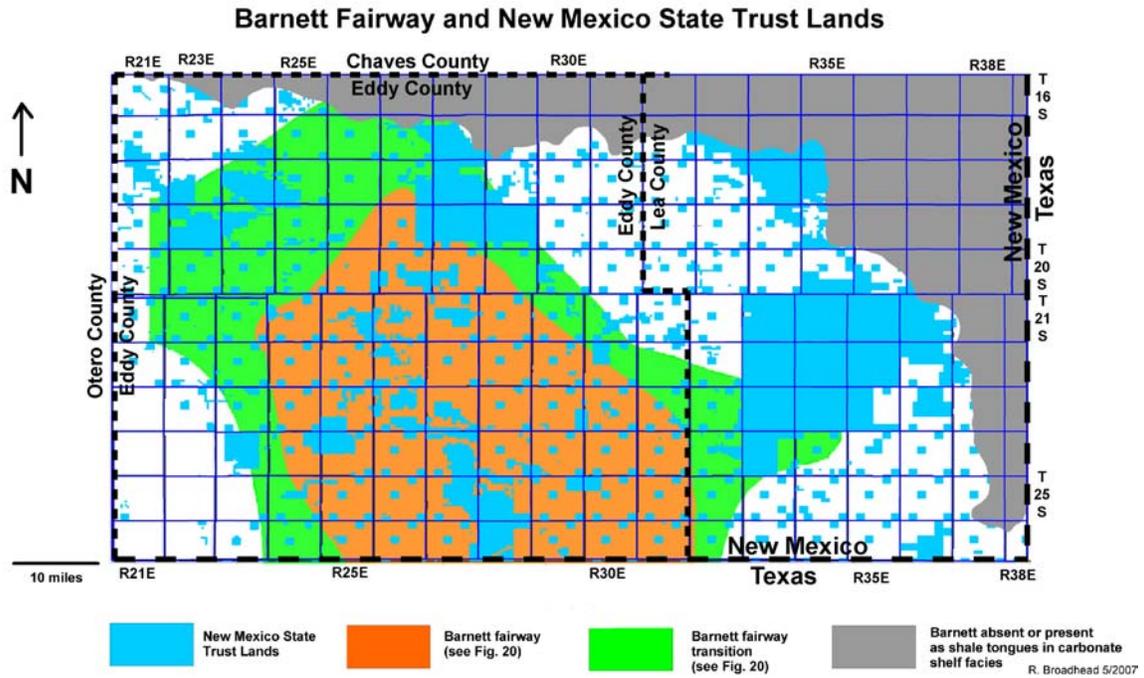


Figure 33. New Mexico State Trust Lands (in blue) superimposed on the area underlain by the Barnett fairway, as defined by Barnett shales with TOC > 2% and the Rock-Eval Productivity Index > 4.5.

Conclusions

Several conclusions were reached concerning the stratigraphy, distribution and petroleum source rock character of the Barnett Shale and overlying Morrowan shales.

Important conclusions are:

1. Basinal dark-gray to black marine shales in the New Mexico part of the Permian Basin that have been traditionally correlated as the Barnett Shale (Upper Mississippian) are late Mississippian to Morrowan (Early Pennsylvanian) in age. The Upper Mississippian Barnett Shale in the south correlates northward with Chesterian and Meramecian strata on the Mississippian shelf. The shelf strata in the north are dominated by marine limestones; tongues of Barnett shales extend northward onto the shelf where they intertongue with the shelf limestones. The overlying Morrowan (Lower Pennsylvanian) shales grade northward into a sandy facies consisting of interbedded dark-gray to black shales and lenticular sandstones.
2. That portion of the Upper Mississippian – Lower Pennsylvanian shale sequence that is correlated as the Barnett Shale consists of 200 to 350 ft of dark-gray to black shale with minor thin sandstones and minor thin limestones.
3. The overlying Morrowan (Lower Pennsylvanian) shales are subdivided into two stratal units, the lower Morrow shale and the upper Morrow shale. The lower Morrow shale consists of 200 to 350 ft of dark-gray to black marine shales and minor thin sandstones. The upper Morrow shale consists of 100 to 800 ft dark-gray to black marine shales and minor thin limestones.
4. Total Organic Carbon (TOC) content of the Barnett Shale ranges from 0.85 to 4.9 percent in the New Mexico part of the Permian Basin. The kerogen population is dominantly gas prone but also appears to contain oil-prone types. The Barnett Shale is thermally mature throughout its extent in the New Mexico part of the Permian Basin.
5. A northwest-southeast trending fairway for Barnett shale gas exploration extends throughout the western portion of the New Mexico part of the Permian Basin. This fairway is defined by a region of maximum thermal maturity and source rocks with TOC contents greater than 2 percent.

6. The lower and upper Morrow shales contain sufficient TOC to be considered source rocks in southeastern New Mexico and are thermally mature. This is expected because the Morrow is one of the principal gas-producing stratal units in southeastern New Mexico. The Morrow shales are less thermally mature than the deeper, underlying Barnett Shale.
7. Production of shale gas from the Barnett has not yet been established and wells are yet to be drilled that will specifically test the Barnett for shale gas potential.

References

- Barker, C., 1980, Organic geochemistry in petroleum exploration: American Association of Petroleum Geologists, Continuing education course note series no. 10, 159 pp.
- Broadhead, R.F., 2006a, Mississippian strata in southeastern New Mexico, including the Barnett Shale: Thickness, structure and hydrocarbon plays: New Mexico Bureau of Geology and Mineral Resources, Open file report 497, CD-ROM.
- Broadhead, R.F., 2006b, Mississippian strata of southeastern New Mexico: Distribution, structure and hydrocarbon plays, *in* Raines, M.A., ed., Resource plays in the Permian Basin: Resources to reserves: West Texas Geological Society, Publication 06-117, p. 12-28.
- Broadhead, R.F., and Speer, S.W., 1995, Oil and gas in the New Mexico part of the Permian Basin, *in* A symposium of oil and gas fields of southeastern New Mexico, 1995 supplement: Roswell Geological Society, p. 32-49.
- Broadhead, R.F., Wilks, M., Morgan, M., and Johnson, R.E., 1998, The New Mexico petroleum source rock database: New Mexico Bureau of Mines and Mineral Resources, Digital data series DB2, 1 CD-ROM.
- Brooks, J., Cornford, C., and Archer, R., 1987, The role of hydrocarbon source rocks in petroleum exploration; *in* Brooks, J., and Fleet, A.J. (eds.), Marine petroleum source rocks: Geological Society of London, Special Publication 26, pp. 17-46.
- Brown, D., 2006, Arkoma shale play expanding, Barnett may have Arkansas cousin: American Association of Petroleum Geologists, Explorer, February 2006, p. 8, 10.

- Casavant, R.R., 1999, Speculations on basement tectonics: Insights from the White City Penn gas field, Eddy County, New Mexico, *in* A symposium of oil and gas fields of southeastern New Mexico, 1999: Roswell Geological Society, p. 204-207.
- Cornford, C., Morrow, J., Turrington, A., Miles, J.A., and Brooks, J., 1983, Some geological controls on oil composition in the North Sea; *in* Brooks, J. (ed.), Petroleum geochemistry and exploration of Europe: Geological Society of London, Special Publication 12, pp. 175-194.
- Dow, W. G., 1978, Petroleum source-beds on continental slopes and rises: American Association of Petroleum Geologists, Bulletin, v. 62, pp. 1584-1606.
- Durham, L.S., 2005, The 17-year overnight sensation, Barnett Shale play going strong: American Association of Petroleum Geologists, Explorer, May 2005, p. 4, 6.
- Dutton, S.P., Kim, E.M., Broadhead, R.F., Breton, C.L., Raatz, W.D., Ruppel, S.C., and Kerans, C., 2005, Play analysis and digital portfolio of major oil reservoirs in the Permian Basin: Bureau of Economic Geology, The University of Texas at Austin, Report of investigations 271, CD-ROM.
- Ewing, T.E., 1990, Tectonic map of Texas: The University of Texas at Austin, Bureau of Economic Geology, scale 1:750,000, 4 sheets.
- Frenzel, H.N., Bloomer, R.R., Cline, R.B., Cys, J.M., Galley, J.E., Gibson, W.R., Hills, J.M., King, W.E., Seager, W.R., Kottowski, F.E., Thompson, S., III, Luff, G.C., Pearson, B.T., and Van Sicken, D.C., 1988, The Permian Basin region, *in* Sloss, L.L., ed., Sedimentary cover – North American craton; U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 261-306.
- Geochem Laboratories, Inc., 1980, Source rock evaluation reference manual: Geochem Laboratories, Inc., Houston TX, pages not consecutively numbered.
- Haigler, L.B., and Cunningham, R.R., 1972, Structure contour map on top of the undifferentiated Silurian and Devonian rocks in southeastern New Mexico: U.S. Geological Survey, Map OM-218, scale 1:250,000.
- Hamilton, D.C., and Asquith, G.B., 2000, Depositional, diagenetic, and production histories of Chester ooid grainstones in the Austin (Upper Mississippian) field: Lea County, New Mexico, *in* Demis, W.D., Nelis, M.K., and Trentham, R.C., eds., The Permian Basin: proving ground for tomorrow's technologies: West Texas Geological Society, Publication 00-109, p. 95-106.
- Hamilton, D.C., Carlson, E.D., Raymond, P.C., Jr., Hathaway, W.L., Reid, A.M., Hillock, R.T., Robbins, S.L., Mahorney, J.R., Schlemmer, J., Martin, R.L.W.,

- and Wacker, H.J., 1991, Cross section from the Delaware Basin to the Midland Basin Lea County, New Mexico to Gaines County, Texas: West Texas Geological Society, Publication 91-98, 2 sheets.
- Hass, W.H., 1953, Conodonts of the Barnett Formation of Texas: U.S. Geological Survey, Professional Paper 243-F, p. 69-94.
- Hills, J.M., 1984, Sedimentation, tectonism and hydrocarbon generation in Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists, Bulletin, v. 68, p. 250-267.
- Hunt, J.M., 1996, Petroleum geology and geochemistry, second edition: W.H. Freeman and Company, New York, 743 pp.
- Jacobson, S.R., 1991, Petroleum source rocks and organic facies, *in* Merrill, R.K. (ed.), Source and migration processes and evaluation techniques: American Association of Petroleum Geologists, Treatise of petroleum geology, Handbook of petroleum geology, pp. 3-11.
- Jarvie, D.M., 1991, Total organic carbon (TOC) analysis, *in* Merrill, R.K. (ed.), Source and migration processes and evaluation techniques: American Association of Petroleum Geologists, Treatise of petroleum geology, Handbook of petroleum geology, pp. 113-118.
- Kerans, C., and Fitchen, W.M., 1995, Sequence hierarchy and facies architecture of a carbonate-ramp system: San Andres Formation of Algerita Escarpment and western Guadalupe Mountains, west Texas and New Mexico: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations 235, 86 p.
- Kosters, E.C., Bebout, D.G., Seni, S.J., Garrett, C.M., Jr., Brown, L.F., Jr., Hamlin, H.S., Dutton, S.P., Ruppel, S.C., Finley, R.J., and Tyler, N., 1989, Atlas of major Texas gas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 161 p.
- Lewan, M.D., 1987, Petrographic study of primary petroleum migration in the Woodford Shale and related rock units; *in* Doligez, B. (ed.), Migration of hydrocarbons in sedimentary basins: Editions Technip, Paris, pp. 113-130.
- Leythauser, D., Hageman, H.W., Hollerback, A., and Schafer, R.G., 1980, Hydrocarbon generation in source beds as a function of type and maturation of their organic matter: a mass balance approach: Proceedings of the 10th World Petroleum Congress, Bucharest, 1979, pp. 31-41.
- Martineau, D.F., 2007, History of the Newark East field and the Barnett Shale as a gas reservoir: American Association of Petroleum Geologists, Bulletin, v. 91,

- p. 399-403.
- Matchus, E.J., and Jones, T.S., *co-chairmen*, 1984, East-west cross section through Permian Basin of west Texas: West Texas Geological Society, Publication 84-79, 1 sheet.
- Merrill, R.K., 1991, Preface to this volume, *in* Merrill, R.K. (ed.), Source rock and migration processes and evaluation techniques: American Association of Petroleum Geologists, Treatise of petroleum geology, Handbook of petroleum geology, pp. xiii-xvii.
- Moore, R.C., and Plummer, F.B., 1922, Pennsylvanian stratigraphy of north central Texas: *Journal of Geology*, v. 30, p. 18-42.
- Mukhopadhyaya, P.K., 1994, Vitrinite reflectance as maturity parameter, *in* Mukhopadhyay, P.K., and Dow, W.G., eds., Vitrinite reflectance as a maturity parameter applications and limitations: American Chemical Society, Symposium Series 570, p. 1-24.
- Peters, K.E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: American Association of Petroleum Geologists, *Bulletin*, v. 70, pp. 318-329.
- Peters, K.E., and Cassa, M.R., 1994, Applied source rock geochemistry, *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system – from source to trap: American Association of Petroleum Geologists, *Memoir* 60, p. 93-120.
- Pollastro, R.M., 2007, Total petroleum system assessment of undiscovered resources in the giant Barnett Shale continuous (unconventional) accumulation, Fort Worth Basin, Texas: American Association of Petroleum Geologists, *Bulletin*, v. 91, p. 551-578.
- Pollastro, R.M., Jarvie, D.M., Hill, R.J., and Adams, C.W., 2007, Geologic framework of the Mississippian Barnett Shale, Barnett-Paleozoic total petroleum system, Bend arch – Fort Worth Basin, Texas: American Association of Petroleum Geologists, *Bulletin*, v. 91, p. 405-436.
- Pray, L.C., 1961, Geology of the Sacramento Mountains escarpment, Otero County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, *Bulletin* 35, 144 p.
- Sentfle, J.T., and Landis, C.R., 1991, Vitrinite reflectance as a tool to assess thermal maturity; *in* Merrill, R.K. (ed.), Source rock and migration processes and evaluation techniques: American Association of Petroleum Geologists, Treatise of petroleum geology, Handbook of Petroleum Geology, pp. 119-125.

- Silver, B.A., and Todd, R.G., 1969, Permian cyclic strata, northern Midland and Delaware Basins, west Texas and southeastern New Mexico: American Association of Petroleum Geologists, Bulletin, v. 53, p. 2223-2251.
- Speer, S.W., 1993, Morrow, *in* Atlas of major Rocky Mountain gas reservoirs: New Mexico Bureau of Geology and Mineral Resources, p. 159-161.
- Staplin, F.L., 1969, Sedimentary organic matter, organic metamorphism and oil and gas occurrence: Bulletin of Canadian Petroleum Geology, v. 17, pp. 47-66.
- Tissot, B.P., and Welte, D.H., 1978, Petroleum formation and occurrence: A new approach to oil and gas exploration: Springer-Verlag, Berlin, 538 pp.
- Tyler, N., Bebout, D.G., Garrett, C.M., Jr., Guevara, E.H., Hocott, C.R., Holtz, M.H., Hovorka, S.D., Kerans, C., Lucia, F.J., Major, R.P., Ruppel, S.C., and Vander Stoep, G.W., 1991, Integrated characterization of Permian Basin reservoirs, University Lands, west Texas: targeting the remaining resource for advanced oil recovery: The University of Texas at Austin, Bureau of Economic Geology, report of Investigations 203, 136 p.
- Tyson, R.V., 1987, The genesis and palynofacies characteristics of marine petroleum source rocks; *in* Brooks, J., and Fleet, A.J. (eds.), Marine petroleum source rocks: Geological Society of London, Special Publication 26, pp. 47-67.
- Vertrees, C.D., Adams, J.E., Fillman, L., Morningstar, C.F., Hall, W.E., Jones, T., Wade, D.E., Hills, J.M., Mear, C.E., Williams, H.L., Humbard, J.W., and Young, A., 1964, Cross section through Delaware and Val Verde Basins from Lea County, New Mexico to Edwards County, Texas: West Texas Geological Society, Publication 64-49, 1 sheet.
- Wright, W.F., 1979, Petroleum geology of the Permian Basin: West Texas Geological Society, Publication 79-71, 98 p.

Appendix A – Cross Sections

Appendix A contains the digital versions of four cross sections (D-D', K-K', W-W' and Z-Z') prepared for this project. The locations of the cross sections are indicated in Figure 3. The cross sections are in pdf format and were produced with a resolution sufficient for printing on a large format plotter.

Appendix B – Maps

Appendix B contains static digital versions of several of the maps prepared for this report. Those maps appear in the main body of the report and are presented in Appendix B as pdf documents that may be printed out separately. Resolution is sufficient to print these maps on a large format plotter. The maps in Appendix B can be viewed with Adobe, Inc.'s Acrobat Reader software which can be downloaded at no charge from the Adobe.com website.

Appendix C - Databases

Appendix C contains two databases in Microsoft Excel format. The *Barnett wells database* contains information of the wells used to construct the cross sections and structure contour and stratigraphic maps presented in this report. The *Barnett source rock database* contains data obtained from the petroleum source rock analyses that were used to construct the various maps pertaining to source rock parameters.

Barnett Wells Database

A database of well data and oil and gas shows as recorded on mudlogs in Microsoft Excel format (*Barnett wells database*) and is presented in Appendix C. This database contains data on well location, surface elevation, structural elevation of the top of several stratigraphic units discussed in this report, thickness of these stratigraphic units, and hydrocarbon shows in the Barnett Shale as recorded on mudlogs. All data were derived from files and records at the New Mexico Bureau of Mines and Mineral Resources Library of Subsurface Data. Longitude and latitude for most wells were with the Geographix Exploration System Landgrid Module and the Whitestar Corp. digital land grid. Depths to the top of the various stratigraphic units were obtained by correlating well logs during the course of this project. The following data fields are present for each well.

Operator

Lease name

Well number

API Number: Some wells in the New Mexico Bureau of Geology databases have no API number in our databases although an API number does exist for these wells.

Township (south): The number of the township south of the regional base line.

Range (east): The number of the range east of the New Mexico Principal Meridian.

Section: The number of the section within the township and range specified above.

Location in section: The footage of the surface location of the well from the section boundaries.

Longitude: The longitude of the surface location of the well.

Latitude: The latitude of the surface location of the well.

Surface elevation: The surface elevation that the well logs are referenced to, in feet above sea level. This is the Kelly bushing for most wells, but may be ground level of the derrick floor in some cases.

Depth to top of the upper Morrow shale: in feet. **NC** = top of upper Morrow shale not correlated. **Absent** = upper Morrow shale was correlated and found to be absent.

Depth to top of the lower Morrow shale: in feet. **NC** = top of lower Morrow shale not correlated. **Absent** = lower Morrow shale was correlated and found to be absent.

Barnett top: Depth to the top of the Barnett Shale, in feet. **Absent** = Barnett Shale was correlated and found to be absent. **Eroded** = correlation work revealed that the Barnett was absent due to erosion prior to deposition of overlying strata. **DNP** = not penetrated, the well was not drilled to a sufficient depth to penetrate the Barnett.

Chester top: Depth to the top of the Chester, in feet. The Chester is only present on the Mississippian shelf in the northern part of the project area. **Absent** = the Chester was correlated and found to be absent. **DNP** = not penetrated, the well was not drilled to a sufficient depth to penetrate the Chester.

Meramec top: Depth to the top of the Meramec, in feet. The Meramec is only present on the Mississippian shelf in the northern part of the project area. **Absent** = the Chester was correlated and found to be absent. **DNP** = not penetrated, the well was not drilled to a sufficient depth to penetrate the Chester.

Lower Miss lime top: Depth to the top of the lower Mississippian limestone, in feet. **DNP** = not penetrated, the well was not drilled to a sufficient depth to penetrate the lower Mississippian limestone.

Woodford top: Depth to the top of the Woodford Shale, in feet. **DNP** = not penetrated, the well was not drilled to a sufficient depth to penetrate the Woodford Shale.

Barnett elevation subsea: The elevation of the top of the Barnett Shale in relation to mean sea level.

upper Morrow shale elevation subsea: The elevation of the top of the upper Morrow shale in relation to mean sea level.

lower Morrow shale elevation subsea: The elevation of the top of the lower Morrow shale in relation to mean sea level.

upper Morrow shale thickness: the thickness of the upper Morrow shale, in feet.

lower Morrow shale thickness: the thickness of the lower Morrow shale, in feet.

Barnett thickness: the thickness of the Barnett Shale, in feet.

Barnett mudlog show: **Y** = a show was present on the gas chromatograph curve or the hotwire mud gas curve on the mudlog. **N** = a mudlog was available for the well and examination revealed no show was encountered.

Nature of show: **C** = confined = the show is discretely confined to a depth interval. **U** = unconfined = the show is diffuse through all or most of the Barnett and is not confined to a discrete depth interval.

Thickness of confined show: For confined show (see above), the thickness of the depth interval the show occurs in.

Type of hydrocarbons in show: The type of hydrocarbon (C_1 , C_2 , C_3 , or C_4) as determined from the chromatograph curve on the mudlog. If the chromatograph does not specifically have a tracing for the higher molecular weight hydrocarbons, the show is described, for example, as C_1 , C_{2+} for mudlogs that only distinguish between C_1 hydrocarbons and those hydrocarbons heavier than C_1 .

Show unit: the stratigraphic unit the show occurs in. For this project, only the Barnett Shale was examined for shows. The lower Morrow shale and the upper Morrow shale were not examined for shows.

Barnett Source Rock Database

This database is a companion to the various maps and analyses of petroleum source rock data presented on this CD. Analytical data are presented for 35 samples from 19 key exploration wells drilled in the Tucumcari Basin. Analyses were performed on composite samples of drill cuttings from 100 ft intervals, but a few of the analyses were obtained from composite samples of thickness other than 100 ft. Several attributes are given for each sample, including:

Sample number: this number is given for those sample analyzed by Humble Geochemical Services, Inc.

Operator: the operator of the well.

Lease name: The well's lease name.

Well number: The number of the well on the lease.

Township: The number of the township south of the regional base line.

Range: The number of the range east of the New Mexico Principal Meridian.

Longitude: The longitude of the surface location of the well.

Latitude: The latitude of the surface location of the well.

Sample depth: the depth of the sampled interval, in feet)

Stratigraphic unit: The stratigraphic unit the samples were obtained from, either the Barnett Shale, the lower Morrow shale, or the upper Morrow shale.

TOC - total organic carbon (weight percent)

TMAX: The Rock-Eval TMAX temperature, in degrees Celsius.

TAI: The visual kerogen Thermal Alteration Index. Available only for samples obtained from the New Mexico Petroleum Source Rock Project (Broadhead et al., 1998) as measured by Geochem Laboratories, Inc.

S1: The value of the Rock-Eval S1 peak, in mg hydrocarbons per gram of rock.

S2: The value of the Rock-Eval S2 peak, in mg hydrocarbons per gram of rock.

S3: The value of the Rock-Eval S3 peak, in mg carbon dioxide per gram of rock.

PI: The Rock-Eval Productivity Index.

S1/S2: The ration of the Rock-Eval S1 and S2 values.

HI: The Rock-Eval Hydrogen Index = $S2 \times 100/TOC$

HI: The Rock-Eval Oxygen Index = $S3 \times 100/TOC$

Algal - percentage of kerogen that is algal material, by visual estimate.

Amorphous - percentage of kerogen that is amorphous material, by visual estimate.

Herbaceous - percentage of kerogen that is herbaceous material, by visual estimate.

Woody - percentage of kerogen that is woody material, by visual estimate.

Inertinite - percentage of kerogen that is inertinite, by visual estimate.

Data source: Humble = samples were analyzed by Humble Geochemical Services, Inc. specifically for this project. NMSRC = samples were analyzed as by Geochem Laboratories, Inc. as part of the New Mexico Petroleum Source Rock Project (Broadhead et al., 1998).

Appendix D – GIS Projects

Appendix D contains a series of Geographic Information Systems (GIS) files that include the major contour maps prepared for this report. The GIS files will work with *ArcInfo* software with fully interactive capabilities as well as *ArcReader* software. *ArcInfo* allows the user to view and edit the maps; the *ArcInfo* software is available for purchase from ESRI Corp. *ArcReader* is a free program made available by ESRI Corp. that allows the user to view the GIS maps and superimpose them on each other after the *ArcReader* software is downloaded from this CD; *ArcReader* does not allow for modification of the maps; administrator privileges may be required to install *ArcReader* on your computer. The maps are also available in static format as pdf documents in Appendix B. The maps in Appendix B can be viewed with Adobe, Inc.'s *Acrobat Reader* software which can be downloaded at no charge from the Adobe.com website. Data is available in MS Excel Format (xls), ERSI Arc9.2 Geodatabase, and ESRI Shapefile formats.

To install ArcReader on your computer, follow these instructions. The files described in these instructions are included in Appendix D. ArcReader .pmf documents can be viewed with the ArcReader program included with the CD. Installation is described below. (ArcMap documents can be viewed and edited with ArcInfo desktop software that can be purchased separately from ERSI Inc.) Pdf documents can be viewed with Adobe Inc's Acrobat software which can be downloaded from the Adobe.com website.

To Install ArcReader 9.2 software in MS Windows:

(You may need administrative privileges to install this software.)

1. Open Windows Explorer and browse to the CDROM drive.
2. Locate and open the folder "ArcExplorer_Setup" which is located in the folder for Appendix D of this report.
3. Run the setup program by double clicking the Setup.exe icon.