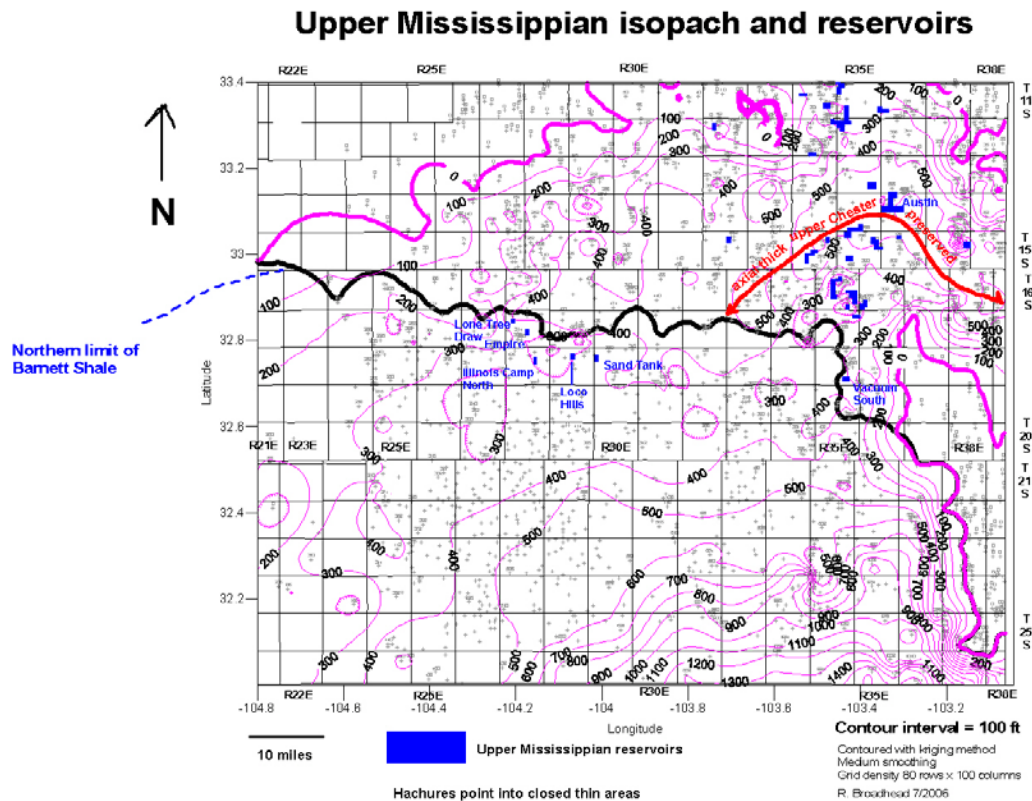


Mississippian Strata in Southeastern New Mexico, Including the Barnett Shale: Thickness, Structure and Hydrocarbon Plays

by

Ronald F. Broadhead

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



Open File Report 497

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

Socorro, NM 87801

Dr. Peter A. Scholle, Director

July 2006

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

Mississippian Strata in Southeastern New Mexico, Including the Barnett Shale: Thickness, Structure and Hydrocarbon Plays

By
Ronald F. Broadhead
New Mexico Bureau of Geology and Mineral Resources
A division of New Mexico Tech
Socorro, NM 87801

Abstract

Mississippian strata of southeastern New Mexico are Kinderhookian to Chesterian in age. In Eddy, Lea, and southern Chaves Counties, depth to the top of the Mississippian ranges from 5,500 ft in the northwest to 18,500 ft in the southeast. Lower Mississippian (Kinderhookian and Osagian) strata are 0 to 800 ft thick and are comprised of marine limestones and minor shales and chert. Upper Mississippian (Meramecian and Chesterian) strata are 0 to 1600 ft thick and are comprised of marine limestones and shales. Within the Upper Mississippian section, there is a sharp transition from shelf deposits dominated by limestones in the north to the basinal Barnett Shale in the south.

Forty gas and oil pools have been productive from Mississippian reservoirs in Eddy, Lea, and southern Chaves Counties. Twenty-four pools have been productive from Upper Mississippian reservoirs and 12 have been productive from Lower Mississippian reservoirs. Four gas pools have been productive from both Upper and Lower Mississippian reservoirs. Productive Upper Mississippian reservoirs are shelfal limestones in the north. The Mississippian play is one of the smallest plays in southeastern New Mexico and has yielded a cumulative 28 BCF gas and 1.3 MMBO from the 40 pools in Eddy, Lea, and southern Chaves Counties. Most production has been obtained from Chesterian limestone reservoirs of the northern shelf. Chesterian reservoirs are concentrated in the San Simon Channel where uppermost Chesterian strata were preserved prior to deposition of Early Pennsylvanian sediments.

Four subplays are identified in the Mississippian of Eddy, Lea, and southern Chaves Counties of southeastern New Mexico: (1) Chester shallow marine limestones in the San Simon Channel and related structurally low areas on the northern shelf; (2) Upper Mississippian limestones interbedded with Barnett shales just south of the shelf-basin transition; (3) small and widely disseminated reservoirs in lower Mississippian limestones in the north; and (4) the as-yet untried Barnett Shale in the south.

Introduction and Purpose

This report presents stratigraphic and structure contour maps of Mississippian strata, brief lithologic descriptions of Mississippian lithofacies, and data and maps on oil gas reservoirs in Mississippian strata in the southeastern part of New Mexico (Figure 1). Although the Permian Basin is commonly subdivided into several tectonic elements including the Northwest Shelf, the deep Delaware and Midland Basins, and the Central Basin Platform (Figure 2), these tectonic elements were not formed until the Pennsylvanian. The present day thickness and distribution of Mississippian strata are affected partially by the Pennsylvanian-age tectonic elements that controlled post-depositional erosion from Pennsylvanian high areas. Internal facies as well as thickness are controlled by tectonic and depositional elements that were present during the Mississippian.

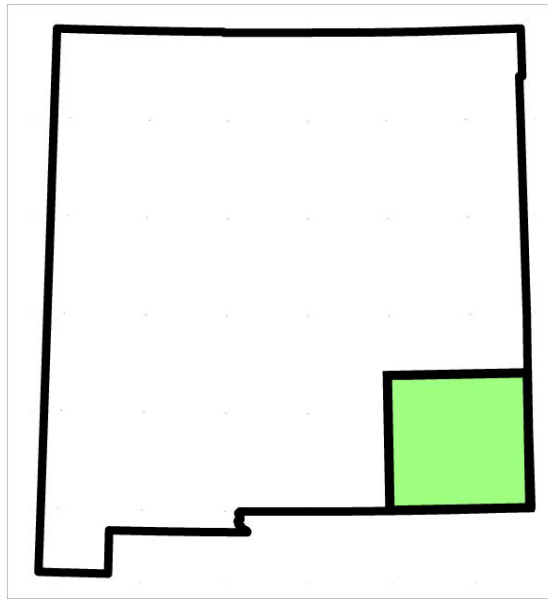


Figure 1. Location of project area in southeastern New Mexico.

Strata of Mississippian age extend throughout large parts of New Mexico and are present in the central, northeastern, northwestern, southwestern, and southeastern parts of the state (Armstrong and others, 1979). In southeastern New Mexico, the Mississippian section is 0 to 2,000 ft thick and therefore constitutes a major part of the stratigraphic section. Mississippian strata are divided into the lower Mississippian limestone and the Upper Mississippian (Figure 3). The lower Mississippian limestone is Kinderhookian and Osagian in age and is composed predominantly of marine limestone with minor chert and shale. It is 0 to 800 ft thick in southeastern New Mexico.

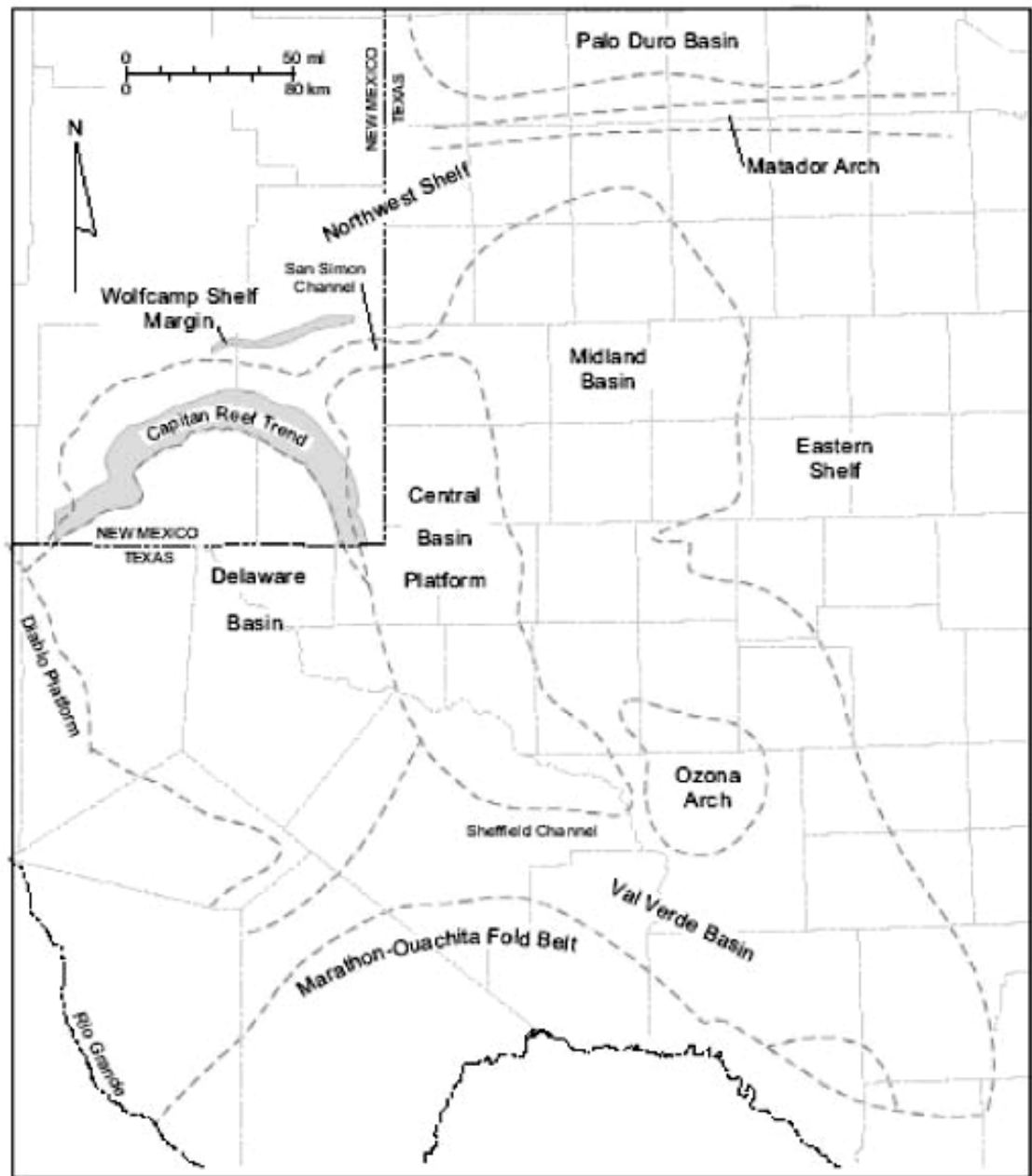


Figure 2. Map of Permian Basin of southeastern New Mexico and west Texas, showing major tectonic and depositional elements. From Dutton and others (2000) after Silver and Todd (1969), Hills (1984), Frenzel and others (1988), Kisters and others (1989), Ewing (1990), Tyler and others (1991), and Kerans and Fitchen (1995).

The Upper Mississippian is 0 to 1600 ft thick in southeastern New Mexico. It is subdivided areally into a northern shelfal facies and a southern basinal facies. The northern shelfal facies is Meramecian to Chesterian in age and consists predominantly of marine limestones and minor marine shales.

The southern basinal facies of the Upper Mississippian is the Barnett Shale and is composed almost entirely of gray to black marine shales. The Barnett is 200 to 1,600 ft thick in southeastern New Mexico. Correlations with shelf strata to the north indicate it is Meramecian to Chesterian in age. In its northernmost part, tongues of Chesterian and Meramecian limestones extend southward into the basinal Barnett Shale. Tongues of Barnett shale also extend northward onto the shelf where they are intercalated with Chesterian and Meramecian limestone strata of the shelf.

Natural gas and oil production from Mississippian reservoirs has been relatively low. A total of 28 billion ft³ (BCF) gas and almost 1.3 million bbls oil (MMBO) have been produced from 40 gas and oil pools in Mississippian strata. This accounts for only 0.02% of the oil and 0.04% of the natural gas that have been produced from New Mexico. Fields are small, but discoveries have increased within the last decade with 18 of the known 40 accumulations discovered since 1996. Reservoirs discovered thus far are productive mostly from Chesterian and Meramecian (Upper Mississippian) carbonate strata of the northern shelf area. Osagian (Lower Mississippian) carbonate shelf strata have yielded

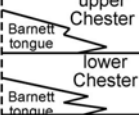
SYSTEM	SERIES	STAGE	Sacramento Mountains (Pray, 1961)	Southeastern New Mexico (subsurface)					
				Northern Lea County (Hamilton and Asquith, 2000)		Lea, Eddy & Chaves Counties (this study)			
				basin (south)	shelf (north)	basin (south)	shelf (north)		
Pennsylvanian	Lower		Atokan	Atokan	Atokan	Morrowan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

Figure 3. Stratigraphic chart of Mississippian rocks in southeastern and south-central New Mexico.

the remainder of oil and gas produced from the Mississippian section. Four reservoirs have been classified as being productive from the Barnett Shale (Upper Mississippian), but the productive reservoir zones are Chesterian and Meramecian limestone tongues of the shelf facies that pinch out to the south and are interbedded with Barnett shales in the northernmost part of the basin.

The Barnett Shale has become a major source of natural gas in the Fort Worth Basin of central Texas where it presently provides more than one-half of the shale gas produced in the United States (Durham, 2005). Because of the extensive production provided by the Barnett in the Fort Worth Basin, strong interest has developed in equivalent Mississippian shales in Oklahoma, Arkansas, and west Texas. Although Barnett shales have not yet been proven productive in southeastern New Mexico, their presence over a 5,000 mi² area in this part of the state suggests that they may hold interest as either a source of natural gas or of oil.

The main purpose of this work was to provide the New Mexico State Land Office with a structure contour map of the top of the Mississippian System in southeastern New Mexico. During the course of this project, the top of the Mississippian was correlated in more than 2,700 wells. In order to accurately correlate the top of the Mississippian, several other lithostratigraphic units were also correlated. The resulting data were used to prepare the various isopach and structure maps presented in this report. Additional work involved identifying and mapping oil and gas reservoirs that have been productive from Mississippian strata in southeastern New Mexico, compiling basic data on these reservoirs, and preparing this report. It was decided to turn the data compiled for the structure map project into this report because the Mississippian System is one of least productive stratigraphic units in southeastern New Mexico and, with the exception of the work by Hamilton and Asquith (2000) on the Austin gas pool, has been only superficially described in southeastern New Mexico. With the attention drawn by the extensive development of unconventional gas resources in the Mississippian Barnett Shale of central Texas, it is thought that this report will provide useful information on those who may become interested in gas and oil resources in Mississippian reservoirs of southeastern New Mexico as well as providing useful regional stratigraphic and structural information to those interested in Mississippian strata for other reasons.

Acknowledgments

This 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. 06-539-P615-0613. 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 Stephen Menicucci, an undergraduate student at New Mexico Tech, who was employed to calculate longitude and latitudes for the wells identified in Appendix A. Stephen also helped enter geologic data into the well database. As always, gratitude is extended to Amy Kracke and Annabelle Lopez of the New Mexico Bureau of Geology and Mineral Resources for their meticulous effort at maintaining the archives in the New Mexico Library of Subsurface Data. Dr. Peter Scholle, Director of the New Mexico Bureau of Geology and Mineral Resources, supported the preparation of this report.

Methodology

This project involved correlating the top, base, and selected internal subdivisions of the Mississippian in 1756 wells throughout southeastern New Mexico (Figure 4; database *Mississippian wells* in Appendix A). Well records and logs from an additional 1002 wells were examined but these additional wells were determined not to have been drilled to a sufficient depth to penetrate Mississippian strata. The following stratigraphic markers were correlated (Figure 3): (1) top of Mississippian; (2) top of Chester; (3) top of Meramec; (4) top of Barnett Shale; (5) top of lower Mississippian limestone; (6) top of the Upper Devonian Woodford Shale; and (7) top of pre-Woodford rocks in places where the Woodford is absent due to pre-Mississippian erosion or nondeposition. Well locations are referenced in well records by section, township, range, and footage from section boundaries; these geographic coordinates were converted to latitude and longitude using the Geographix well base module (Geographix is a registered trademark of Halliburton Corp.) and the Whitestar digital land grid of New Mexico referenced to the 1927 North American datum.

Correlations were made primarily with geophysical well logs and sample logs on file at the New Mexico Bureau of Geology and Mineral Resources Library of Subsurface Data. The sample logs, used in conjunction with the geophysical logs, proved very useful in distinguishing the Barnett Shale from overlying shale-rich Pennsylvanian strata. Also utilized were unpublished descriptions of well cuttings by the late R.V. Hollingsworth for several dozen wells throughout the project area; a set of Hollingsworth's sample descriptions is on file in the Library of Subsurface Data. Dr. Hollingsworth's reports include descriptions of cuttings and his determinations of stratigraphic tops. For Pennsylvanian and Permian strata, the Hollingsworth reports include fusulinid data. Other invaluable aids to correlation include published stratigraphic cross sections based on well logs (Meyer, 1966; Hamilton and Asquith, 2000).

A correlation network of cross sections throughout the project area was constructed to provide quality assurance. Six of these cross sections have been prepared in digital format (Figure 4) and are presented as Plates 1-6 in Appendix B.

Well locations were plotted via computer using Surfer 8 (Surfer 8 is a registered trademark of Golden Software, Inc.). Well data were then gridded with a kriging method with Surfer 8. The various contour maps presented in this report were contoured with

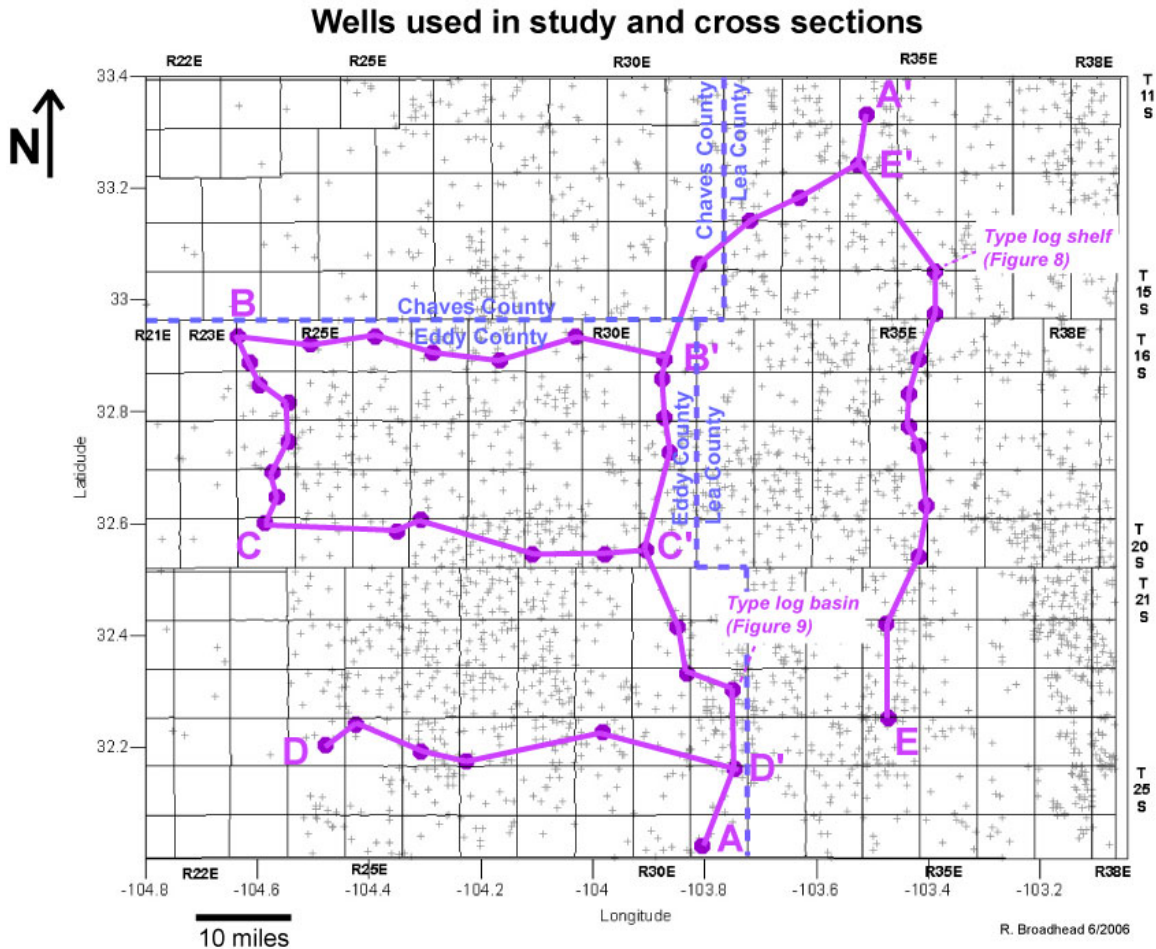


Figure 4. Locations of wells used in this project and locations of selected cross sections constructed for this project. See Appendix A for database of wells and Appendix B for cross sections.

Surfer 8. Gridding and contouring parameters are listed on the maps. Structure contour maps were prepared for the top of the Mississippian and the top of the lower Mississippian limestone. These are presented as small-format maps with a contour interval of 250 ft in this text and as large-format maps with a contour interval of 100 ft in Appendix C. Isopach maps were prepared for the entire Mississippian, the Upper Mississippian, the lower Mississippian limestone, and the Barnett Shale. These are presented as small-format maps with a contour interval of 100 ft in this text and as large-format maps with a contour interval of 50 ft in Appendix D.

Oil and gas pool boundaries portrayed on maps in this report were drawn based upon geographic pool limits established by the New Mexico Oil Conservation Division (NMOCD). Data regarding these boundaries are listed in R-Orders issued by NMOCD.

Boundary, expansion, and contraction data for each pool as given in the R-Orders are compiled and catalogued at the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources.

The following approach was used to determine cumulative production data for each reservoir.

1. Cumulative production data for each reservoir were obtained from the 1993 Annual Report of the New Mexico Oil and Gas Engineering Committee. The cumulative production data tabulated by reservoir are available only in the hardcopy report of the Engineering Committee and are not available digitally. The production data were entered into an Excel spreadsheet along with the reservoir name and the productive stratigraphic unit. Cumulative production data tabulated by reservoir in pre-1994 reports of the New Mexico Oil and Gas Engineering Committee are generally valid. The 1993 report lists cumulative data as of December 31, 1993.
2. Annual oil production data for each reservoir for years subsequent to 1993 were obtained from the 1994, 1995, and later Annual Reports of the New Mexico Oil and Gas Engineering Committee. These data are now published annually by BL Resources of Hobbs, New Mexico. These production data were entered into the Excel spreadsheet that contains the 1993 cumulative production data. The annual production data in the post-1993 reports, as tabulated by reservoir, are generally valid. However, cumulative production data by reservoir, as tabulated by reservoir, in the post-1993 reports are not valid because they do not include historical production from several types of wells, including:
 - a. Older wells that had formerly produced from the reservoir but were subsequently plugged and abandoned;
 - b. Older wells that had formerly produced from the reservoir but were subsequently recompleted to another zone;
 - c. Production from some wells whose operator had changed during the lifetime of the well; production prior to an operator name change is not included in the cumulative production totals for many wells and reservoirs in the post-1993 reports.

The problems with post-1993 cumulative production data result from a change in the New Mexico production data system in 1994 which omitted data described in a, b, and c above. Therefore the use of cumulative production data as published in

the 1994 and later reports will result in totals that may be significantly less than what has actually been produced.

3. Cumulative production for each reservoir was calculated by taking the annual production from 1994 through 2003 and adding it to the cumulative production data obtained from the 1993 annual report.

The Well Database

A database of oil and gas wells with structural and thickness data for the stratigraphic subdivisions of the Mississippian is presented in *Appendix A* in Microsoft Excel Format (*Mississippian wells database.xls*). This database contains information on well location, surface elevation, and depth and subsea elevation of the top of several stratigraphic units including the top of the Mississippian System, the Barnett Shale, the Chester, the Meramec, the lower Mississippian limestone, the Woodford Shale, and the stratal unit below the Woodford (for wells in which the Woodford is not present). All of the tops presented in the database were correlated with electric and gamma-ray logs and/or sample logs. Also presented are thickness values for the entire Mississippian section, the Upper Mississippian, the Barnett Shale, and the Lower Mississippian. The abbreviation **DNP** indicates the well was not drilled sufficiently deep to penetrate the stratal unit indicated. The term **absent** indicates that the stratal unit is not present in the well and that the well was drilled sufficiently deep to penetrate the stratal unit that underlies the unit indicated – in other words, the indicated unit was either never deposited, was deposited and then subsequently eroded, or has been removed by normal faulting.

The following data fields are presented for each well:

Operator: The name of the company or individual that operated the well.

Lease name: The name of the lease the well was drilled on.

Well number: The lease number of the well.

API number: The unique API well number, if present in the records of the New Mexico Bureau of Geology and Mineral Resources.

Township (south): The township south of the regional base line that the well is located in.

Range (east): The range east of the New Mexico Principal Meridian that the well is located in.

Section: The section within the given township and range that the well is located in.

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

Latitude: The location of the well in decimal degrees latitude.

Longitude: The location of the well in decimal degrees longitude.

Elevation: The elevation of the well in feet above sea level.

Mississippian top: The depth to the top of the Mississippian System, in feet.

Mississippian subsea: The elevation of the top of the Mississippian System in feet above or below sea level.

Barnett top: The depth to the top of the Barnett Shale, in feet.

Chester top: The depth to the top of the Chester, in feet.

Meramec top: The depth to the top of the Meramec, in feet.

Lower Miss lime top: The depth to the top of the lower Mississippian limestone, in feet.

Woodford top: The depth to the top of the Woodford Shale, in feet.

Pre-Woodford top: The depth to the top of the stratal unit below Woodford Shale if the Woodford Shale is not present, in feet.

Mississippian thickness: Thickness of the Mississippian System, in feet, if the entire Mississippian section was penetrated by the well.

Upper Mississippian thickness: Thickness of the Upper Mississippian, in feet, if the entire Upper Mississippian section was penetrated by the well.

Lower Mississippian thickness: Thickness of the Lower Mississippian, in feet, if the entire Lower Mississippian section was penetrated by the well.

Comments: Selected observations made during well correlation are listed here.

Stratigraphy

Introduction

The Mississippian System in southeastern New Mexico is 0 to 2000 ft thick (Figure 5; Plate 9 in Appendix D). For this report, the Mississippian has been subdivided into two stratigraphic units, the *Upper Mississippian* and the *lower Mississippian limestone* (Figure 3). These subdivisions generally reflect common usage and simplify the published stratigraphy of some local studies in order to accommodate the regional correlations made as part of this study.

The lower Mississippian limestone is 0 to 800 ft thick in southeastern New Mexico (Figure 6; Plate 10 in Appendix D). All but the lowermost 20 to 50 ft thick are considered to be Osagian in age; the lowermost 20 to 50 ft are thought to be Kinderhookian in age. Most, but not all, scout cards and completion reports place the top of the Mississippian at the top of the lower Mississippian limestone. Therefore, structure maps drawn on the basis of scout card stratigraphic calls will place the top of the Mississippian at the top of the lower Mississippian limestone in most places and at the top of the Upper Mississippian in other places, thereby producing structural elevation changes that are not actually present.

The Upper Mississippian is 0 to 1600 ft thick in southeastern New Mexico (Figure 7; Plate 11 in Appendix D). The Upper Mississippian is Meramecian to Chesterian in age and is subdivided into three stratigraphic units based on both vertical and lateral facies changes (Figure 3). In the southern part of the project area, the Upper Mississippian is the basinal Barnett Shale. To the north, the shale facies of the Barnett intertongues with shelf limestones. In northern Lea County, Hamilton and Asquith (2000) have subdivided these shelf limestones into an upper Chester unit, a lower Chester unit, and a Meramec unit (Figure 3) and indicate northward thinning tongues of the Barnett that extend up onto the shelf. For this project, the stratigraphy of Hamilton and Asquith has been simplified into a Chester unit and a Meramec unit (Figures 3, 8) in order to accommodate stratigraphic subdivisions recognized by the regional correlations made for this study. The lower part of the Chester is the main upper tongue of the Barnett and the base of this tongue marks the contact between the Chester and the underlying Meramec unit. The base of the Meramec coincides with the base of a lower tongue of the Barnett and marks the contact between the Meramec and the underlying lower Mississippian

Isopach map of Mississippian strata

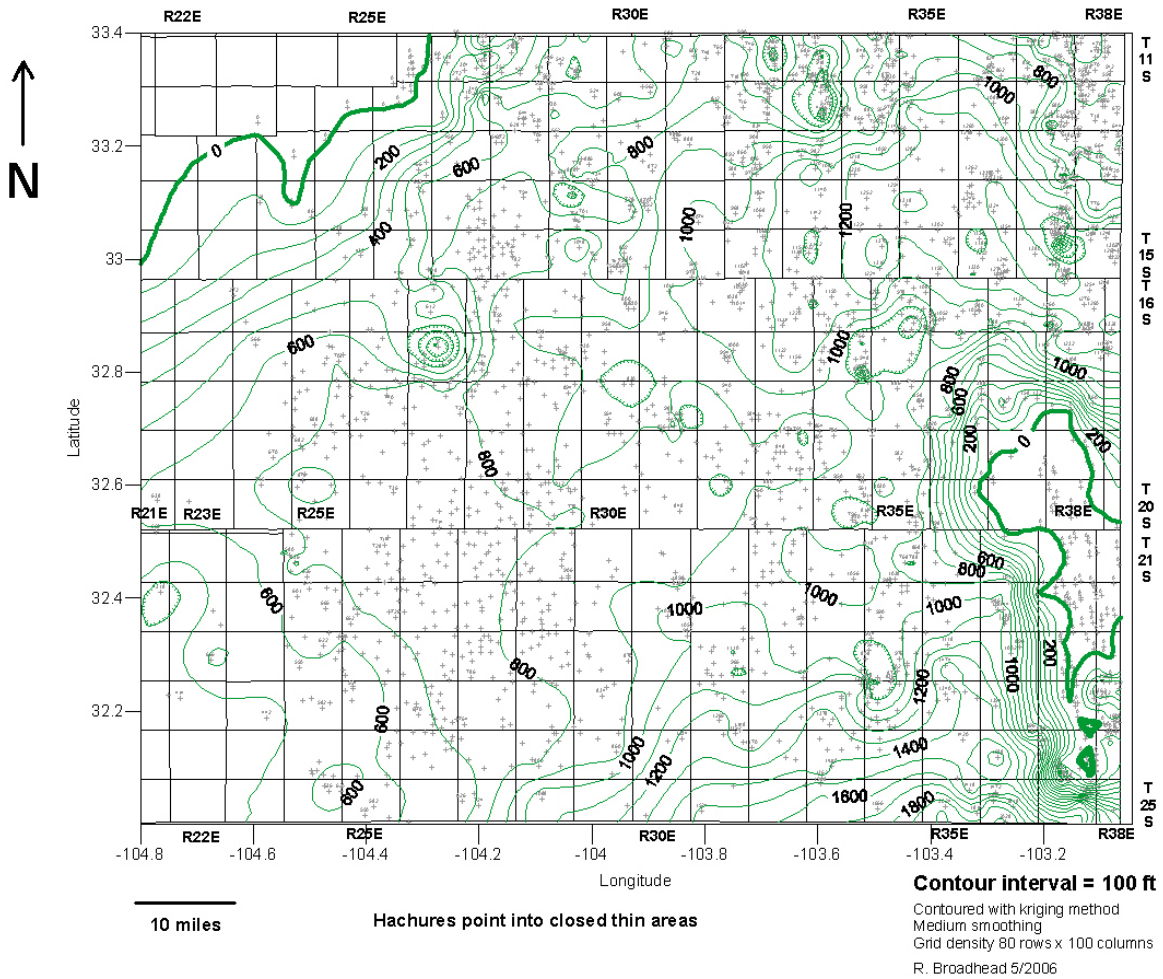


Figure 5. Isopach map of Mississippian strata in southeastern New Mexico.

limestone. Both of the Barnett tongues laterally interfinger to the north with limestones and are considered to be parts of the Chester and Meramec for this report. The Chester unit is equivalent to the “Austin cycle” reported on completion reports for some wells; in those reports where the term Austin cycle is used, the Meramec of Hamilton and Asquith (2000) and this report is identified as Chester. Toward the south, the Upper Mississippian limestones are not present and the entire Upper Mississippian section is correlated as the Barnett Shale (Figure 9; Plates 1, 6 in Appendix B; Figure 7, Plate 11 in Appendix D).

Isopach map of lower Mississippian strata

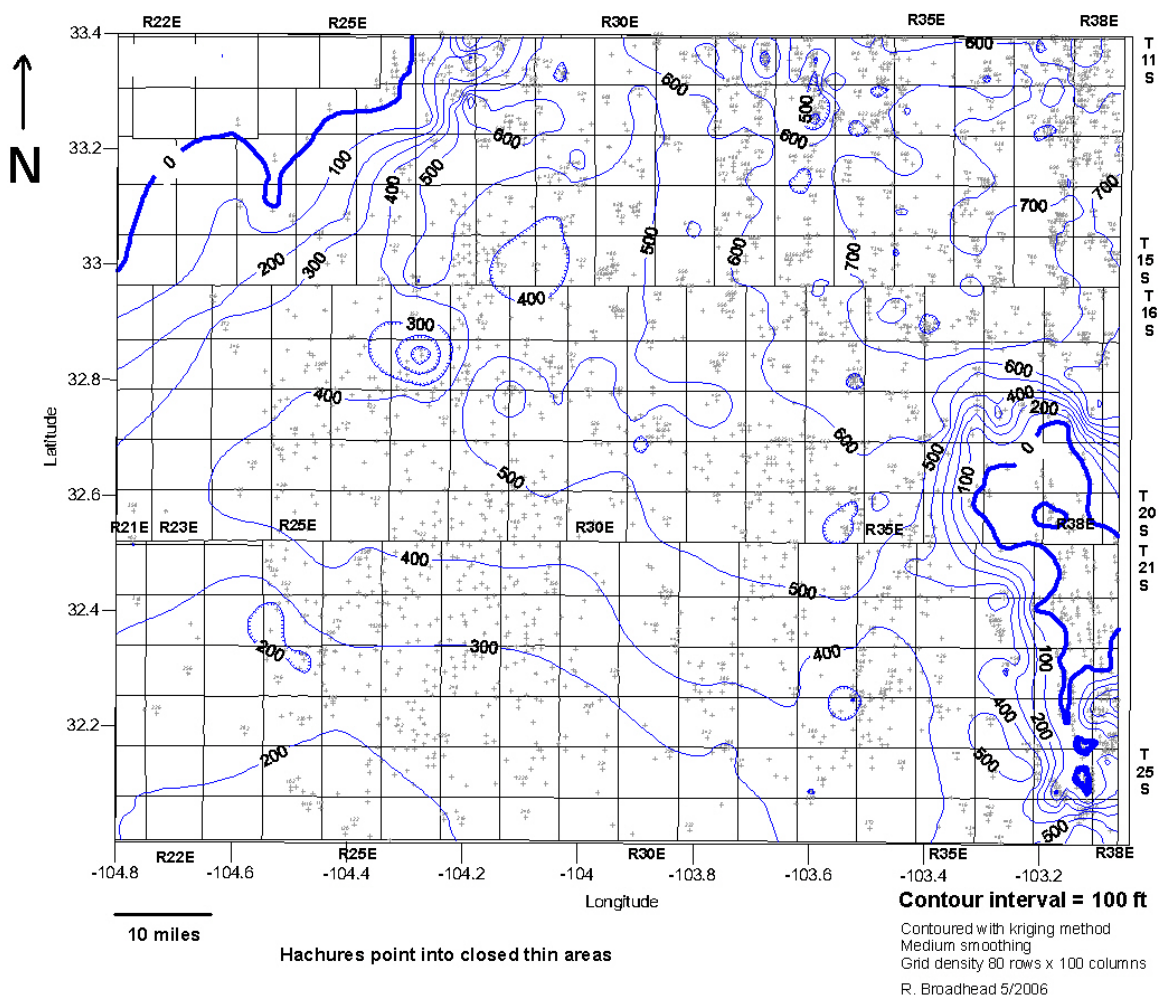


Figure 6. Isopach map of Lower Mississippian strata in southeastern New Mexico.

Isopach map of upper Mississippian strata

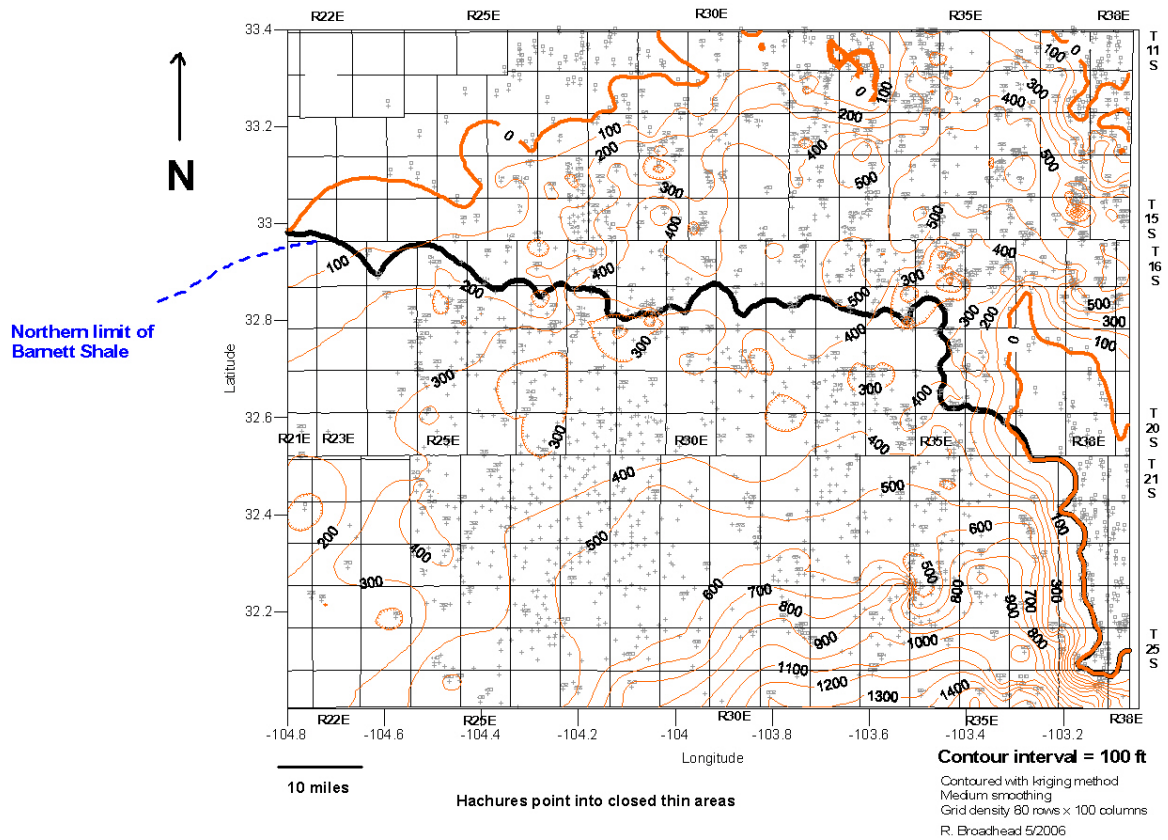


Figure 7. Isopach map of Upper Mississippian strata in southeastern New Mexico.

**Neville G. Penrose
No. 1 Fairweather Unit
Sec. 3-T15S-R35E**

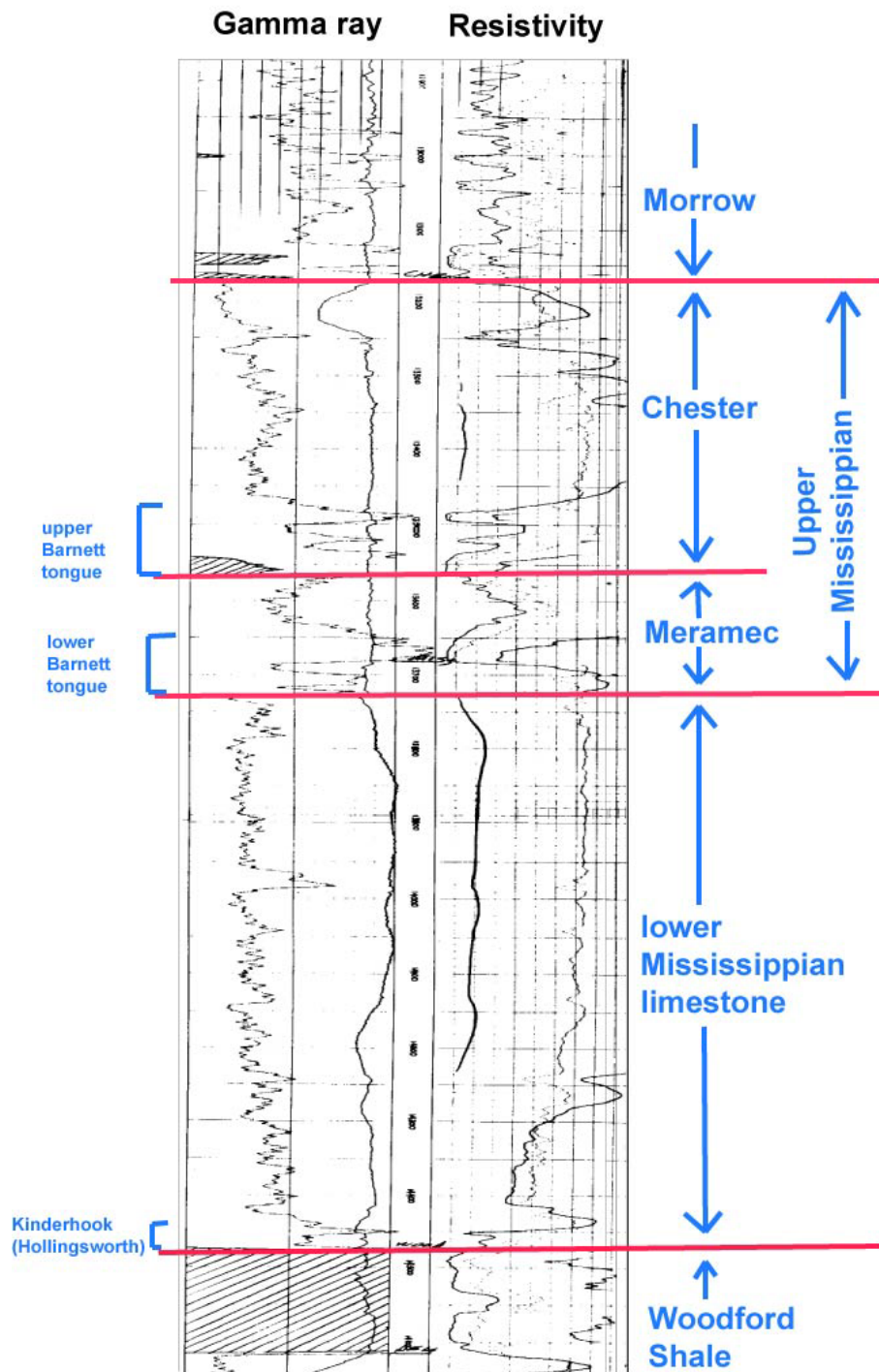


Figure 8. Typical well log of Mississippian strata on shelf areas of southeastern New Mexico. In this well, Upper Mississippian strata are subdivided into a Chester unit and a Meramec unit simplified from the nomenclature of Hamilton and Asquith (2000). See Figure 4 for location of well.

The Mississippian in outcrop, Sacramento Mountains

Extensive outcrops of Mississippian strata are exposed in the Sacramento Mountains, 60 miles west of the western boundary of the project area. Stratigraphic relationships in these outcrops have been studied and discussed extensively by several workers including Pray (1961), Loudon and Bowsher (1941, 1949), Lane (1974), and Bowsher (1986). As these are the nearest outcrops of Mississippian strata with extensive exposure that exhibit regional north-south stratigraphic variations, the stratigraphy of these outcrops is an important consideration when examining the stratigraphy of the subsurface of southeastern New Mexico. The following section summarizes the work of these researchers in the Sacramento Mountains.

In the Sacramento Mountains, the Mississippian section is subdivided into four formations (ascending, Figure 3): Caballero Formation, Lake Valley Formation, Rancheria Formation, and Helms Formation. The Caballero Formation is Kinderhookian in age. It is 15 to 60 ft thick and rests disconformably on gray and black shales and nodular limestones of the Sly Gap Formation (Upper Devonian) and black shales of the Percha Formation (Upper Devonian). The Caballero Formation is composed of interbedded gray, nodular, argillaceous limestones and gray calcareous shale. A wide variety of marine invertebrate fossils are present.

The Lake Valley Formation is Osagian in age. It has a maximum thickness of 400 ft in the Sacramento Mountains. A disconformity separates the Lake Valley Formation from the underlying Caballero Formation. The Lake Valley Formation is composed predominantly of crinoidal limestones. Calcareous, quartzose siltstones and gray to black calcareous shales are minor facies. The Lake Valley Formation is characterized by complex internal facies variations. Large numbers of crinoidal bioherms are prominent features in outcrops of the lower part of the Lake Valley Formation in the Sacramento Mountains. The upper part of the formation is generally devoid of bioherms and is in places dominated by dark-gray calcareous shales and argillaceous limestones.

The Rancheria Formation overlies the Lake Valley Formation and is Meramecian in age. It consists of up to 300 ft of dark-gray, thin-bedded argillaceous and silty limestones and calcareous siltstones. Minor thin beds of medium-gray, silty to sandy crinoidal limestones are also present. The lower contact with the Lake Valley Formation is a pronounced low-angle unconformity.

The Helms Formation is Chesterian in age. It has a maximum thickness of 60 ft in the Sacramento Mountains. It consists of thinly interbedded argillaceous limestone,

yellow shale, and gray shale. Thin beds of oolitic limestone are present in the upper part of the Helms. Pray (1961) concluded on the basis of scant evidence that the lower contact of the Helms with the Rancheria is a disconformity.

In the Sacramento Mountains, the contact between the Mississippian section and overlying Pennsylvanian strata is an angular unconformity. In places, the Helms, Rancheria, and upper Lake Valley Formations have been removed by pre-Pennsylvanian or earliest Pennsylvanian erosion. Morrowan (earliest Pennsylvanian) strata, so prevalent in the subsurface of the area covered by this report (see Meyer, 1966), are thin or absent in the Sacramento Mountains and consist dominantly of dark-gray shales, medium- to coarse-grained quartzose sandstone, and minor dark-gray, generally argillaceous limestone of the Gobbler Formation.

Lane (1974) utilized conodont zonation to analyze internal facies relations of Mississippian strata in the Sacramento Mountains and outcrops in the Hueco and Franklin Mountains of west Texas. Lane came to several important conclusions, including:

1. The Caballero Formation (Kinderhookian) thins southward in the Sacramento Mountains but is not present to the south in the Franklin Mountains near El Paso. No time equivalent strata are present in the southern Sacramento Mountains or in the Franklin Mountains.
2. The Lake Valley Formation attains a maximum thickness of 400 ft in the northern Sacramento Mountains but thins to a featheredge in the southern Sacramento Mountains.
3. The Rancheria Formation is younger than the Lake Valley Formation. Therefore, the two are not laterally equivalent to each other, as some workers had postulated.
4. The Late Mississippian Rancheria and Helms Formations form a northward thinning wedge that overlaps a southward thinning wedge formed by the Early Mississippian Caballero and Lake Valley Formations.

Lower Mississippian in the subsurface of southeastern New Mexico

Lower Mississippian strata vary in thickness from 0 to more than 800 ft (Figure 6). Lower Mississippian strata are thickest in the San Simon Channel north of the Central Basin Platform. They thin to the west and southwest and are absent from the Central Basin Platform where they were eroded by uplift during the Pennsylvanian. They

pinchout to the northwest underneath the overlying Pennsylvanian System. The presence of a maximum area of thickness in the San Simon Channel, where the Lower Mississippian is overlain by the Upper Mississippian, suggests the channel may have been present as a subtle structural low as early as the Early Mississippian although major development probably did not occur until the Pennsylvanian.

Lower Mississippian strata are generally referred to as the *lower Mississippian limestone* or more simply as the *Mississippian limestone*. They are comprised predominantly of limestones. Shale beds generally less than 10 ft thick are a minor amount of the section and generally occur in the lowermost and uppermost parts of the lower Mississippian limestone. As discussed previously, the lower Mississippian is considered to be mostly Osagian in age, although the lowermost 20 to 50 ft may be Kinderhookian.

Hollingsworth's descriptions do not indicate the presence of Kinderhookian strata south of T23S and also west of approximately R23-24E. This distribution of Kinderhookian strata is similar to the distribution of Kinderhookian strata in the Sacramento and Franklin Mountains (Lane 1974). Where Hollingsworth's reports identify a Kinderhookian interval, his sample tops generally seem to coincide with the top of a 5 to 10 ft thick gray to dark-gray shale bed in the lowermost part of the Mississippian. This shale bed is underlain by 10 to 20 ft of greenish-gray to medium-gray to light-brown, fine-grained or finely crystalline argillaceous limestone. In places, a white to light-gray siltstone is present at the base of Hollingsworth's Kinderhookian interval.

The 300 to 800 ft of the lower Mississippian limestone that overlie Hollingsworth's Kinderhook are thought to be Osagian in age (Hamilton and Asquith, 2000; unpublished well reports by R. V. Hollingsworth). The Osagian section is comprised almost entirely of limestone, although beds of gray to dark-gray shale are locally present in the uppermost and lowermost parts, especially in the northern and western parts of the project area.

Few published reports describe the Osagian section in the subsurface of southeastern New Mexico. In the area around the Austin gas field in northern Lea County, Hamilton and Asquith (2000) described the Osagian section as comprised of brown to tan lime mudstones with minor sponge spicules and brachiopod spines in a lime mud matrix and containing minor dolomite rhombs and chert. Sample logs indicate the Osagian section is comprised of tan to dark-brown, finely crystalline dense limestone. The limestones are darker to the west and southwest, coinciding with a general thinning

of the lower Mississippian in those directions (Figure 6; Plate 10 in Appendix D). Gray to dark-brown chert is also indicated on the sample logs. Sample logs indicate that the percentage of chert seems to generally increase toward the west and southwest. This increase in chert content coincides with increasing radioactivity as indicated by gamma-ray logs (see cross section D-D', Plate 5 in Appendix B).

Upper Mississippian in the subsurface of southeastern New Mexico

Upper Mississippian strata vary in thickness from 0 to more than 1600 ft (Figure 7; Plate 11 in Appendix D). As discussed above, the upper Mississippian section is of Meramecian and Chesterian age. The upper Mississippian has been described more fully in the literature than the lower Mississippian because of the reservoir study by Hamilton and Asquith (2000). Hamilton and Asquith (2000) provided a well log cross section and lithologic descriptions of the Upper Mississippian in northern Lea County. The Chester and Meramec are comprised mostly of limestones with some interbedded shales. There is a facies transition from a shelfal limestone-dominated facies in the north to the basinal Barnett Shale in the south. Tongues of Barnett Shale extend northward onto the shelf where they interfinger with shelf limestones. Hamilton and Asquith indicate that the transition from the Barnett in the south to shelf limestones in the north occurs within a distance less than two townships wide (10-12 miles). As discussed below, this study supports that conclusion.

At the Austin Mississippian gas pool, Hamilton and Asquith (2000) describe the upper Chester as dominated by bioclastic oolitic grainstones and bioclastic oolitic packstones. In addition to oolites, the grainstones contain fragments of bryozoans, crinoids, trilobites, and brachiopods. Where not completely cemented by calcite, porosity is present and this facies forms reservoirs. The bioclastic oolitic packstones contain fragments of bryozoans, crinoids, trilobites, brachiopods, and minor oolites. In this facies, intergranular areas are filled with lime mud so that porosity is minimal; this facies does not form reservoirs.

Underlying Hamilton and Asquith's upper Chester unit are their lower Chester and Meramec units and intercalated tongues of the Barnett Shale. The limestones in these units are bioclastic grainstones and bioclastic packstones (Hamilton and Asquith, 2000). The bioclastic grainstones consist of fragments of bryozoans, crinoids, trilobites and brachiopods; no oolites are present. Pore spaces have been completely filled by calcite cements so that the grainstones in the Meramec and lower Chester do not form reservoirs.

The bioclastic packstones consist of fragments of bryozoans, crinoids, trilobites, and brachiopods. No oolites are present. Intergranular areas are filled with lime mud so that porosity is minimal; the packstones do not form reservoirs. Intercalated Barnett tongues are described by Hamilton and Asquith as black marine shales.

The productive oolitic zones trend northeast-southwest in the Austin pool (Hamilton and Asquith, 2000). The location and trend of some the productive reservoirs coincide with the crest of a northeast-southwest trending structure that is thought to have formed primarily during the Pennsylvanian. Another oolite sand body is also oriented northeast-southwest but occurs on the northwestern flank of the structure. However, the location of Chesterian oolite shoals over the crest of this structure suggests that minor structural movement may have taken place during the Late Mississippian and created a high-energy environment that localized shoal deposition (Hamilton and Asquith, 2000).

For this project, the Upper Mississippian section is subdivided into a Chesterian section and a Meramecian section north of the shelf-basin transition (Figures 3, 8). This subdivision reflects the cyclic nature of the Mississippian on the northern shelf. The Meramec constitutes the lower cycle and consist of a lower tongue of black, marine Barnett shale overlain by shelfal/ramp limestones. The Chester constitutes the upper cycle and also consists of a lower tongue of black, marine Barnett shale overlain by shelfal/ramp limestones. Smaller-scale cycles are present within both of these larger cycles. Toward the south, there is a sharp facies transition to a section composed entirely of basinal marine Barnett shales (Figures 3, 9; Plates 1, 3, 6 in Appendix B). The work done for this study corroborates the suggestion of Hamilton and Asquith that the transition from the shelfal dominated facies in the north (consisting of the Chesterian and Meramecian limestones with interbedded Barnett shale tongues) to a facies consisting almost entirely of basinal Barnett shales in the south (and interbeds of shelf limestones) occurs over a fairly short distance; the width of this transition is less than two townships (12 miles) in most places. The boundary between the basinal facies to the south and the shelf facies to the north is indicated on the cross sections (Plates 1, 3, 6 in Appendix B) as well as the isopach map of the Upper Mississippian (Figure 7; Plate 11 in Appendix D). In places, a few tongues of Chesterian and Meramecian limestones are present within the Barnett; these tongues pinch out toward the south and in places form gas reservoirs.

The Barnett Shale thickens southward from 200 to 300 ft thick near its northernmost extent to more than 1600 ft thick in the southeastern part of the project area along the New Mexico-Texas border (Figure 10; Plate 12 in Appendix D). Although

some of the southward thickening may be depositional, regional correlation (Cross section A-A'; Plate 1 in Appendix B) indicates much of it appears to be erosional; the Barnett consists of a southward-dipping wedge of shale that is truncated to the north by a regional angular unconformity at the base of the Pennsylvanian. This correlation indicates that the upper parts of the Barnett (and its northern shelfal equivalents) were removed by erosion prior to deposition of overlying Lower Pennsylvanian strata. If this correlation is correct, then a substantial part of Late Mississippian time is not represented by strata in the northern part of the project area (but rather by the unconformity between the Mississippian and the Pennsylvanian) but is represented by the upper parts of the Barnett Shale in the southern part of the project area. Therefore, only the lower part of the Barnett is time equivalent to the Meramec and Chester units on the northern shelf. Given the 1600+ ft thickness of the Barnett in the south, a substantial lacuna is represented by the Mississippian-Pennsylvanian unconformity in the north. This stratigraphic association is in agreement with the statement by Hamilton and Asquith (2000) that "the Barnett has been thought by some to be younger than Chester" or at least indicates that the Chester as recognized on the northern shelf area is early Chesterian and that the bulk of the Barnett is later Chesterian.

In localized areas, the isopach map of the Upper Mississippian (Figure 7; Plate 11 in Appendix D) indicates substantial local thinning of the Upper Mississippian section. In some places the entire Upper Mississippian is absent. These areas of thin or absent Upper Mississippian coincide with localized highs on the Mississippian structure contour map (Figure 11; Plate 7 in Appendix C) and represent removal of upper Mississippian strata over rising positive elements of the Ancestral Rocky Mountains before deposition of Pennsylvanian strata. The Upper Mississippian and the Lower Mississippian have been removed by erosion from most of the Central Basin Platform in the southeastern part of the project area and from the northwestern part of the Northwest Shelf in the northwestern part of the project area (Figures 5-7; Plates 9-11 in Appendix D). On the highest parts of the Central Basin Platform, Precambrian crystalline rocks are overlain by Lower Permian strata. On somewhat lower areas, Mississippian strata have been preserved and are unconformably overlain by either Middle to Upper Pennsylvanian strata or by Lower Permian strata.

Texas American Oil Corp.
No. 1 Todd 14
Sec. 14-T23S-R31E

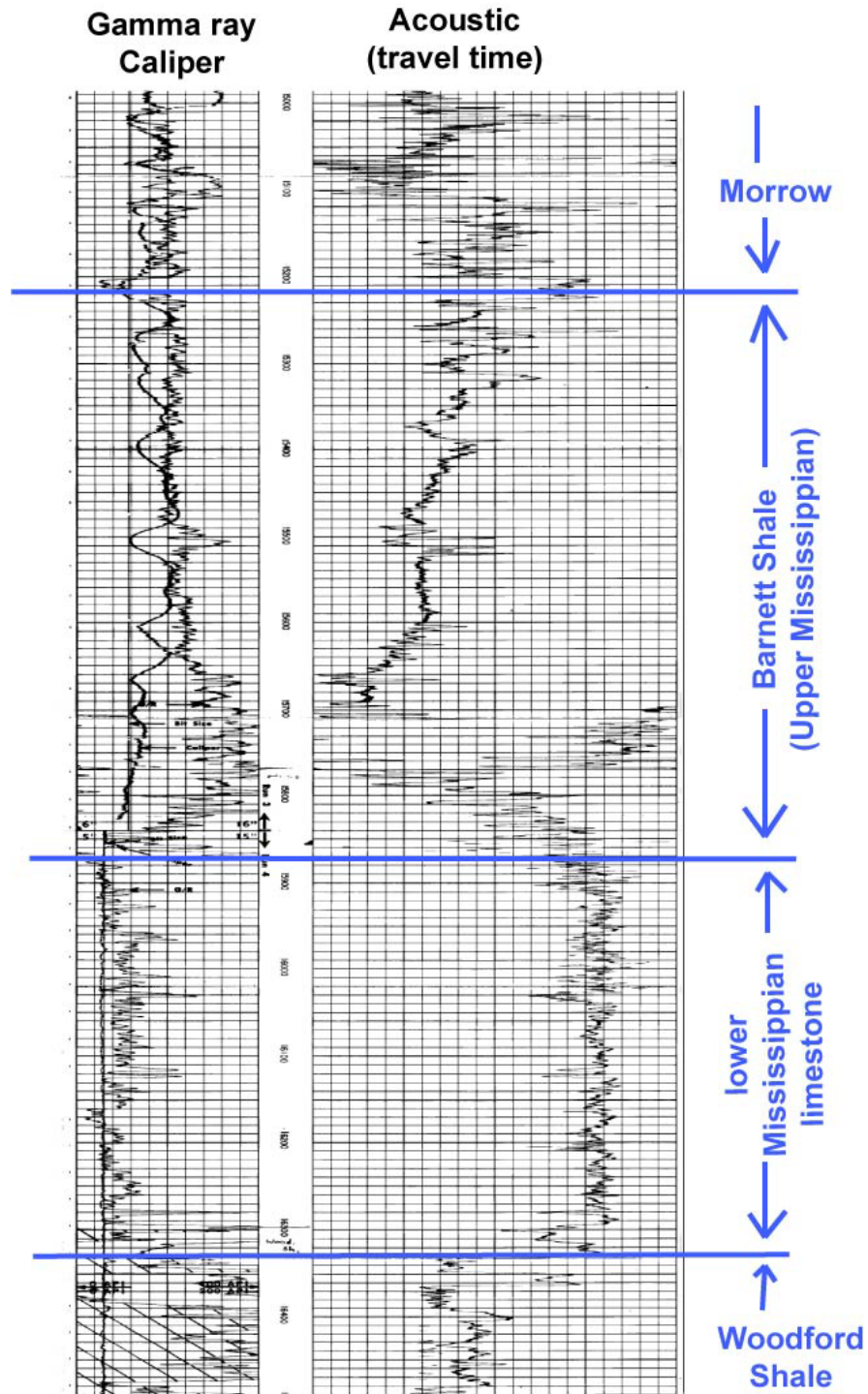


Figure 9. Typical well log of Mississippian strata in basinal areas of southeastern New Mexico. In this well, Upper Mississippian strata are represented by the Barnett Shale. See Figure 4 for location of well.

Isopach map of Barnett Shale (Upper Mississippian) southeastern New Mexico

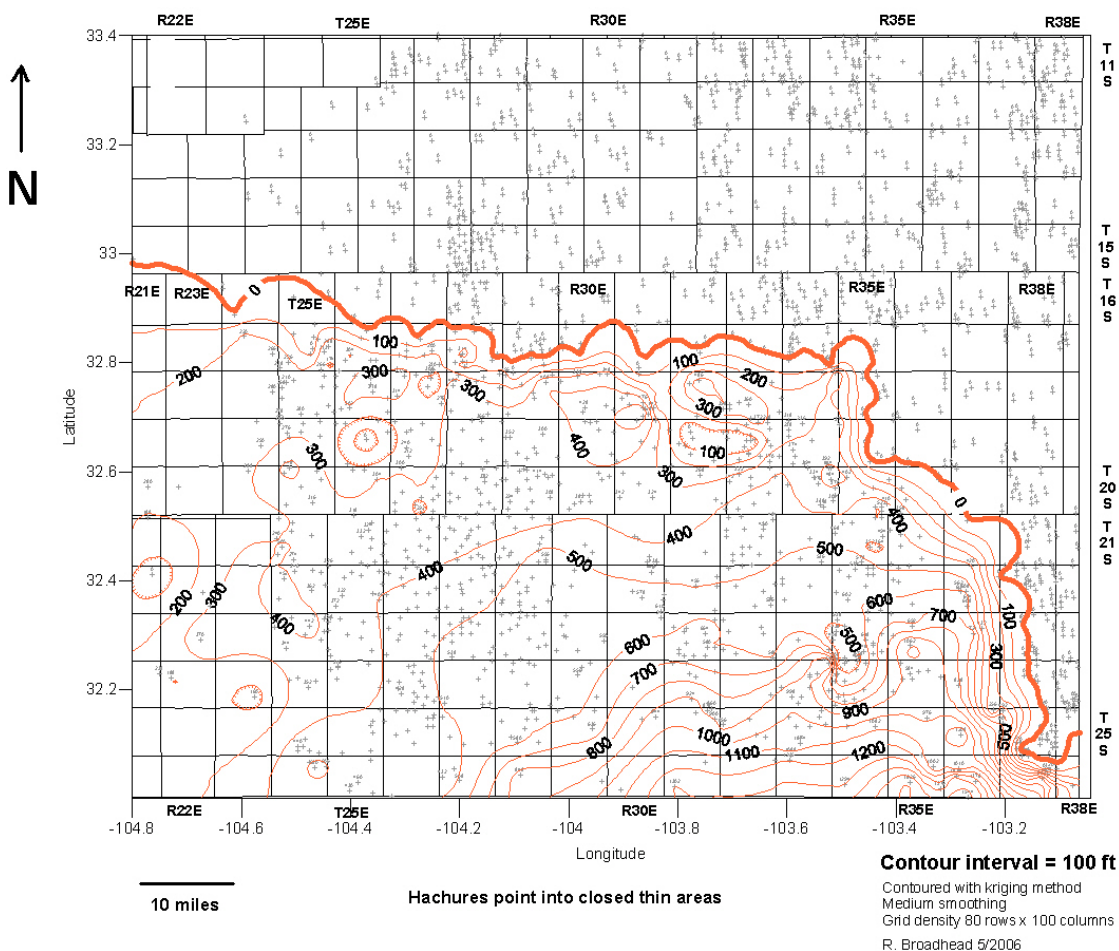


Figure 10. Isopach map of Barnett Shale in southeastern New Mexico. The thickness values do not reflect tongues of the Barnett that extend and pinchout northward within the Upper Mississippian section north of the zero isopach line.

Structure contours on top of Mississippian strata (Contoured with kriging method)

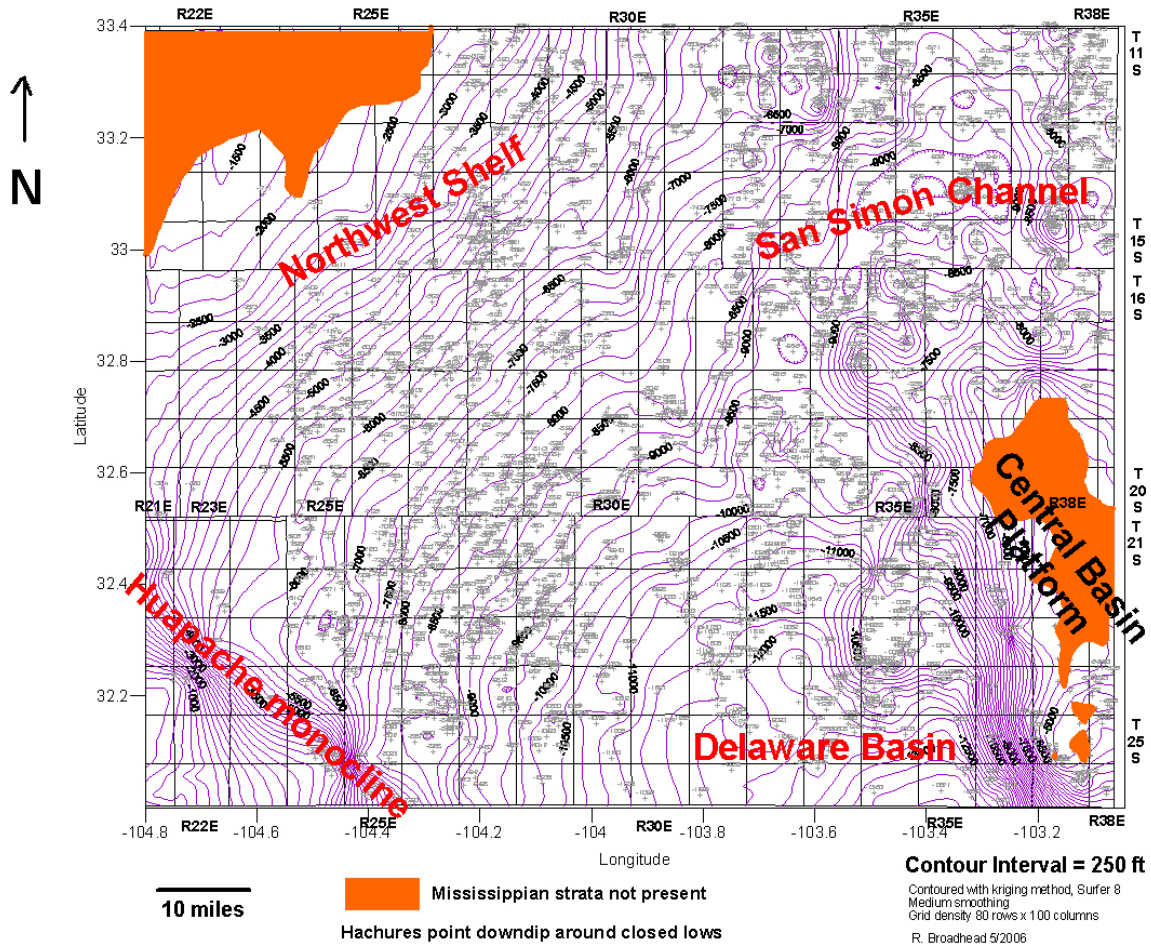


Figure 11. Structure contours on top of Mississippian strata in southeastern New Mexico.

Structure

Introduction

For this report, two structure contour maps were prepared: structure on top of the Mississippian System (Figure 11; Plate 7 in Appendix C) and structure on top of the lower Mississippian limestone (Figure 12; Plate 8 in Appendix C). The structure map on top of the Mississippian System is the more definitive of the two maps because it utilized more wells (1612). The structure map on top of the lower Mississippian limestone used fewer wells (761) because a large number of wells that have been drilled to establish production from Morrow (Lower Pennsylvanian) reservoirs penetrated the top of the Mississippian, but relatively few wells have been drilled sufficiently deep to penetrate the top of the deeper lower Mississippian limestone.

Depth to top of the Mississippian ranges from 5,496 ft in T14S R24E in the northwestern part of the project area to 16,850 ft in the southeastern part of the project area. Depth to top of the lower Mississippian limestone ranges from 5,496 ft in T14S R24E in the northwestern part of the project area to 18,476 ft in T26S R35E in the southeastern part of the project area.

Regional tectonic features

The structure maps clearly indicate the major tectonic elements in the region: the deep Delaware Basin, the Northwest Shelf, the Central Basin Platform, the San Simon Channel, and the Huapache monocline. 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 a depositional phenomenon that may have been caused by localization of Pennsylvanian and Lower Permian (Abo) shelf-margin reef complexes over pre-existing subtle 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 reader has the freedom to draw the fault where he pleases based on these contours and the data, bearing in mind that the Humble Oil Company No. 1 Huapache well, located in Section 35, T23S, R22E, intersected the Huapache fault and encountered the top of the Mississippian at an approximate subsea

Structure contours on top of lower Mississippian limestone

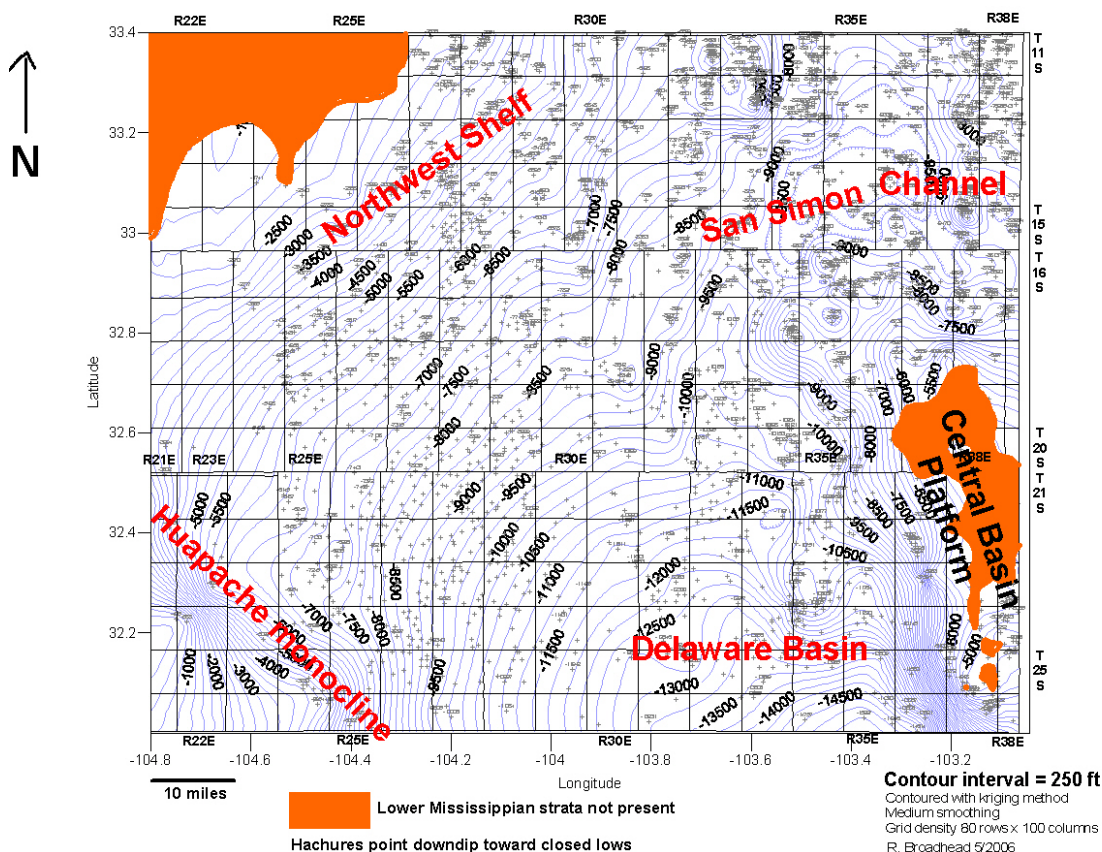


Figure 12. Structure contours on top of the lower Mississippian limestone in southeastern New Mexico.

elevation of -2000 ft and again at an approximate subsea elevation of -6040 ft as the Mississippian section was repeated by the reverse fault.

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.

The San Simon Channel, the narrow east-west trending structurally low area that separates the Central Basin Platform from the Northwest Shelf, is clearly depicted on the structure contour maps. As discussed previously, Lower Mississippian strata are somewhat thicker in the San Simon Channel than in adjacent areas. This is suggestive that

minor structural development of this feature may have occurred as early as the Early Mississippian, although most movement occurred during the Pennsylvanian.

Local structural features

Numerous smaller structures are superimposed over the regional structural elements. These smaller structures generally cover areas 1 mi² (one section) to 36 mi² (one township). These smaller structures are depicted on the structure contour maps as enclosed structurally high areas or as southeast-dipping structural noses superimposed on the regional slope that defines the transition between the Northwest Shelf and the Delaware Basin. The structure map on top of the Mississippian System (Figure 11; Plate 7 in Appendix C) indicates these structures have a relief of 50 ft to 500 ft; most have a structural relief less than 250 ft. In general, Upper Mississippian strata (Figure 7; Plate 11 in Appendix D) thin over these structures. Over some structures the Upper Mississippian is absent entirely and Pennsylvanian strata unconformably overlie the lower Mississippian limestone. Where the Upper Mississippian is absent, the lower Mississippian limestone is thinner over the structures than in adjacent areas; where the Upper Mississippian is present, the lower Mississippian limestone is not thinner over the structures compared to adjacent off-structure areas. These stratigraphic relations indicate that most, perhaps all, of these smaller structures were formed primarily during Pennsylvanian Ancestral Rocky Mountain tectonism, uplifted structures were subjected to erosion on their crests, and the structures were subsequently buried beneath Pennsylvanian and Permian sediments.

The smaller structures discussed above are generally fault-bounded and form either tilted fault blocks bounded on one side by a high-angle, normal or reverse fault or are elongated horst blocks bounded on two sides by parallel or semi-parallel high-angle faults (see Hanagan, 2002; Speer and Hanagan, 1995; Haigler and Cunningham, 1972).

Structures as oil and gas traps

Many of these fault-bounded structures form traps in Silurian and Ordovician reservoirs (see Hanagan, 2002; Speer and Hanagan, 1995; Broadhead, 2005). Many of these fault blocks formed topographically positive elements during the Pennsylvanian and Early Permian and were gradually buried by Pennsylvanian and Early Permian sediments. As such, they controlled deposition of Pennsylvanian reservoirs. A number of gas reservoirs in Morrow (Lower Pennsylvanian) sandstones are formed by channel

complexes that were deposited in paleotopographic low areas adjacent to or between Mississippian positive elements (see Derrick et al., 1999). Other Morrow gas accumulations are formed by thick sand accumulations that were deposited on top of paleostructures, an association that led Casavant (1999) to conclude that the structures were originally paleotopographically low but were subsequently structurally inverted to become high areas. Alternatively, these positive structure areas may have formed paleotopographic highs during Morrowan time that localized deposition of sand by being the sites of higher energy depositional environments than surrounding structurally low areas. Yet higher in the section, Strawn (Middle Pennsylvanian) patch reefs were formed over the top of pre-Strawn paleostructures; reef growth was localized over the tops of pre-existing structures that had bathymetric expression (Thornton and Gaston, 1967; Harris, 1990). These Strawn patch reefs form numerous and significant oil and gas reservoirs in the New Mexico portion of the Permian Basin (see Broadhead et al., 2004; Dutton et al., 2005).

Mississippian Oil and Gas Reservoirs

Introduction

Forty gas and oil pools have been productive from Mississippian strata within the area in southeastern New Mexico covered by this report (Table 1; Figure 13). Twenty-four of these pools have been productive from Upper Mississippian strata, 12 have been productive from Lower Mississippian strata, and four pools have been productive from both Upper and Lower Mississippian strata. A cumulative total of 28 billion ft³ (BCF) gas and almost 1.3 million bbls oil and condensate (MMBO) have been produced from the 40 Mississippian pools; 24.6 BCF, or 87%, of the Mississippian gas have been produced from reservoirs in Upper Mississippian strata and 389 thousand bbls oil and condensate (MBO), or 31% of the Mississippian oil and condensate, have been produced from Upper Mississippian strata. Most of the reservoirs produce gas and associated light hydrocarbon liquids (generally referred to as condensate). A few pools are classified as oil pools and produce light oils along with associated gas. The Austin Mississippian gas pool is the largest reservoir thus far discovered; a cumulative 14.9 BCF gas and 176 MBO have been produced from the Austin pool. Discovered in 1957, the Austin pool still had 7 active

Table 1. Oil and gas pools productive from Mississippian strata in the part of southeastern New Mexico covered by this report. **O**, oil pool; **G**, gas pool, **MMCF**, million ft³ gas; **MBO**, thousand bbls oil or condensate. Pool names are those used by the New Mexico Oil Conservation Division.

Pool name	Reservoir unit	O/G	Discovery year	Number active wells 2003	Depth to production (feet)	2003 gas production MMCF	2003 oil production MBO	Cumulative gas production MMCF 12/31/03	Cumulative oil production MBO 12/31/03
Upper Mississippian pools									
Vacuum South (Mississippian)	Barnett (carbonate in lower Barnett)	O	2004	0	10,720	0	0	0	0
Empire (Barnett)	Barnett (Chester tongue)	G	1999	1	10,210	99	0.649	542	0.6
Sand Tank (Chester)	Barnett (Chester tongue)	G	1996	1	11,690	0	0	390	5
Lone Tree Draw (Mississippian)	Barnett (Meramec tongue)	O	2003	1	9,712	77	1.721	77	2
Austin (Mississippian)	Chester	G	1957	7	13,200	163	0.891	14688	178
Austin Northwest (Mississippian)	Chester	G	1964	1	13,440	0	0	93	0.5
Austin Southwest (Mississippian)	Chester	G	1964	1	12,900	0	0	39	0.4
Dempster Mill (Mississippian)	Chester	G	2003	2	12,680	15	0.122	16	0.1
Denton (Mississippian)	Chester	O	1950	0	11,240	0	0	0	5
Eight Mile Draw (Mississippian)	Chester	G	2000	2	12,160	19	0.08	64	0.9
Feather North (Mississippian)	Chester	G	1998	2	12,460	2	0	22	0
Grassland (Austin)	Chester	G	2002	2	13,440	974	14.153	1346	26
Grassland Northeast (Mississippian)	Chester	G	2003	0	13,030	0	0	0	0
Morton (Mississippian)	Chester	G	1996	2	13,550	284	4.218	363	7
Ranger Lake South (Austin)	Chester	G	2001	1	12,730	31	0.557	31	0.6
Shoe Bar (Mississippian)	Chester	G	1962	1	12,180	37	0.276	873	23
Shoe Bar South (Mississippian)	Chester	G	1986	0	13,030	0	0	118	4
Townsend (Mississippian)	Chester	G	1980	2	12,150	98	0.574	101	0.5
Townsend North (Mississippian)	Chester	G	1980	3	12,430	799	14.71	1726	49
Caprock North (Mississippian)	Meramec	O	1979	2	11,120	119	0.628	2711	70
Illinois Camp North (Chester)	Meramec	G	1997	0	11,040	0	0	11	0.1
Loco Hills (Chester)	Meramec	G	1998	2	11,400	133	1	1170	19.0
Ranger Lake South (Chester)	Meramec	G	2003	1	12,400	4	0.011	4	0.01
Shoe Bar East (Chester)	Meramec	G	1964	1	12,500	0.7	0	1	0
Subtotals, Upper Mississippian				35		2655.7	39.59	24606	399
Lower Mississippian pools									
Big Dog (Mississippian)	lower Mississippian limestone	G	1990	0	13,400	0	0	0	0
Bronco (Mississippian)	lower Mississippian limestone	O	1959	0	10,940	0	0	350	417
Caudill (Mississippian)	lower Mississippian limestone	G	1961	0	13,280	0	0	11	0
Chisum (Mississippian)	lower Mississippian limestone	G	1969	0	6,820	0	0	0	0
Gladiola (Mississippian)	lower Mississippian limestone	O	1980	1	11,400	0	0.626	307	202
Gladiola Southwest (Mississippian)	lower Mississippian limestone	O	1963	1	11,150	0	0.341	0	24
King (Mississippian)	lower Mississippian limestone	G	1978	0	11,430	0	0	16	0
Lowe Ranch (Mississippian)	lower Mississippian limestone	G	1964	0	11,900	0	0	78	3
Mescalero Sands (Mississippian)	lower Mississippian limestone	G	1977	1	9,750	42	0.068	1208	9
Ranger Lake South (Lower Mississippian)	lower Mississippian limestone	G	2003	1	13,160	0.3	0	0.3	0
White Ranch (Mississippian)	lower Mississippian limestone	G	1977	0	8,320	0	0	843	207
White Ranch West (Mississippian)	lower Mississippian limestone	G	1993	0	7,760	0	0	62	0.4
Subtotals, Lower Mississippian				4		42.3	1.035	2675	663
Lower and Upper Mississippian pools									
Eight Mile Draw Northwest (Mississippian)	Chester lower Mississippian limestone	G	2004	0	12,270 (Chester) 12,620 (Lower Mississippian)	0	0	0	0
Sand Springs	Chester lower Mississippian limestone	G	2001	1	12,280 (Chester) 12,600 (Lower Mississippian)	1.4	0.04	11	0.3
Sand Springs	Chester lower Mississippian limestone	G	2001	1	12,280 (Chester) 12,600 (Lower Mississippian)	1.4	0.04	11	0.3
Big Dog Northwest (Mississippian)	Meramec lower Mississippian limestone	G	2002	1	13,080 (Meramec) 13,250 (Lower Mississippian)	11	0	22	0
Four Lakes (Mississippian)	Meramec lower Mississippian limestone	G	2000	2	12,610	185	1.547	621	5
TOTALS				43		3095	42	28135	1258

wells at the end of 2003, the most of any of the reservoirs productive from Mississippian strata within the area covered by this report. The first Mississippian pool discovered in southeastern New Mexico was Denton, in 1950 (Table 1). Eighteen of the 40 gas and oil pools have been discovered since 1996.

The 40 Mississippian gas and oil pools were productive of 3.1 BCF gas and 42 MBO during 2003. Almost 2.9 BCF, or 92% of the gas, were produced from Upper Mississippian reservoirs. Almost 39.6 MBO, or 94% of the liquid hydrocarbons, were produced from Upper Mississippian reservoirs. The 40 pools had only 43 active wells among them at the end of 2003; 14 reservoirs had no active wells at then end of 2003 (Table 1). The Grassland pool yielded 974 million ft³ (MMCF) gas during 2003, the most of any of the Mississippian pools. The second most productive Mississippian pool during 2003 was Townsend North with an annual production of 799 MMCF gas.

Upper Mississippian reservoirs

There are 24 oil and gas pools that have been productive from Upper Mississippian strata in the part of southeastern New Mexico covered by this report (Table 1; Figure 13). An additional 4 pools have been productive from both Lower and Upper Mississippian strata. Most of the pools are productive from the Chester at depths of 11,240 to 13,550 ft. Five pools are productive from the Meramec at depths of 11,040 to 12,500 ft. Productive strata in the Meramecian pools have been classified as Chester by the New Mexico Oil Conservation Division but the productive intervals are within the Meramec as correlated in this report.

Four of the pools (Vacuum South, Empire, Sand Tank, and Lone Tree Draw) are classified as productive from the Barnett Shale by the New Mexico Oil Conservation Division. Although this stratigraphic classification may be true in the grossest sense, these pools are productive from limestones in the Barnett and not from shale reservoirs. All four pools are located near the northern limit of the Barnett Shale as defined in this report (Figure 14). Empire and Sand Tank are productive from limestone tongues of the Chester that pinchout southward within the Barnett. The reservoir at Lone Tree Draw is a limestone tongue of the upper Meramec that pinches out southward within the Barnett. Vacuum South is productive from a lower-Meramec equivalent limestone in the

lowermost part of the Barnett Shale; this limestone may also be a southward-extending tongue of the Meramec shelf facies.

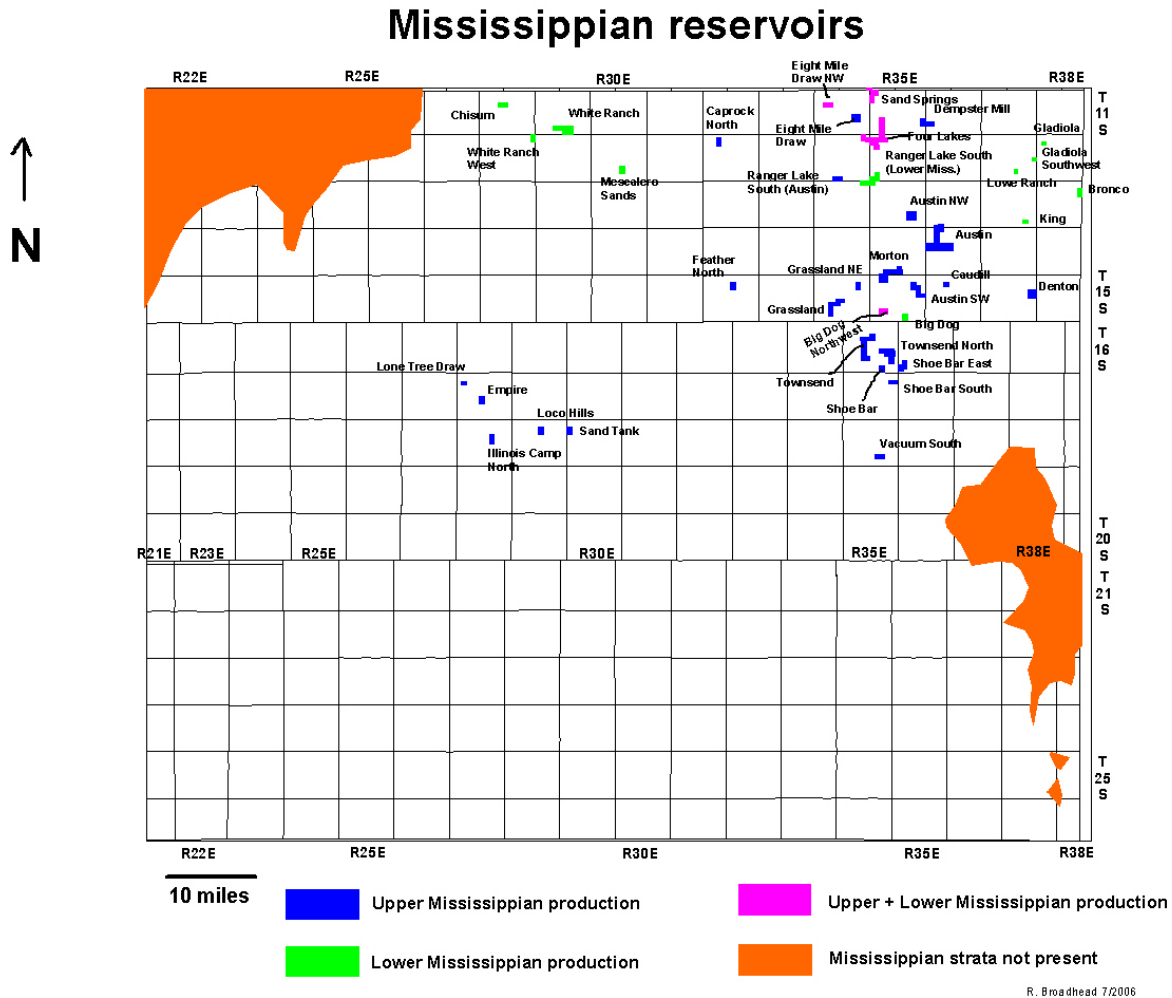


Figure 13. Location of oil and gas pools that are productive from Mississippian reservoirs in southeastern New Mexico.

The Austin gas pool is the only Mississippian reservoir to have been described in detail within the published literature (see Hamilton and Asquith, 2000). The pool is located approximately 20 miles north of the Chester-Barnett transition (Figure 14). Reservoirs at Austin are bioclastic ooid grainstones in the upper Chester (Hamilton and Asquith, 2000). Although the ooid grainstones are cemented by calcite, porosity is preserved in grainstones that have incomplete cementation. Other ooid grainstones are cemented completely by calcite that occludes all porosity. Hamilton and Asquith (2000) concluded that the reservoirs were formed as ooid grainstone shoals deposited in upward-shoaling sequences.

Upper Mississippian isopach and reservoirs

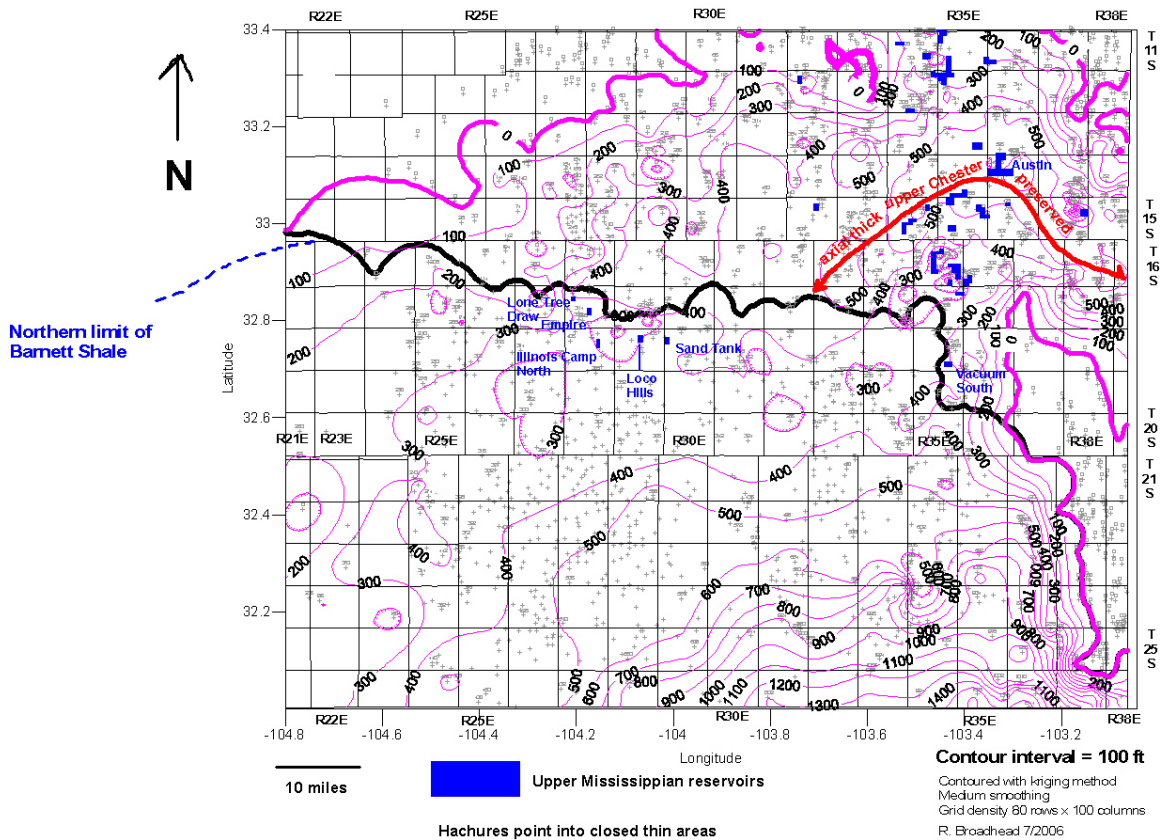


Figure 14. Isopach map of Upper Mississippian strata (from Figure 7) and oil and gas pools that are productive from Upper Mississippian reservoirs.

The Austin pool is located along a thick axis of the Upper Mississippian (Figure 14) that coincides with the downwarped San Simon Channel (Figure 15). In this area, the Mississippian was downwarped prior to deposition of the Lower Pennsylvanian, resulting in preservation of the uppermost part of the Chester (see Plate 6, cross section E-E' in Appendix B - the Penrose No. 1 Fairweather well located in Sec. 3 T15S R35E). Strata equivalent to those that are productive at Austin are absent from large parts of the Mississippian shelf, having been removed by erosion prior to deposition of Lower Pennsylvanian sediments. However, the upper Chesterian section is preserved in the arc-shaped area coincident with the San Simon Channel. A large number of Upper Mississippian gas pools are present within the boundaries of this arc-shaped area and are productive from the upper Chester.

Mississippian structure and reservoirs

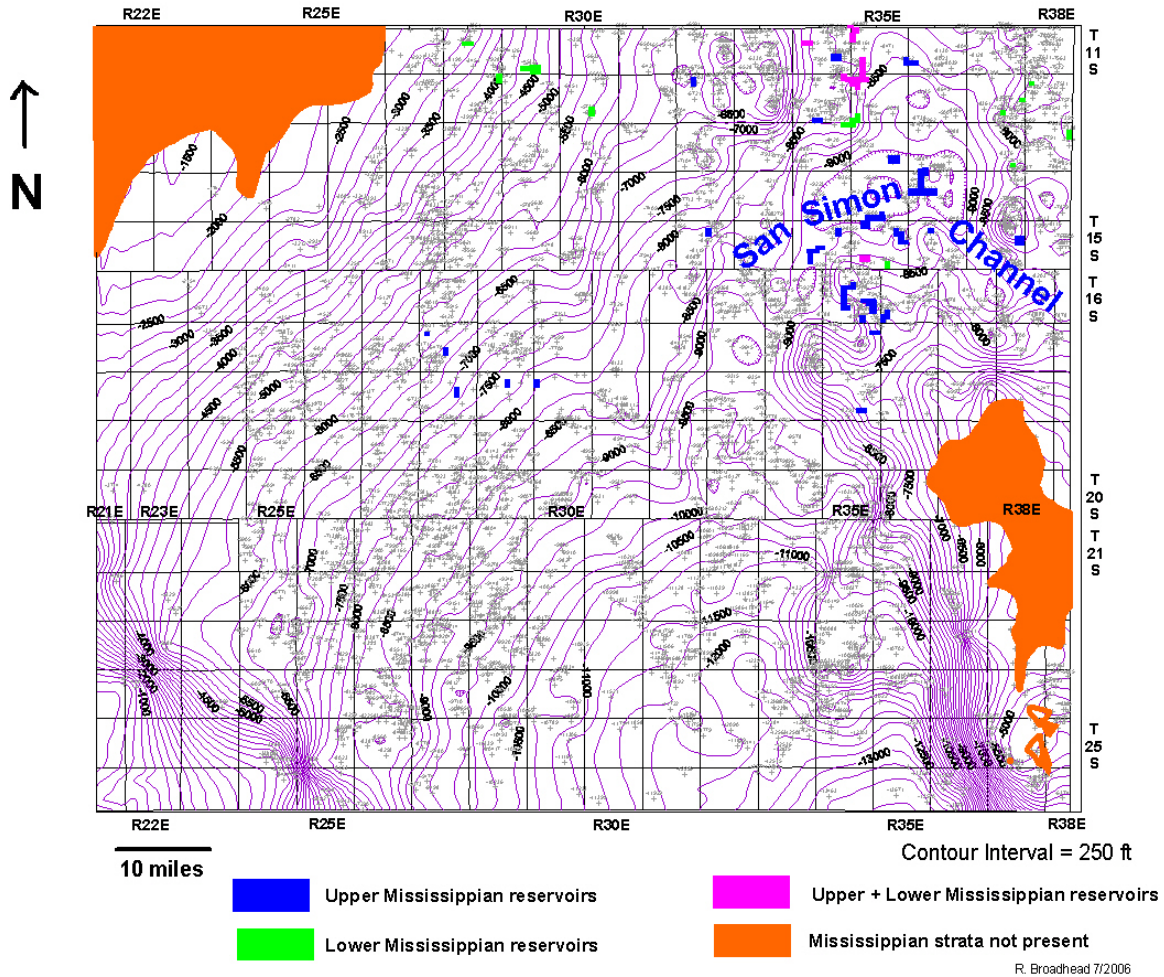


Figure 15. Structure contour map on top of Mississippian strata (from Figure 11) and oil and gas pools that are productive from Mississippian reservoirs.

Other Upper Mississippian gas pools are productive from the flanks of the thick area. Many seem to be associated with the flanks of large structures (Figure 15). These gas pools produce from older Chesterian limestones than are productive at Austin. Some of the pools are productive from Meramecian limestones. As discussed above, a few reservoirs to the south classified as “Barnett” are productive from southward extending tongues of Upper Mississippian shelfal limestones and not from shales.

Lower Mississippian reservoirs

Twelve gas and oil pools have been productive from the lower Mississippian limestone (Table 1; Figure 13). An additional four pools have been productive from both Upper and Lower Mississippian strata. The pools in Lower Mississippian strata are

productive from depths varying from 7,760 ft at White Ranch to 13,400 ft at Big Dog. Reservoirs are limestones mostly located either in the upper or middle parts of the lower Mississippian limestone. Reservoir lithology and trapping mechanisms have not been described in the literature.

Discovery of gas and oil accumulations in the lower Mississippian limestone is generally serendipitous and has been accomplished by testing oil or gas shows encountered while drilling to deeper objectives. Production from Lower Mississippian reservoirs has been modest. There appears to have been no systematic attempt to explore for or develop oil and gas accumulation within Lower Mississippian strata. There is no association of known reservoirs with regional isopach trends (Figure 16).

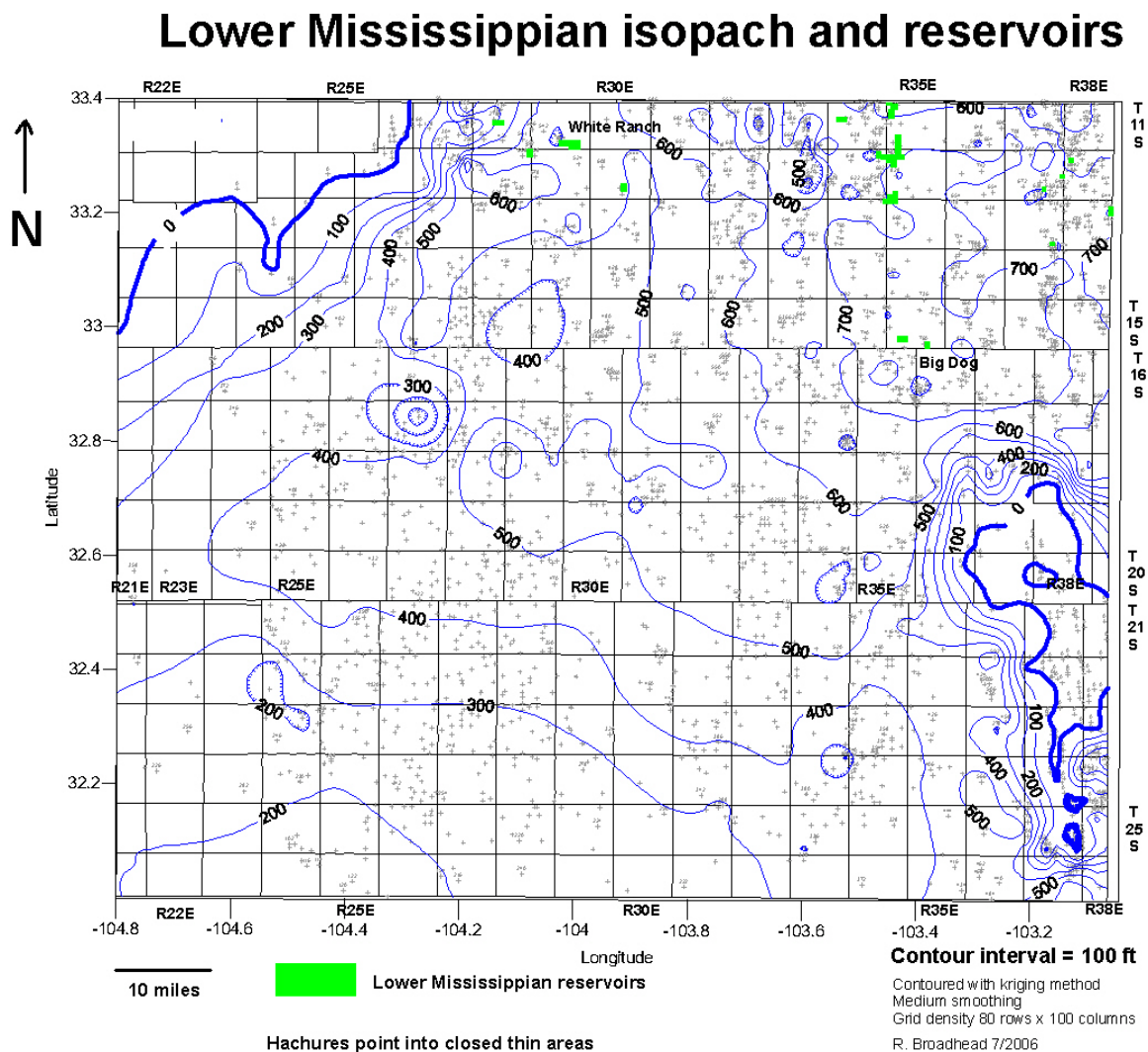


Figure 16. Isopach map of Lower Mississippian strata (from Figure 6) and oil and gas pools that are productive from Lower Mississippian reservoirs.

“False” Mississippian reservoirs

“False” Mississippian reservoirs are oil or gas pools that are classified as being productive from Mississippian strata but are actually productive from strata other than the Mississippian as revealed by correlations performed for this project. These oil and gas pools include: Bar-U (Mississippian), Caprock East (Mississippian), Eidson Northeast (Mississippian), Shoe Bar East (Chester), Shoe Bar Northeast (Mississippian), and Walters Lake (Mississippian). These reservoirs are productive from lowermost Pennsylvanian (Morrowan or Atokan) strata and not from the Mississippian. They are not further described in this report.

Oil and Gas Plays

Four oil and gas plays are identified in Mississippian strata in southeastern New Mexico (Table 2):

1. Chester shallow marine limestones in structurally low areas of the northern shelf;
2. Upper Mississippian limestones interbedded with Barnett shales at and south of the shelf-to-basin transition;
3. Lower Mississippian limestones;
4. the as-yet untried Barnett Shale.

These plays are identified on the basis of stratigraphic position of the reservoir. For the Upper Mississippian plays, they are also identified on the basis of reservoir location with respect to the Upper Mississippian shelf-basin boundary. Play boundaries are drawn on the basis of these factors plus the geographic location of reservoirs that have already been discovered.

Table 2. Mississippian plays and oil and gas pools that have been discovered in those plays. * Also produces from lower Mississippian limestone. ** Also produces from Chester limestones. *** Also produces from Meramec limestones.

Play	Oil and gas pools in play
Chester shallow marine limestones	Austin, Austin Northwest, Austin Southwest, Dempster Mill, Denton, Eight Mile Draw, Feather North, Grassland, Grassland Northeast, Morton, Ranger Lake South, Shoe Bar, Shoe Bar South, Townsend, Townsend North, Eight Mile Draw Northwest*, Sand Springs*
Upper Mississippian limestones interbedded with Barnett shales	Empire, Illinois Camp North, Lone Tree Draw, Sand Tank, Vacuum South
Lower Mississippian limestone play	Big Dog, Bronco, Caudill, Chisum, Gladiola, Gladiola Southwest, King, Lowe Ranch, Mescalero Sands, Ranger Lake South, White Ranch, White Ranch West, Eight Mile Draw Northwest**, Sand Springs**, Big Dog Northwest***, Four Lakes***
Barnett Shale play	none

Chester shallow marine limestone play

The *Chester shallow marine limestone play* is located on the northern shelf of the Mississippian basin (Figure 17). Reservoirs are Chester limestones deposited north of the shelf-basin transition. To date, a cumulative total 19.7 BCF gas and 293 MBO have been produced from the 15 gas and oil pools (Table 2) that are productive solely from Chester reservoirs. Two additional pools, Eight Mile Draw and Sand Springs, are productive from reservoirs in the lower Mississippian limestone as well as reservoirs in the Chester. The most prolific pool in the play is Austin and has produced a cumulative total of almost 15 BCF gas from oolite shoal reservoirs in the upper part of the Chester (see Hamilton and Asquith, 2000). This play is confined to the San Simon Channel; in this structurally low area, upper Chesterian strata were prior to deposition of Early Pennsylvanian sediments. The play boundary has been drawn to reflect the distribution of Upper Chesterian strata within the boundaries of the San Simon Channel.

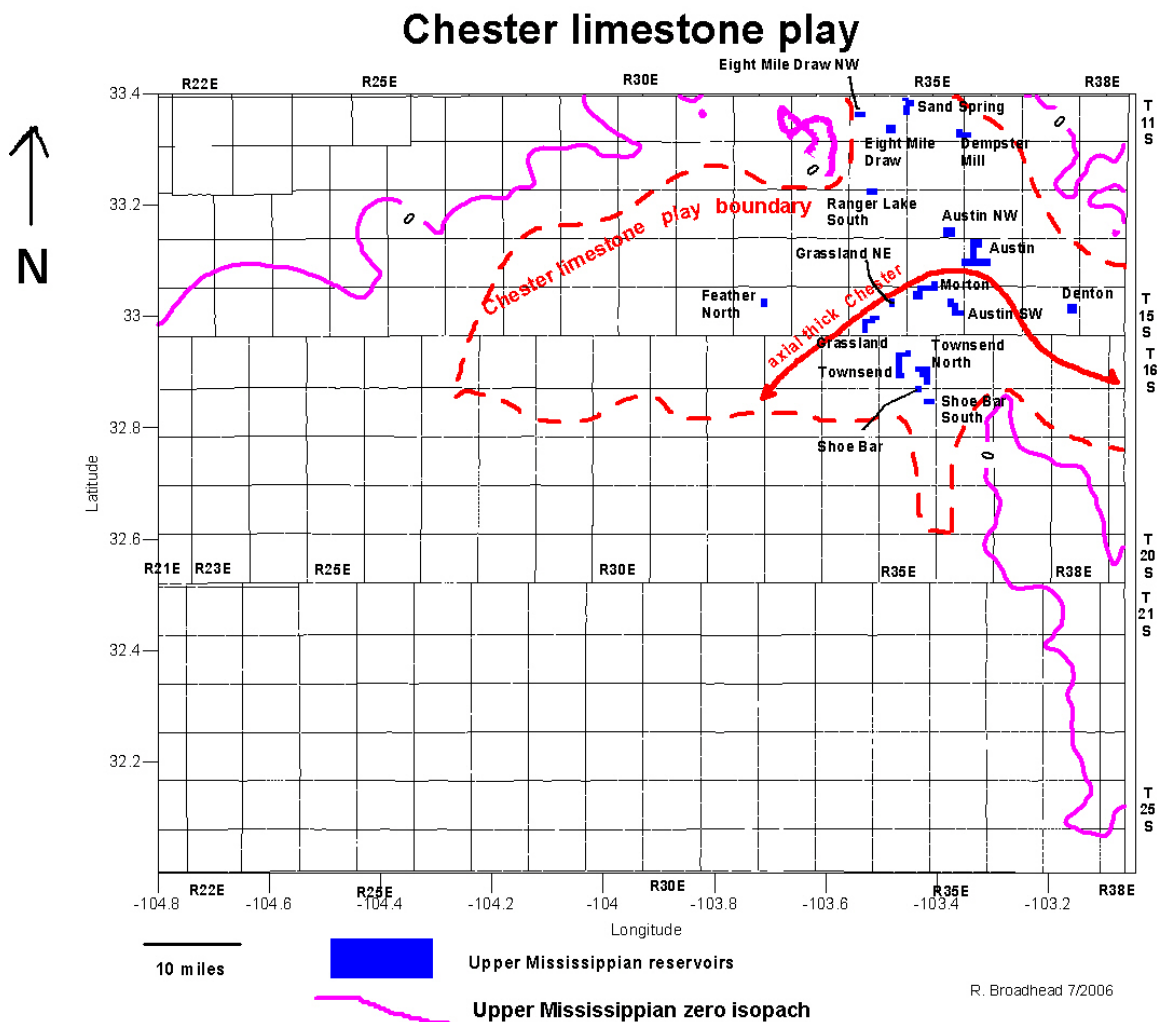


Figure 17. Play boundary and reservoirs of the Chester shallow marine limestone play.

Upper Mississippian limestones interbedded with Barnett shales play

This play is located near the northern limit of the Barnett Shale south of the shelf-to-basin transition (Figures 10, 18). North of this boundary, Barnett shales intertongue with Upper Mississippian shelfal limestones. The five pools in this play (Table 2) are productive from tongues of Chester and Meramec limestones that extend southward from the shelf and are intercalated with basinal Barnett shales. The limestones thin to the south and pinchout a few miles south of the shelf-to-basin transition. As of December 2003, 1 BCF gas and 7.7 MBO have been produced from the four pools that have been discovered in this play. The play boundary has been drawn to reflect the position of the play just south of the shelf-to-basin transition.

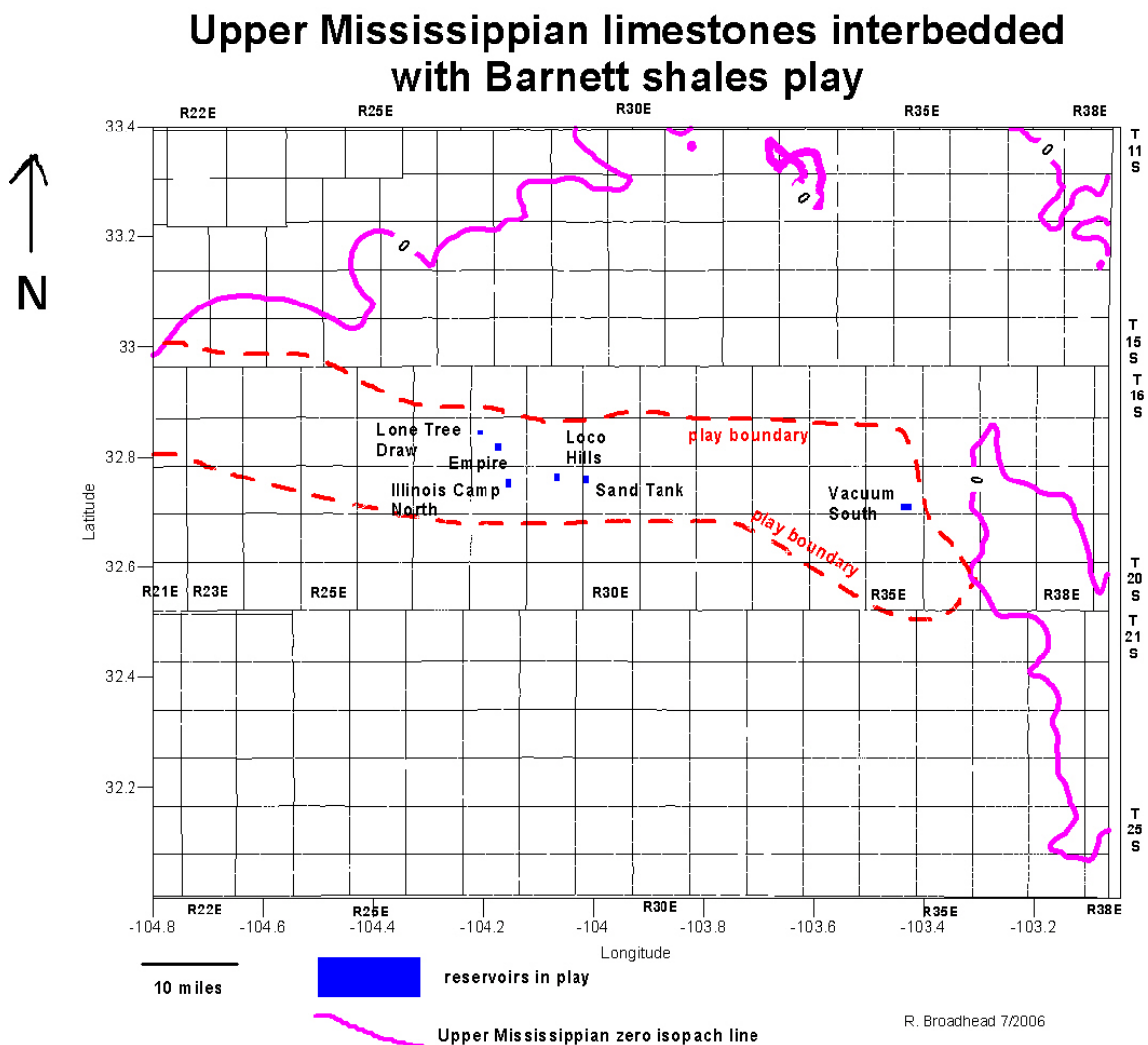


Figure 18. Play boundary and reservoirs of the Upper Mississippian limestone interbedded with Barnett shales play.

Lower Mississippian limestone play

The *Lower Mississippian limestone play* is located in the northern part of the area covered by this report (Figure 19). The twelve oil and gas pools that produce solely from reservoirs in the lower Mississippian limestone yielded a cumulative total of 2.9 BCF gas and 863 MBO as of December 2003. As previously discussed, the locations of discovered oil and gas pools do not appear to bear any relationship to the regional isopach patterns of the lower Mississippian limestone (Figure 16). Therefore, the boundary of this play has been drawn empirically to include all reservoirs productive from the lower Mississippian limestone.

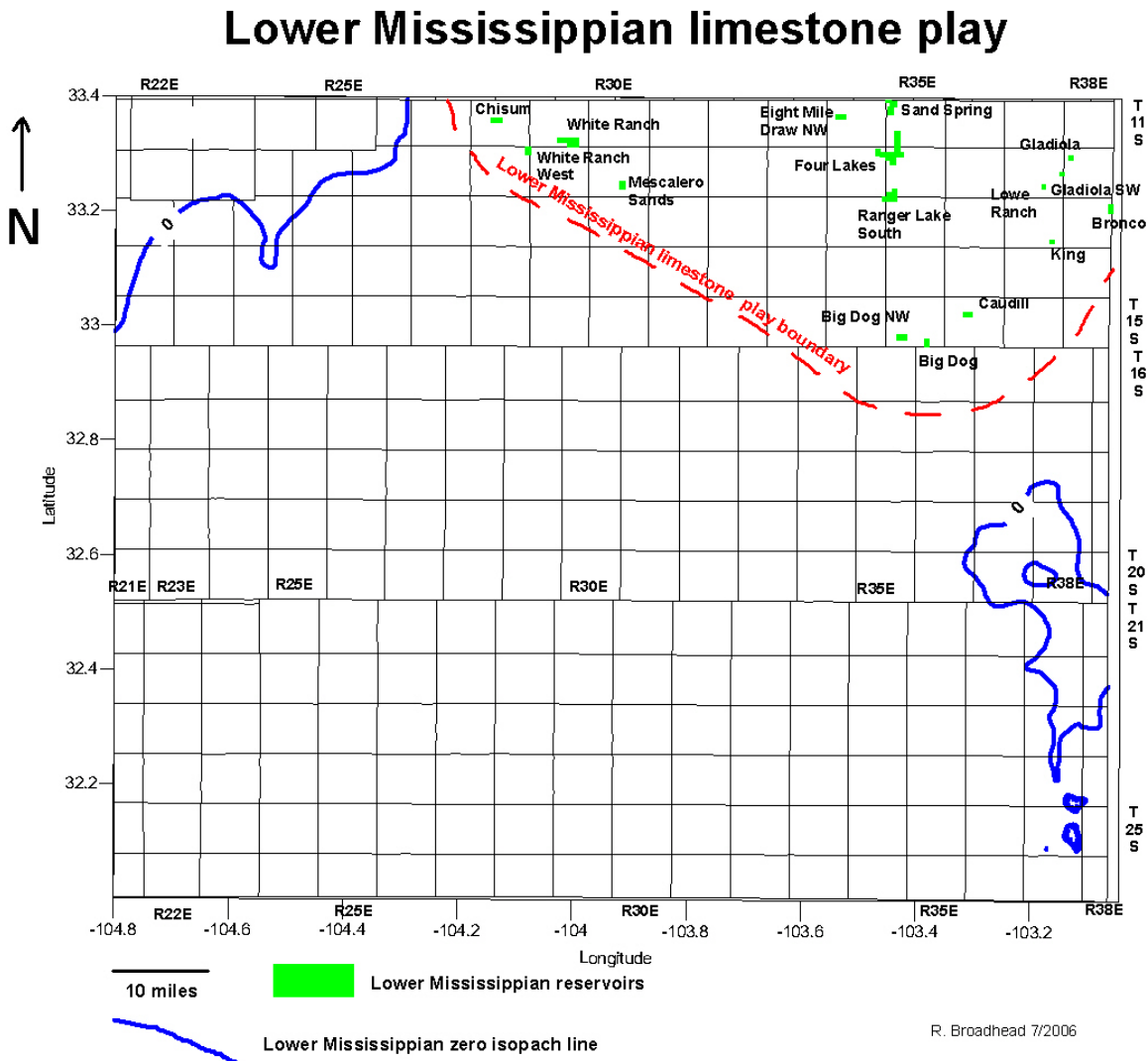


Figure 19. Play boundary and reservoirs of the Lower Mississippian limestone play.

Barnett Shale play

The Barnett Shale has become a major source of gas in the Fort Worth Basin. More than 1 trillion ft³ (TCF) gas have been produced from the Barnett in the Fort Worth Basin and the Fort Worth Barnett currently provides more than one-half of the shale gas produced in the United States (Durham, 2005). Montgomery and others (2005) provided a recent comprehensive review of Barnett geology, geochemistry and production in the Fort Worth Basin. 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).

Hydrocarbons have not yet been commercially produced from the Barnett Shale in New Mexico. As discussed previously, reservoirs currently classified as “Barnett” in southeastern New Mexico are productive from Chester and Meramec limestones interbedded with the Barnett and not from shales within the Barnett.

The Barnett Shale is 0 to more than 1500 ft thick in southeastern New Mexico (Figure 10). Insufficient petroleum source rock analyses are available to map organic content and thermal maturity of the Barnett throughout its extent in southeastern New Mexico. The sparse data available (Figure 20) indicate the shales are mature and within the upper part of the oil window along the shelf-basin transition. As might be expected, thermal maturity increases to the south as a result increasing present-day burial depth. Within the basinal areas, the Barnett is within the middle and lower parts of the oil window and possibly in the thermal gas window. The two analyses available in the basin indicate that thermal maturity of the Barnett increases toward the west and may not primarily be a function of present-day burial depth within the Delaware Basin.

Total organic carbon (TOC) in the Upper Mississippian shales ranges from 0.85% to 2.39%. TOC for all but one of the 6 available analyses exceeds 1.5%, sufficient for oil and gas generation. Kerogens in the Barnett are a mix of aquatic and terrestrial types.

As yet, the Barnett Shale in southeastern New Mexico has not been tested specifically by exploratory wells. Exploratory wells that have penetrated the Barnett have either targeted Lower Pennsylvanian sandstones and have penetrated the uppermost part of the Barnett or they have targeted deeper lower Paleozoic reservoirs and have drilled through the Barnett in order to test the lower Paleozoic section. Additional source rock analyses are needed to identify and map portions of the basin where the Barnett is favorable to shale gas. The thickness of the Barnett Shale and its high content of organic

matter indicates that a significant potential may be present in the 5,000 mi² area south of the zero isopach line (Figure 20).

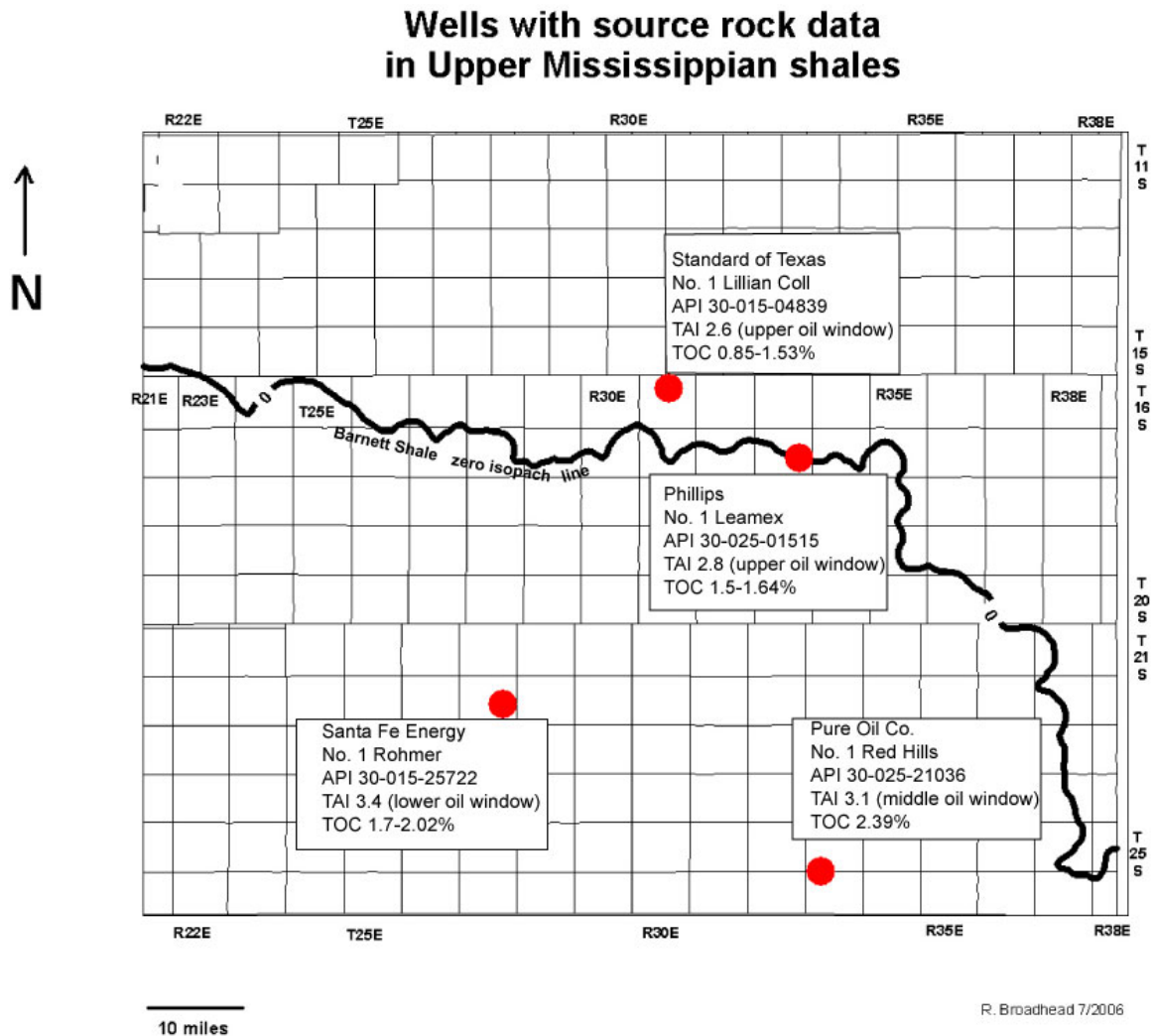


Figure 20. Summary of petroleum source rock data in Upper Mississippian shales. **TAI**, Thermal Alteration Index; **TOC**, Total organic carbon. Data from Broadhead and others (1998).

References

- Anderson, C.A., 1999, Logan Draw/Crow Flats Morrow gas play Eddy County, New Mexico (abstract), *in* A symposium of oil and gas fields of southeastern New Mexico, 1999: Roswell Geological Society, p. 23.
- Armstrong, A.K., Kottowski, F.E., Stewart, W.J., Mamet, B.L., Baltz, E.H., Jr., Siemers, W.T., and Thompson, S., III, 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States – New Mexico: U.S. Geological Survey, Professional Paper 1110, Chapter W, 27 p.
- Bowsher, A.L., 1986, Late Paleozoic reef complexes of the northern Sacramento Mountains, New Mexico, *in* Ahlen, J.L., and Hanson, M.E., eds., Southwest Section of AAPG transactions and guidebook of 1986 convention, Ruidoso, New Mexico: New Mexico Bureau of Mines and Mineral Resources, p. 49-72.
- Broadhead, R.F., 2005, Regional aspects of the Wristen petroleum system, southeastern New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open File Report 485, CD-ROM.
- Broadhead, R.F., Jianhua, Z., and Raatz, W.D., 2004, Play analysis of major oil reservoirs in the New Mexico part of the Permian Basin: Enhanced production through advanced technologies: New Mexico Bureau of Geology and Mineral Resources, Open File Report 479, CD-ROM.
- 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, Database DDS DB2, CD-ROM.
- 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.
- Derrick, N., Hart, D., Justman, H., Leiphart, D., Medford, D., Robinson, R., Sande, T., Trivitt, A., and Broadhead, R., 1999, Kemnitz (Morrow), *in* A symposium of oil and gas fields of southeastern New Mexico, 1999: Roswell Geological Society, p. 25-53.
- Durham, L.S., 2005, The 17-year overnight sensation, Barnett Shale play going strong: American Association of Petroleum Geologists, Explorer, May 200, 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: The University of Texas at Austin, Bureau of Economic Geology, 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 Siclen, D.C., 1988, The Permian Basin, *in* Sloss, L.L., ed., Sedimentary cover – North American craton: Geological Society of America, Geology of North America, v. D-2, p. 261-306.
- 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.
- Hanagan, M., 2002, Overview of 3D seismic based Siluro-Devonian exploration efforts in Chaves County, New Mexico: West Texas Geological Society, Bulletin, v. 42, no. 3, p. 4-9.
- Harris, D.C., 1990, Ramp buildups in the lower Strawn limestone (Penn.): Controls on stratigraphic reservoir variability, *in* Flis, J.E., and Price, R.C., eds., Permian Basin oil and gas fields: Innovative ideas in exploration and development: West Texas Geological Society, Publication 90-87, p. 91-101.
- Hills, J.M., 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.
- Hodges, J.W., 1960, Bronco Mississippian, *in* A symposium of oil and gas fields of southeastern New Mexico, 1960 supplement: Roswell Geological Society, p. 23.
- 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.
- Lane, R.H., 1974, Mississippian of southeastern New Mexico and west Texas – a wedge-on-wedge relation: American Association of Petroleum Geologists, Bulletin, v. 58, p. 269-282.

- Laudon, L.R., and Bowsher, A.L., 1941, Mississippian formations of the Sacramento Mountains, New Mexico: American Association of Petroleum Geologists, Bulletin, v. 25, p. 2107-2160.
- Laudon, L.R., and Bowsher, A.L., 1949, Mississippian formations of southeastern New Mexico: Geological Society of America, Bulletin, v. 60, p. 1-88.
- Meyer, R.F., 1966, Geology of Pennsylvanian and Wolfcampian rocks in southeast New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 17, 123 p.
- Montgomery, S.L., Jarvie, D.M., Bowker, K.A., and Pollastro, R.M., 2005, Mississippian Barnett Shale, Fort Worth Basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential: American Association of Petroleum Geologists, Bulletin, v. 89, p. 155-175.
- 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.
- 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., and Hanagan, M.W., 1995, 3-D seismic exploration for Siluro-Devonian reservoirs in Chaves County, New Mexico, *in* A symposium of oil and gas fields of southeastern New Mexico, 1995 supplement: Roswell Geological Society, p. 22-31.
- Thornton, D.E., and Gaston, H.H., Jr., 1967, Lusk Strawn field, *in* A symposium of oil and gas fields of southeastern New Mexico, 1967 supplement: Roswell Geological Society, p. 15-20.
- 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 Land, 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.