Energy and Mineral Resources of New Mexico

Petroleum Geology

Ronald F. Broadhead

VOLUME A

NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES
Memoir 50A

NEW MEXICO GEOLOGICAL SOCIETY
Special Publication 13A

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Petroleum Geology

Ronald F. Broadhead

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and Maureen Wilks

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NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

The New Mexico Bureau of Geology and Mineral Resources is a research and service division of New Mexico Institute of Mining and Technology. We are a non-regulatory agency that serves as the geological survey for the state of New Mexico.

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PREFACE

Virginia T. McLemore, Ronald F. Broadhead, Gretchen K. Hoffman, and Fraser Goff

New Mexico is called the Land of Enchantment, in part because of the diverse geologic formations of the state, which give rise to spectacular landscapes of mountains, valleys, mesas, canyons, rivers, deserts, and plains. Major cities are concentrated along the Rio Grande, including Albuquerque, Las Cruces, Rio Rancho, and Santa Fe, with smaller population centers in the southeast, eastern plains, and northwest, such as Roswell, Hobbs, Alamogordo, Carlsbad, Clovis, and Farmington (Fig. 1). New Mexico is the 5th largest state in terms of land area in the lower United States and contains five major physiographic provinces (Fig. 2): Great Plains, Basin and Range, Transition Zone, Colorado Plateau, and Southern Rocky Mountains. The rocks, which date back nearly two billion years, have undergone multiple major tectonic events that were accompanied by faulting and igneous activity (Figs. 3, 4). This rich geologic history has yielded a diversity of valuable energy and mineral deposits, which occur in all of the physiographic provinces in New Mexico, and in a variety of tectonic and geologic settings (Fig. 3). For more information on the geology of New Mexico, see Mack (1997), Mack and Giles (2004), and Price (2010). In addition, mining districts and prospect areas are shown and briefly described in McLemore (2017).

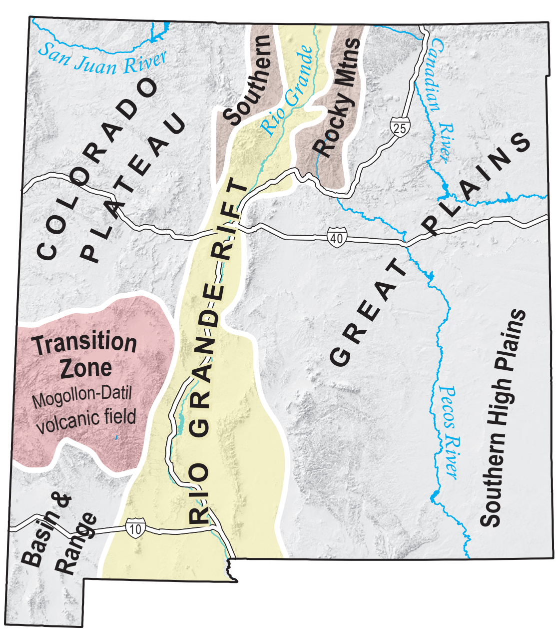

Figure 2. Physiographic provinces of New Mexico.

Rock collecting (or rock hounding), prospecting, and non-commercial gold panning are considered a casual use of public lands under most circumstances. **However, it is up to each individual to know the laws and land ownership.** For more information on mining claims and mineral leasing in New Mexico see McLemore (2017), BLM website (http://www.blm.gov/lr2000/), and New Mexico Mining and Minerals Division website (http://www.emnrd.state.nm.us/MMD/MARP/marpmainpage.html).

Importance of Energy and Minerals in New Mexico

New Mexico's mineral wealth is among the richest of any state in the United States. Oil and gas are the most important extractive industries in New Mexico in terms of production value (McLemore, 2017). In 2015, New Mexico ranked 6th in oil production, 8th in gas production, 10th in coal production, and 15th in non-fuel minerals production. Most of the state's mineral production comes from oil, gas, coal, copper, potash, industrial minerals and aggregates (Tables 1, 2). Other important commodities include a variety of industrial minerals (perlite, cement, zeolites, etc.), sulfuric acid, molybdenum, gold, uranium, and silver. New Mexico is fortunate to have geothermal resources in many locations. In December 2013, the Dale Burgett Geothermal Plant in the Animas Valley of southwest New Mexico started delivering up to 2 MW of electricity to the Public Service Company of New Mexico. Development of the Lightning Dock No. 2 project is underway with an additional 6 MW of generation planned.

A healthy energy and mineral industry is vitally important to the economy of New Mexico and to maintenance of public education and services (Table 2). The minerals industries provide property and corporate income taxes, while their ~35,000 direct employees contributed millions of dollars of personal

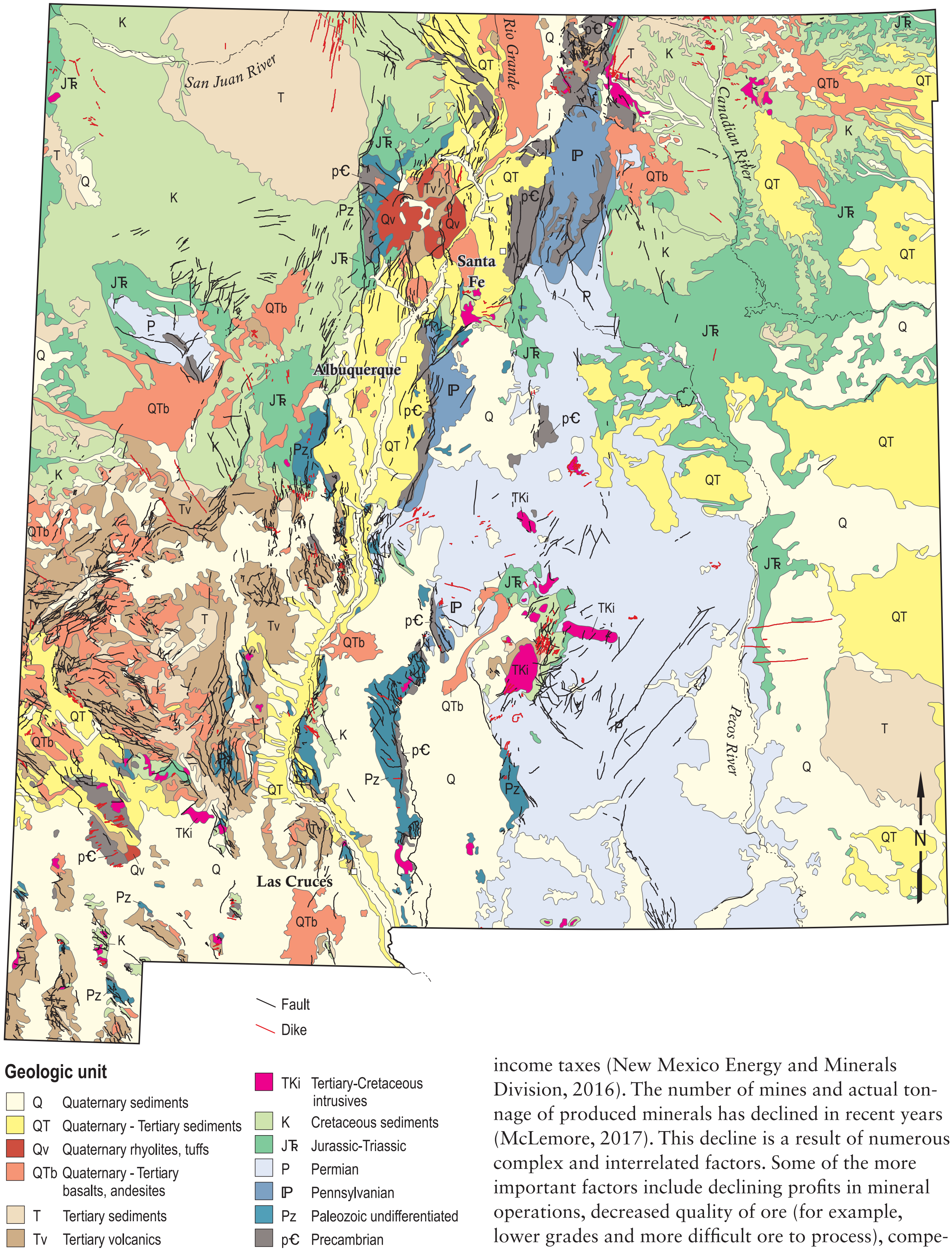

Figure 3. Simplified geologic map of New Mexico.

income taxes (New Mexico Energy and Minerals Division, 2016). The number of mines and actual tonnage of produced minerals has declined in recent years (McLemore, 2017). This decline is a result of numerous complex and interrelated factors. Some of the more important factors include declining profits in mineral operations, decreased quality of ore (for example, lower grades and more difficult ore to process), competition from the global market, and a shift from coal-generated electricity to alternative energy sources.

Table 1. Estimated total production of major commodities in New Mexico, in order of estimated cumulative value (data from USGS, 1902–1927; USBM, 1927–1990; Kelley, 1949; Harrer, 1965; USGS, 1965; Howard, 1967; Harben et al., 2008; Energy Information Administration, 2015; New Mexico Energy, Minerals and Natural Resources Department, 1986–2016). Figures are subject to change as more data are obtained. Estimated cumulative value is in real, historic dollars at the time of production and is not adjusted for inflation.

Commodity	Years of production	Estimated quantity of production	Estimated cumulative value ($)
Natural Gas	1921–2015	>75 trillion cubic feet	$169 billion
Oil	1922–2015	>6.4 billion barrels	$119 billion
Coal	1882–2015	>1.46 billion short tons	>$21.7 billion
Copper	1804–2015	>11.7 million tons	>$21.6 billion
Potash	1951–2015	>113 million short tons	>$15.6 billion
Uranium	1948–2002	>347 million pounds	>$4.8 billion
Industrial minerals**	1997–2015	>41 million short tons	>$2.7 billion
Aggregates***	1951–2015	>674 short tons	>$2.6 billion
Molybdenum	1931–2013	>176 million pounds	>$852 million
Carbon dioxide	1931–2015	>3.3 trillion cubic feet	>$726 million
Gold	1948–2015	>3.3 million troy ounces	>$486 million
Zinc	1903–1991	>1.51 million tons	>$337 million
Silver	1848–2015	>119 million troy ounces	>$280 million
Lead	1883–1992	>367,000 tons	>$56.7 million
Iron	1888–2015	>6.7 million long tons	>$23 million
Fluorspar	1909–1978	>721,000 tons	$12 million
Manganese	1883–1963	>1.7 million tons	$5 million
Barite	1918–1965	>37,500 tons	>$400,000
Tungsten	1940–1958	113.8 tons (>60% WO_3)	na
Niobium-tantalum	1953–1965	34,000 pounds of concentrates	na
TOTAL	**1804–2015**	**—**	**>$359 billion**

*Oil and gas values are estimated from production data provided by https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx (New Mexico Oil Conservation Division Natural Gas and Oil Production, continuously updated, accessed 2/1/16) and estimated average commodity price. Minerals data are from New Mexico Energy, Minerals and Natural Resources Department (2016). **Industrial minerals include the combined total of several industrial minerals (e.g., perlite, cement, decorative stone, pumice, zeolites, etc.), but excluding potash and aggregates. ***Aggregates include only sand and gravel from 1951–1997, after 1997 aggregates include crushed stone and scoria. na–not available.

Table 2. Summary of mineral production in New Mexico in 2015, including oil and natural gas (New Mexico Energy, Minerals and Natural Resources Department, 2016, https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx; Gould, 2015). na—not available.

Mineral	Production in 2015	Production rank in the U.S. in 2015	Production value in NM in 2015	Employment in NM (# full time jobs)	Reclamation employment in NM (# full time jobs)	State revenue generated from extractive industries	Federal revenue generated from extractive industries
Oil	147 million bbls oil	6	~$7,143,000,000	~30,000*	na	~$1,600,000,000*	na
Gas	1.27 trillion ft^3 gas	8	~$6,470,000,000	—	na	—	na
Copper	397,441,145 lbs	2	$996,838,033	1,878	4	$8,086,903	—
Coal	19,676,277 short tons	12	$691,047,434	1,341	118	$17,656,313	$10,243,850
Gold	20,438 troy oz	—	$23,708,980	—	—	$191,947	—
Industrial minerals	1,411,731 short tons	—	$87,305,356	413	11	$269,261	$213,816
Aggregates	8,169,753 short tons	—	$62,625,896	837	53	$3,092,285	—
Other metals (iron, manganese)	18,358 short tons	—	$165,223	18	—	$761,027	—
Potash	1,433,245 short tons	1	$659,505,518	1,194	12	$6,542,580	$8,133,012
Silver	56,983 troy oz	—	$895,610	—	—	$9,737	—
Uranium	none	—	—	11	11	—	—
Carbon dioxide	106 billion ft^3	—	$112,000,000	—	—	—	na
Total	**—**	**15 (excluding oil, gas, and coal)**	**~$16,247,000,000**	**~35,000**	**209**	**~$1,636,000,000**	**$18,590,678**

*Estimate includes oil, gas, and carbon dioxide.

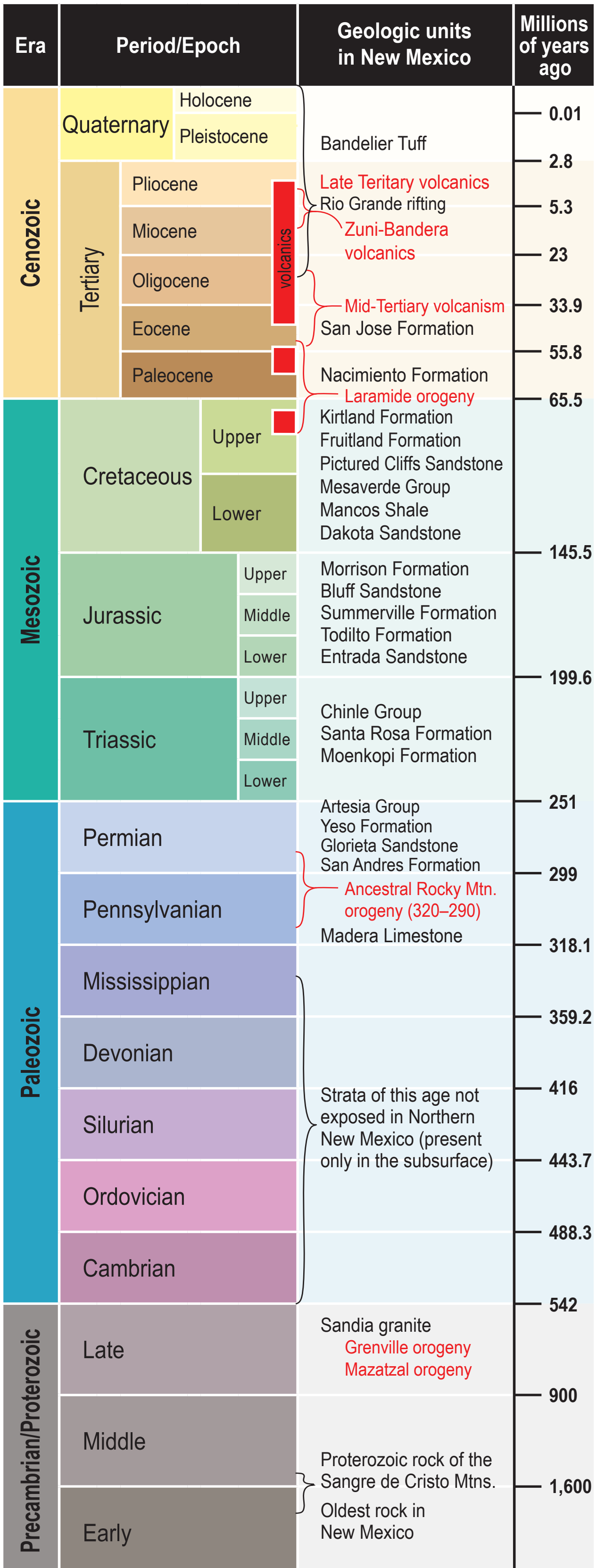

Figure 4. Geologic time scale. "Tertiary" is often used in these chapters to describe timing of events in the Paleogene and Neogene geologic periods.

New mines and petroleum drilling face a multitude of challenges, including water availability, water rights issues, public perceptions, a complex regulatory process and public opposition to petroleum drilling and mining.

Minerals and Society

The minerals industries (including oil and gas) play a vital role in the world economy by filling a persistent demand for the raw materials that are the foundation of our civilization. Our modern lifestyles are heavily dependent upon mining commodities that Americans use on a daily basis (Table 3). For example, petroleum, metals, and industrial minerals are used in every sector of construction and manufacturing. Coal, oil, gas, and uranium provide electricity and fuels. They are used in urban and industrial applications. Geothermal resources also provide electricity and heating (Table 3). Agriculture depends upon minerals for fertilizers and pesticides.

Mineral production in New Mexico and the world has increased dramatically in the last 100 years (Fig. 5, Wagner, 2002). Most industries no longer follow the casual mining and safety practices of the past. "*One of the greatest challenges facing the world today is integrating economic activity with environmental*

Table 3. Selected uses of commodities found in New Mexico.

Commodity	Selected Uses
Oil	Fuel, electricity generation, pesticides, fertilizers, chemicals, plastics
Gas	Fuel, electricity generation
Copper	Electrical wire, pipe, plumbing, motors, machinery, computers
Coal	Electricity generation, steel production, manufacture of cement, liquid fuel, chemical and pharmaceutical industries
Aggregates	Manufacture concrete and cement, road construction, railroad ballast
Molybdenum	Stainless and structural steel, superalloys, chemicals, cast iron
Potash	Agricultural fertilizers
Silver	Currency, jewelry, electronics, photography, silverware, mirrors
Gold	Currency, jewelry, electronics, computers, dentistry, glass
Uranium	Fuel for nuclear reactors, projectiles, shielding of radioactive materials
Perlite	Building construction materials, soil amendment, filter aid
Zeolites	Water purification, animal feed, sorbents
Rare earth elements	Catalyst, glass, polishing, re-chargeable batteries, magnets, lasers, glass, TV color phosphors
Geothermal resources	Electricity generation, space heating, greenhouse heating, aquaculture (fish farms), spas, and bath houses

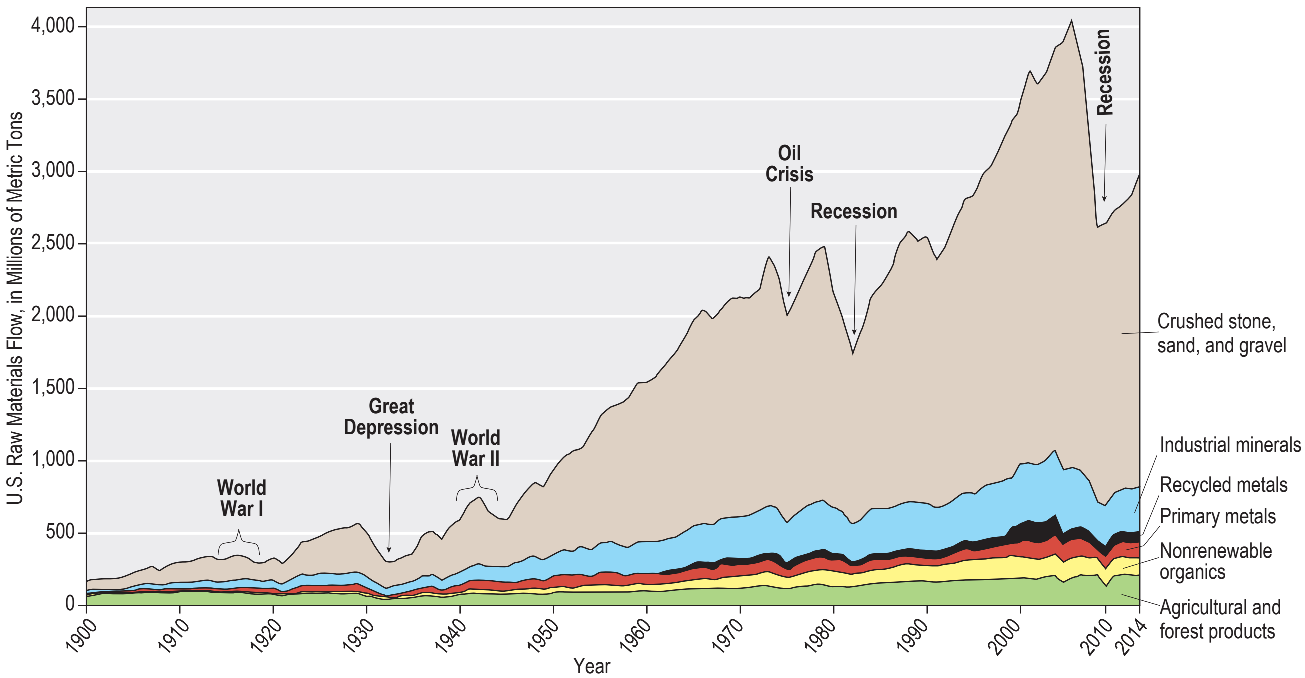

Figure 5. United States flow of raw materials by weight from 1900–2014. The use of raw materials increased dramatically during the last 100 years (modified from Wagner, 2002).

integrity and social concerns… The fulfillment of 'needs' is central to the definition of sustainable development" (IIED, 2002). The permitting process applied to most extractive industries includes archeological surveys, identification of rare and endangered species, and environmental monitoring during and after production. Today, another important aspect of mine planning in a modern regulatory setting is the philosophy, and often the requirement, that new mines and mine expansions must have plans and designs for closure. This philosophy is relatively new. It attempts to prevent environmental accidents common in the past and has increased the cost of mining.

Organization of this Series

This Memoir/Special Publication is the first modern summary of New Mexico's energy and mineral resources since work by the U.S. Geological Survey (USGS, 1965) and Howard (1967). This series of volumes is a joint publication of the New Mexico Bureau of Geology and Mineral Resources and the New Mexico Geological Society. This publication consists of six individual volumes under the theme of Energy and Mineral Resources of New Mexico.

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New Mexico Geological Society, Special Publication 13

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SUMMARY

Petroleum (oil and natural gas), carbon dioxide and helium

Production of oil and natural gas resources is a major economic engine in New Mexico. In 2015, 147 million barrels of oil with a value of $7.1 billion and 1.27 trillion cubic feet (ft^3) of natural gas with a value of $6.5 billion were produced from New Mexico reservoirs. Taxes and royalties derived from oil and natural gas production have contributed approximately 30% of the state's budget in recent years. Approximately 30,000 jobs in New Mexico are dependent on the petroleum industry.

Approximately 95% of the oil and one-third of the natural gas is produced from the Permian Basin in southeastern New Mexico. Important reservoirs are present in Permian, Pennsylvanian, Silurian and Ordovician strata. Historically, Permian and Pennsylvanian limestone, dolostone and sandstone reservoirs on the Northwest Shelf and Central Basin Platform have contributed most of the production. In recent years with the advent of modern horizontal drilling techniques, Permian deep-marine sandstones and shales have come to dominate production and now account for more than 60% of New Mexico oil. Approximately 5% of the state's oil and two-thirds of the natural gas are produced from the San Juan Basin of northwestern New Mexico. Primary gas reservoirs are low-permeability Upper Cretaceous sandstones. Coalbed methane has been produced since the late 1980s and presently accounts for 22% of New Mexico gas production. Recent exploration in Upper Cretaceous shales in the San Juan Basin has revealed the presence of producible oil in the southern part of the basin and natural gas in the deep northern part of the basin. Coalbed methane has been produced from the Raton Basin of north-central New Mexico since 1999 and presently accounts for 2% of New Mexico natural gas production. Underexplored and presently nonproductive frontier basins also have potential for petroleum resources. These include the Tucumcari, Las Vegas, Dalhart, Tularosa, Pedregosa and Albuquerque Basins. Any oil or natural gases that are eventually produced from these basins would have not only regional economic impact but would help alleviate future decline in statewide production from the major producing basins.

Carbon dioxide (CO_2) is another type of natural gas that has been produced in New Mexico. The main accumulation is the Bravo Dome field of northeastern New Mexico. Current production is approximately 106 billion ft^3 per year. The CO_2 produced from the Bravo Dome field is transported to the Permian Basin via underground pipeline where it is used to recover oil not producible through conventional, primary production. This gives CO_2 a value-added economic impact.

Helium is a natural gas that has been produced from eight small reservoirs in northwestern New Mexico since 1943. In addition, exploratory drilling has encountered helium-rich gases under Chupadera Mesa of central New Mexico and in the Tucumcari Basin of east-central New Mexico. Helium is essential to the manufacture of computer chips and fiber optic cables as well as the cooling of electromagnets in magnetic resonance imaging (MRI) instruments. Current national supplies are in decline.

Oilfield pulling unit, Chaves County, October 2015. *Photo by Ron Broadhead.*

I. INTRODUCTION

A cumulative 75 trillion ft³ (TCF) of natural gas and 6.4 billion bbls of oil (BBO) have been produced in New Mexico since the first commercial oil and natural gas production began in the early 1920s. Oil and natural gas have been produced from three basins in the state (Figs. 1, 2): the San Juan Basin in the northwest; the Permian Basin in the southeast, which is composed of the deep Delaware Basin, the Northwest Shelf, and the Central Basin Platform (separating the Delaware Basin from the deep Midland Basin of

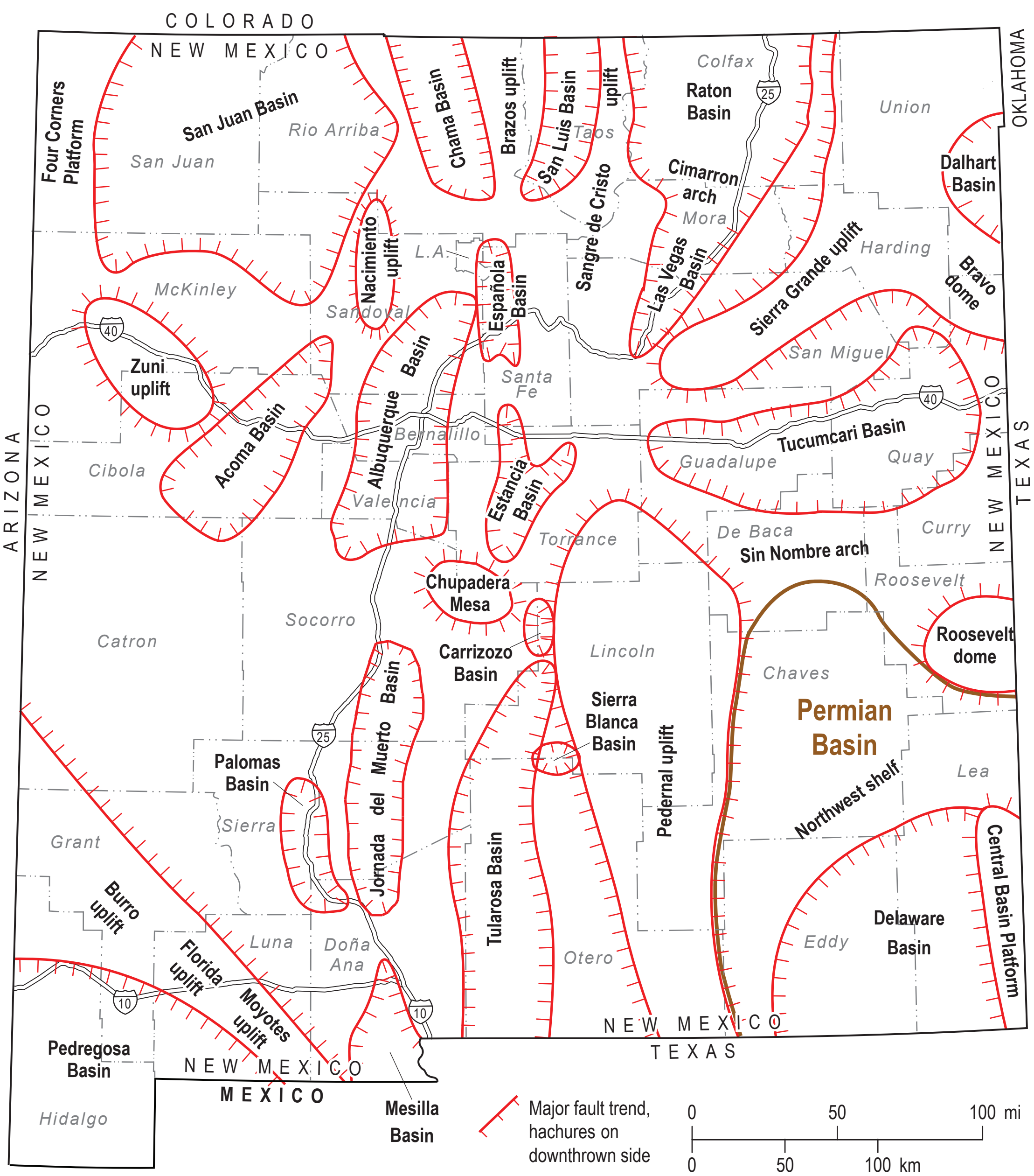


Figure 1. Major basins and uplifts in New Mexico.

west Texas); and most recently, the Raton Basin. In 2015, 147 million bbls of oil (MBO) and 1.27 TCF of natural gas were produced in New Mexico. In 2011 New Mexico was sixth in oil production and fifth in natural gas production among all states in the U.S. More than 95% of the oil is produced from the Permian Basin with the remainder coming from the San Juan Basin. A very minor volume of oil has been produced from a single well in the Española Basin. Approximately two-thirds of the state's gas is produced from the San Juan Basin, and one-third is produced from the Permian Basin. In addition, 2% of New Mexico gas comes from the Raton Basin.

Natural gas production in New Mexico dates from 1921 with the discovery of the Aztec field in the San Juan Basin (Fig. 1). The gas was discovered in the Farmington Sandstone (Upper Cretaceous) while drilling for oil. The reservoir was encountered at the shallow depth of 890 ft. In the 1920s there was little demand for gas in New Mexico or anywhere in the American southwest. The gas was piped to the nearby community of Aztec where it was used for home heating and cooking. Exploration for and development of gas reservoirs was minimal until after World War II when, with modernization of homes and industries, the

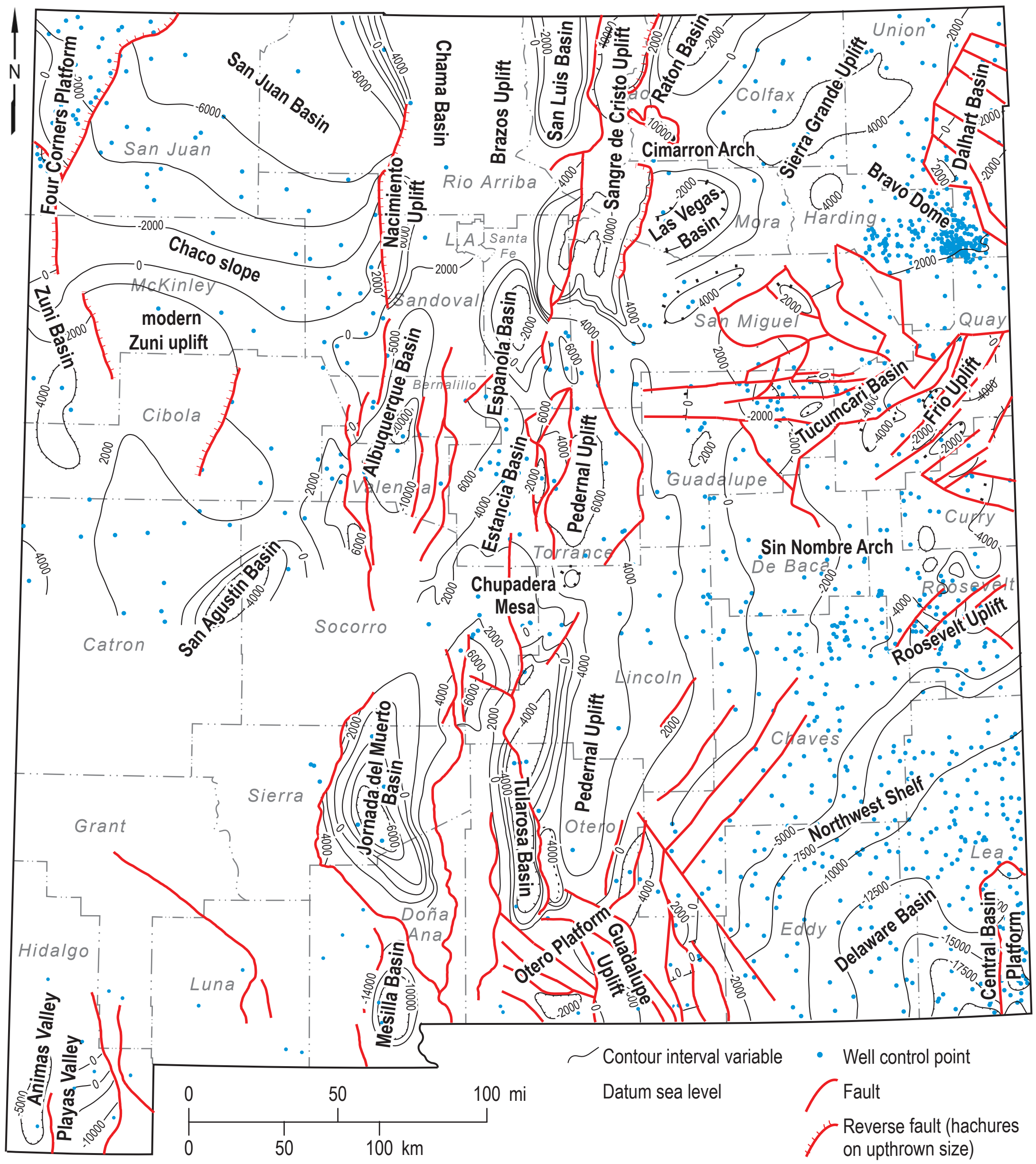


Figure 2. Structure contour map of New Mexico on top of Precambrian basement. Contours refer to feet above or below (-) sea level. Simplified from Broadhead (Broadhead et al., 2009).

demand for natural gas as an energy source soared, exploratory drilling increased, and production increased (Fig. 3).

In southeastern New Mexico, shallow water wells drilled in the Pecos Valley in the early part of the twentieth century encountered free oil, leading explorationists into the region (Richardson, 1913; Winchester, 1933). Commercial oil production was first established in New Mexico in 1922 at the Hogback field in the San Juan Basin (Fig. 1); the reservoir was the Dakota Sandstone (Upper Cretaceous). Commercial oil production was first established in southeastern New Mexico in 1924 with the discovery of the Artesia field, which produced oil and associated natural gas from dolostones and sandstones in the Grayburg and San Andres Formations (Permian: Leonardian through Guadalupian). Additional exploratory drilling quickly followed, and by the middle of the 1930s, oil production in New Mexico increased quickly (Fig. 4). The increase was due mostly to the discovery of large oil reservoirs in the Artesia Group and San Andres Formation in southeastern New Mexico. Oil production from these giant, newly-found Permian Basin reservoirs soon dwarfed production from the smaller oil reservoirs in the San Juan Basin. Most of the oil reservoirs in southeastern New Mexico produced substantial volumes of associated natural gas along with the oil. As no widespread markets existed for the gas prior to the late 1940s, much of the gas was flared at the wellsite. Reservoirs that contained gas with little or no oil were either bypassed or ignored.

In spite of the limited gas market, oil production increased steadily through the 1940s, 1950s and 1960s until 1969 when peak oil production was reached at the annual rate of 129 million bbls (Fig. 4). Through the 1950s and 1960s, the economics of exploration, drilling, and production were helped by the soaring demand for natural gas, which now was transported to end users via pipeline instead of being flared. Approximately 10% of the state's produced gas was utilized in New Mexico with the remainder exported out of state. California became the chief export market for New Mexico natural gas. During this period, natural gas reservoirs in southeastern New Mexico that contained little or no oil were increasingly sought, drilled, and developed. During this same period, continued exploration in the San Juan Basin steadily revealed that this was primarily a gas basin. The giant San Juan gas reservoirs were drilled and developed with the shallow Pictured Cliffs sandstones developed first and, then, successively deeper Cretaceous sandstones of the Mesaverde

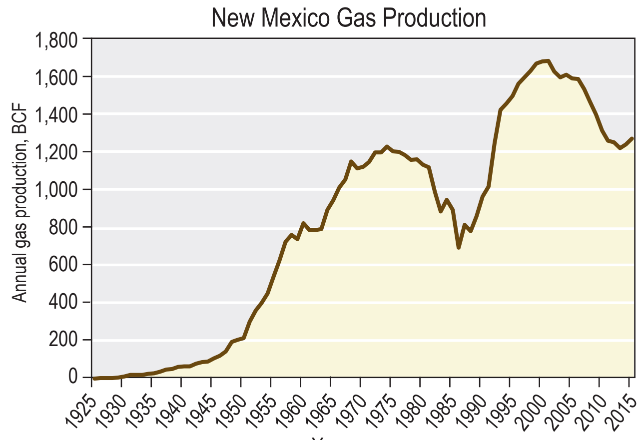


Figure 3. Annual New Mexico natural gas production from 1924–2015 in billion ft³ (BCF). Compiled from data obtained from U.S. Bureau of Mines, U.S. Department of Energy, and New Mexico Oil Conservation Division.

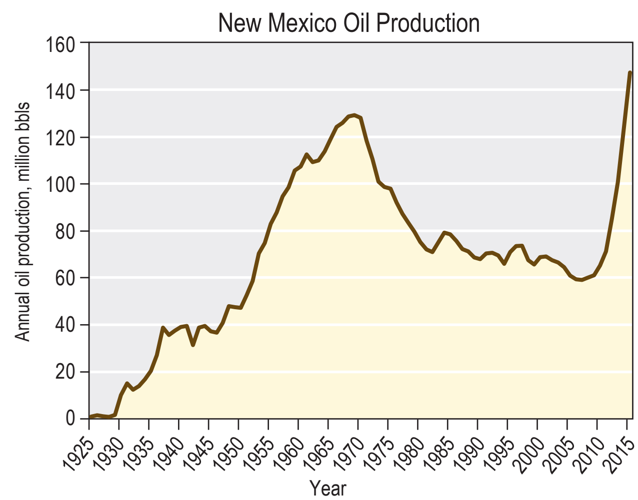


Figure 4. Annual New Mexico oil production from 1924–2015 in millions of bbls. Compiled from data obtained from U.S. Bureau of Mines, U.S. Department of Energy, and New Mexico Oil Conservation Division.

Group and the Dakota Sandstone. Gas production from the San Juan Basin soon rivaled gas production from the Permian Basin in southeastern New Mexico. Production from both basins contributed substantially to the economy of their regions as well as to the state as a whole.

After peak oil production was attained in 1969, a steep decline set in (Fig. 4). Hubbert's peak had been reached in the state, and it appeared to many that an inevitable decline to near-zero production volumes of oil would soon ensue. The decline (right side) of the oil production curve (Fig. 4) was expected to mirror the buildup (left side) of the curve. However, in the 1980s the decline leveled off, and a series of small increases in oil production soon occurred. These increases can be ascribed to the new discoveries of stratigraphically-trapped, rather than structurally-trapped oil and the implementation of enhanced recovery techniques (Broadhead, 2009a). The recent and very significant rise in New Mexico oil production is the result of production from unconventional reservoirs such as low-permeability lenticular sandstones within the Bone Spring Formation (Lower Permian) and the Avalon shale member of the Bone Spring. With general similarity to the gigantic Bakken reservoirs of North Dakota (see Grau and Sterling, 2011), this recent increase in production, from hitherto ignored and largely unrecognized reservoirs, indicates that New Mexico is heading toward a second Hubbert's peak. The deviation from the Hubbert curve since 1980 has been caused by production of oil that had not been found, produced, or anticipated during the buildup side of the curve and would not have been found or produced with the geologic concepts and technologies generally employed prior to 1980.

Similarly, overall natural gas production attained a peak of 1.2 TCF/year in 1974 and then seemed to be in permanent decline, declining 40% to just under 0.7 TCF in 1986 (Fig. 5). However, in 1988 a new gas resource, coalbed methane in the Fruitland Formation (Upper Cretaceous), was developed and gas production correspondingly increased to a new peak and an all-time high of 1.68 TCF/year in 2001.

As the known, productive coalbed methane and other gas reservoirs have gradually become depleted, gas production has again fallen. This time, the gas production fell by almost 27% to 1.23 TCF/year. Over the past decade, coalbed methane was developed aggressively in the Raton Basin and

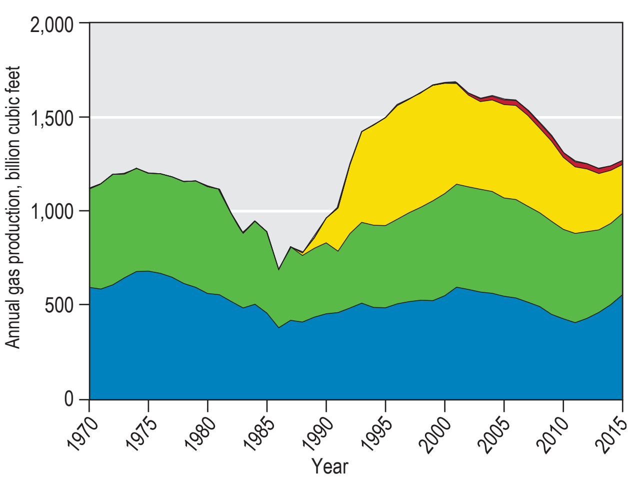


Figure 5. Annual natural gas production in billion ft^3 in New Mexico from 1970–2015. Compiled from data obtained from New Mexico Oil Conservation Division.

now accounts for 2% of the total New Mexico gas production. Over the last two years, new discoveries of Permian oil reservoirs in the Permian Basin, which produce gas along with the oil have reversed the decline in New Mexico gas production.

Shale gas resources are, at this time, not fully understood and remain almost entirely undeveloped in New Mexico. They are some of the most obvious untapped resources that may help prevent further decline in natural gas production. Possible targets for shale gas are present in Upper Cretaceous shales in the San Juan and Raton Basins as well as Permian, Pennsylvanian and Mississippian shales in the Permian Basin. Newly discovered conventional and tight gas in frontier basins such as the Tucumcari Basin also holds significant future promise. Therefore, continued irreversible decline in gas production is not inevitable. Large untapped, and presently inadequately understood, natural gas resources remain undeveloped and unproduced.

Another type of naturally occurring gas, carbon dioxide (CO_2), is also produced in New Mexico. Almost all of the CO_2 has been produced from the Bravo Dome field in the northeastern part of the state. In the past, minor volumes of CO_2 were also produced from the Des Moines field on the Sierra Grande uplift and from two small accumulations in the Estancia Basin. These minor accumulations have been abandoned for several decades. More than 99% of the CO_2 that is currently produced is shipped via underground pipeline to the Permian Basin, where it is injected into old oil fields for enhanced oil recovery. A very minor amount is converted into dry ice. In past years, small volumes of produced CO_2 were turned into liquid form and used in fire extinguishers and in the carbonation of beverages. The Bravo Dome field was discovered in 1917 by an exploration well that was drilled for oil. Bravo Dome remained unproduced until 1931 when additional wells were drilled, and a plant was erected to turn the CO_2 into dry ice and bottled liquid. The small Des Moines field was discovered in 1935 and was produced until abandonment in 1966. The Estancia fields were discovered in 1928 and 1931 and produced from 1934 until 1942. New Mexico CO_2 production was minimal until the 1980s when demand skyrocketed as a result of its new use for enhanced oil recovery in the Permian Basin (Fig. 6).

Helium is a natural gas that has been produced from small natural gas fields on the Four Corners Platform of northwestern New Mexico since

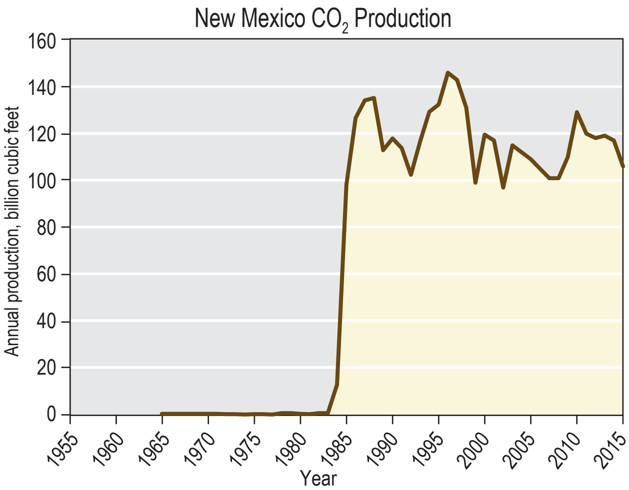


Figure 6. Annual volume of CO_2 gas produced from natural geological accumulations in New Mexico in billion ft^3. Production data not available prior to 1965. Compiled from data obtained from New Mexico Oil Conservation Division.

1943. Helium is a minor component of almost all natural gases. In the rare cases where it is present in concentrations above approximately 0.3%, it may be separated from the produced natural gas stream and sold as a byproduct. In the extremely rare cases where it is present in concentrations exceeding 3%, the other gas in the reservoir is often inert and consists mostly of nitrogen. In these cases, the gas is produced for the helium only. The earliest use of helium was as a lifting gas for observation blimps during World War II. The inert nature of the helium made it preferable to hydrogen, which is volatile and can easily catch fire or explode. In recent years, however, helium has become indispensable in the modern technologies that encompass our lives. These include magnetic resonance imaging (MRI), and the production of computer chips, fiber optic cables, and LCD screens. Since 1943, cumulative helium production from New Mexico reservoirs is estimated to be approximately one billion ft^3 (BCF), (Broadhead and Gillard, 2004). This is dwarfed by annual U.S. production of 2.9 BCF in 2011 and annual U.S. sales of 4 BCF in 2011 (Madrid, 2012). Currently identified and developed U.S. helium sources are declining and insufficient to meet demand. The difference between production and sales is compensated by withdrawals from underground storage. The need for new sources of economically recoverable helium is becoming critical. Possible future sources of helium in New Mexico include undiscovered accumulations in middle to upper Paleozoic reservoirs on the Four Corners Platform, middle to upper Paleozoic reservoirs in the San Juan Basin of northwestern New Mexico, Pennsylvanian reservoirs in the Tucumcari Basin, continental Permian reservoirs on the Northwest Shelf of the Permian Basin, and beneath Chupadera Mesa.

Oil processing facility north of Hobbs, Lea County, October 2015. *Photo by Ron Broadhead.*

II. PERMIAN BASIN

The Permian Basin extends into southeastern New Mexico from adjacent areas of west Texas. Approximately 80% of the basin lies within Texas. Within New Mexico, the Permian Basin is subdivided into three major elements (Fig. 7): the relatively shallow Northwest Shelf and Central Basin Platform and the deep Delaware Basin. Depth to the Precambrian basement ranges from 3,500 ft on the Northwest Shelf in northwestern Chaves County to 12,000 ft on the shelf in southeastern Chaves and southern Roosevelt Counties and from 8,000–10,000 ft on the Central Basin Platform (Fig. 2). Depth to Precambrian basement exceeds 21,000 ft in the deepest parts of the Delaware Basin in southwestern Lea County. From there, the basin deepens southward into Texas. The Central Basin Platform separates the Delaware Basin from the deep-marine Midland Basin of Texas. In New Mexico, the Permian Basin is bounded on its west side by the Capitan Mountains, Sierra Blanca Range, and Sacramento Mountains (see Preface, Fig 1). The Pedernal uplift, a broad north-trending tectonic highland, formed the western flank of the Permian Basin during the Late Paleozoic (Fig. 1). To the north, the subsurface Sin Nombre arch separates the Permian Basin from the Tucumcari Basin.

Differential depth to Precambrian between the Delaware Basin and the bordering higher elements of the Central Basin Platform, Northwest Shelf, and Pedernal uplift is accommodated by thickening of strata in the Delaware Basin. The Permian and Pennsylvanian sections are thicker in the basin than on the shelf and the platform, marking the differentiation of the Permian Basin into its subsidiary tectonic elements during the Pennsylvanian and Early Permian (see Adams, 1965). The boundary between the Northwest Shelf and the Delaware Basin may have originated during the Late Mississippian (Broadhead, 2009b). Additionally, the Tatum Basin, an intrashelf basin that affected deposition of reservoirs during the Pennsylvanian and Early Permian, existed at least as far back as the Early Mississippian (Broadhead, 2009b).

The Delaware Basin is not only structurally deeper than the Northwest Shelf and Central Basin Platform but was also the locus of deposition of deep-water sediments from the Late Mississippian to the end of the Permian in contrast to shallow water deposition on the Northwest Shelf and Central Basin Platform. This differentiation of water depths has resulted in different stratigraphic nomenclatures in the Delaware Basin and the shallower areas of the Northwest Shelf and the Central Basin Platform (Figs. 8, 9). These differing nomenclatures reflect the deposition of shallow shelf, shelf margin, and nonmarine siliciclastic and carbonate sediments on the shelf and platform contrasted with deep marine

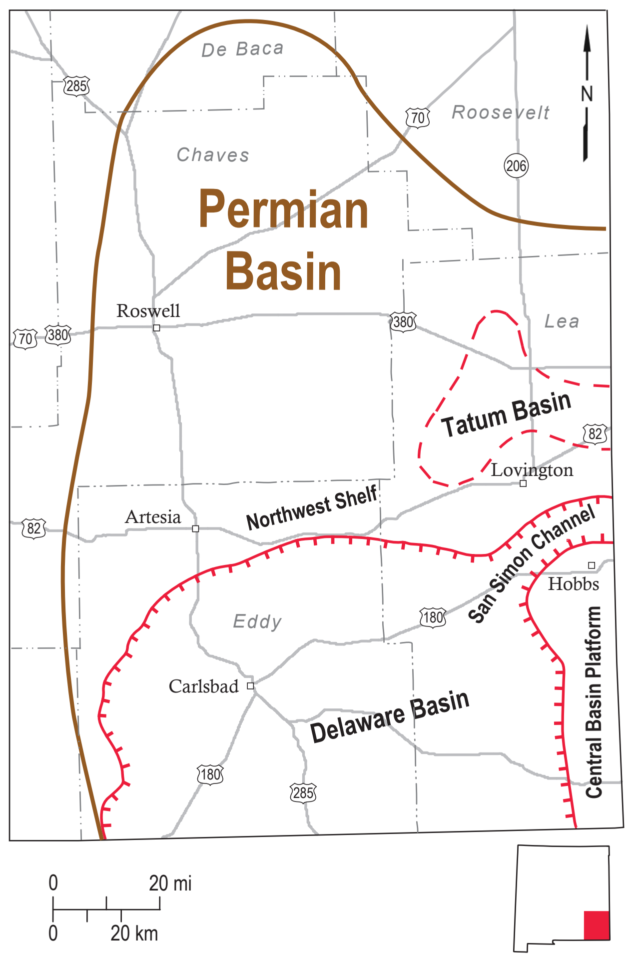


Figure 7. Map of southeastern New Mexico indicating major Pennsylvanian to Permian paleobathymetric elements. Geologic elements after Hills (1984) and Dutton et al. (2005). Red lines indicate boundaries between major paleobathymetric elements.

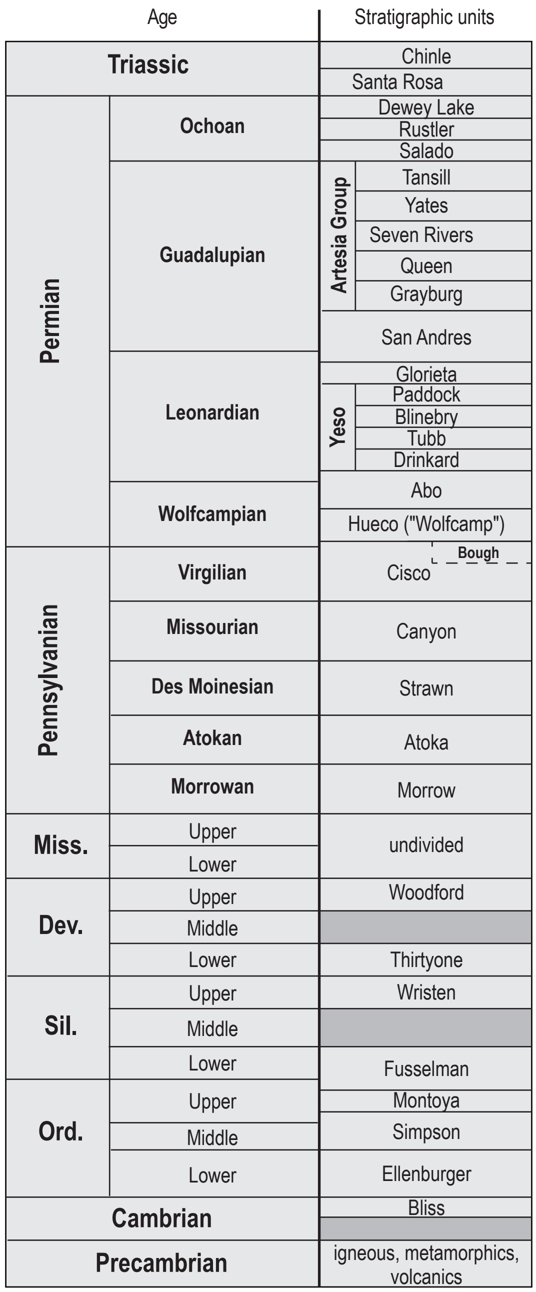


Figure 8. Stratigraphic chart of the Northwest Shelf and Central Basin Platform.

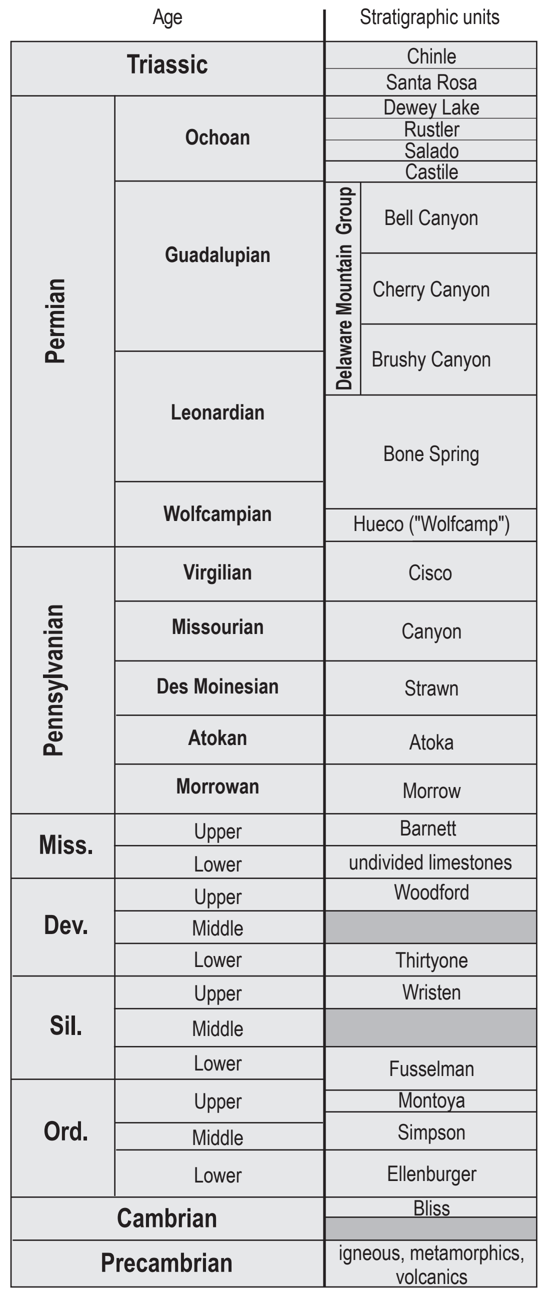


Figure 9. Stratigraphic chart of the Delaware Basin.

autochthonous and allochthonous siliciclastic and carbonate sediments in the Delaware Basin. Prior to development of the Delaware Basin as a separate tectonic entity, southeastern New Mexico was occupied by the Tobosa Basin, a gently downwarped structural element.

Substantial oil and natural gas production is obtained from almost the entire stratigraphic section in southeastern New Mexico, with major reservoirs ranging in age from Ordovician to Late Permian. In the early years of exploration, drilling was performed with cable tool rigs that could penetrate, at most, to depths of a few thousand feet. Exploration and production, therefore, concentrated on shallower reservoirs in the Permian section. By the 1930s, however, rotary drilling rigs had largely displaced cable tools, and explorationists increasingly sought deeper targets with increased depth capacities provided by the rotary drilling methods. Drilling for targets in Ordovician reservoirs at depths exceeding 20,000 ft reached its heyday in the 1950s through the 1970s.

As a result, the entire post-Precambrian sedimentary section was brought into production. Although most traps in the Permian Basin are primarily stratigraphic in nature, the locations of favorable reservoir facies have often been influenced by depositional relationships to paleostructure. Stacked pay zones are common with traps formed at multiple stratigraphic levels at a single location by a single paleostructure. The presence of stacked pay zones reduces exploratory risk and enhances the possibilities of success in an exploratory well compared to basins where stacked pays are the exception.

Upper Permian

Major reservoirs of oil and associated gas are found in Upper Permian strata on the Northwest Shelf and Central Basin Platform and in the Delaware Basin. On the shelf and platform, significant reservoirs are found in the Artesia Group (Permian: Guadalupian; Fig. 8) and in the San Andres Formation (Permian: Leonardian to Guadalupian; Fig. 8). Upper Permian reservoirs constitute the largest and most productive group of reservoirs in southeastern New Mexico. Upper Permian reservoirs in the Delaware Basin belong to the three formations that constitute the Delaware Mountain Group (in descending order): Bell Canyon, Cherry Canyon, and Brushy Canyon Formations (Fig. 9). Ochoan strata, which form the uppermost part of the Permian section, are nonproductive except for a few very small, isolated reservoirs in the Castile Anhydrite in the northern part of the Delaware Basin. Overlying Triassic strata are devoid of production except for very minor gas accumulations in the Santa Rosa Sandstone along the eastern margin of the Delaware Basin.

Artesia Group

The five formations of the Artesia Group (descending: Tansill, Yates, Seven Rivers, Queen, Grayburg) have provided significant oil and gas production in southeastern New Mexico (Fig. 10). Sandstones provide the major component of production in Yates and Queen reservoirs. Traps are primarily stratigraphic (Ward et al., 1986). Widespread reddish-colored evaporitic shales and evaporites provide effective vertical and lateral seals within the Artesia Group. Dolostones provide secondary reservoirs. Oil and gas produced from the dolostone reservoirs are commingled with the oil and gas produced from the more prolific sandstone reservoirs in most fields. Drive mechanisms are most commonly solution gas drive, water drive, and combination solution gas-water drives. Depth to production in the Yates Formation ranges from 1,300 to 3,800 ft along the edge of the Northwest Shelf and is approximately 3,000 ft on the Central Basin Platform. Depth to production in the Queen Formation is a maximum of 4,000 ft on the eastern part of the Northwest Shelf. Grayburg reservoirs are discussed later in this section with San Andres reservoirs because production from the two formations is commingled in many of the fields.

San Andres Formation and Grayburg Formation

The San Andres Formation is 600–1,600 ft thick in southeastern New Mexico. The San Andres is thinnest in northwestern Chaves County and thickens to the southeast. It is not present in the Delaware Basin where the Delaware Mountain Group represents time-equivalent strata. The San Andres is prolifically productive from both the Northwest Shelf and the Central Basin Platform (Fig. 11).

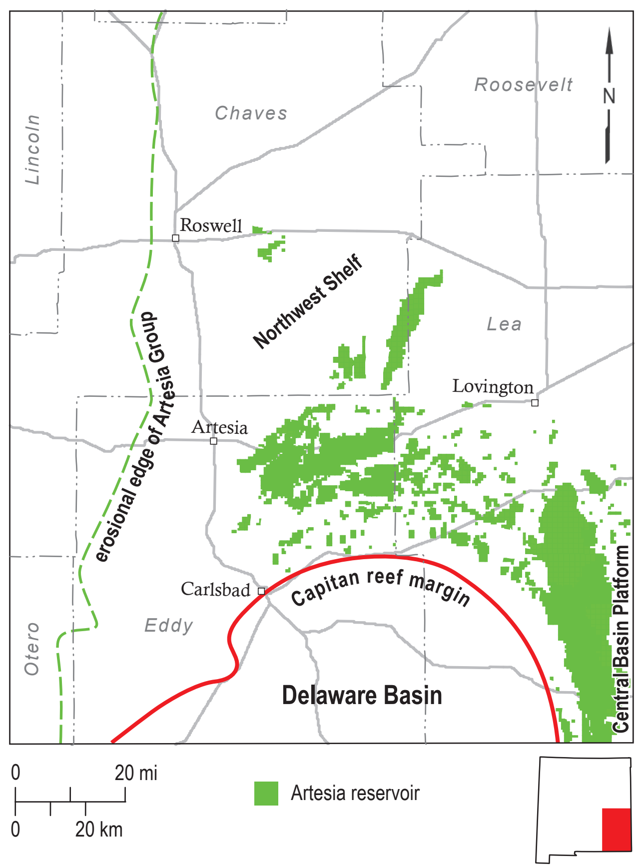


Figure 10. Oil and gas reservoirs in the Artesia Group (Permian), exclusive of the Grayburg Formation, southeastern New Mexico. Capitan reef margin from Garber et al. (1989). Red line indicates the Capitan reaf margin, which separates the Northwest Shelf and the Central Basin Platform from the deep-marine Delaware Basin.

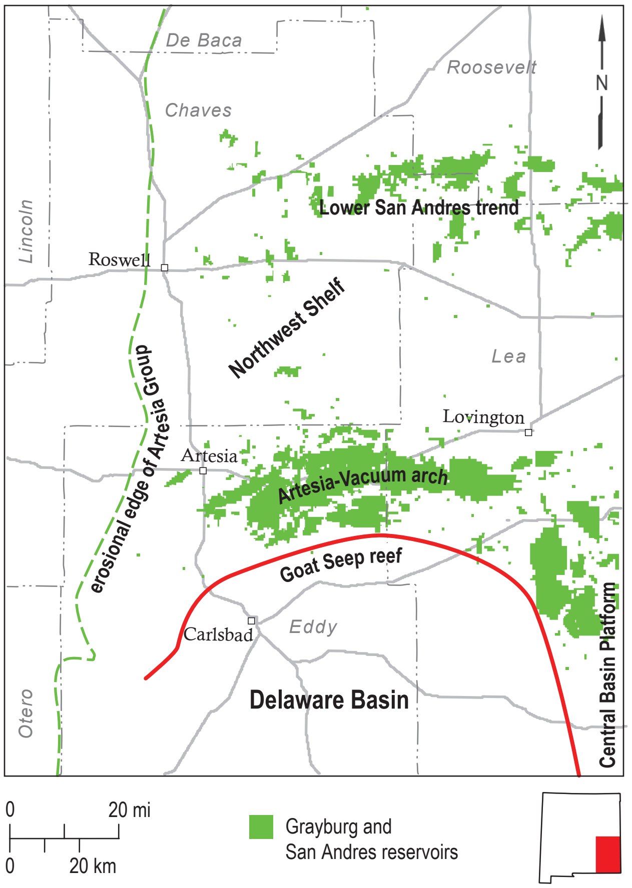


Figure 11. Oil and Gas reservoirs of the Grayburg and San Andres Formations (Permian), southeastern New Mexico. Goat Seep reef margin from Garber et al. (1989). Red line indicates the Goat Seep reef margin which separates the deep-marine Delaware Basin from the Northwest Shelf and the Central Basin Platform.

The lower part of the San Andres produces from a trend that cuts across the northern part of the shelf. Traps along this trend are formed by updip pinchouts of dolostone reservoirs that dip to the south (Gratton and LeMay, 1969; Elliott and Warren, 1989). Average reservoir porosity typically ranges from 6–10%. Updip seals are formed by occlusion of porosity by anhydrite cement. Many traps have a structural component provided by a drape of porosity pinchouts over south-plunging structural noses, resulting in a combination trap. Multiple, stacked reservoir zones are generally present within the San Andres. Depth to productive reservoirs ranges from 3,200–4,500 ft. The primary drive mechanism in most reservoirs is solution gas with a gas cap present in some reservoirs.

The upper part of the San Andres is productive on the southern part of the Northwest Shelf and on the Central Basin Platform. On the Northwest Shelf, oil and associated gas are trapped along the Artesia-Vacuum arch, an east-west trending structure that overlies the deeper, older Abo shelf margin and Bone Spring flexure (Broadhead, 1993a; Broadhead et al., 2004). San Andres reservoirs are typically subtidal dolostones that are overlain by low-permeability peritidal carbonates; multiple sequences vertically compartmentalize the reservoirs (Purves, 1986; Handford et al., 1996; Modica and Dorobek, 1996; Stoudt and Raines, 2001; Pranter et al., 2004). Average reservoir porosities typically vary between 8–20%. Traps are combination structural-stratigraphic with the Artesia-Vacuum arch providing the primary structural component. Northerly updip pinchouts of the reservoirs into impermeable evaporitic facies, which form the seals, provide the stratigraphic component (Ward et al., 1986).

Production from the San Andres Formation is commingled with production from the overlying Grayburg Formation along the Artesia-Vacuum arch. In this area, the Grayburg consists of 200–400 ft of interbedded sandstones, siltstones, dolomitic carbonates, and evaporates. Grayburg production is obtained principally from sandstones that were deposited in coastal, sabka, sandflat and eolian environments (Handford et al., 1996; Modica and Dorobek, 1996). Pores in the interbedded Grayburg carbonates have generally been plugged by anhydrite. Depth to productive reservoirs ranges from 1,500–4,500 ft. Solution gas drives predominate in the reservoirs along the Artesia-Vacuum trend.

On the Central Basin Platform, the San Andres produces oil and associated gas from subtidal to supratidal dolostones as well as from subtidal dolomitic sandstones (Garber and Harris, 1986; Lindsay, 1991). Reservoir porosity varies from 8–25%. Most traps are formed by gentle, north-south trending anticlines. Vertical seals are typically formed by impermeable evaporitic facies. Depth to production varies from 3,400–5,100 ft. Water drives and combination solution gas-water drives predominate in these reservoirs.

Delaware Mountain Group

Reservoirs of the Delaware Mountain Group (Permian: Guadalupian) stretch from the northern part of the Delaware Basin in Eddy and Lea Counties (Fig. 12) south into Texas. The Delaware Mountain Group attains a maximum thickness in New Mexico of 3,500 ft in southwestern Lea County and thickens southward into Texas. Reservoirs are deep-basin, fine- to very fine-grained submarine fan and channel sandstones. The reservoir sandstones were deposited by turbidity currents and density flows in channels and on the lobes of submarine fans

(Jacka, 1979; Harms and Williamson, 1988). Bell Canyon and Cherry Canyon reservoirs are formed mostly by channel-shaped sands (Meissner, 1972; Berg, 1975; Jacka, 1979; Harms and Williamson, 1988; Montgomery et al., 2000). Brushy Canyon reservoirs are formed by channel-shaped sands and sands deposited on fan lobes that occur in linear trends perpendicular to the depositional slope (May, 1996; Broadhead et al, 1998; Montgomery et al., 1999; Broadhead and Justman, 2000). Traps are predominantly stratigraphic. Reservoir sandstones are complexly interbedded with non-reservoir siltstones and lower-permeability, non-reservoir sandstones. The interbedded siltstones are kerogen-rich and are mature source rocks (Justman and Broadhead, 2000). Porosities of as much as 25% are not uncommon, but the fine grain size of the sandstones results in high irreducible water saturation. As a result, production is typically obtained from multiple separate sandstone layers within a single reservoir, and the lateral extent of individual permeable zones is limited. Reservoirs are thought to have no single oil-water contact but rather have multiple oil-water contacts within a single complex reservoir (Montgomery et al., 1999).

Development of the Delaware Mountain Group Basinal Sandstone play began with the shallowest reservoirs in the Bell Canyon Formation. It is only within the last 25 years that exploration and development has concentrated on the deeper zones. Bell Canyon reservoirs lie at depths of 2,500–5,000 ft in the New Mexico part of the Delaware Basin. Cherry Canyon reservoirs lie at depths of 3,000–6,000 ft. Brushy Canyon reservoirs lie at depths of 6,000–8,500 ft. Most Bell Canyon reservoirs were discovered prior to 1970.

Delaware sandstone reservoirs produce oil and associated gas via solution gas drive. Initial production may typically exceed 2,500 bbls per month in a well but typically declines to a few hundred bbls a month (or less) after about four years as the solution gas is produced and reservoir pressures decrease below the bubble point (Broadhead et al., 1998; Montgomery et al., 1999). Only about 10% of the original oil in place is thought to be recovered through primary production (Montgomery et al., 1999). Injection of produced water for pressure maintenance can yield a good production response in some reservoirs (Broadhead et al., 1998) and needs to be initiated early so that a secondary gas cap is not allowed to form (Mark Murphy, personal commun., 2003). In recent years, the drilling of horizontal wells in the Brushy Canyon has substantially increased per well recovery.

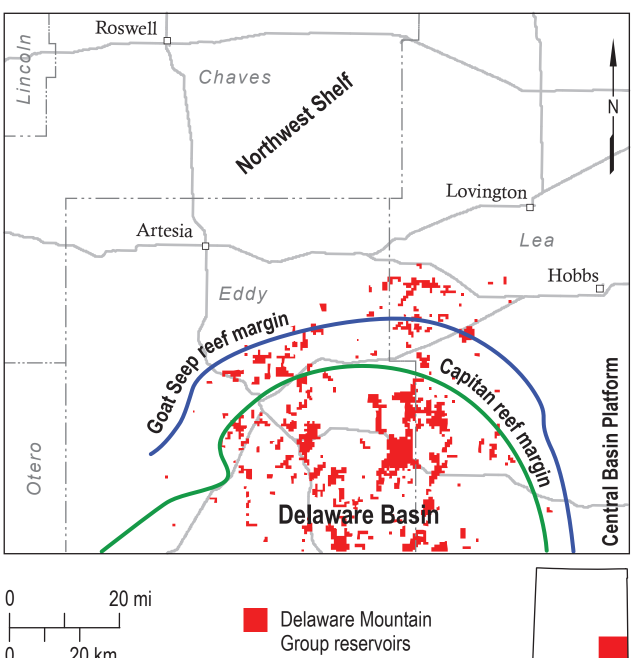


Figure 12. Oil and gas reservoirs in the Delaware Mountain Group (Permian), southeastern New Mexico. Blue line indicates the Goat Seep reef margin and the green line indicates the younger Capitan reef margin.

Lower Permian

The Wolfcampian and Leonardian (Lower Permian) sections have been prolific reservoirs of oil and natural gas in the Delaware Basin, on the Northwest Shelf, and on the Central Basin Platform (Figs. 13, 14). By the Early Permian, the Permian Basin in southeastern New Mexico saw full development of the three distinct paleobathymetric elements: the deep Delaware Basin, the Northwest Shelf, and the Central Basin Platform. The boundary between the Northwest Shelf and the Delaware Basin may have had its roots in a subtle tectonic flexure dating as far back as the late Mississippian (Broadhead, 2009b), but over time became a constructional shelf margin that developed during the Late Pennsylvanian. By the Early Permian, the shelf margin consisted of a system of almost continuous fringing barrier reef complexes that separated the Delaware Basin from the Northwest Shelf (Fig. 14; Malek-Aslani, 1970, 1985; LeMay, 1960, 1972). Major Lower Permian reservoirs occur in the Hueco Group (often referred to as "Wolfcamp") on the Northwest Shelf, in the Abo and Yeso Formations on the Northwest Shelf and on the Central Basin Platform, and in the Bone Spring Formation in the Delaware Basin (Figs. 8, 9).

The Yeso Formation, like the underlying Abo, covers the Northwest Shelf and the Central Basin Platform. It is 1,500–2,500 ft thick. Age-equivalent strata in the Delaware Basin belong to the deep-marine Bone Spring Formation. In southeastern New Mexico, the Yeso has been subdivided into four informal members (Fig. 8). Although the Yeso is largely a clastic unit with minor carbonates and gypsum at its type section in central New Mexico (Needham and Bates, 1943), it is dominated by carbonates that were deposited on a restricted marine platform in southeastern New Mexico (Broadhead, 1993b; Broadhead et al., 2004). Dolostone and limestone reservoirs dominate the Paddock, Blinebry, and Drinkard sections, and average reservoir porosity varies from 5–20%. Fine-grained dolomitic sandstones are the primary reservoirs within the Tubb in some areas, but dolostones are prevalent in other areas.

Glorieta Formation

The Glorieta Formation overlies the Paddock Member in southeastern New Mexico. Although the Glorieta is defined as a sandstone at its type section in north-central New Mexico (Needham and Bates, 1943), it is dominantly a dolostone in the southeast, though sandstones form the Glorieta reservoirs in a number of fields. Depth to production ranges from 5,000–7,000 ft. Solution gas provides the primary drive mechanism, although combination gas-cap assisted water drives are also present.

Yeso Formation

Yeso reservoirs (Fig. 13) are major contributors to oil and gas production in southeastern New Mexico. Production is mostly oil with associated gas. Large volumes of saline water are typically produced along with the oil. Productive reservoirs are primarily located on top of the Central Basin Platform as well as on the shelf margin at the northern edge of the Delaware Basin. Traps are generally formed by low-relief anticlines. In recent years, exploration and substantial development have been concentrated along the western half of the shelf margin where development has added substantial volumes to New Mexico oil production. Also, in recent years, drilling of horizontal wells with long laterals in the Yeso has greatly assisted production. Depth to production ranges from 5,000–7,000 ft. Solution gas provides the primary drive mechanism although combination gas-cap assisted water drives are also present.

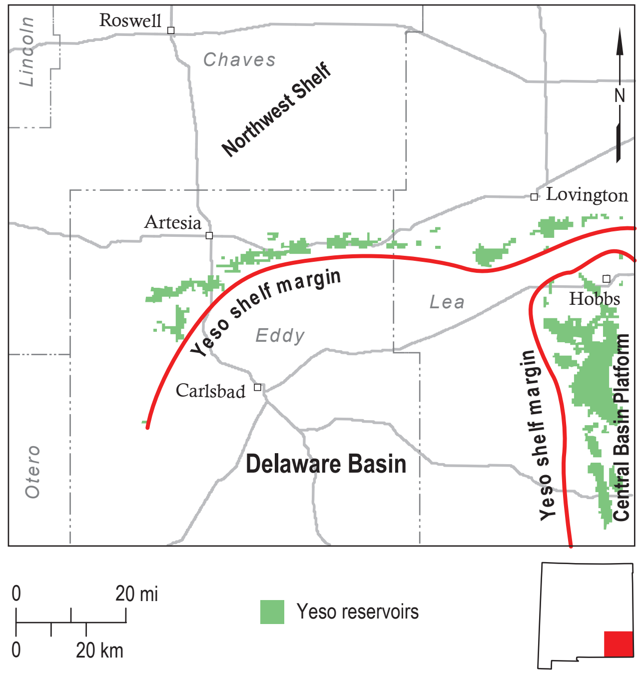


Figure 13. Oil and gas reservoirs in the Yeso Formation (Permian), southeastern New Mexico. Red line indicates the margins of the Yeso shelf which separates the Northwest Shelf and Central Basin Platform from the deep-marine Delaware Basin.

Abo Formation

The Abo Formation has been prolifically productive of oil and associated gas from dolomitized carbonates on the Central Basin Platform and along the margin of the Northwest Shelf. Lesser production has been obtained from dolostone reservoirs in the backreef setting north of the shelf margin (Fig. 14). Northward, the marine Abo carbonates grade into a clastic red bed facies of fluvial-deltaic sandstones and shales that produce nonassociated gas. The Abo attains maximum thickness of 1,200–1,400 ft near the shelf margin and thins shelfward to 700–800 ft on the Northwest Shelf and on the Central Basin Platform.

The Abo shelf margin reservoirs were discovered primarily during the 1950s and early 1960s. They consist of pervasively dolomitized shelf-margin buildups and associated facies; reservoirs are fine- to coarse-crystalline dolostones (LeMay, 1960, 1972; Snyder, 1962). Dolomitization is less pervasive along the eastern part of the trend as it enters Texas. Porosity typically varies from 5–15%. Fine-crystalline, often anhydritic dolostones and green siliciclastic shales form vertical seals as well as seals on the backreef side of the reservoirs. Toward the basin on the south, the seals are formed by the sharp transition to non-porous, black argillaceous lime mudstones of the Bone Spring Formation. The dark-colored, fine-grained sediments of the Bone Spring are organic rich and are the source rocks for the oil in the shelf-margin carbonates. East-west limits of the shelf margin reservoirs are formed by gentle structural or morphologic plunging of the reef top underneath the oil-water contact. Depth to production ranges from 6,000 ft to more than 8,500 ft along the shelf margin barrier reef reservoirs. Primary drive mechanisms are gas caps with a solution drive assist, although a partial water drive is present in several reservoirs.

Abo reservoirs in the back-reef region and on the Central Basin Platform are dolostones that were deposited on an evaporitic marine shelf (Broadhead et al., 2004). Traps appear to be formed by broad, low-relief anticlines. Generally, reservoirs are smaller than the Abo reservoirs along the shelf margin.

To the northwest, the Abo carbonates grade into red, fine-grained sandstones and shales (Scott et al., 1983; Broadhead, 1984a, 1993c; Bentz, 1992). These clastics were deposited in fluvial settings that transitioned into a deltaic environment at their distal, southern end. Abo streams flowed southward into the Permian Basin from source areas of Precambrian rocks north of the Tucumcari Basin that were uplifted and exposed during the Pennsylvanian. Production is obtained from lenticular sandstones deposited in south-flowing channels with an average net pay of 30 ft. Average depth to production ranges from 2,800 ft along the west side of the gas accumulations to 4,200 ft as the reservoirs dip eastward into the basin. Porosity is a moderate 13%, average in situ permeability is low, 0.0067 millidarcies (New Mexico Oil Conservation Division Case file 7093) so that wells need to be artificially fractured in order to produce economic volumes of natural gas. Reservoirs produce by pressure depletion drive.

In recent years, a new oil play has emerged in back-reef dolostones (Fig. 14; Gawloski, 2011). Production is obtained from laterally and vertically discontinuous porous lenses in the lower Abo. Economic levels of production are mostly made possible by drilling horizontal wells through the lower Abo. The horizontal wells are able to produce from multiple, isolated porous lenses of dolostone whereas a vertical well will only be productive from a single porous lens. As a result, the volume of oil production from horizontal wells in this play may be up to 15 times more than the volume of oil production from vertical wells (Gawloski, 2011).

Bone Spring Formation

The Bone Spring Formation is present only in the Delaware Basin where it is stratigraphically equivalent to the Abo and Yeso Formations of the Northwest Shelf and Central Basin Platform (see LeMay, 1960; Saller et al., 1989; Tyrrell, 2009). It attains a maximum thickness of approximately 4,000 ft in southern Eddy County. The Bone Spring has been productive from several plays.

The first play is present along the northern edge of the basin. Here, the Bone Spring is productive from reservoirs deposited as carbonate debris flows that originated as carbonate detritus derived from the Abo and Yeso shelf margins (Saller et al., 1989; Montgomery, 1997a). The reservoirs are dolomitized conglomerate breccias within the Bone Spring carbonate units (Fig. 14). Most porosity is secondary. Traps are mainly stratigraphic and formed by reservoir

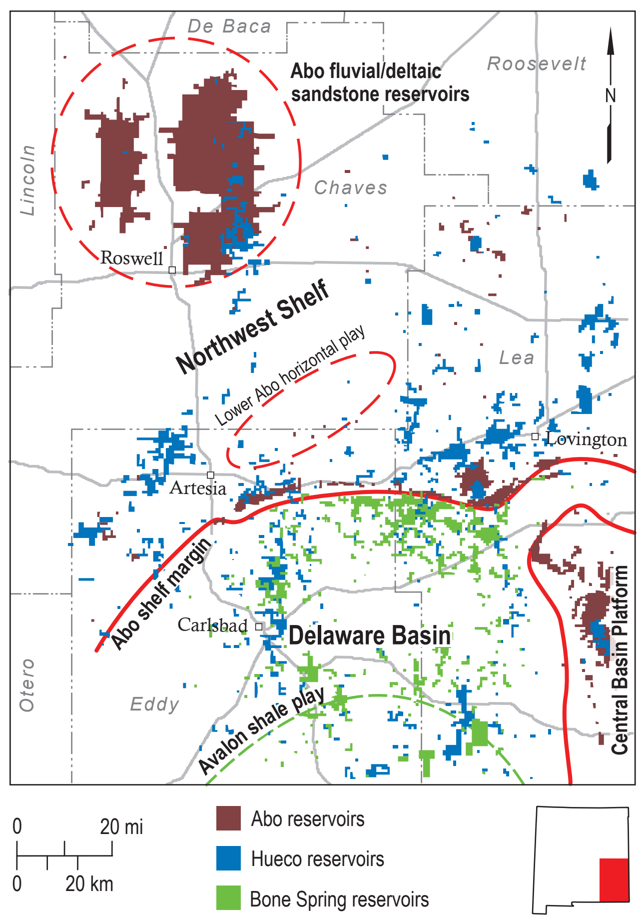


Figure 14. Oil and gas reservoirs in the Hueco Group, Abo Formation and Bone Spring Formation (Permian), southeastern New Mexico. Solid red lines indicate the Abo shelf margins, which separates the deep-marine Delaware Basin from the Northwest Shelf and Central Basin Platform. Dashed red and green lines indicate approximate play boundaries.

facies deposited on debris flow fans at the toe of the submarine slope. These Bone Spring reservoirs produce oil and associated gas. Depth to production ranges from 5,500–10,000 ft. Solution gas provides the drive mechanism in many reservoirs.

Siliciclastic turbidites are widespread in the sandstone members of the Bone Spring and constitute the second play. Reservoirs are fine-grained sandstones deposited in a channel and fan system at the base of the slope and on the basin plain (Montgomery, 1997b). In contrast to the debris flow carbonate reservoirs that are found at the toe of slope, the sandstone turbidite reservoirs are found further south (Fig. 14). Porosity typically averages 7–20%. Source rock and seals for both plays are the interbedded, organic-rich, dark lime mudstones. Depth to production ranges from 9,000 to more than 12,000 ft. Solution gas drives are dominant.

Within the past three years, new and prolifically productive plays have emerged within the Bone Spring Formation in the Delaware Basin (Fig. 14). Reservoirs in these plays include laterally extensive, kerogen-rich, fine-grained clastics within the upper part of the Bone Spring referred to as the Avalon shale (Hardie, 2011; Worrall, 2011). These fine-grained clastic rocks are both the reservoir and the source rock. More significantly, deep basinal sandstones in the middle and lower parts of the Bone Spring (Second and Third Bone Spring sandstones) have formed new, important plays. With limited lateral extent and relatively low permeability, the Bone Spring sands have seen only limited development with conventional vertical wells. Interbedded deep basinal shales are source rocks. Development of these plays has been made possible by the emergence of economically feasible horizontal drilling and the advent of multi-stage hydraulic fracturing techniques that increase reservoir permeability and, consequently, production rates and ultimate recovery. Development of these plays has been primarily responsible for the marked increase in New Mexico oil production in recent years (Fig. 4) and represents a major contribution to the reserve base of the state. These are new and previously unrecognized reserves.

Hueco Group

The Hueco ("Wolfcamp") Group produces oil and associated gas on the Northwest Shelf and on the shelf margin (Fig. 14). The Hueco is almost 400 ft thick over most of the Northwest Shelf, but is more than 1,000 ft in the Tatum Basin. It is more than 2,000 ft thick in the deepest part of the Delaware Basin near the Texas line. Production is largely derived from the lower part of the Hueco. Reservoirs are similar in depositional setting to those in the underlying Upper Pennsylvanian section. Shelf-margin reservoirs were formed by a barrier reef complex, with reservoir facies consisting of reefal (hydrozoan boundstone), back-reef (skeletal grainstone), and forereef (talus slope) facies (Malek-Aslani, 1970). On the shelf to the north of the barrier reef, reservoirs are formed by phylloid-algal bioherms deposited on pre-existing paleobathymetric highs or as grainstones capping and flanking the bioherms (Cys and Mazzullo, 1985; Malek-Aslani, 1985; Cys, 1986). Porosity is typically 7–10%. The paleobathymetric high areas generally trend north-south and are thought to be bounded by low-relief faults of Wolfcampian age that developed as part of Ancestral Rocky Mountains deformation. Traps are largely stratigraphic, although on the shelf margin, structurally high areas act to trap oil and gas along the barrier reef trend. Because of the relationship of Hueco reservoirs to positive paleotectonic elements, Hueco oil and gas accumulations are commonly found stacked atop structurally controlled accumulations in older, deeper strata. Depth to production ranges from 7,500 ft to almost 11,000 ft. Reservoir drive mechanisms vary from pressure depletion in nonassociated gas reservoirs to solution gas drives in oil reservoirs, the latter with a partial water drive in some cases.

Upper Pennsylvanian

The Missourian and Virgilian (Upper Pennsylvanian) sections contain prolific oil reservoirs in southeastern New Mexico (Fig. 15).

Canyon and Cisco strata

Strata are informally referred to as the Canyon (Missourian) and Cisco (Virgilian) groups by most geologists who work in the Permian Basin. These strata are composed of interbedded carbonates, shales, and minor sandstones. Shales are mostly dark-gray to black and constitute an organic source facies over large parts of the region, especially in the basinal areas where shales dominate the Upper Pennsylvanian section. Sandstones are a minor component and are present mostly along the western pinchout as these strata onlap the Pedernal uplift. Depth to the top of the Upper Pennsylvanian section ranges from 4,300–8,400 ft in Chaves County to 15,000 ft in the deepest parts of the Delaware Basin in southwestern Lea County. The Upper Pennsylvanian section is absent from most of the Central Basin Platform, where it was either never deposited or removed by erosion prior to deposition of Early Permian sediments. Throughout most of southeastern New Mexico, the Virgilian section is 250–500 ft thick and is absent from the Central Basin Platform as well as the Roosevelt uplift (Meyer, 1966). Maximum thickness is 1,000 ft in a depocenter in northwestern Eddy County. It pinches out along the flanks of the Pedernal uplift in western Eddy and Chaves Counties. It thins to approximately 200 ft as it crosses the Sin Nombre arch to the north and from there thickens as it plunges northward into the Tucumcari Basin. The Missourian section attains a maximum thickness of 1,200 ft in west-central Lea County and, similar to the Virgilian section, pinches out to the west against the Pedernal uplift in western Eddy and Chaves Counties (Meyer, 1966). To the north, it is absent from the Roosevelt uplift and thins to approximately 200 ft over the crest of the Sin Nombre arch. From there, it pinches out along the flanks of the Pedernal uplift in western Eddy and Chaves Counties.

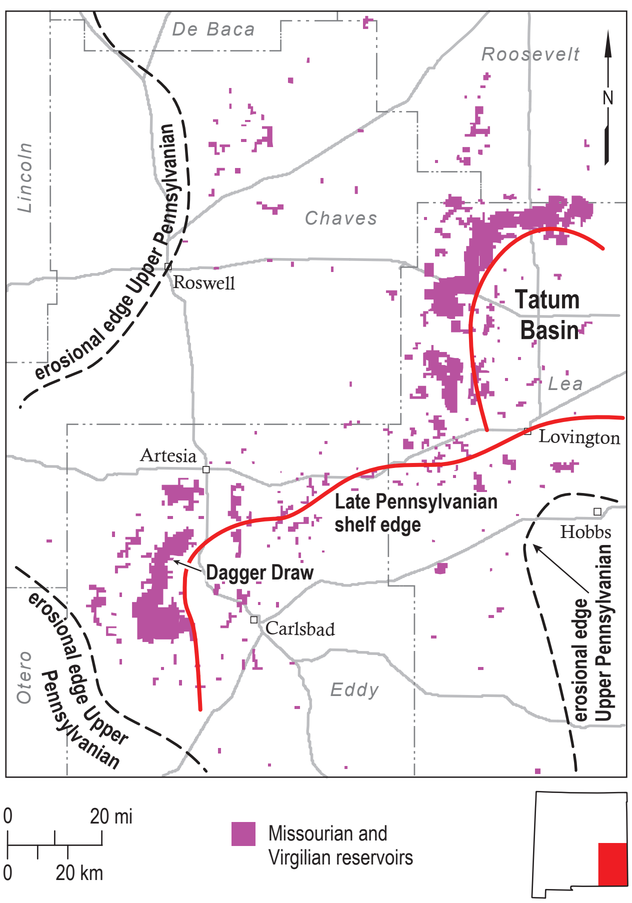


Figure 15. Oil and gas reservoirs in Missourian and Virgilian (Upper Pennsylvanian) strata, southeastern New Mexico. Erosional edge of Upper Pennsylvanian from Meyer (1966). Red lines indicates boundaries of major paleobathymetric elements.

Upper Pennsylvanian carbonates constitute some of the most productive oil trends in southeastern New Mexico. Production is obtained mostly from phylloid-algal mud mound complexes. In northern Lea and southern Roosevelt Counties, these complexes extend upward into the lowermost Wolfcampian (Lower Permian) section. Reservoir facies are formed by phylloid-algal bafflestones, bioclastic wackestones and intermound grainstones (Cys, 1986; Speer, 1993a; Cox et al., 1998).

The largest and most prolific phylloid-algal mound reservoirs are present in two areas (Fig. 15). One area is along the late Pennsylvanian boundary at the margin between the Northwest Shelf and the deep Delaware Basin to the south in western Eddy County. The Dagger Draw reservoir (Reddy, 1995a, 1995b), with cumulative production exceeding 70 million bbls of oil, is found in this area. The second area is in northern Lea County where carbonate banks rimmed the Tatum Basin. Mounds on the edge of the Northwest Shelf in western Eddy County have been pervasively dolomitized. Mounds around the rim of the Tatum Basin have seen lesser degrees of dolomitization. Porosity is typically 7–12% and is mostly vuggy and intercrystalline. The best reservoirs are generally developed in the algal bafflestone facies. Reservoirs of lesser quality are present in intermound areas characterized by grainstones, packstones, and wackestones (see Cox et al., 1998). Upper Pennsylvanian algal mound reservoirs generally hold large volumes of moveable water in addition to the oil and solution gas and produced water: oil ratios are

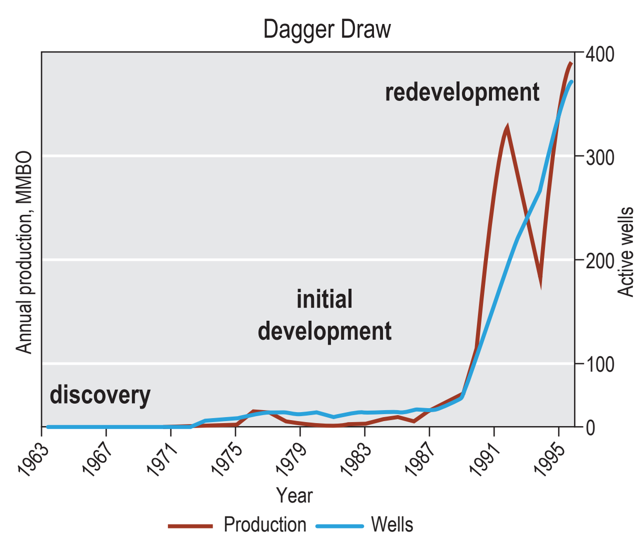


Figure 16. Historical oil production curve of an Upper Pennsylvanian algal mound reservoir, Dagger Draw, that had been underdeveloped. MMBO, million bbls oil. Adapted from Broadhead (1999).

typically 5:1 or greater. Reservoir drive mechanisms are water drive with solution gas and gas-caps assisting in several reservoirs.

Many of the reservoirs that rim the Tatum Basin and the Eddy County shelf-edge areas share a common facet in the history of drilling and development (Fig. 16). For the large reservoirs, initial discovery was followed only by minimal development. After a period of nondevelopment and production from only a few wells, a second period of development ensued during which the bulk of the wells were drilled. Production peaked after the second phase of development, dwarfing the volume of oil produced during the first phase of development. In several reservoirs, a second period of redevelopment ensued in which substantial additional reserves were brought into production (Broadhead, 1999). Each phase of development brought into production previously undrilled and unrecognized parts of the reservoirs.

Middle Pennsylvanian

The Desmoinesian (Middle Pennsylvanian) section in southeastern New Mexico is informally referred to as the Strawn group by most subsurface geologists who work in the Permian Basin. These strata are composed of ramp limestones interbedded with marine shales and minor sandstones. The Strawn section is 250–500 ft thick throughout most of southeastern New Mexico (Meyer, 1966). A depocenter with more than 1,000 ft of Strawn is present in central Eddy County, just west of the city of Carlsbad.

Strawn strata

The Strawn is productive (Fig. 17) from both limestone and sandstone reservoirs. Production from limestone reservoirs is dominant. The reservoir facies in the limestones are patch reefs (Caughey, 1988; Speer, 1993b; Cox, 1995). Major reefal reservoir facies are coralgal and foraminiferal wackestones and packstones (Harris, 1990). The patch reefs were deposited on a ramp that rimmed both the Delaware and Tatum Basins (Speer, 1993b). The interbedded organic-rich, dark-gray to black shales are source rocks. The patch reefs grew in shallow water over paleostructural highs, primarily anticlines. Porosities are typically less than 10% with, predominantly vuggy and moldic types (Harris, 1990). However, in spite of the low porosities, production is typically prolific, because of high-reservoir permeabilities caused by fracture systems within the bioherms that do not extend into the surrounding and sealing shales (Thornton and Gaston, 1967; Caughey, 1988;

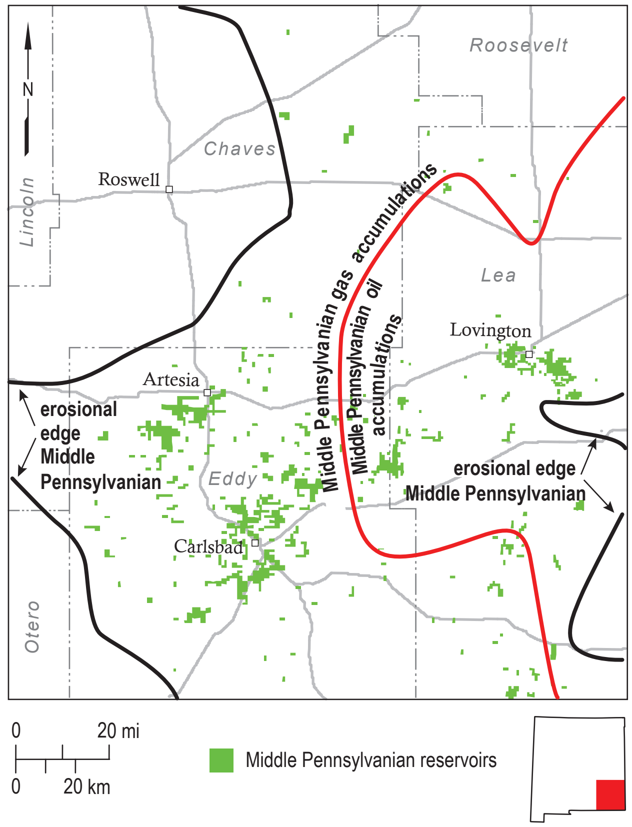


Figure 17. Oil and gas reservoirs in Desmoinesian (Middle Pennsylvanian) reservoirs, southeastern New Mexico. Erosional edge of Middle Pennsylvanian from Meyer (1966).

Harris, 1990). Trapping is stratigraphic with reefs either elongated parallel to paleoslope (Caughey, 1988) or morphologically mimicking underlying paleostructures. Reservoirs in the eastern part of the Strawn play produce oil with associated gas while reservoirs in the western part of the play produce mostly gas (Fig. 17). Depth to Strawn reservoirs ranges from 10,000 ft in the eastern oil-part of the play to 8,000–10,000 ft in the western gas area. Pressure depletion drives dominate in the western nonassociated gas reservoirs and solution gas drives are dominant in the eastern oil area.

Lower Pennsylvanian

Lower Pennsylvanian strata in southeastern New Mexico are composed of (descending) the Atoka and Morrow Formations. The multitude of reservoirs in these formations constitutes the largest gas plays in southeastern New Mexico (Fig. 18). Most Lower Pennsylvanian reservoirs are productive of natural gas, and many have associated condensate or light oils. Depth to the top of the Lower Pennsylvanian section ranges from 7,000–9,000 ft on the Northwest Shelf in Chaves County to more than 16,000 ft in the deepest parts of the Delaware Basin in southwestern Lea County. Atokan strata attain a maximum thickness of 500 ft in southwestern Lea County and thin northward and westward to their pinchout underneath Des moinesian (Middle Pennsylvanian) strata in southeastern Chaves and southern Roosevelt Counties (Meyer, 1966). Morrowan strata attain a maximum thickness of more than 2,000 ft in the deeper parts of the Delaware Basin and thin to a pinchout to the north and northwest in southeastern Chaves and southernmost Chaves Counties (Meyer, 1966). The Morrow is not present on the Central Basin Platform.

Atoka Formation

Atokan strata are dominantly siliciclastic. Sandstones and shales were deposited in southerly prograding fluvial-deltaic and strandline environments (James, 1985; Speer, 1993c). The sedimentary detritus that formed the Atokan clastics was eroded from exposed Precambrian highlands to the north and west of the Early Pennsylvanian basin. A bank of carbonate patch reefs developed distal from sources of clastic input in southern Eddy and southwestern Lea Counties (James, 1985; Fig. 18).

Atoka production, mostly gas, is obtained from both the sandstone reservoirs to the north and the patch reefs to the south. The clastic reservoirs are generally productive from stacked sandstone bodies of limited areal extent; some of the sandstones are lenticular and others are channel form. Reservoir porosities typically vary from 8–12%. Traps are typically formed by stratigraphic pinchout of the reservoir sandstone on a structural nose or monocline. Most Atokan reservoirs along the carbonate patch reef trend have reported porosities less than 7%. They are fine-crystalline, fossiliferous limestones characterized by vugular and cavernous porosity (Harvard, 1967). Permeability appears to be provided mostly by natural fracture systems (Speer, 1993c). Depth to Atoka production is as shallow as 8,000–10,000 ft in on the Northwest Shelf but ranges between 11,000–13,000 ft in most places. Pressure depletion provides the drive mechanism in most Atoka reservoirs.

Morrow Formation

Morrowan strata are dominantly siliciclastic. They consist of interbedded shales and lenticular sandstones deposited in multiple regressive sequences. They represent basinward migration of nearshore, sand-rich facies tracts that derived their sedimentary materials from erosion of exposed Precambrian rocks north and west of the Morrow pinchout. Facies tracts prograded to the southeast into the deeper basin where shales are dominant (Mazzullo and Mazzullo, 1984; James, 1985). Nearer shore deposits to the north and west consist of dark-gray to black shales interbedded with lenticular sandstones deposited in deltaic channels, on beaches, and in delta-front environments (Mazzullo and Mazzullo, 1984; James, 1985). To the south, the lower part of the Morrow consists of shales interbedded with thin sandstones; this lowermost Morrow section had previously been considered by many workers to be the upper part of the Barnett Shale (Upper Mississippian; Broadhead and Gillard, 2007; Broadhead, 2009b). The upper 300–400 ft of the Morrow consists of transgressive oolitic limestones interbedded with shales and minor sandstones (Anderson, 1977; Mazzullo and Mazzullo, 1984; James, 1985; Speer, 1993c).

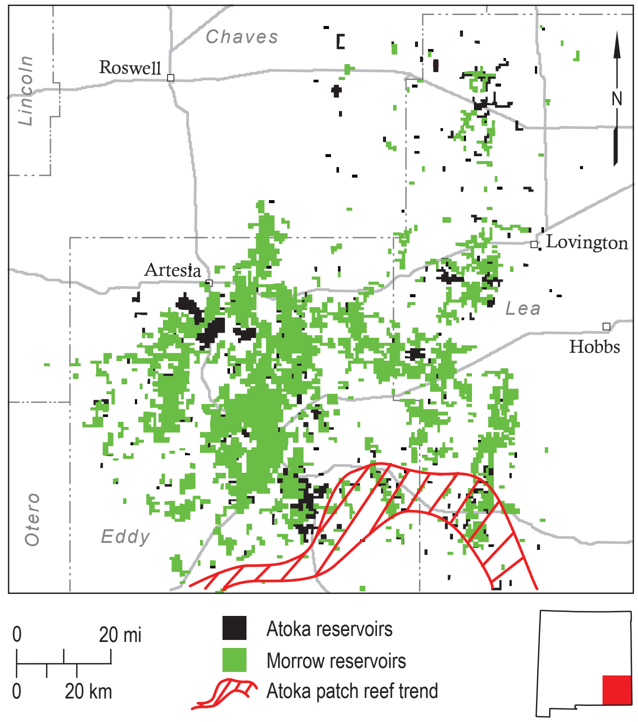


Figure 18. Oil and gas reservoirs in Atokan and Morrowan (Lower Pennsylvanian) strata, southeastern New Mexico. Atoka patch reef trend from James (1985).

Almost all of the production from the Morrow (Fig. 18) is gas and obtained from lenticular sandstones in the lower and middle parts of the formation. Depositional environments of productive reservoirs are variable and include deltaic distributary channels, channel mouth bars, beaches, delta front shelf sands and pro-delta submarine fans (Anderson, 1977; Mazzullo and Mazzullo, 1984; James, 1985; Martin et al., 1986; Speer, 1993d). Traps generally have a stratigraphic component and many are combination traps formed by the drape of the reservoir sandstone across a structural nose. Individual reservoirs are relatively restricted in areal extent, with most reservoirs occupying less than 5,000 acres. Porosity of most reservoirs ranges from 8–5%. Cementation by carbonate, silica, or clay minerals partially defines trap boundaries in many reservoirs and adds a diagenetic component to trapping (Anderson, 1977; James, 1985; Mazzullo and Mazzullo, 1984). Source rocks undoubtedly are the interbedded organic-rich shales. Depth to Morrow production is 8,000–10,000 ft in Chaves, northernmost Eddy, and westernmost Eddy Counties. However, it is 12,000–15,000 ft in eastern Eddy and western Lea Counties. Reservoirs produce via pressure depletion.

Mississippian

Mississippian strata constitute the least developed of the major stratigraphic units in southeastern New Mexico. Production has been obtained from relatively small and widely scattered reservoirs (Fig. 19). Production has been mostly gas with subsidiary oil and condensate. Yet, the Mississippian section attains a maximum thickness of 1,400 ft in the Tatum Basin and, therefore, constitutes a major portion of the stratigraphic section.

The Mississippian section unconformably overlies the Woodford Shale (Upper Devonian) throughout most of southeastern New Mexico. North and west of the Woodford pinchout (Fig. 20), the Mississippian unconformably overlies the Fusselman Formation (Silurian) or, in places, Ordovician strata.

The Mississippian section in southeastern New Mexico is subdivided into the lower Mississippian limestone of Kinderhookian to Osagean age and various Upper Mississippian units. The Upper Mississippian section consists of the Barnett Shale in the basinal area to the south and the Meramec and Chester units on the shelf to the north. Four poorly developed oil and gas plays have been identified in Mississippian strata of southeastern New Mexico (Broadhead, 2009b): 1) Chester shallow marine limestone play, 2) the Upper Mississippian limestone interbedded with Barnett shale play, 3) Barnett shale play, and 4) lower Mississippian limestone play.

Chester and Meramec strata

Production from Upper Mississippian strata has been mostly from Chester shallow marine limestones in the Tatum Basin. The Chester shallow marine limestones are productive primarily from oolitic shoals, although associated grainstones may also be productive (Hamilton and Asquith, 2000). Reservoir porosity ranges from less than 10% up to 18%, and the permeability generally appears to be relatively high (Broadhead, 2009b). In general, Chester reservoirs are more fully developed than other Mississippian reservoirs. Offsets to discovery wells are common with most reservoirs having had multiple productive wells.

South of the shelf margin, thin Mississippian limestones are interbedded with the Upper Mississippian Barnett Shale. Production is obtained from one to two well reservoirs in these limestones with the interbedded Barnett Shales acting as vertical seals as well as source rocks (Broadhead, 2009b). It is unknown if the limestone reservoirs are progradational tongues of the shelf margin, debris flows of carbonate material that originated on the shelf margin, or microbial mounds deposited on the promargin slope. The reservoirs in this play have 3–6%

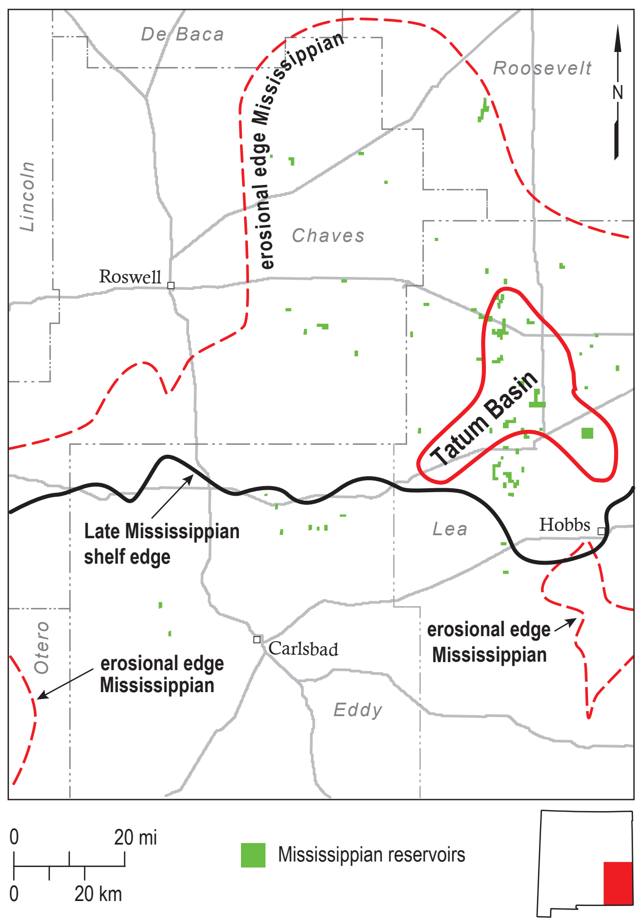


Figure 19. Oil and gas reservoirs in Mississippian strata and the location of the late Mississippian shelf edge, southeastern New Mexico. Modified from Broadhead (2009b). Red lineindicates boundary of Tatum Basin. Dashed red line indicates erosional edge of Mississippian strata.

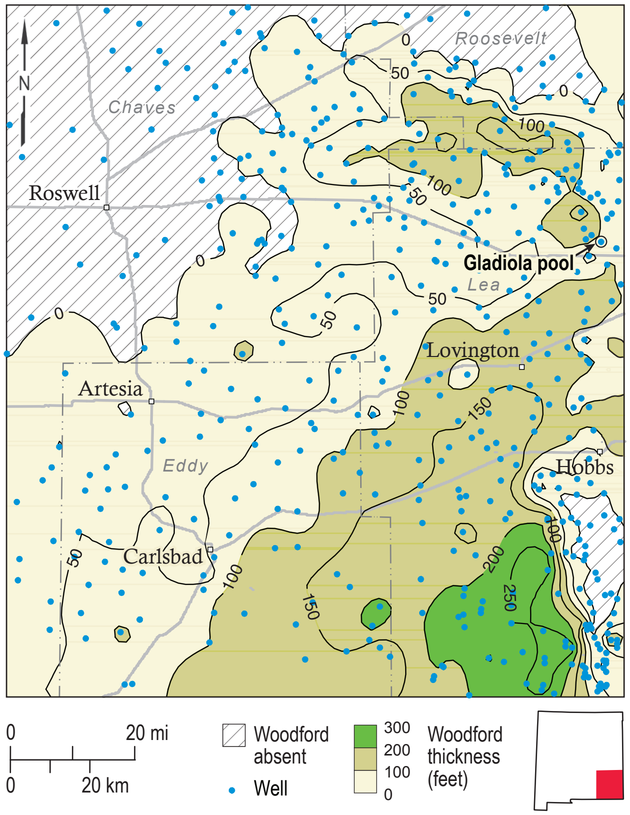


Figure 20. Isopach map of the Woodford Shale (Upper Devonian), southeastern New Mexico. From Broadhead (2010b).

porosity. The permeability appears to be variable but is low for most reservoirs. Discovery has been serendipitous when Mississippian shows were tested only after deeper, pre-Mississippian objectives proved unsuccessful. Production has been primarily gas with minor condensate.

Barnett Shale

The Barnett Shale, south of the Mississippian shelf edge, has not yet proven to be productive in New Mexico, and active exploration for Barnett shale-gas resources has not been attempted in the state. The Barnett is 0–400 ft thick in southeastern New Mexico. Present-day, post-maturation total organic carbon (TOC) ranges from 0.85–4.9% and kerogens are dominantly gas prone. In most areas of southeastern New Mexico, the Barnett is within the oil window, but a gas exploration fairway of higher thermal maturity lies along a depth-independent northwest-southeast trend in Eddy County (Broadhead, 2009b). Shows along this maturity trend are dry gas. Wet gas shows are found outside of this trend where thermal maturity is lower (Broadhead and Gillard, 2007).

Lower Mississippian limestone

The lower Mississippian limestone constitutes the Kinderhookian to Osagean (Lower Mississippian) section. It is 0–800 ft thick in southeastern New Mexico. It pinches out to the north and west where it is erosionally truncated underneath the Lower Pennsylvanian section. It is also absent from large parts of the Central Basin Platform where it was removed by erosion during the Pennsylvanian. The lower Mississippian limestone consists primarily of dark-colored lime mudstones although siliciclastic shales and dark-colored cherts are locally present (Broadhead, 2009b).

Production from the lower Mississippian limestone is from small scattered reservoirs in northern Lea and eastern Chaves Counties (Fig. 19). Depth to production ranges from 6,900–13,400 ft. Reservoir porosity is low, ranging from 4–9% and permeability also appears to be low. Most reservoirs, as presently developed, consist of one or two productive wells, and reservoir boundaries have seldom been defined by drilling. Discovery is serendipitous when shows are tested only after deeper, pre-Mississippian objectives were tested unsuccessfully or when deeper productive reservoirs have been abandoned. As has happened recently in the U.S. mid-continent, the overall characteristics of this play may lend themselves to exploration and production with extended-reach horizontal wells.

Siluro-Devonian

Siluro-Devonian carbonate strata produce substantial volumes of oil and natural gas in southeastern New Mexico. Productive reservoirs are present in all three stratigraphic subdivisions of the Siluro-Devonian section in southeastern New Mexico (Figs. 8, 9; descending): Thirtyone Formation, Wristen Group, and Fusselman Formation. These units form a wedge that thins to the north and west where it is truncated under the unconformity at the base of the Woodford Shale (Upper Devonian; Fig. 21).

Thirtyone Formation

The Thirtyone Formation (Lower Devonian) is present only in southeastern Lea County where it is approximately 8,000 ft deep. It is 250 ft thick at the Dollarhide reservoir (Saller et al., 2001). The Thirtyone thickens to a maximum of 1,000 ft in Crane County, Texas, 40 mi southeast of the southeastern corner of New Mexico

(Ruppel and Holtz, 1994). The formation in New Mexico consists of an upper dolostone unit and a lower chert unit (Keener, 1957; Saller et al., 2001).

In New Mexico, production is mostly obtained from dolostones in the upper part of the Thirtyone Formation. Reservoirs are primarily coarse-crystalline cherty dolostone; thin interbeds of white chert are present (Sharp, 1956). The trap at Dollarhide, the largest productive Thirtyone reservoir in New Mexico, is formed by an anticline bounded by high-angle faults (Keener, 1957; Saller et al., 2001). Because of its limited areal distribution (Fig. 21), the Thirtyone Formation contributes minor production relative to the entire Siluro-Devonian carbonate section.

Wristen Group

The Wristen Group (Middle to Upper Silurian) is 0–1,400 ft thick in southeastern New Mexico. It is comprised of interbedded limestones and dolostones. From its maximum thickness in southern Lea County, the Wristen gradually thins to the north and the west as it is beveled under the unconformity at the base of the Woodford Shale (Upper Devonian). Depth to the Wristen varies from 7,500–8,000 ft on the shallower parts of the Central Basin Platform to almost 19,000 ft in the deeper parts of the Delaware Basin just west of the Central Basin Platform. From there, the Wristen rises northward and westward to depths of 10,000–12,000 ft near its pinchout underneath the Woodford Shale.

Wristen strata have been historically referred to as Devonian, Siluro-Devonian, or Silurian. Barrick et al. (1993) and Barrick (1995) utilized conodont biostratigraphy to conclude that the overlying Thirtyone Formation is Early Devonian and that the underlying Wristen Group is Middle to Late Silurian in age. Ruppel and Holtz (1994), using regional stratigraphic analysis, indicated that the Thirtyone Formation is limited to southeastern Lea County and that the Wristen strata extend northward and westward into northern Lea, Chaves, and Eddy Counties (Fig. 21).

The Wristen shelf margin extends westward from Texas into southernmost Lea County (Fig. 21). Shelf-margin strata are characterized by buildups of coral, stromatoporoid, pelmatazoan and bryozoan boundstones and rudstones and oolitic grainstones with significant primary porosity (Ruppel and Holtz, 1994). In the shelf area to the north, reservoirs are typically dolomitic with vugular and fractured porosity (Speer, 1993e). Reservoir zones are associated with subaerial exposure at the tops of shallowing-upward cycles (Entzminger and Loucks, 1992).

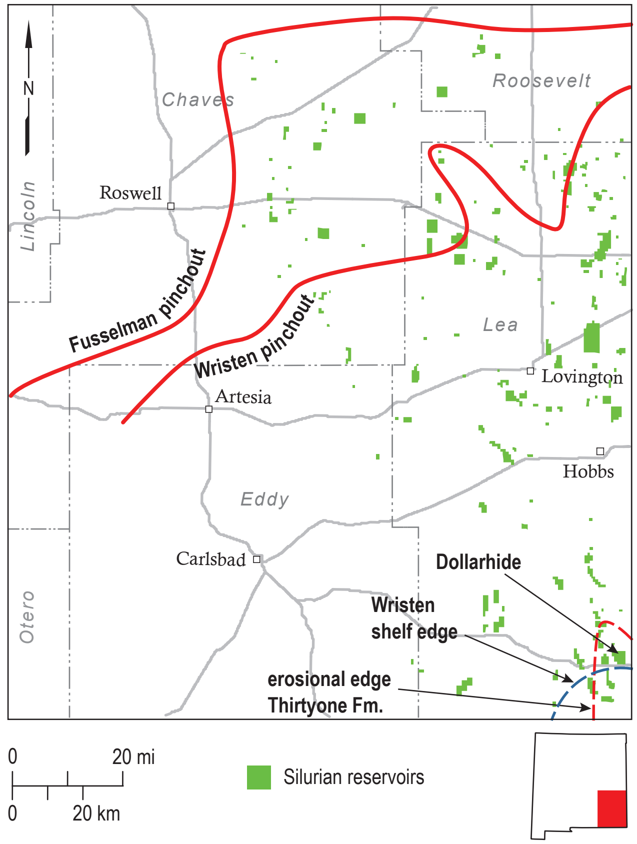


Figure 21. Oil and gas reservoirs in Silurian strata, southeastern New Mexico. Erosional edge of Thirtyone Formation from Ruppel and Holtz (1994). Wristen pinchout by Bill Raatz from Broadhead et al. (2004). Fusselman pinchout modified from Grant and Foster (1989). Red dash line indicates the erosional edge of Thirtyone Formation. Red lines indicate erosional edges of Wristen Group and Fusselman Formation.

Traps that have been discovered are generally structural and small; most cover only one to a few square miles. They are formed by uplifted Ancestral Rocky Mountain fault blocks of Pennsylvanian age. The overlying Woodford Shale (Upper Devonian) was involved in the faulting and acts as both the vertical seal and as the source rock for the Wristen and Thirtyone reservoirs (Broadhead, 2010b). Although produced extensively since the 1950s, exploration for Wristen traps saw a resurgence in the 1990s as newly developed 3-D seismic techniques allowed explorationists to more precisely locate and define the small, hidden paleostructures that form most of the Wristen oil and gas accumulations (Hanagan, 2002).

Fusselman Formation

The Fusselman Formation unconformably underlies the Wristen Group and is Late Ordovician to Early Silurian in age (Barrick et al., 1993). The Fusselman is composed of dolostones and was deposited in a shallow water setting. The Fusselman is 0–1,500 ft thick in southeastern New Mexico. It thins to the north and northwest where it is truncated underneath the pre-Woodford unconformity north of the Wristen pinchout. From its erosional pinchout in Chaves and Roosevelt Counties, where it lies at depths of 5,000–10,000 ft, the Fusselman thickens to its maximum in southern Lea County where it lies at depths of more than 18,000 ft. On the Central Basin Platform, the Fusselman lies at depths of 7,000–8,000 ft but is absent where it was removed by erosion from the highest areas during the Pennsylvanian and Early Permian.

Fusselman reservoirs in southeastern New Mexico are coarse-crystalline dolostones that are generally vugular, fractured, and brecciated (Speer, 1993e). Most porosity is secondary. Permeability enhancement associated with fractures, vugs, and karstic collapse breccias appears to be essential for economic production in most reservoirs. Karst-related permeability enhancement is associated with not only the unconformity at the top of the Fusselman, but with several intraformational unconformities as well (Ruppel and Holtz, 1994; LeMone, 1996). Most known traps in the Fusselman are formed by anticlines bounded on one or more sides by high-angle faults where Silurian or Devonian-age strata are unconformably overlain by Pennsylvanian strata; the structures are Pennsylvanian in age. In many cases, the trap is formed by Fusselman strata that have been erosionally truncated under Pennsylvanian strata on the flanks of the anticlines. Mazzullo (1990) concluded that significant potential remains in the Fusselman and Wristen sections for subtle traps formed by intraformational unconformities.

Ordovician

The Ordovician System is the oldest geologic system in southeastern New Mexico that has major oil and gas production. Productive reservoirs are present in all three major stratigraphic units that constitute the Ordovician (Figs. 8, 9; descending): Montoya Formation, Simpson Group, and Ellenburger Formation. Because these stratigraphic units are the oldest productive units in southeastern New Mexico, they are the least drilled, least explored, and among the most poorly understood strata in this region of the state.

Montoya Formation

The Montoya Formation (Middle to Upper Ordovician) is 0–600 ft thick in southeastern New Mexico. The basal Cable Canyon Sandstone is overlain by dolostones of the Upham, Aleman and Cutter Members. Depth to the Montoya ranges from 5,500 ft near its northern pinchout in Chaves County (Fig. 22) to approximately 20,000 ft in southern Lea County. Depth to the Montoya is 7,000–12,000 ft on the Central Basin Platform. From its northern pinchout in Chaves and Lea Counties, the Montoya gradually thickens to the south. The Montoya was removed by erosion from the higher parts of the Central Basin Platform during the Late Pennsylvanian and Early Permian.

Montoya reservoirs are dolostones with intercrystalline and vugular porosity. Matrix porosity is generally only a few percent, but has been enhanced by fracturing or karstic brecciation in many reservoirs. Traps are generally structural and formed by anticlines and faulted anticlines. Some traps are formed by a combination of anticlinal geometry and porosity pinchouts. Most established Montoya production is on the Central Basin Platform where traps have an anticlinal component. Production is oil with associated gas. Near the northern pinchout of the Montoya, significant gas production has been established from unconformity traps formed by truncated strata on the flanks of Ancestral Rocky Mountain structures. Although Montoya production is concentrated on the Central Basin Platform where solution gas drive mechanisms predominate, scattered non-associated gas reservoirs are found on the Northwest Shelf as far north as Tule (Ahlen, 1988), the northernmost productive field on the New Mexico side of the Permian Basin (Fig. 22).

Simpson Group

The Simpson Group (Middle to Upper Ordovician) is composed of limestones, dolostones, sandstones, and green shales that were deposited in the gently downwarped Tobosa Basin. It is 0–1,000 ft thick in southeastern New Mexico. The Simpson Group consists of five formations (descending): Bromide Formation, Tulip Creek Formation, McLish Formation, Oil Creek Formation, and the Joins Formation. Depth to the Simpson ranges from 6,700–11,000 ft on the Central Basin Platform and to more than 21,000 ft in the deeper parts of the Delaware Basin in southwestern Lea County.

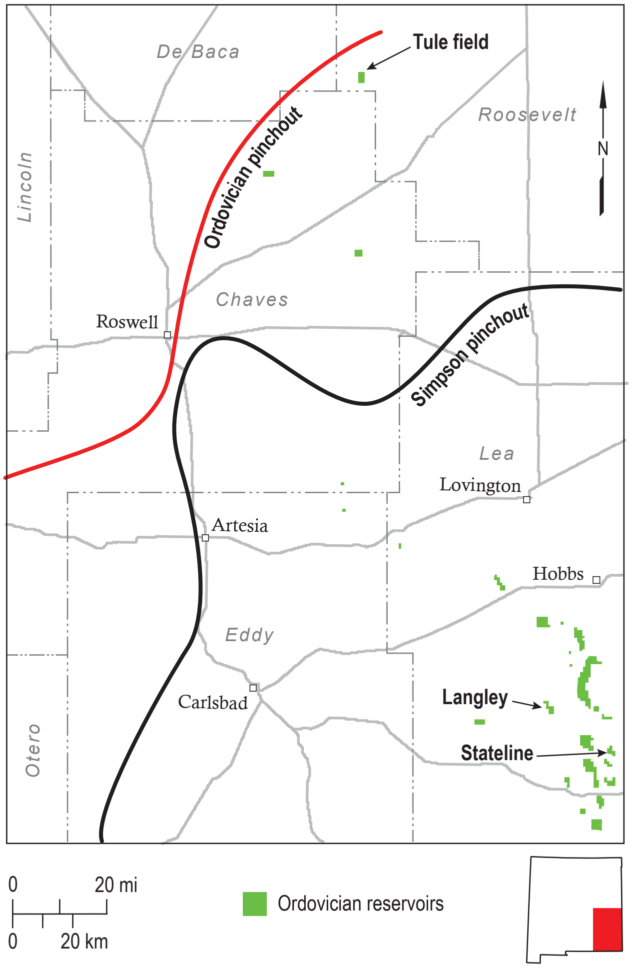


Figure 22. Oil and gas reservoirs in Ordovician strata, southeastern New Mexico. Simpson and Ordovician pinchouts from Grant and Foster (1989). Black line indicates pinchout of Simpson Group. Red line indicates pinchout of Ordovician strata.

In New Mexico, Simpson reservoirs are rounded, friable, fine- to coarse-grained shoreline sandstones (Wright, 1979; Speer, 1993f). Sandstones comprise approximately 5% of the Simpson section with 55% waxy, greenish shale and 40% limestones and dolomitic limestones (Wright, 1979). Traps for Simpson reservoirs include fault-bounded anticlinal closures and unconformity traps along the edges of late Paleozoic positive structures where Simpson sands are truncated by younger strata (Speer, 1993f). Reservoir porosity is typically 14%. Simpson shales are not only seals, but are the source rocks for hydrocarbons within the Simpson sandstones, the underlying Ellenburger carbonates (Katz et al., 1994), and probably some of the accumulations in overlying Montoya reservoirs. Solution gas is the primary drive mechanism in Simpson reservoirs, most of which produce oil and associated gas.

Ellenburger Formation

The Ellenburger Formation (Lower Ordovician) is composed of dolostones and limestones. It is 0–1,000 ft thick in southeastern New Mexico and thickens southward from its northern pinchout (Fig. 22). Depth to the Ellenburger varies from 7,500–10,000 ft on the Central Basin Platform to more than 22,000 ft in the deeper parts of the Delaware Basin in southwestern Lea County.

In New Mexico, the Ellenburger consists of inner platform cyclic dolostones deposited in waters with restricted circulation. Extensive subaerial diagenesis is associated with changes in relative sea level (Clemons, 1989; Kerans and Lucia, 1989; Goldhammer et al., 1993). Ellenburger porosity types include intercrystalline matrix, vugs, major karst dissolution, karst breccia, and fractures (Mazzullo, 1989). The most significant porosity types are dissolution and collapse karst breccias (see Loucks, 1999). Isolated zones of greater porosity are preserved in some deeper water, muddy carbonate facies that underwent late burial dolomitization, resulting in coarse-grained textures (Kerans and Lucia, 1989). In the Langley reservoir, maximum intergranular porosity is 5% and permeability is 0.5 md (millidarcies). Reservoirs are peloidal-algal mat boundstones and peloid/ooid grainstones (Verseput, 1989). Fractures and solution collapse breccia also occur and enhance both porosity (up to 8%) and permeability (up to 50 md). Although dolomitized, the Langley reservoir contains identifiable intertidal to supratidal facies successions that include alternations of laminated mudstone/wackestone, peloid/ooid grainstone, peloid-algal mat boundstone, intraclast breccia, and pebble breccia (Verseput, 1989).

In the Stateline reservoir, the Ellenburger is composed completely of fabric-destructive dolomite (Amthor and Friedman, 1989). Largely tight upper Ellenburger strata are underlain by lower units interpreted as cave-roof facies that contain abundant stylolites, fractures, molds, vugs, and dissolution cavities with porosities as high as 15% (Amthor and Friedman, 1989).

Traps in the Ellenburger have a strong anticlinal component. The primary drive mechanism within the oil reservoirs on the Central Basin Platform is solution gas. Pressure depletion drives are present in the gas reservoirs located in the Delaware Basin west of the Platform where deeper burial has thermally cracked oils to gas.

III. SAN JUAN BASIN

The San Juan Basin extends northward into Colorado from New Mexico (Figs. 1, 2). Ninety percent of the basin lies within New Mexico. The San Juan Basin is an asymmetric basin, with a gently dipping south limb, a steeply dipping north limb, and the deep basin axis located north of the geographic mid-point of the basin (Fig. 23). Late Cretaceous and Paleocene strata dip steeply into the basin on the northwest margin along the Hogback monocline, and to the east along the Archuleta arch and Nacimiento uplift. The Hogback monocline separates the San Juan Basin from the Four Corners Platform on the west and the San Juan uplift, and San Juan volcanic field to the north. The monocline is the surface expression of reverse aspect faults at depths that do not extend upward to the ground surface. The gently north-dipping Chaco slope forms the southern flank of the basin, separating it from the Zuni Mountains and the Acoma Basin. The basin formed as a result of regional compression during the Laramide orogeny at the very end of the Cretaceous and during the Early Tertiary (Kelley, 1950, 1951). Although the Precambrian basement is exposed at elevations greater than 9,000 ft in the Nacimiento Mountains and in the Zuni Mountains, it lies at depths of more than 14,000 ft in the deep northern part of the basin, rendering a maximum structural relief of greater than 16,000 ft (Fig. 2). From the deep basin axis, the basement gently rises southward to depths of less than 6,000 ft on the Chaco slope before it is exposed in the core of the Zuni Mountains. On the Four Corners Platform, the Precambrian is present at depths of 6,000–8,000 ft in most places.

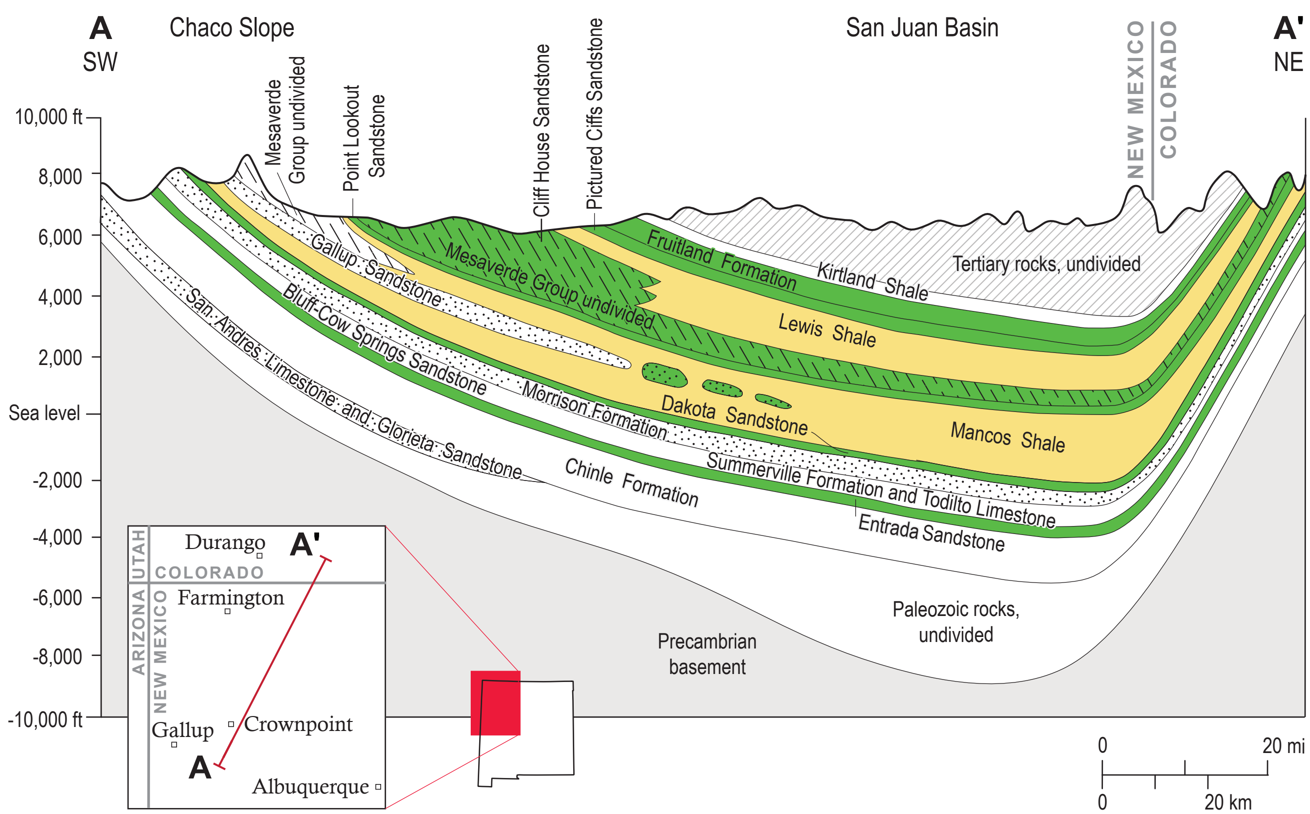


Figure 23. Southwest-northeast structural cross section through San Juan Basin, indicating major gas and oil productive strata. Yellow strata are shale reservoirs, while green indicates other non-shale productive strata. Modified from Stone et al. (1983).

More than 95% of oil and gas production in the San Juan Basin has been obtained from reservoirs in Upper Cretaceous strata with only relatively small amounts of production obtained from Jurassic, Permian, Pennsylvanian, and Devonian reservoirs. Most known Paleozoic reservoirs are located on the Four Corners Platform and several have produced helium-rich gases. Oil productive Jurassic reservoirs are located on the Chaco slope. Cretaceous reservoirs contain nonassociated gas and gas condensate, except for small oil-bearing reservoirs located on the Four Corners Platform and on the Chaco Slope.

Upper Cretaceous

Fruitland Formation

The Fruitland Formation (Upper Cretaceous) is the youngest major productive stratigraphic unit in the San Juan Basin. Natural gas is produced from coals (coalbed methane) and also from discontinuous fluvial sandstones in the lower part of the Fruitland (Fig. 24). Depth to gas production ranges from 800–3,700 ft. Wells drilled prior to the late 1980s were completed in sandstone reservoirs and most wells drilled after that period were completed in the coals. Coalbed methane production increased rapidly (Fig. 5), and production from Fruitland coal reservoirs soon dwarfed production from the Fruitland sandstone reservoirs. Peak production was attained in 1999 when 612 billion ft^3 (BCF) were produced, approximately one-third of annual New Mexico gas production during that year. Annual production from the coals has subsequently decreased by 58% to 259 BCF as the coal-gas reservoirs have started to deplete. Figure 24 indicates the area with densest coalbed methane production. Wells outside of this area, but within the Fruitland-Pictured Cliffs contact on the outcrop, are more scattered.

Gas shows in the Fruitland coals were ignored for decades as deeper sandstone reservoirs were targeted, leaving the coals sealed off behind casing (Fassett and Hinds, 1971). Production was not attempted because of the large flows of water that accompanied the gas. However, almost all of the methane in coals is adsorbed onto the organic matter of the coal. The methane is held in place by weak molecular bonding on the coal surface and by the pressure exerted in the cleat system by the water column present in the cleats throughout the coal reservoir. When water is produced from the cleats, the hydrostatic pressure head within the cleat system is reduced and the gas desorbs from the organic matter in the coals. The gas becomes a free gas phase in the cleat system and can then be produced. Therefore,

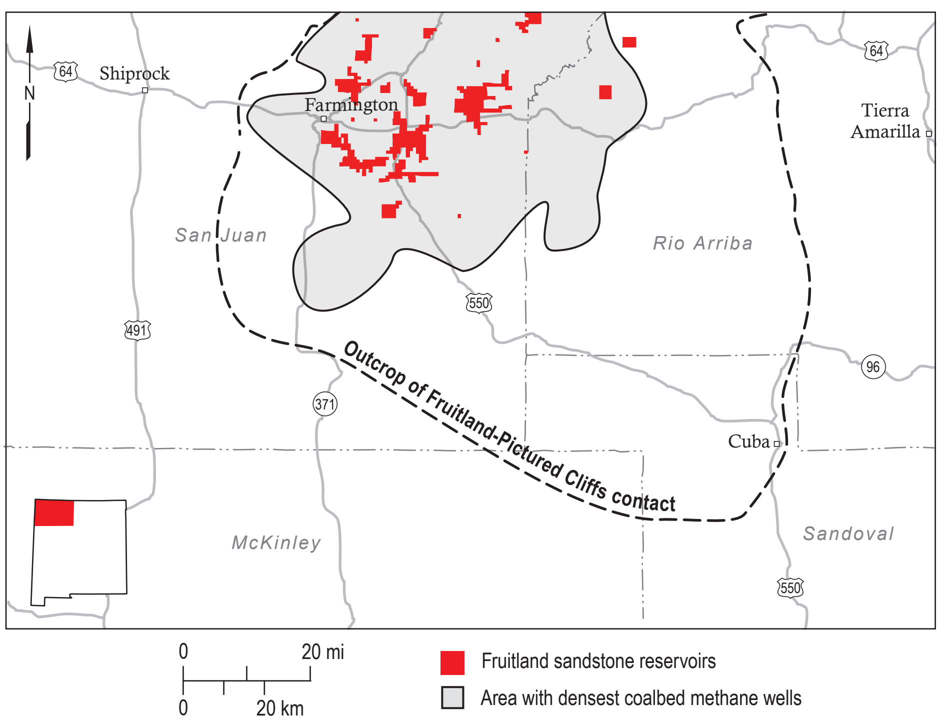


Figure 24. Natural gas reservoirs in the Fruitland Formation (Upper Cretaceous), northwestern New Mexico showing area of densest concentration of Fruitland gas wells. Scattered wells produce gas from Fruitland coals outside of the indicated area of dense wells.

if gas is to be produced from the coals, the pressure must be lowered by the production. During the early stages of water production, little gas will generally be produced, but later, after water has been produced, the hydrostatic pressure head within the cleat system will be lowered sufficiently so that increased amounts of gas will be produced. At this point, water production generally decreases, sometimes sharply. Until the dynamics of coal gas production were recognized, it was generally thought that the initial water to gas ratios were too high to yield economic levels of production. From the late 1970s into the mid-1980s, several exploration wells were drilled to evaluate the commercial potential of coalbed methane reservoirs (Whitehead, 1993a). Drilling for coalbed methane increased markedly in 1988 when federal tax credits were promulgated for gas produced from coals. As a result, a large part of the San Juan Basin, with potential for gas production from Fruitland coals, was quickly drilled and developed.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone (Upper Cretaceous) underlies the Fruitland Formation. It has produced major volumes of nonassociated gas and gas condensate. The reservoirs in the Pictured Cliffs (Fig. 25) are formed by northwest-southeast trending coastal barrier sandstones with seaward marine deposits (Lewis Shale) and landward nonmarine deposits (Fruitland Formation; Molenaar, 1977). The Pictured Cliffs Sandstone forms an overall regressive sequence, overstepping the Lewis Shale and overstepped by the Fruitland Formation in a seaward (northeast) direction. Sandstones are fine to medium grained and grain size coarsens upward (Flores and Erpenbeck, 1981). The sand grains typically have a coating of authigenic clays that decrease porosity, permeability, and pore throat diameter (Cumella, 1981). Depth to production varies from 1,200 ft in the southeast part of the trend to 4,000 ft in the northwest.

The Pictured Cliffs trap has long been interpreted as a basin-centered gas accumulation (Law and Dickinson, 1985; Whitehead, 1993b) characterized by gas downdip, free water updip in a continuous reservoir, and no updip lithologic seal to the gas accumulation. The gas is produced with little water. The updip seal is thought to be caused by a relative permeability barrier where water-saturated, fine-grained sandstones have no permeability to gas (Masters, 1979). Cumella (1981) concluded that grain-coating authigenic clays in Pictured Cliffs sandstones form the major control on gas accumulation and production. The clays were precipitated prior to the formation of the Laramide basin. Authigenic clay content increases to the northeast with increasing distance from the

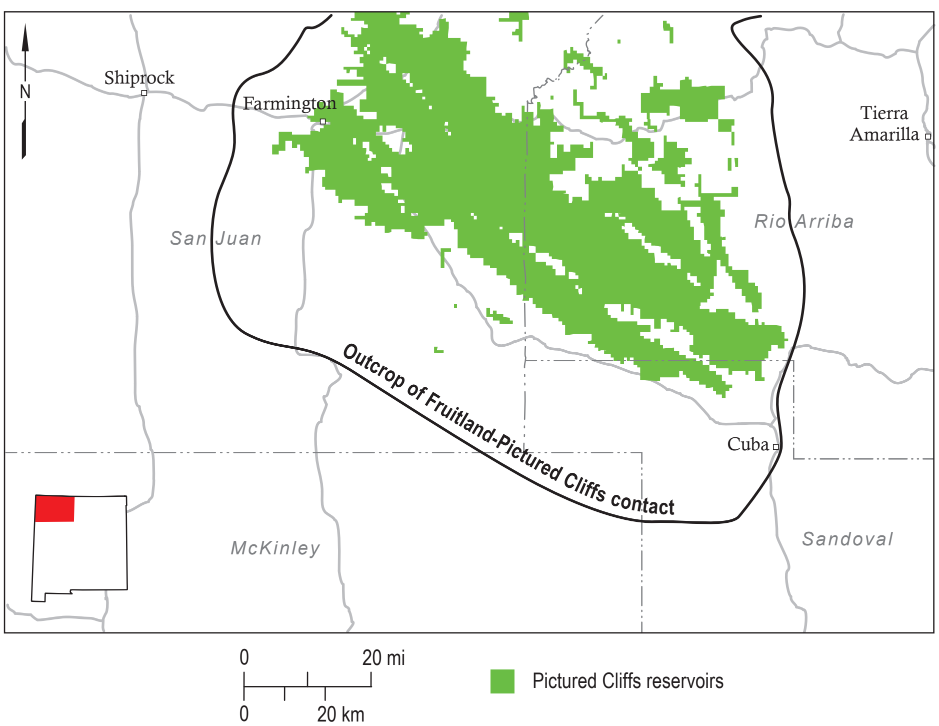


Figure 25. Natural gas reservoirs in the Pictured Cliffs Formation (Upper Cretaceous), northwestern New Mexico.

paleoshoreline. Gas-saturated zones, related to clay content, are parallel to depositional strike. To the southwest, where clay content is lower, permeabilities are high and sandstones are water saturated. To the northeast, the sandstones have higher clay content, lower permeability, and are gas saturated. Yet, further to the northeast, clay content is higher and the sandstones, although gas saturated, are impermeable and, therefore, not productive. More recently, however, Fassett and Boyce (2005) concluded that the trapping mechanism is stratigraphic and that the gas accumulations coincide with lithologic transitions of the reservoir sandstones to marine shales on the northeast and to impermeable continental and back-barrier lagoonal deposits on the southwest. Nelson and Condon (2008) used pressure-depth analyses to conclude that the Pictured Cliffs contains several compartments, each with its own pressure-depth gradient that approximates hydrostatic conditions and each with its own gas-over-water contact, indicating the conventional nature of the gas accumulations. Pressure depletion is the production mechanism.

Lewis Shale and Chacra sandstones

The Lewis Shale (Upper Cretaceous) is 1,000–1,500 ft thick in the San Juan Basin. The Lewis is composed of shale, siltstone, and minor sandstone (Dube et al., 2000). Natural gas has been produced from the Lewis Shale in the San Juan Basin since the mid-1990s. Gas production has been obtained from fractured, silty to sandy, more distal equivalents of the offshore bars that form the Chacra trends (Fig. 26; Dube et al., 2000; Fassett and Boyce, 2005; Fassett, 2010). In the New Mexico part of the basin, Lewis production has been added to pre-existing wells that had previously produced from deeper Mesaverde sandstones; these wells were recompleted uphole and incremental Lewis gas production was added to Mesaverde gas production in the well. Only 16 wells, all in the Colorado part of the basin, appear to have produced solely from the Lewis (Dube et al., 2000). Because Lewis production is commingled with production from the Mesaverde Group, the cumulative production from the Lewis alone is unknown. Fassett (2010) estimated that the Lewis had contributed 1 BCF gas in 318 wells. Because this value represents artificially fractured completions in vertical wells and not multi-stage fractured completions in extended-reach horizontal wells, Fassett's estimate of cumulative production may not represent the full productive potential of the Lewis Shale in the San Juan Basin. However, five horizontal wells have been drilled in the Chacra and production from these wells has been less than auspicious (Tom Ann Casey, personal communication, 2014).

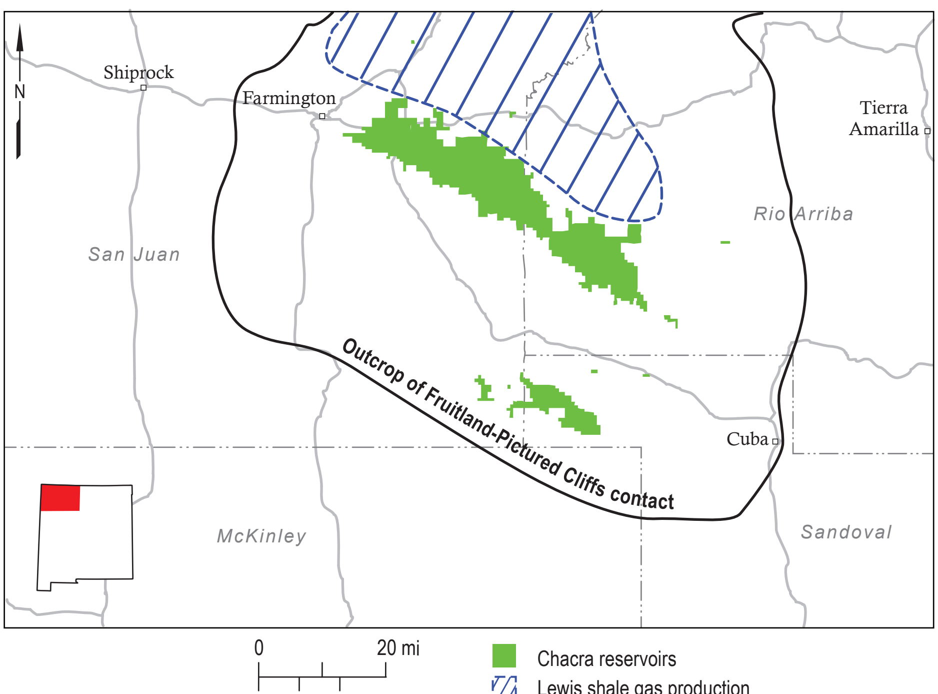


Figure 26. Natural gas reservoirs in the Chacra sandstones and Lewis Shale (Upper Cretaceous), northwestern New Mexico. Outline of Lewis Shale gas production after Fassett and Boyce (2005).

The Chacra reservoirs are isolated sandstone bodies within the more proximal parts of the Lewis Shale, which acts as both source rock and seal. These are time-equivalent to the Cliff House Sandstone but were deposited offshore (northeast) as isolated submarine bars (Palmer and Scott, 1984). Porosity of Chacra reservoirs averages approximately 5%. Depth to production is 3,500–4,000 ft.

Mesaverde Group

Sandstones of the Mesaverde Group (Upper Cretaceous) are major gas-producers in the San Juan Basin (Fig. 27). The Point Lookout Sandstone is the stratigraphically lowest and most productive unit in the Mesaverde (Fig. 23). Significant production has also been obtained from the shallower Cliff House Sandstone. Gas-productive reservoirs occur in the northern, deeper part of the basin and oil-productive reservoirs occur in the southern, shallower part of the basin.

Different from other major reservoirs in the Upper Cretaceous of the San Juan Basin, the Cliff House was deposited during a transgressive phase of the Late Cretaceous interior sea. Thicker areas of the Cliff House represent still-stand or short-term regressive buildups of sandstones in the overall transgressive sequence and are stacked barrier island sequences (Molenaar, 1977; McCubbin, 1982; Palmer and Scott, 1984). Wave-dominated deltaic complexes may be present in places along the paleoshoreline. The Cliff House intertongues with the marine Lewis Shale in a seaward (northeast) direction and the nonmarine, paludal to lagoonal Menefee sediments in a landward (southwest) direction. Sandstone bodies within the Cliff House are elongated in a northwest-southeast direction, parallel to the paleoshoreline. Cliff House sandstones are well cemented, very fine grained, and contain laminae of carbonaceous shales (Pritchard, 1973). Porosity averages approximately 10% (Reneau and Harris, 1957). Sandstone bodies were deposited in upward-shoaling sequences (McCubbin, 1982). Depth to production is 4,000–5,300 ft.

The Point Lookout Sandstone was deposited in an overall regressive setting (Sears et al., 1941; Pike, 1947). It overlies and intertongues with the Mancos Shale in a seaward (northeast) direction and is overlain by and intertongues with the nonmarine Menefee Formation in a landward (southwest) direction (Fig. 23). In general, the Point Lookout forms an upward coarsening transition from offshore marine (Mancos) shales, to very fine-grained sandstones and siltstones of the lower shoreface to fine-grained, storm-influenced sandstones of the nearshore zone. The nearshore zone includes shoreface and barrier island sequences. At the top, back-barrier finer-grained lagoonal deposits prograde over the barrier

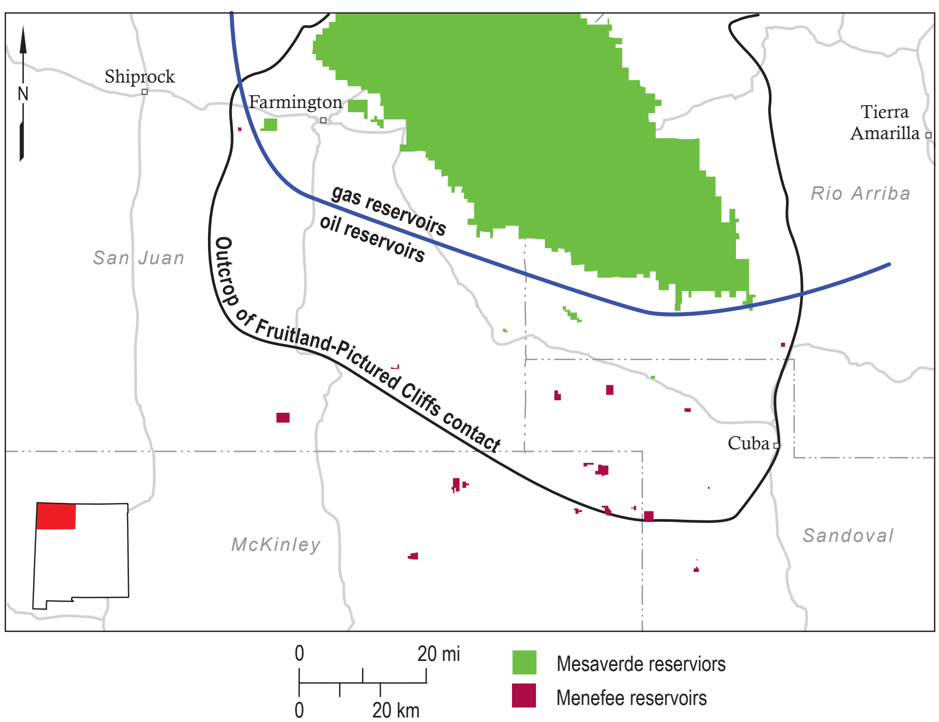


Figure 27. Natural gas reservoirs in the Mesaverde Group (Upper Cretaceous), northwestern New Mexico.

island facies (Devine, 1991). Beach ridges prograded seaward and were transected by distributary channels that formed northeast-prograding channel bar sands (Devine, 1991). Shorter-term transgressive cycles periodically resulted in the deposition of coarser-grained (fine- to medium-grained sandstones) in back-barrier estuaries that formed the best reservoirs in the Point Lookout (Devine, 1991). The result of this intermixing of facies tracts along with uneven distribution of natural fractures is an inhomogeneous reservoir with uneven gas production and internal production discontinuities (Fassett and Boyce, 2005). Porosity of productive reservoirs averages 10%. Depth to Point Lookout production varies from 4,500–6,200 ft.

Several different trapping mechanisms have been proposed for the Mesaverde gas accumulations, including hydrodynamic, stratigraphic, and relative permeability/capillary pressure phenomena. Hydrodynamic trapping was proposed by Berry (1959) and Meissner (1987) who hypothesized centripetal flow of water downward into the basin center and, thence, vertically downward across formation boundaries. Obstacles to this hypothesis include a hydrostatic rather than a hydrodynamic system within the Mesaverde (Douglass, 1984; Berg, 1989), the absence of moveable water around the edges of the gas accumulation (Whitehead, 1993c), lack of an identified output of water for the postulated downward movement in the basin center (Magara, 1981; Cumella, 1981), and overall low groundwater flows in the basin (Nelson and Condon, 2008).

Stratigraphic entrapment was proposed by Hollenshead and Pritchard (1961). Their cross sections indicate that the Mesaverde sandstones grade to the northeast into siltstones and then into shales of the Lewis and Mancos Shales. To the southwest, the Mesaverde reservoir sandstones terminate against the low-permeability back-barrier, paludal deposits of the Menefee Formation. Fassett and Boyce (2005) have reinforced the concept of stratigraphic entrapment of gas in the Mesaverde sandstones. However, Cumella (1981) concluded that distribution of authigenic clays in the Point Lookout Sandstone is similar to that in the Pictured Cliffs Sandstone as previously discussed and that this distribution exerts the primary control on gas distribution in the Point Lookout.

The prevailing concept of entrapment was first formulated by Riggs (see Masters, 1979). Riggs concluded that higher water saturations in low-permeability Mesaverde sandstones created an updip relative permeability barrier that prevented updip leakage of gas to the outcrop. Water-saturated sandstones are located updip of gas-saturated sandstones in a laterally continuous reservoir unit with an intermediate transitional area where the reservoir will produce both water and gas. In this type of trap, gas continually migrates updip from the basin center where it is generated; the gas accumulation is dynamic rather than static. Gies (1984) presented a thorough pressure analysis of this type of trap for the Cadomin Formation (Cretaceous) of the Alberta Basin. Nelson and Condon (2008) presented a thorough analysis of reservoir pressures in the Mesaverde sandstones and concluded that the gas column within the Mesaverde system is underpressured and that there is no internal reservoir compartmentalization within the Mesaverde. Gas is trapped by interfacial tension in the lower permeability sandstones downdip, but gas has escaped from sandstones with larger pores updip because the upward buoyant force exerted by the gas overcomes interfacial tension and allows the gas to migrate updip. However, Fassett and Boyce (2005) maintained that updip, conventional lithologic seals are present in the Mesaverde and that water is not present updip of the gas in the same continuous reservoir system. This idea was supported by Whitehead (1993c) who noted the lack of moveable water updip. Pressure depletion appears to be the drive mechanism in Mesaverde reservoirs.

The Menefee Formation is the middle nonmarine part of the Mesaverde Group. It is overlain by the Cliff House Sandstone and underlain by the Point Lookout Sandstone. It attains a maximum thickness of approximately 1,800 ft on the southwest flank of the San Juan Basin and pinches out to the far northeast as the Cliff House and Point Lookout converge. The pinchout forms a northwest-southeast trending line that runs across the northeastern part of the San Juan Basin. As such, the Menefee forms a wedge that thins to the northeast. It is time-equivalent to the Lewis Shale to the northeast. The lowermost beds of the Menefee intertongue northeastward with the underlying, time transgressive Point Lookout Sandstone as the Menefee overrides the Point Lookout to the northeast. The uppermost beds of the Menefee intertongue with the overlying, time-transgressive Cliff House Sandstone as the Cliff House overrides the Menefee to the southwest. The Menefee was deposited in fluvial channel, floodplain, and paludal environments separated from the marine Lewis shales by the coastal and shallow marine Cliff House and Point Lookout sandstones. Major Menefee lithologies are lenticular channel sandstones, thin overbank sandstones, floodplain shales, and coals.

Oil reservoirs in the Menefee are situated southwest of the main Mesaverde reservoirs, which are productive from the Cliff House and Point Lookout Sandstones (Fig. 27). Petroleum accumulations in the Cliff House and Point Lookout occur deeper in the basin than petroleum accumulations in the Menefee. As a result, the Cliff House and Point Lookout reservoirs are in the thermogenic gas window and the shallower Menefee reservoirs are in the oil window. Depth to production ranges from 300 ft in central McKinley County to 4,000 ft to the northeast in the panhandle of Sandoval County.

Menefee reservoirs are lenticular, fluvial channel sandstones. Traps are generally combination structural-stratigraphic formed by a drape of sandstone pinchouts over anticlinal noses. Reservoirs are small and have less than 10 wells. Several of the Menefee fields are multipay with each well productive from a different sandstone. Oil gravity ranges from 29–46º API and, in general, increases to the northeast with increasing depth and thermal maturity. Individual sandstone reservoirs in the same field may have differences in API gravities of as much as 6º perhaps indicating stratal differences in the kerogen character of stratigraphically associated source rocks. Porosity is 26–29% in the shallow, southern reservoirs and decreases to 15–20% to the north where burial is deeper. Most of the sandstone reservoirs are 10–15 ft thick. The drive mechanism for most Menefee oil accumulations is water drive, with a solution-gas drive assist where sufficient gas is present along with the oil. In a couple of the reservoirs, gravity drainage provides the production energy.

Published information indicates that ultimate recovery from primary production is as large as 400,000 bbls oil for the larger reservoirs but is considerably less than 100,000 bbls oil for most Menefee reservoirs. Reservoirs appear to be water floodable.

Lower Niobrara (“Gallup”) sandstone reservoirs

The lower Niobrara (Upper Cretaceous) sandstones encompass a series of reservoirs within the lowermost part of the upper Mancos Shale. These sandstones have variously been referred to as the basal Niobrara sandstones, the Tocito Sandstone Lentil (or Tocito sandstones), or the transgressive Gallup sandstones (Fig. 23; Molenaar, 1977). Originally thought to be offshore equivalents of the Upper Cretaceous Gallup Sandstone (or the “true” Gallup), these sand bodies were subsequently revealed to be separated from the true Gallup by a regional unconformity that separates the Upper Mancos Shale from the Lower Mancos Shale (Molenaar, 1973). However, the term Gallup “stuck” even though these sand bodies are post-Gallup in age. The lower Niobrara was deposited during transgression of the Mancos sea over the unconformity. The lower Niobrara sandstones (Fig. 28) form the most important oil reservoirs discovered and produced thus far in the San Juan Basin.

The lower Niobrara sandstones were deposited as a series of offshore bars that formed northwest-southeast trending shoestring sandstones that run parallel to the paleoshoreline (Sabins, 1963; McCubbin, 1969; Bottjer and Stein, 1994). Landward organic-rich shales that bear a restricted marine fauna are suggestive that the bars, at least the larger ones, may have been emergent and, therefore, formed barrier islands. Seaward (northeast) are dark-gray, organic-rich shales that host a diverse fauna; these were deposited as open-marine muds (Sabins, 1963). Traps are stratigraphic and are formed by encasement of the shoestring sandstone bodies in shales that act as both seals and the source rock. Average reservoir porosity typically ranges from 10–15%. Depth to production ranges from 2,000 ft on the northwestern part of the trend to almost 7,000 ft on the southeast. Solution gas provides the drive mechanism in these reservoirs.

Fractured Mancos Shale

Oil and associated gas have been produced from fractured Mancos Shale (Upper Cretaceous) in six fields along the southeastern and northwestern margins of the San Juan Basin (Fig. 28; Mallory, 1977; Greer and Ellis, 1991). Most production has been obtained from the upper part (Niobrara Shale) of the Mancos Shale but some production has been obtained from the lower part (Carlile Shale) of the Mancos Shale. Fractured shaly limestones of the Greenhorn Member of the lower Mancos contribute to production (Fassett et al., 1978). In the upper Mancos Shale, the basal Niobrara (“Gallup”) interval is the dominant reservoir (Greer and Ellis, 1991). Production is generally confined to stratigraphic zones of silty or carbonate-rich, brittle shale that lay astride Laramide-age monoclines and structural noses that have deformed the brittle shales. This deformation induced pervasive natural fracture systems in the process. Overlying and underlying ductile shales provide vertical seals and the reservoirs are limited laterally by the extent of the natural fracture systems (see Greer and Ellis, 1991). Depth to production varies from 1,500 ft on the eastern flank to more than 7,000 ft as the Mancos dips westward into the basin. Structural relief is more

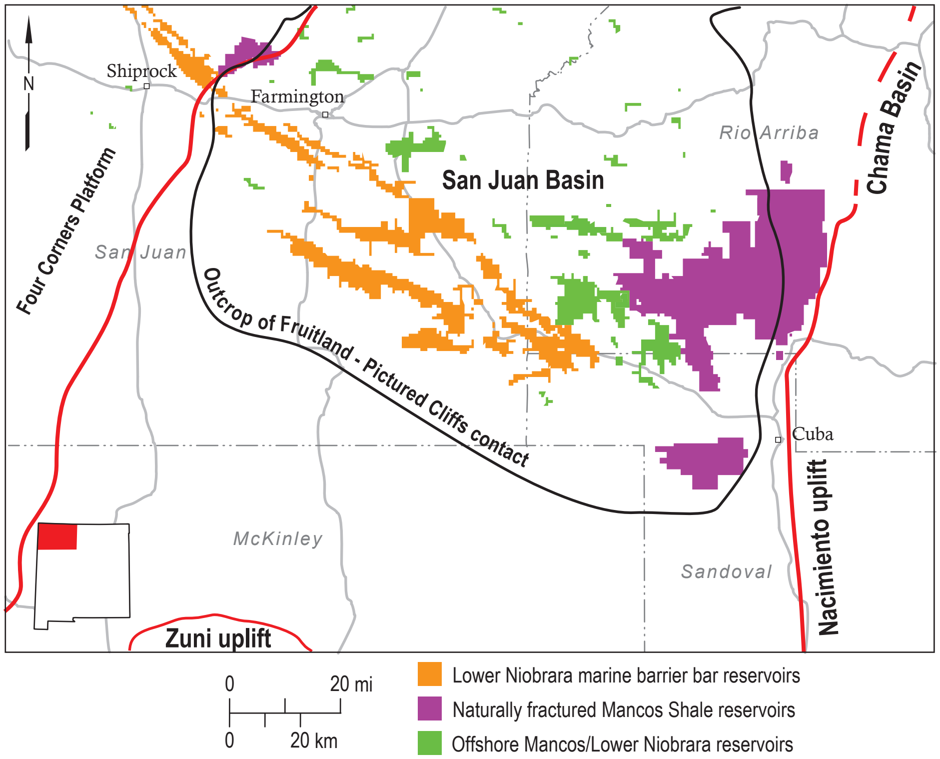


Figure 28. Oil reservoirs in lower Niobrara sandstones and fractured Mancos shales (Upper Cretaceous), northwestern New Mexico.

than 2,500 ft in some reservoirs. The principal drive mechanism in the fractured Mancos shale reservoirs is gravity drainage with a solution gas assist (Greer and Ellis, 1991).

In the last few years, following enormous success in development of oil resources in the Bakken Shale (Mississippian) of North Dakota (see Nordeng et al., 2010), explorationists have become interested in the possibilities of finding additional oil resources in the Mancos Shale of the San Juan Basin. Although historic exploratory efforts and production concentrated on oil accumulations formed by naturally fractured reservoirs, the advent of economically feasible, extended-reach horizontal drilling and the development of multi-stage hydraulic fracturing techniques has brought a sea of change to oil and natural gas exploration and production. Shales worldwide constitute approximately 65% of the sedimentary section (Blatt, 1970). Shales have been mostly historically nonproductive and conventionally thought of as seals, petroleum source rocks, or unwanted strata that contribute heavily to drilling problems, but are now increasingly seen as exploration targets. As this chapter is being written, there are ongoing, new exploration efforts to explore for oil in the Mancos Shale on the south flank of the San Juan Basin where the Upper Cretaceous shales are within the oil window. Of particular interest are stratigraphic intervals where laminations and thin beds of siltstone or very fine-grained sandstone are concentrated within the shales. One such interval is within the lower part of the Niobrara but northeast of the oil-productive basal Niobrara (Tocito or "Gallup") sandstone reservoirs. This stratigraphic interval had been identified by Reese (1977) as having significant oil potential long before the advent of horizontal drilling and associated multi-stage hydraulic fracturing.

Further north in the deeper parts of the San Juan Basin where the Tertiary-age San Juan volcanic field of southern Colorado is approached, the Upper Cretaceous section is within the thermogenic gas window. Significant potential exists for shale gas. Shale gas discoveries have recently been made in the Mancos Shale (Natali, 2012).

Lower to Upper Cretaceous

Dakota Sandstone

The Dakota Sandstone (Lower to Upper Cretaceous) is a primary reservoir of natural gas and gas liquids in the San Juan Basin (Fig. 29). Although many wells are productive from only the Dakota, with no other strata contributing to production, production from the Dakota reservoir in most wells is commingled with production from other strata within the Lower Mancos Shale, especially the Greenhorn Limestone Member and sandstones in the Graneros Shale Member. Dakota sandstones are fine grained. The largest reservoir is the giant Basin Dakota pool, which produces natural gas and gas liquids and has an average porosity of 7% (Deischl, 1973). Smaller reservoirs present on the shallower southern flank of the basin produce primarily oil and have average porosities in the 10–15% range.

Smaller accumulations of oil that are formed by structural traps are found in the northwestern part of the San Juan Basin and also on the Four Corners Platform. These structural traps were the source of early oil production within the San Juan Basin. Stratigraphically associated shale seals in the lower part of the Mancos Shale also function as source rocks. The distribution of oil-filled reservoirs and gas-filled reservoirs in the San Juan Basin and Four Corners Platform is a function of the thermal maturity of the source rocks. In the deeper, northern part of the basin, the lower Mancos source rocks are within the thermogenic gas window, while those on the shallower southern flank and on the Four Corners Platform are within the oil window. Depth to production averages approximately 7,000 ft in the giant Basin Dakota reservoir and is 2,500–3,000 ft in the shallow, structurally controlled reservoirs to the northwest. The shallow reservoirs produce primarily by solution gas drive and the Basin Dakota reservoir has a pressure depletion drive.

As with gas trapped in the shallower Point Lookout and Mesaverde reservoirs, several distinctly different trapping mechanisms have been proposed for the Basin Dakota reservoir. Berry (1959), Deischl (1973) and Meissner (1987) invoked a hydrodynamic trapping mechanism. In this model, it was proposed that influent water obtained from recharge of water along Dakota outcrops at the basin margins flows downdip into the basin center and thence vertically downward across formation boundaries, with trapping provided by the downdip movement of water through a laterally continuous blanket reservoir à la Hubbert (1953, 1967). Obstacles to this hypothesis include an underpressured hydrostatic rather than hydrodynamic pressure system within the Basin Dakota reservoir (Nelson and Condon, 2008), the absence of moveable water around the edges of the Basin Dakota pool (Whitehead, 1993d), a lack of downward discharge beneath the Dakota at the basin center (Magara, 1981), and overall low groundwater flows in the basin (Nelson and Condon, 2008).

Nelson and Condon (2008), following Gies (1984), proposed that gas is trapped within the Basin reservoir by an underlying low-permeability layer (Brushy Basin Member of the Jurassic Morrison

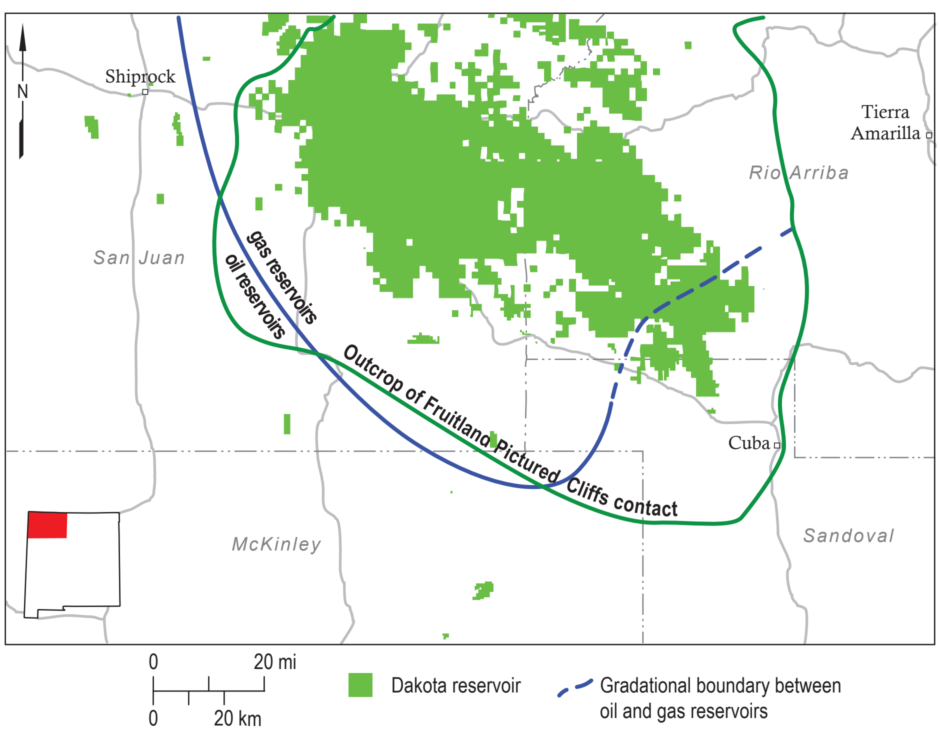


Figure 29. Natural gas and oil reservoirs in the Dakota Sandstone (Lower to Upper Cretaceous), northwestern New Mexico.

Formation) and a lateral change from downdip gas-saturated sandstone to updip water-saturated sandstone with gas retained in the downdip sandstones, because of lower permeability associated with smaller pore sizes.

Head and Owen (2005) concluded that trapping in the Basin Dakota reservoir is largely stratigraphic, but that the reservoir boundary on the west side of the accumulation is marked by a downdip gas to updip water transition in an otherwise continuous reservoir; gas limits to the south and east are controlled by stratigraphic pinchouts of the reservoir sandstones in Dakota-equivalent shales. Head and Owen (2005) also presented data that indicate there are three main compartments in the Basin Dakota reservoir that are not in pressure communication with each other and that the boundaries of these pressure compartments are controlled by depositional facies within the Dakota. Fassett and Boyce (2005) similarly concluded that the Basin Dakota trap is formed primarily by lenticular Dakota sandstones encased in marine shales with additional compartmentalization and barriers to fluid flow provided by north-south trending fractures. Fassett and Boyce (2005) also stated that the southwestern (updip) boundary of the Basin reservoir is formed by a series of marine Dakota reservoirs pinching out updip into marine Dakota-equivalent shales.

Jurassic

Entrada Sandstone

Oil without gas has been produced from nine small reservoirs in the Entrada Sandstone (Middle Jurassic) in the south-central San Juan Basin (Fig. 30). The Entrada is a blanket sand of eolian origin that covers most of the basin. Oil is trapped stratigraphically by relict eolian dunes that form local, closed paleotopographic highs on top of the sheet-like Entrada sand body (Vincelette and Chittum, 1981). The overlying lacustrine anhydrites and dark, fetid, organic-rich limestones of the Todilto Formation (Middle Jurassic) provide the seal for the traps and the source rocks for the oil found in the traps. Reservoir pay ranges from 16–29 ft, porosity ranges from 22–25% and permeability ranges from 180–430 md (Vincelette and Chittum, 1981). Vertical permeability is high so that significant coning of the oil-water contact occurs during pumping of the oil. Produced water to oil ratios can be as large as 20:1. Depth to production ranges from 5,100–5,900 ft.

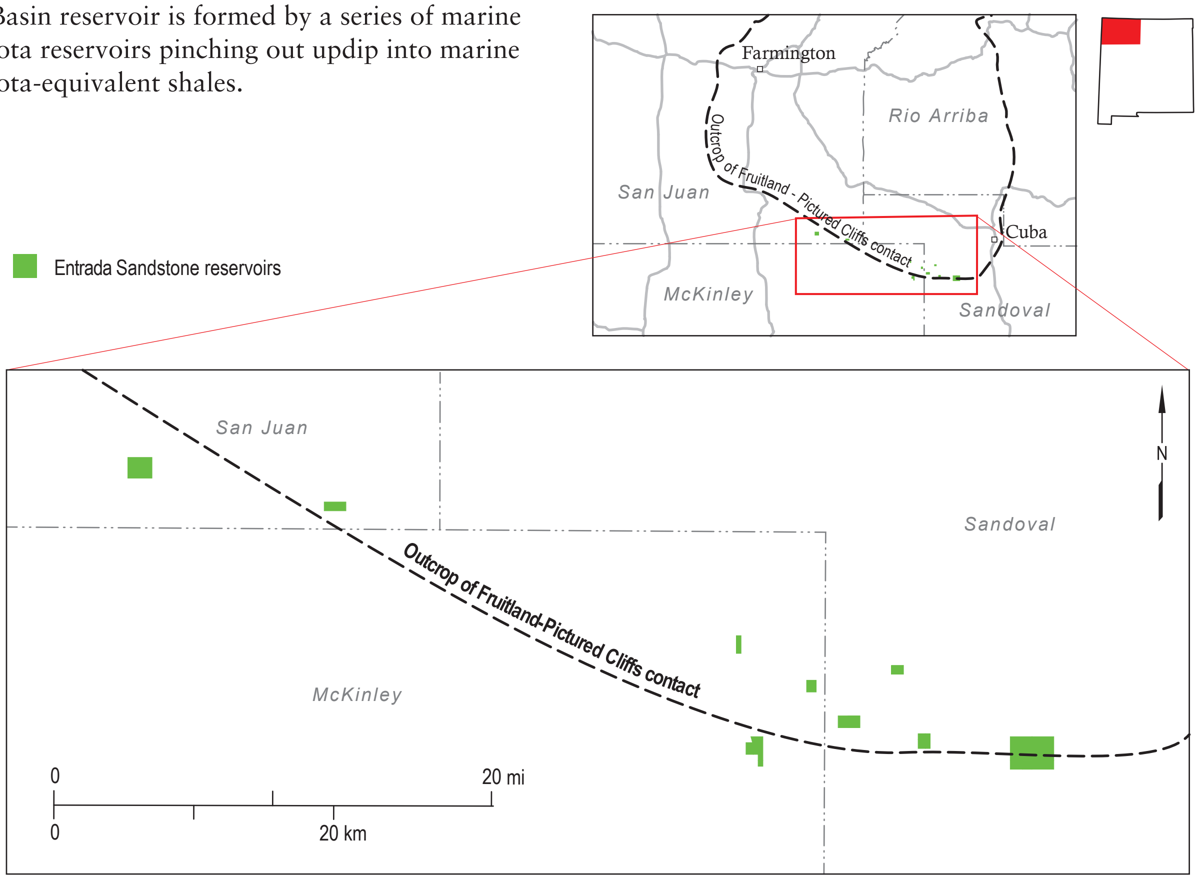


Figure 30. Oil reservoirs in the Entrada Sandstone (Jurassic), northwestern New Mexico.

Paleozoic

Significant oil and natural gas production has been obtained from small oil and gas accumulations in Middle to Upper Paleozoic strata on the Four Corners Platform (Fig. 31). Most production has been obtained from Pennsylvanian phylloid-algal mounds and bioherms, but significant production has also been obtained from Mississippian carbonates. Very minor production has been obtained from Lower Permian sandstones of the Cutler Formation at the Big Gap field and also from Devonian sandstones in the now-abandoned Tom and Akah Nez fields. Gases in Permian, Pennsylvanian, Mississippian, and Devonian reservoirs contain as much as 7.5% helium and have been produced for their helium as well as for their hydrocarbons (Casey, 1983; Broadhead and Gillard, 2004; Broadhead, 2005). Sources of helium include radiogenic decay of granitic basement rocks and local intrusive rocks; anticlinal geometry is integral to trapping and deep fault systems acted as migration conduits from source to reservoir (Casey, 1983). In general, Mississippian gases contain more than 50% CO_2 throughout most of the San Juan Basin (Broadhead et al., 2009).

Exploration has been very limited for oil and gas accumulations in Paleozoic reservoirs in the deep San Juan Basin. With exploration and development concentrated on shallower Cretaceous gas and oil accumulations and with leases in large portions of the basin held by production, only a handful of wells have been drilled below the uppermost part of the Jurassic. Despite sparse sub-Mesozoic drilling, several wells have yielded gas flows on drill-stem tests (Schoderbek, 1998).

One small reservoir, the Buena Suerte Pennsylvanian oil pool (Brown, 1978) was produced in the deep San Juan Basin (Fig. 31). This reservoir, discovered in 1971, was productive for two years from a single well. Cumulative production was 5,296 bbls oil and 4,021 MCF gas. Although most Pennsylvanian exploratory wells in the deep basin have targeted bioherms, the reservoir at Buena Suerte is a 6 ft thick medium- to coarse-grained sandstone at a depth of 10,956 ft. Porosity is 12% and the trap is stratigraphic (Brown, 1978). The oil was light with an API gravity of 53°. Because no offset wells were drilled, the size of the oil accumulation is unknown. The production mechanism was solution gas drive (Brown, 1978). Source rocks are likely interbedded dark-gray Pennsylvanian marine shales.

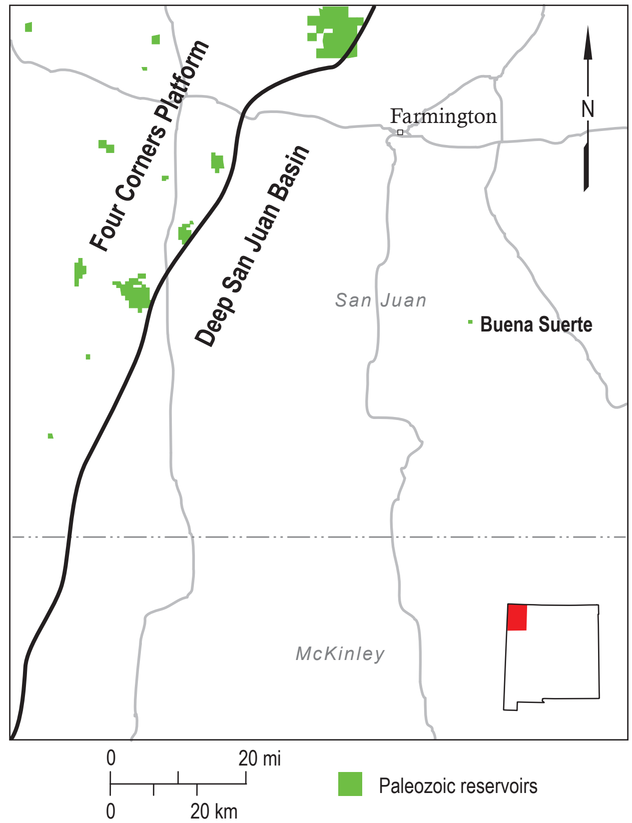


Figure 31. Natural gas and oil reservoirs in the Paleozoic strata, northwestern New Mexico.

Storage tanks, separator and pump jack in the San Juan Basin. *Photo by Shari Kelley*.

IV. SAN LUIS BASIN

The San Luis Basin lies west of the Sangre de Cristo uplift and east of the Brazos uplift (Figs. 1, 2, 32). It is a Tertiary-age extensional basin that is one of the northernmost basins of the Rio Grande rift (Hawley, 1978). The San Luis Basin is an east-tilted graben that extends northward into Colorado (Burroughs, 1981). Precambrian rocks are exposed at high elevations in the mountain ranges that form the uplifts east and west of the basin. Several deep exploratory wells have been drilled in the Colorado part of the basin, but none have been drilled in the New Mexico part of the basin.

In Colorado, wells indicate that up to 10,000 ft of Tertiary-age valley fill sediments rest unconformably on Precambrian basement (Burroughs, 1981). The valley fill consists of alluvial sandstones and shales, andesitic to latitic lava flows, volcaniclastic sedimentary rocks, ash-flow tuffs and lacustrine claystones (Lipman, 1975; Burroughs, 1981; Brister and Gries, 1994).

Absence of Cretaceous strata from the Colorado part of the basin as well as its absence from adjacent uplifts in New Mexico suggests that the Cretaceous is absent from the New Mexico part of the basin. The area currently occupied by the San Luis Basin along with the bordering uplifts appears to have been an erosional highland during the Laramide, with basin bounding faults not formed until post-Laramide extension. The absence of a Cretaceous section with its organic-rich marine shales and its reservoir sandstones, present both to the east in the Raton Basin and to the west in the San Juan Basin, is a large negative factor when considering the petroleum potential of this rift basin, especially since the Tertiary valley fill is devoid of a petroleum source facies and widespread seals.

It is uncertain whether Pennsylvanian sedimentary rocks are present within the New Mexico part of the San Luis Basin. Casey (1980) and Soegaard (1990)

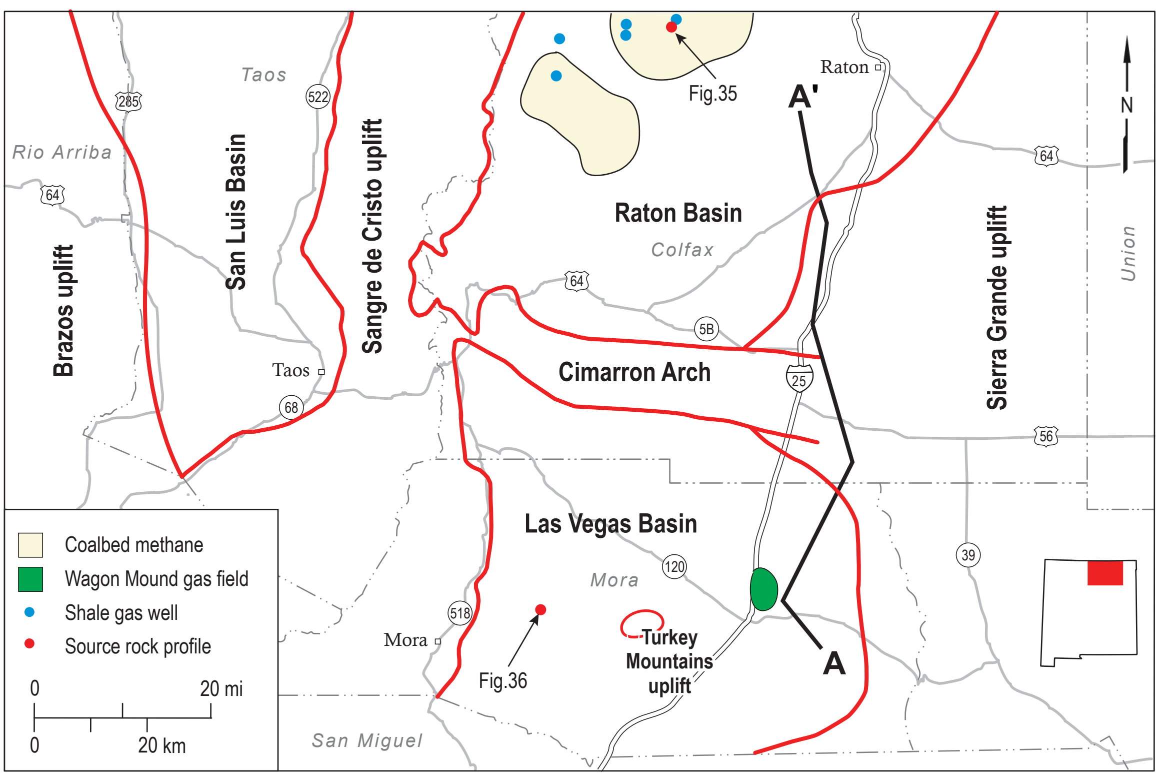


Figure 32. The Raton, Las Vegas, and San Luis Basins, indicating areas of coalbed methane and conventional (Wagon Mound field) natural gas production, shale gas evaluation wells, and the location of cross section of Figure 34.

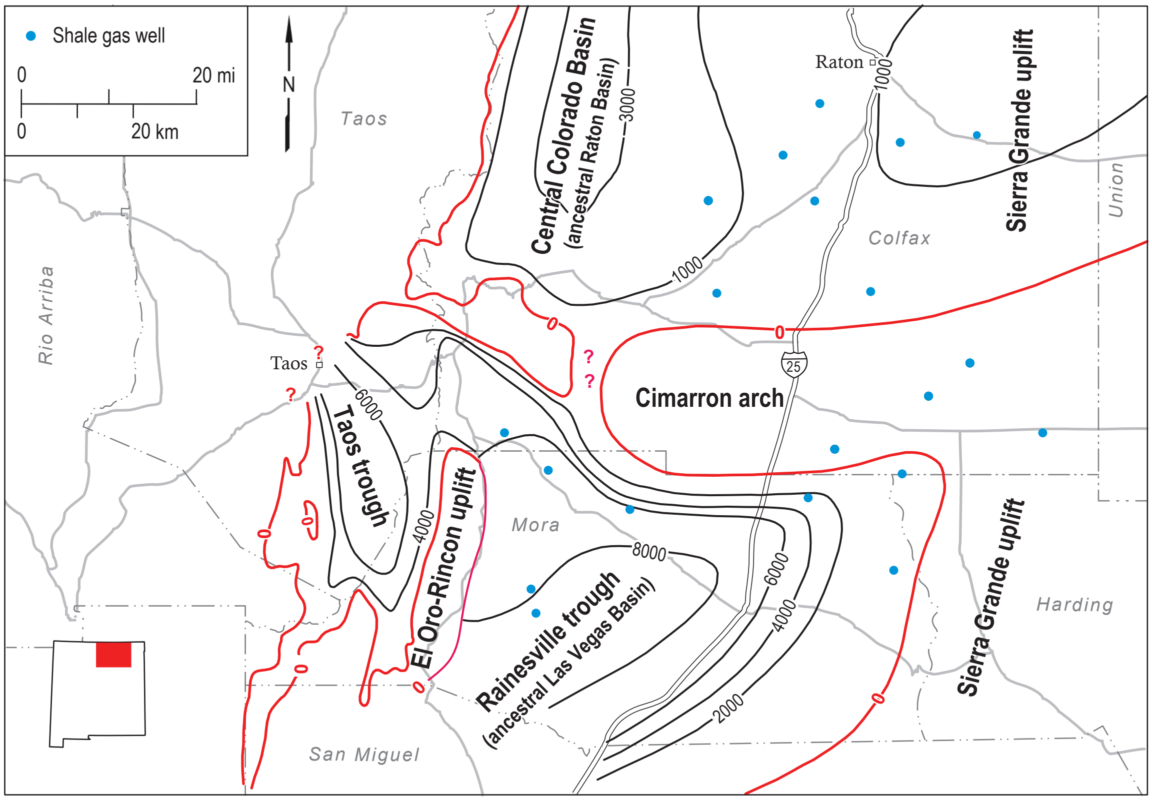


Figure 33. Isopach of Pennsylvanian strata, Raton and Las Vegas Basins. After Broadhead (2008). Contours are in feet. Red line is pinchout (zero value isopach) of Pennsylvanian strata.

concluded that the area now occupied by the basin was an emergent highland during the Pennsylvanian and that this highland was eroded and shed its debris eastward into the Taos trough (Fig. 33), where this debris was deposited as syntectonic sandstones, conglomerates, and shales. The Pennsylvanian sedimentary fill of the Taos trough is now exposed in the Sangre de Cristo Mountains, where it was uplifted during the Laramide. If this is the case, then Pennsylvanian strata are not present in the subsurface of the San Luis Basin. Because pre-Pennsylvanian Paleozoic strata are not present on the adjacent uplifts, they will be absent from the basin as well. Petroleum possibilities are extremely low.

Baltz and Myers (1999) cast doubt on the presence of a Pennsylvanian uplift west of the Taos trough in the area now occupied by the San Luis Basin. Instead, they placed the ancestral Brazos uplift southwest of the Taos trough. Utilizing gravity data, their own outcrop examination of strata in the Taos trough and the work of Just (1937) and Sutherland (1963), Baltz and Myers (1999) concluded that the Taos trough extended west of its present-day exposures and was down-dropped into the San Luis Basin during post-Laramide extension, where it is now preserved. If this hypothesis is correct, then the southern end of the San Luis Basin contains a Pennsylvanian section that rests on the Precambrian and is overlain by Tertiary valley fill. This portion of the basin may have limited petroleum potential. The organic-rich, dark-gray to black Pennsylvanian shales provide source rocks that are mature and within the thermogenic gas window; the interbedded alluvial and fluvial sandstones provide the primary reservoir targets (Broadhead, 2008).

V. RATON BASIN

The Raton Basin is an asymmetric north-south elongated foreland basin that straddles the New Mexico-Colorado border (Figs. 1, 2, 32; Wanek and Read, 1956; Baltz, 1965; Woodward and Snyder, 1976). After the Permian and San Juan Basins, the Raton is the third most productive basin in New Mexico. The basin formed during regional Laramide (Late Cretaceous to Early Tertiary) east-west compression. It is bordered on the west by reverse-aspect faults that separate it from the Sangre de Cristo uplift. To the east, the basin merges over a gentle ramp with the Late Paleozoic Sierra Grande uplift. To the south, the Cimarron Arch, a late Paleozoic feature reactivated during the Laramide, separates the Raton Basin from the Las Vegas Basin (Fig. 34). Tertiary-age igneous rocks are widespread with extensive flows of basalts to the south and southeast of the basin as well as intrusive rocks on the Sierra Grande uplift to the east and the Sangre de Cristo uplift to the west. Tertiary-age igneous intrusions have been penetrated by exploratory wells in the basin (Speer, 1976), and a major laccolith forms the core of the Vermejo Park anticline (Winchester, 1933; Broadhead, 2008).

Natural gas has been produced from coals of the Vermejo (Upper Cretaceous) and Raton (Upper Cretaceous-Early Tertiary) Formations since 1999 (Fig. 32; Hoffman and Brister, 2003; Higley et al., 2007). More than 300 BCF have been produced from 800 wells. Depth to production ranges from 700–2,700 ft.

Gas has also been produced from the Pierre and Niobrara Shales (Upper Cretaceous), but attempts at major production have not yet been pursued. A single well produced a cumulative 173 MMCF gas from the Pierre and Niobrara Shales between 1981 and 1991 (Broadhead, 2008). The productive interval between depths of 3,383–3,737 ft straddles the Pierre-Niobrara contact. The gas was used to power operations on the Vermejo Ranch. From 2008 through 2011, four vertical wells were drilled to evaluate the gas potential of the Niobrara Shale

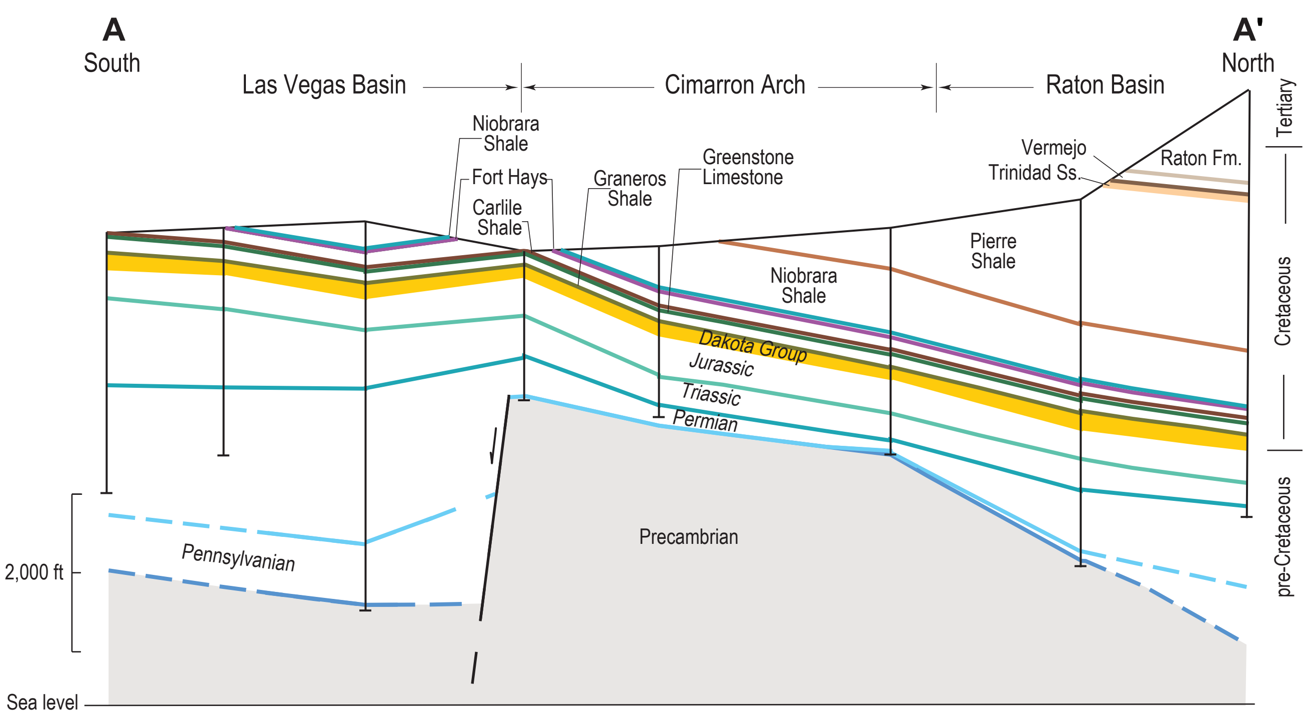


Figure 34. North-south cross section from Raton Basin to Las Vegas Basin. Simplified from Broadhead (2010a). See Figure 32 for location.

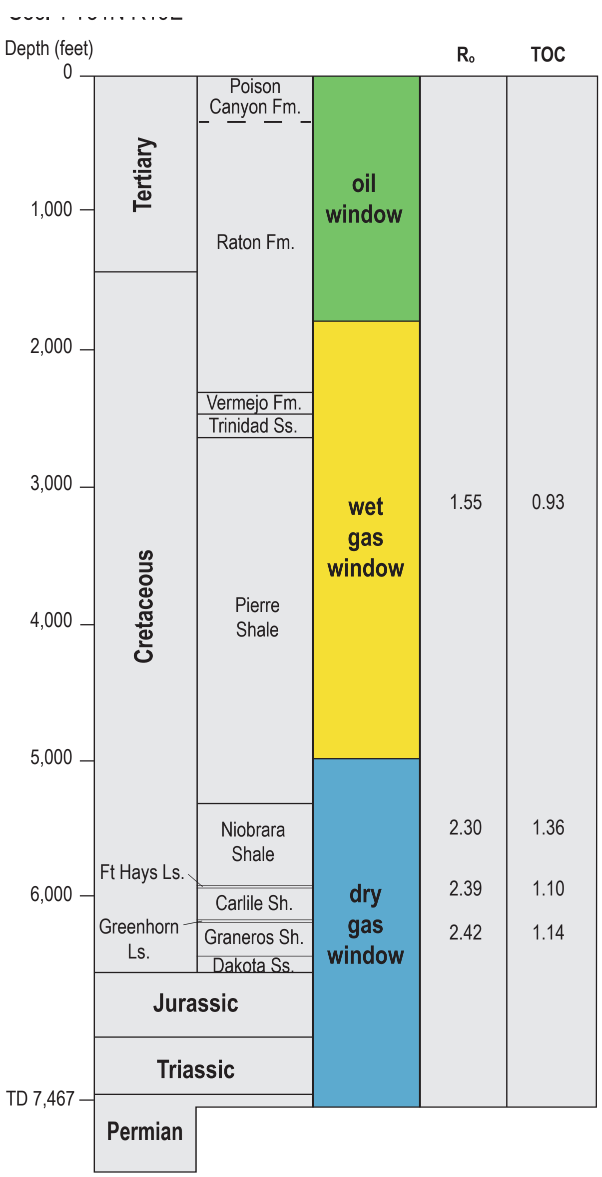


Figure 35. Thermal maturation and source rock profile, El Paso Natural Gas no 7WDW well, axis of Raton Basin. R_o = vitrinite reflectance; TOC = total organic carbon. See Figure 32 for location. After Broadhead (2008).

(Fig. 32). These wells produced a cumulative total of 603 MMCF through early 2013. Because most modern shale gas wells are drilled horizontally, these vertically drilled Niobrara wells may not necessarily indicate the full productive potential of the Niobrara in the Raton Basin.

The dark-gray, organic rich Niobrara and Pierre shales have good source rock characteristics. They contain sufficient organic matter for petroleum generation, with the Pierre Shale having 0.5–1.67% TOC and the Niobrara having 0.95–2.03% TOC (Broadhead, 2008). Along the deep basin axis, both stratigraphic units are within the thermogenic gas window (Fig. 35) and are within the biogenic gas window where they crop out along the basin flanks (Broadhead, 2008, 2012).

Pre-Cretaceous stratigraphic units are an exploration frontier and have potential for hydrocarbons and CO_2 (Broadhead, 2012). Those stratigraphic units that are associated with thermally mature, organic-rich source rocks (Jurassic Morrison Formation and Entrada Sandstone; Permo-Pennsylvanian Sangre de Cristo Formation; Pennsylvanian Madera Group and Sandia Formation) have yielded oil and hydrocarbon gas shows in exploratory wells and have hydrocarbon potential. All of these strata are within the thermogenic gas window in the deeper, axial parts of the basin and are within the oil window on the basin flanks. Units devoid of source facies and not stratigraphically associated with a source facies (Triassic Chinle Group and Santa Rosa Sandstone; Permian Bernal Formation, Glorieta Sandstone, and Yeso Formation) have yielded CO_2 shows in exploratory wells. Analogy with large CO_2 accumulations within the American southwest (see sections on Bravo Dome and west-central New Mexico in this volume) indicates the CO_2 was derived from the degassing of rising Tertiary-age magmas that formed the intrusive and extrusive igneous rocks so pervasive in the Raton Basin region.

VI. LAS VEGAS BASIN

The Las Vegas Basin underlies western Mora and northwestern San Miguel Counties (Figs. 1, 2). To the north, the Late Paleozoic Cimarron Arch separates the Las Vegas Basin from the Raton Basin (Figs. 32, 34). To the east and southeast, the Las Vegas Basin rises over a gentle ramp onto the late Paleozoic Sierra Grande uplift. On the west, the boundary with the Sangre de Cristo uplift is sharp and is formed by reverse aspect faults that developed during Laramide (Late Cretaceous–Early Tertiary) compression. Depth to Precambrian basement ranges from more than 10,000 ft in the deepest part of the basin to 2,000 ft on its eastern flank. To the west, the Precambrian is exposed at elevations of more than 6,000 ft in the Sangre de Cristo Mountains. Maximum structural relief is approximately 10,000 ft.

Sedimentary fill in the Las Vegas Basin is mostly Pennsylvanian to Early Permian in age (Baltz and Myers, 1999; Broadhead, 2008; Figs. 32, 34). Unlike the Raton Basin to the north, only the lower parts of the Cretaceous section have been preserved, and the Dakota Sandstone (Lower to Upper Cretaceous) and Jurassic strata are exposed in Holocene fluvial drainages. Triassic strata are exposed in the Turkey Mountains uplift (Fig. 32). The Turkey Mountains uplift is a domal structure formed by arching over a Tertiary age laccolith (Hayes, 1957; Boyd, 1983; Broadhead, 2008). Approximately 160 ft of Mississippian limestones and arkosic sandstones unconformably overlie Precambrian basement in the western part of the Las Vegas Basin. To the east on the western flank of the Sierra Grande uplift, Pennsylvanian strata rest on the Precambrian. Thickness of the Pennsylvanian and Early Permian section varies from 2,000–9,000 ft (Fig. 34). This section consists of dark-gray to red shales, arkosic sandstones, and minor marine limestones. Areas of the increased thickness resulted from tectonic subsidence of the fault-bounded Rainesville trough or basin (the ancestral Las Vegas Basin) and the Taos trough or basin (now uplifted in the Sangre de Cristo Mountains west of the present-day Las Vegas Basin). Sedimentary fill was derived primarily from Pennsylvanian and Early Permian-age erosion of exposed basement rocks on the Cimarron Arch, the Sierra Grande uplift, and the El Oro-Rincon uplift. Part of the extra thickness of the Pennsylvanian and Early Permian section in the deeper parts of the Las Vegas Basin is tectonic and is caused by eastward-directed thrust faults of Pennsylvanian age that repeat the Pennsylvanian section (Baltz and Myers, 1999).

In the deeper parts of the basin, the Pennsylvanian section is within the thermogenic gas window (Fig. 36). Present-day, post-maturation values of TOC exceed

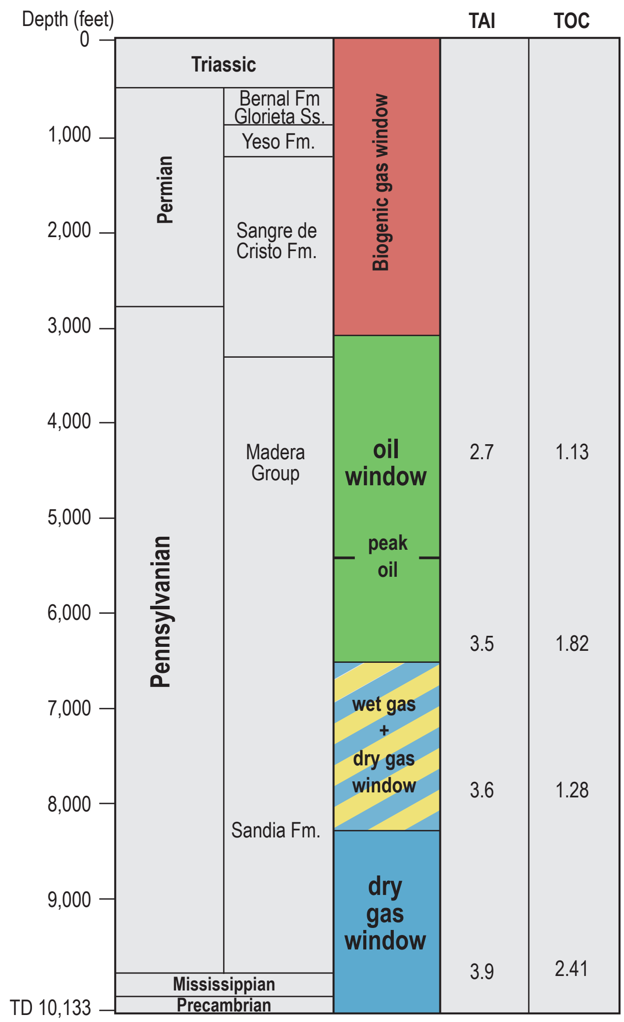


Figure 36. Thermal maturation and source rock profile, Amoco No. 1 Salman Ranch well, Las Vegas Basin. TAI = Thermal Alteration Index; TOC = total organic carbon. See Figure 32 for location. After Broadhead (2008).

2% in some intervals, more than sufficient for petroleum generation. Sandstones in the Pennsylvanian section are typically 5–20 ft thick with porosities around 10% in many cases. Gas shows and recoveries of dry hydrocarbon gases have been reported from exploratory wells drilled in the basin (Broadhead, 2008).

Wells drilled on the Turkey Mountains uplift have encountered CO_2 gas in Pennsylvanian sandstones. The CO_2 was apparently derived from degassing of the magma that formed the laccolith at the core of the uplift. The laccolith, therefore, not only provided the domal trapping mechanism, but the magmas that formed it provided the source for the gas trapped by the dome.

Natural gas was produced from the Wagon Mound gas field on the eastern flank of the basin. Reservoirs were lenticular shallow marine sandstones of the Dakota Sandstone (Cretaceous) and lenticular fluvial sandstones of the Morrison Formation (Jurassic) (Brooks and Clark, 1978). The trap is formed by a low-relief anticline with a closure of 150 ft. Depth to production ranged from 300–700 ft. The Wagon Mound field was discovered in 1973. Production began in 1976 and continued until field abandonment in 1979. Although porosities of productive zones were high at 15–25%, reservoir pressure was low at 5 psi, and therefore production rates were low. Cumulative production was 97 MMCF gas from eight wells and was used to supply the town of Wagon Mound. The produced gas was 81–83% methane and 15–18% nitrogen (Brooks and Clark, 1978). Produced waters were described as fresh, as are most waters recovered from the Dakota and Morrison Formations in the Las Vegas Basin (Broadhead, 2008). This indicates that these shallow reservoirs have been flushed. Thus the potential for the Dakota and Morrison throughout the Las Vegas Basin is limited.

VII. BRAVO DOME AND SIERRA GRANDE UPLIFT

The Sierra Grande uplift separates the Tucumcari Basin on the southeast from the Raton and Las Vegas Basins on the northwest (Figs. 1, 2). The Bravo Dome is a southeast plunging nose of the Sierra Grande uplift. It separates the Tucumcari Basin on the southwest from the Dalhart Basin on the northeast. The Sierra Grande uplift and the Bravo dome were uplifted along bounding faults during the Pennsylvanian and Early Permian. During uplift, the cores of these tectonic elements became eroded down to Precambrian basement and shed their detritus into adjacent basins (Baltz, 1965; Broadhead and King, 1988; Broadhead, 1990, 2008; Baltz and Myers, 1999). As a result, Pennsylvanian strata are not present on these uplifts except for local erosional remnants. Over most of the uplifts, continental red beds of the Wolfcampian (Lower Permian) Abo Formation rest unconformably on the Precambrian. On some of the highest areas continental to marginal marine, orange sandstones of the Leonardian (Lower Permian) Yeso Formation overstep the Abo and rest unconformably on Precambrian.

A major accumulation of carbon dioxide (CO_2) gas is present on the Bravo Dome (Fig. 37; Anderson, 1959; Foster and Jensen, 1972; Broadhead, 1990, 1993d). The Bravo Dome CO_2 gas field is a combined structural-stratigraphic trap. The main reservoir is the Tubb sandstone member of the Yeso Formation. The drape over the Bravo dome structure controls the downdip limits of the field on the northeast, southeast, and southwest flanks. The northwestern boundary of the field is formed by a facies change from downdip, permeable orange, feldspathic Tubb sandstones to updip orange-red mudstones that provide the trap-forming permeability barrier (Fig. 38). This facies change is accompanied by a regional thinning of the Tubb from 400 ft to less than 100 ft. The vertical seal is provided by the Cimarron Anhydrite member of the Yeso Formation, which overlies the Tubb. The Cimarron is 10–20 ft thick over the Bravo dome and also provides an

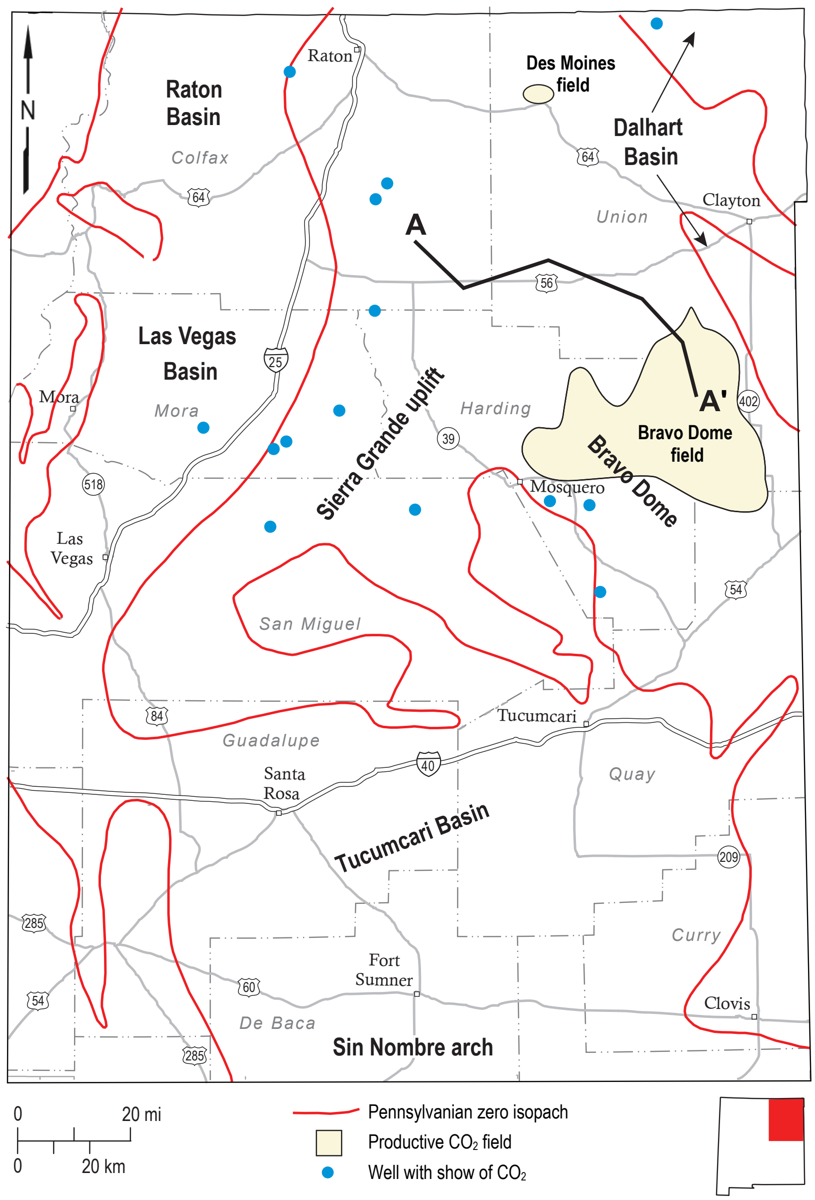


Figure 37. Bravo Dome and Sierra Grande uplift indication locations of the Bravo Dome and Des Moines CO_2 gas fields, wells that encountered CO_2 gas shows, and the location of the cross section of Figure 38.

effective vertical seal for the high-angle faults that cut through the Bravo dome field. Depth to production in the Tubb reservoir is 1,900 ft on the northwestern, updip edge of the field and 2,950 ft on the southeastern, downdip edge of the field. A small amount of CO_2 has locally leaked upward along faults and has accumulated in the fluvial Santa Rosa Sandstone (Triassic). The overlying red, lacustrine, plastic shales of the Chinle Group (Triassic) provide the vertical seal for the Santa Rosa reservoir.

The gas in the Bravo dome reservoirs consists of 98–99% CO_2. The non-CO_2 component consists of trace amounts of noble gases, nitrogen, and helium. Hydrocarbons are present in trace amounts in some areas, but are absent from most wells (Broadhead et al., 2009).

The CO_2 at Bravo dome is juvenile. Isotopic analyses of the CO_2 and associated noble gases indicate that the gas has a mantle rather than a crustal origin (Staudacher, 1987; Gilfillan et al., 2008). Tertiary-age magmas that formed the basalts in the region acted as the transport mechanisms that conveyed the gas from the mantle to the upper part of the crust, where it subsequently migrated to the traps where it is now found.

The Bravo dome CO_2 field was discovered in 1917 by the American Production Co. No. 1 Bueyeros well. The well was drilled as an oil exploration well but encountered CO_2 gas in the Tubb sandstone at a depth of 2,000 ft. The well flowed CO_2 at a rate of 25 million ft^3 per day. There was no market for the CO_2 gas, and the well was plugged (Anderson, 1959). The field lay dormant and undeveloped until 1931 when additional wells were drilled, establishing production in the Santa Rosa Sandstone as well as in the Tubb. The CO_2 was compressed into dry ice that was used for refrigeration and bottled liquid CO_2 that was used in the carbonation of beverages. An additional 19 wells were drilled in the 1930s, which satisfied the demand for CO_2. During this period, the field was named after the nearby town of Bueyeros. During the 1980s a new use emerged for CO_2, enhanced oil recovery. When injected into an oil reservoir that is in a mature stage of production, the injected CO_2 mixes with the oil and makes it more mobile. This allows production of oil that would otherwise remain in the reservoir. As a result of this new use, exploration and development drilling in search of CO_2 rapidly increased, and more than 270 wells were drilled to the Tubb on 640-acre spacing. During this period, the field was renamed Bravo dome. Production increased as a result of this drilling (Fig. 6). The produced CO_2 is compressed and shipped to the Permian Basin via underground pipeline for use in enhanced oil recovery. More than 3.2 trillion ft^3 CO_2 have been produced from the Bravo dome field.

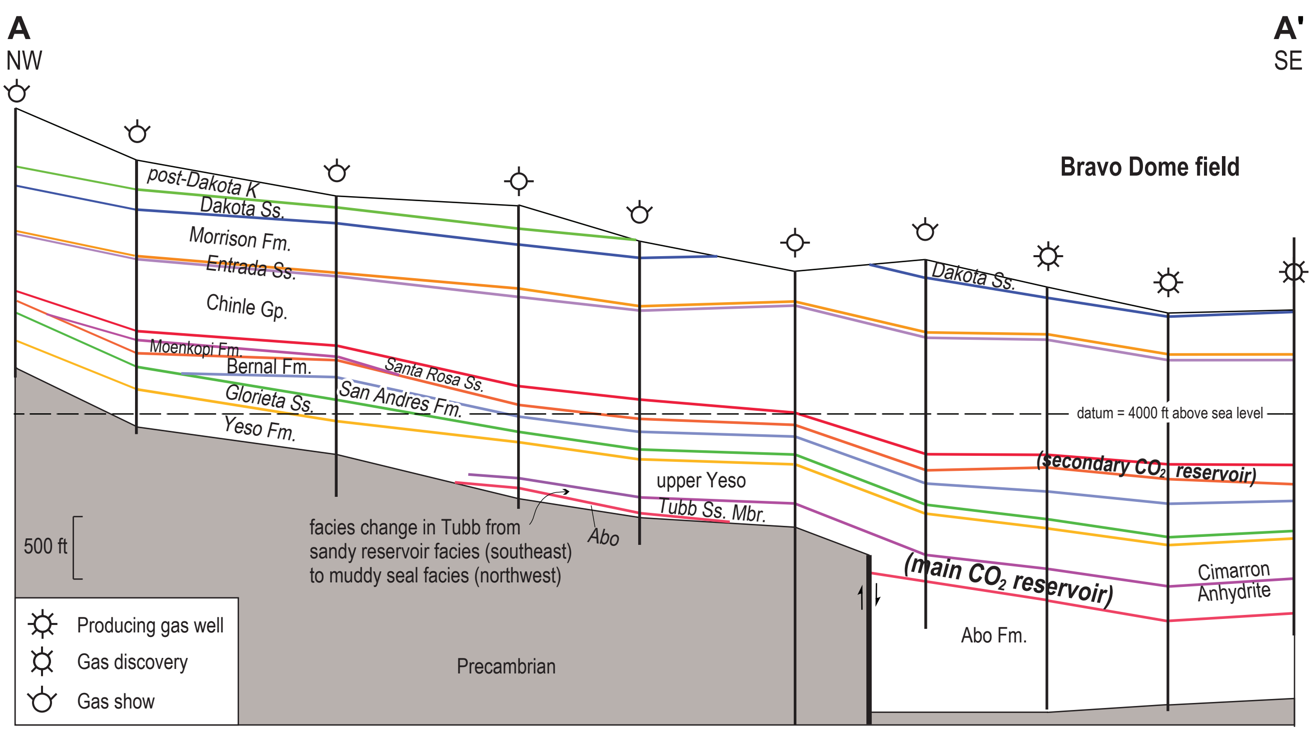
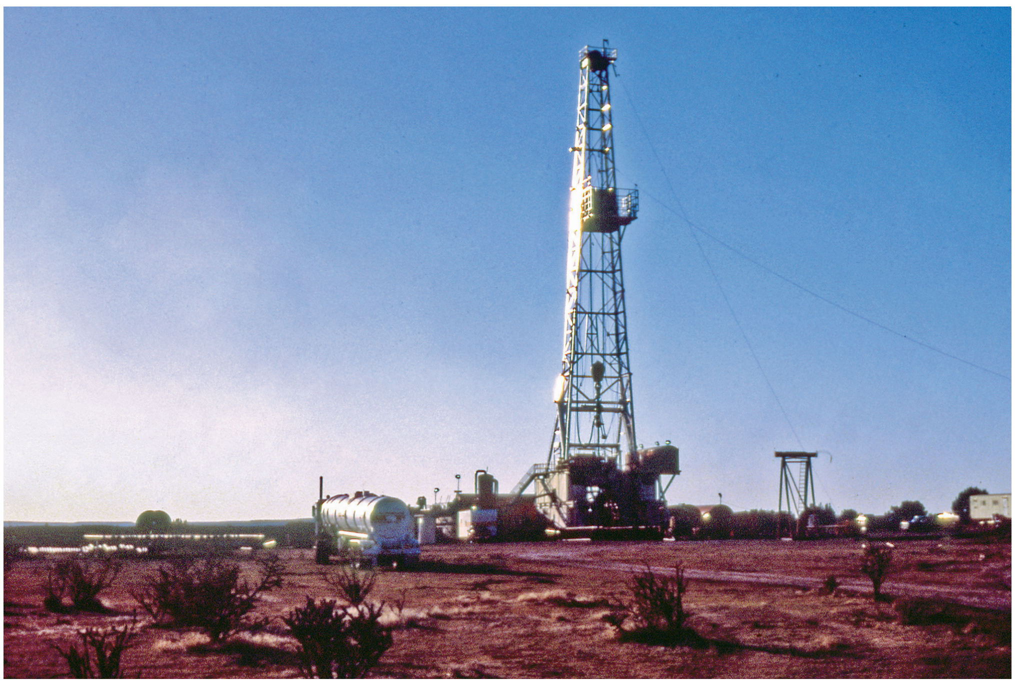


Figure 38. Northwest-southeast structural cross section from Sierra Grande uplift to Bravo Dome. All shows and production are CO_2. See Figure 37 for location.

The field does not appear to be fully developed. New wells are still occasionally drilled to offset declining production from older wells.

The axis of the Sierra Grande uplift is situated northwest and updip of Bravo dome. Exploratory wells have encountered CO_2 on the Sierra Grande uplift since the 1930s (Fig. 37; Anderson, 1959; Foster and Jensen, 1972; Broadhead et al., 2009). Reservoirs include Triassic sandstones, dolostones of the Bernal and San Andres Formations (Upper Permian), the Glorieta Sandstone (Upper Permian), and sandstones of the Yeso and Abo Formations (Lower Permian). Gases are composed of more than 90% CO_2 except for nitrogen-rich gases in sandstones of the Chinle Formation (Triassic; Broadhead et al., 2009). CO_2-rich gases appear to be nearly ubiquitous on the Sierra Grande uplift. The area should be considered as a CO_2 province rather than as an oil and hydrocarbon gas province. Lack of a CO_2 pipeline as well as low pressures in at least some of the CO_2 reservoirs may inhibit further exploration.

The Des Moines CO_2 field is located near the axis of the Sierra Grande uplift (Fig. 37). It was discovered in 1935 and was produced from five wells. Reservoirs at depths of 2,060–2,600 ft are lenticular arkosic fluvial sandstones and conglomerates of the Abo Formation (Wolfcampian: Lower Permian), which rest unconformably on Precambrian crystalline basement. The produced CO_2 was converted to dry ice and bottled, liquid forms (Anderson, 1959). The field was abandoned in 1966 because of problems related to gas processing and not because reserves were depleted (Foster and Jensen, 1972). The areal limits of the field have not been defined by drilling.



Labrador Oil Co. No. 1 Jones well, drilling in Guadalupe County part of Tucumcari Basin, May 1995. *Photo by Ron Broadhead*.

VIII. TUCUMCARI BASIN

The Tucumcari Basin of east-central New Mexico is an emerging gas basin in which recent discoveries of natural gas and petroleum liquids have been made (Fig. 1). It is an asymmetric structural basin that existed as a structural and depositional basin from the Early Pennsylvanian through the Early Permian (Broadhead and King, 1988). The Tucumcari Basin is bounded on the north by the Sierra Grande uplift and on the northeast by the Bravo dome. Both were emergent highlands that were eroded to their Precambrian cores and supplied sedimentary detritus to adjacent basins during the Pennsylvanian and Early Permian. To the east, the fault-bounded Frio uplift separates the Tucumcari Basin from the Palo Duro Basin of the Texas panhandle. To the south, the Sin Nombre Arch separates the Tucumcari Basin from the Permian Basin (Broadhead et al., 2002). Over both Frio and Sin Nombre uplifts, the Lower and Middle Pennsylvanian sections are absent and the Upper Pennsylvanian section thins, indicating the Pennsylvanian origin of these features as well. A Lower Permian dolomitized carbonate bank complex sits astride the Frio uplift. To the west of the Tucumcari Basin lies the Pedernal uplift, also Pennsylvanian to Early Permian in age.

The Tucumcari Basin is subdivided into several structural elements of Pennsylvanian to Early Permian age (Fig. 39). The southern two-thirds of the basin consist of a gently north-dipping shelf that comes off of the Sin Nombre Arch (Broadhead and Jones, 2002; Broadhead, 2003). Depth to Precambrian basement ranges from 6,000–8,000 ft over most of the shelf. The northern third of the basin is subdivided into a series of fault-controlled elevator basins and intervening uplifts (Fig. 40; Broadhead, 2001a; Broadhead et al., 2002): the Cuervo, Quay, Trementina and Trigg Ranch sub-basins and the intervening Newkirk and Pablo Montoya uplifts (or "highs"). The elevator basins developed during the Pennsylvanian and Early Permian. The Pennsylvanian and Early Permian

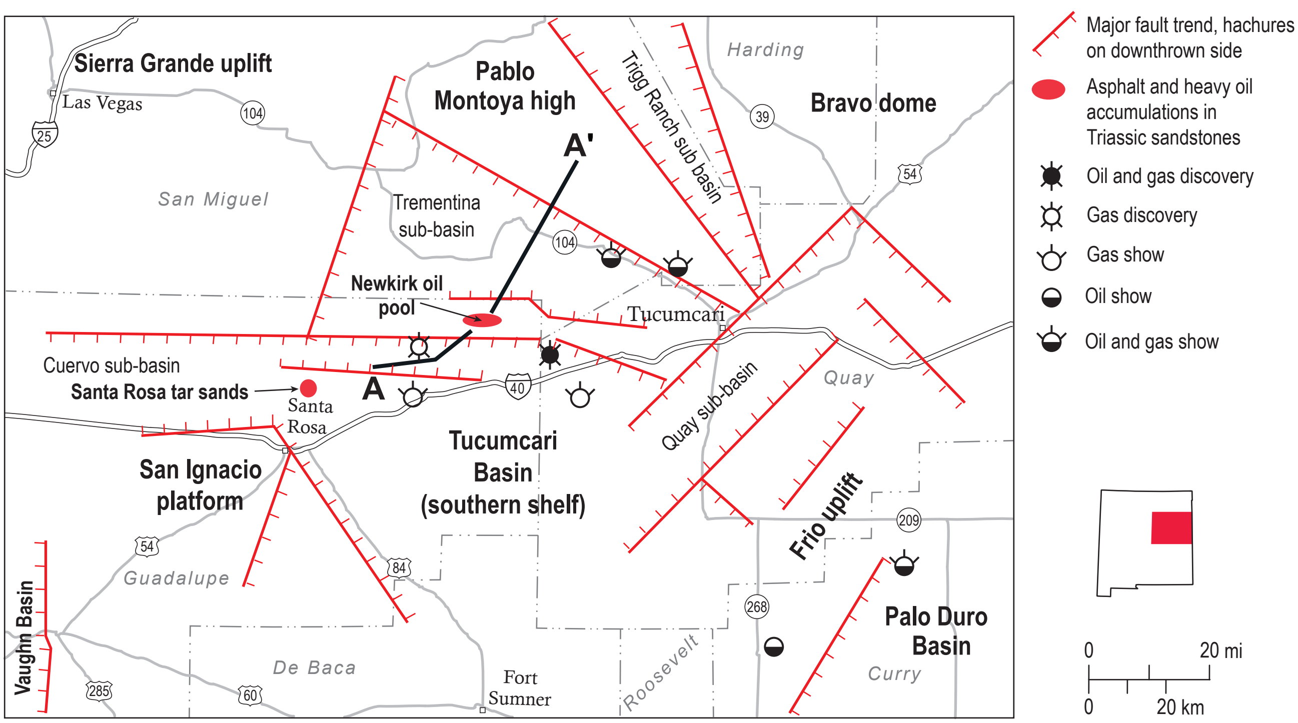


Figure 39. Generalized tectonic map of Tucumcari Basin showing major structural elements, location of heavy oil and asphalt deposits in Triassic sandstones, gas and oil discoveries in Pennsylvanian sandstones, and location of cross section of Figure 40. Modified from Broadhead (2001a).

sedimentary sections are substantially thicker in the basins than on the adjacent uplifts on the shelf to the south. Depth to Precambrian basement exceeds 14,000 ft in the deepest part of the elevator basins. Although most of the sedimentary thickening in the basins is depositional, some is tectonic, resulting from Late Pennsylvanian thrust faulting. Sedimentary fill in the elevator basins consists of arkosic sandstones and conglomerates and interbedded shales derived from erosion of adjacent highlands, especially the Sierra Grande uplift. Fan deltas rimmed the highlands, dumping their sediment load into the basins where the sands were redistributed in a marine environment. The elevator basins were paleobathymetric lows with restricted marine circulation that resulted in reducing conditions in the water column (Broadhead, 2001c). As a result, the Pennsylvanian shales in the basins were enhanced in kerogen content with total organic carbon (TOC) contents ranging from 2–10% (Broadhead et al., 2002; Broadhead, 2001d). This resulted in interbedding of reservoir sandstones and kerogen-rich shales that function as both source rocks and seals over several thousand feet of section in the deeper parts of the elevator basins. To the south on the shelf, temporally equivalent sediments are interbedded finer-grained sandstones, red to dark-gray shales and marine limestones with maximum TOC contents in the shales of 2%. Deeper burial has led to enhanced thermal maturity in the elevator basins and the Pennsylvanian source rocks are within the thermogenic gas window in the deeper parts. On the shelf, source rocks are within the oil window and are thermally immature in some of the structurally shallowest areas. Kerogens are generally a mixture of oil- and gas-prone types that generated oil and associated gas upon maturation.

Several exploratory wells drilled since the 1950s have encountered encouraging shows of oil and natural gas in Pennsylvanian strata. Most shows are in sandstones located within the elevator basins (Broadhead, 2001a; Broadhead et al., 2002; Broadhead and King, 1988). Of exploratory wells that indicate commercial potential (Fig. 39), those in shallower parts of the elevator basins have recovered oil or gas with natural gas liquids. Wells in deeper parts of the elevator basins have recovered dry gas. In addition, recent exploratory wells have encountered gases with concentrations of helium exceeding 1%, rendering increased value and interest to the undeveloped and underexplored gas resource within the basin.

Two major shallow accumulations of asphalt and heavy oil are known to exist in the Santa Rosa Sandstone: the Santa Rosa tar sands and the Newkirk oil field (Fig. 39). The Santa Rosa tar sands crop out 7 miles north of Santa Rosa (Winchester, 1933; Gorman and Robeck, 1946). The fluvial Santa Rosa sandstones are impregnated with asphalt with an API gravity of 5º. Oil in place is estimated at 91 million bbls (Budding, 1980). The heavy asphaltic nature of the hydrocarbons is thought to be due to post-emplacement biodegradation and a relatively low maturity level of the source rock (Budding, 1980; Budding and Broadhead, 1987). Chemical analyses of the asphalt indicate a dominance of marine over terrestrial kerogens, and carbon isotopes are suggestive of either a Permian or Pennsylvanian source. The underlying limestones of the San Andres Formation (Permian) have long been considered to be a source of the asphalt (Gorman and Robeck, 1946; Budding, 1980). However, San Andres source facies in the area are thin, organically lean, and thermally immature in the areas around the tar sands, but deeper, thermally mature, organic-rich shales in the Pennsylvanian section could provide the oil source (Broadhead, 2001a, d; Broadhead et al., 2002). If this is the case, migration paths are Pennsylvanian to Early Permian faults that formed the elevator basins and were reactivated during Laramide compression and post-Laramide Tertiary extension. The reactivated faults penetrated the post-Early Permian section, but were vertically sealed by the plastic, lacustrine red shales of the Chinle Group, which directly overlie the Santa Rosa Sandstone. These same faults acted as the conduits for the magmas that form a Tertiary-age basaltic dike that crops out one mile northeast of and downdip of the tar sand deposit. The Santa Rosa tar sands were quarried as a source of road-surfacing material from 1930 until 1939 (Winchester, 1933; Gorman and Robeck, 1946). Santa Rosa Lake was formed when Los Esteros dam was built on the Pecos River in 1980 and the lake now covers the tar sand deposit, rendering further development inopportune.

The other major known accumulation of heavy oil in the Santa Rosa Sandstone is the Newkirk oil field. Newkirk was discovered in 1962. At Newkirk, the trap is formed by anticlinal drape of the Santa Rosa over a Pennsylvanian-age horst block that separates the Cuervo sub-basin from the Trementina sub-basin (Figs. 39, 40; Broadhead, 1984b; McKallip, 1984). Depth to reservoirs is 400–800 ft. As with the tar sands, the source may either be limestones of the San Andres Formation, which directly underlie the Santa Rosa Sandstone, or the oil source may be the organic-rich Pennsylvanian shales in the elevator basins to the north and the south of the Newkirk structure. Limitations on the San Andres as a source

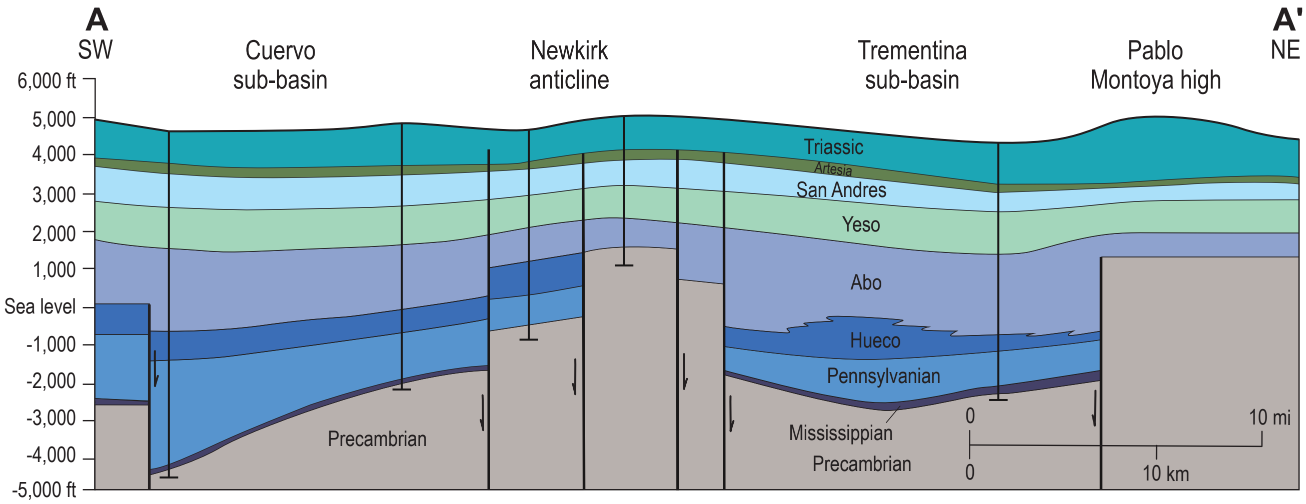


Figure 40. Structural cross section through Tucumcari Basin showing Ancestral Rocky Mountain paleostructures buried by Lower Permian strata of the Yeso and Abo Formations. See Figure 39 for location. After Broadhead (2001a).

are the same as at the tar sands: thin, organically lean source facies that have low levels of thermal maturity (Broadhead et al., 2002). The off-structure Pennsylvanian shales, on the other hand, are mature and within the oil window and are organically rich. Kerogen content is especially high in the Trementina sub-basin where present-day, post-maturation TOC is everywhere more than 2% and approaches 10% over large parts of the basin (Broadhead, 2001d; Broadhead et al., 2002). Within the San Andres, updip porosity plugging by salt within dolostones resulted in the formation of several mappable porosity pinchouts (Pitt and Scott, 1981). With the San Andres 100–200 ft deep throughout most of the basin and 500–1,000 ft thick, these pinchouts are shallow exploration targets that will be of most interest when located updip of areas where the San Andres has maximum thermal maturity and maximum TOC.

Tom L. Ingram No. 1 Gihon well drilling in the San Miguel County part of the Tucumcari Basin, March 1988. The late geologist Jack Ahlen in foreground. *Photo by Ron Broadhead*.

IX. DALHART BASIN

The Dalhart Basin of the Texas panhandle protrudes into the eastern part of Union County, northeastern New Mexico (Figs. 1, 2). The Dalhart Basin is productive of oil and natural gas in Texas (Smith, 1961a, 1961b; Stratigraphic Committee, 1961a, 1961b; Montgomery, 1986). Productive reservoirs in the basin are primarily Late Pennsylvanian to Early Permian arkosic sandstones ("granite wash") deposited in fan delta and coastal settings (Walker, 1993) and Late Pennsylvanian to Early Permian limestones deposited as carbonate banks (Montgomery, 1986). The granite washes were derived by erosion of the exposed uplifts that encircled the basin, including the Bravo dome and Sierra Grande uplift during the Pennsylvanian and Early Permian (McCasland, 1980). The portion of the Dalhart Basin that protrudes into New Mexico contains at least one deep elevator basin that is infilled with more than 4,000 ft of interbedded arkosic sandstones, conglomerates and shales. Black-organic-rich shales as well as thin coal beds are present in the lower part of the Pennsylvanian section in the New Mexico part of the Dalhart Basin.

In places, the basal part of the Pennsylvanian section rests unconformably on Precambrian basement. In other places, such as in the Texaco No. 1 Cruz well in northeastern Union County, 460 ft of Ordovician strata rest on basement and are in turn unconformably overlain by 362 ft of Mississippian strata (Fig. 41). The Ordovician section consists predominantly of marine dolostones, minor greenish-colored shales, and a basal conglomerate or sandstone derived from the underlying Precambrian. Ordovician strata are truncated to the west by the Mississippian section that, in turn, is truncated further to the west by the base of the Pennsylvanian section that unconformably overlies basement west of the Mississippian pinchout (Baldwin and Muehlberger, 1959). Given this overlapping arrangement of strata, multiple possibilities exist for unconformity traps along the western margin of the Dalhart Basin. Karstic enhancement of porosity beneath the unconformities at the top of the Ordovician and the top of the Mississippian seems likely. Petroleum source facies include the organic-rich strata in the lower part of the Pennsylvanian as well as a basal Mississippian shale that overlies the Ordovician. This shale would also act as a seal for underlying Ordovician reservoirs. Limited data suggest maximum thermal maturity in the New Mexico part of the Dalhart Basin is within the upper part of the oil window.

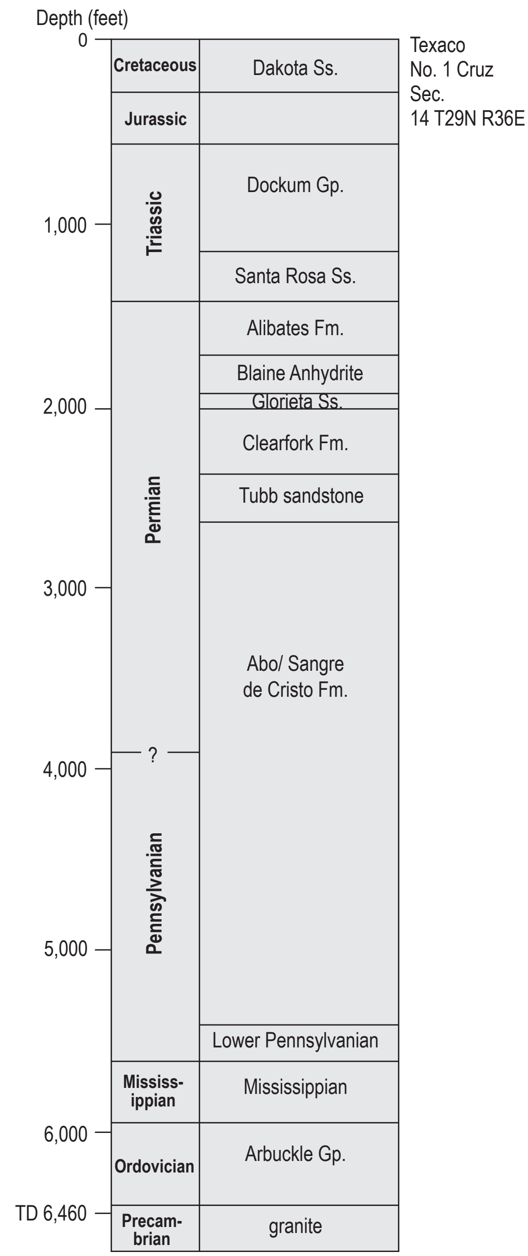


Figure 41. Stratigraphic profile of Texaco No. 1 Cruz well, Dalhart Basin.

View across Estancia Basin looking west. Laguna del Perro in foreground and Manzano Mountains on skyline. The late Chewy in foreground. *Photo by Ron Broadhead*.

X. ALBUQUERQUE AND ESPAÑOLA BASINS

The Albuquerque and Española Basins are north-south aligned segments of the Rio Grande rift (Figs. 1, 2). The basins are bounded by normal faults that formed during Tertiary extension that accompanied rifting (Fig. 42).

The Albuquerque Basin contains a thick fill of terrestrial and lacustrine Tertiary-age sands, gravels and clays more than 20,000 ft thick in some places. This fill reflects the history of Late Tertiary faulting, subsidence, and sedimentary infilling of the basin. Beneath the Tertiary sediments are 5,000 ft of Cretaceous strata similar in overall aspect to the Cretaceous section that is so prolifically productive in the San Juan Basin. The Cretaceous rests on 300–1,100 ft of Jurassic terrestrial sandstones and variegated shales; the thin lacustrine Todilto Limestone overlies the eolian Entrada Sandstone at the base of the Jurassic. The Jurassic rests on 400–1,200 ft of fluvial to lacustrine sandstones and red shales of the Triassic Chinle Group and Santa Rosa Formation. The Paleozoic section consists of Permian and Pennsylvanian strata; the Pennsylvanian rests unconformably on Precambrian basement in most places although thin erosional remnants of Mississippian carbonates may be locally present. The Permian section, 600–2,500 ft thick, consists of (descending): the marine San Andres Limestone, the marginal marine quartzose Glorieta Sandstone, marginal marine to shallow marine, evaporitic orange sandstones, shales and gypsum/anhydrite of the Yeso Formation, and the red fluvial sandstones and shales of the Abo Formation. The Pennsylvanian section consists of marine, deltaic and fluvial limestones, sandstones, conglomerates, and shales of the Madera Group and Sandia Formation (Myers, 1982). Depth to Precambrian basement may be as great as 30,000 ft in the deepest parts of the Albuquerque Basin.

Exploratory drilling in the basin dates to 1912. Early drilling efforts were sporadic. Most of the early wells were drilled to depths of less than less than 5,000 ft and, except where located on upthrown fault blocks on the basin margins, reached total depth in Tertiary basin fill. Then in 1953 the Humble No. 1 Santa Fe Pacific well was drilled in the west-central part of the basin to a total depth of 12,691 ft. The base of Tertiary fill/top of Cretaceous was encountered at a depth of 9,930 ft. This well marked

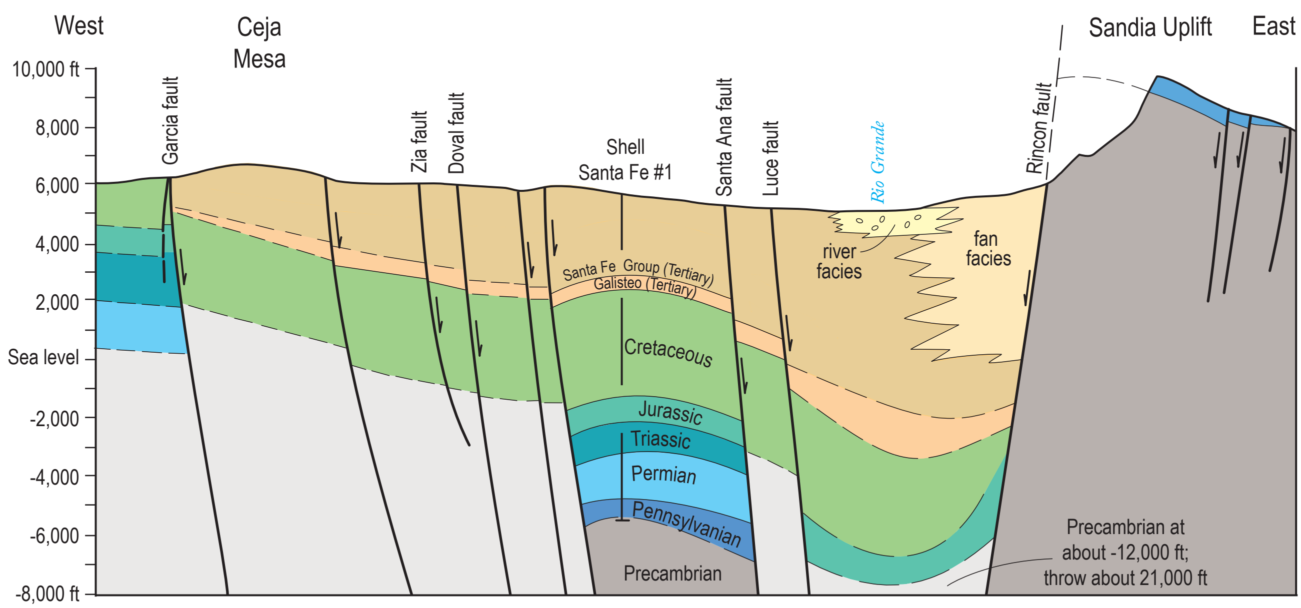


Figure 42. West-east structural cross section through the Albuquerque Basin showing distribution of strata and major structures. Cretaceous strata (shown in green) are the major targets for natural gas exploration in the basin. From Broadhead (2009c) after Kelley (1977).

the beginning of modern exploration in the basin and provided the first geologic information on the great depth, deep structure, and rift origin of the basin. However, it wasn't until 1972 that the next well was drilled in the basin.

During the 1970s and early 1980s, the first sustained exploratory effort was conducted in the Albuquerque Basin. This resulted in the drilling of nine deep wells by Shell Oil Company and its partners (Black, 1982, 1999a; Broadhead, 2009c). While no production was established, gas shows were encountered in Cretaceous sandstones in several of the wells. Geologic data obtained from these nine wells led to a much better geologic understanding of the basin and its petroleum potential. These new wells provided the foundation for all subsequent exploratory efforts. Wells subsequently drilled within the Albuquerque Basin have primarily pursued Cretaceous targets at the northern and southern ends of the basin and along the western flank. On the west side of the basin, targets, including coals, are shallower. Although gas shows have been reported, no production has been established.

Primary targets in the Albuquerque Basin are Cretaceous sandstones with interbedded organic-rich shales providing both seals and source rocks. In shallower parts of the basin, which are mostly located near the edges on shallower fault blocks, the Cretaceous shales are thermally immature, but in the deeper central parts of the basin the shales are fully mature and are within the thermogenic gas window. Deeper objectives in the Paleozoic may hold interest as well. The dark-gray Pennsylvanian shales may be gas source rocks, and limited data suggest that there are favorable organic-rich source facies in the Yeso Formation (Permian), as well. Permian and Pennsylvanian sandstones are potential reservoirs. Traps are most likely to be structural and associated with the block faults that form the rift. Where thermally mature, thicker sections of Cretaceous shales may be shale gas targets.

The Española Basin is a right-relayed offset of the Rio Grande rift (Kelley, 1982). In the northern and central parts of the basin, Tertiary basin-fill sediments consisting of sandstones, conglomerates and clays are exposed at the surface. Drilling has been sporadic and mostly concentrated at the southern end of the basin where primary targets are Cretaceous strata. Cather (1992) reported that Tertiary sediments rest on Precambrian basement in the central part of the basin but to the south the Tertiary rests on a thick section of Mesozoic strata that in turn overlie Permian and Pennsylvanian sedimentary units. The southern end of the basin wraps around the eastern edge of the Sandia Mountains and has been referred to as the Hagan embayment (Black, 1979, 1999b). In this area, Cretaceous, Jurassic, and Triassic sedimentary rocks crop out at the surface and dip northward into the Española Basin.

Several exploratory wells have been drilled in the Hagan embayment. Oil and gas shows have been encountered in sandstone intervals within the Mancos Shale, the Dakota Sandstone (Upper Cretaceous), and the Entrada Sandstone (Jurassic). One well, the Black Oil No. 1 Ferrill, was completed as an oil producer during 1985. It has since produced a cumulative 880 bbls oil from a 20 ft thick basal Niobrara sandstone at 2,740 ft. The oil was light with a gravity of 48° API. Although this single well may not have been commercial, it demonstrated the presence of thermally mature oil source rocks within the Niobrara section. With fine grain size and relatively low permeability, basal Niobrara sandstones may be opportunities for horizontal wells.

XI. ESTANCIA BASIN

The Estancia Basin of central New Mexico is a temporally hybrid basin. On the west, it is separated from the Albuquerque Basin by the Manzano Mountains (see Preface, Fig. 1), a boundary that formed during the Tertiary. The eastern edge of the basin is formed by the fault-bounded Late Paleozoic Pedernal uplift of the Ancestral Rocky Mountains. To the north, a structurally high divide of both Late Paleozoic and Tertiary age separates the Estancia Basin from the Española Basin. To the south, the Estancia Basin transitions to Chupadera Mesa, a broad tectonic upland. The eastern flank of the Estancia Basin developed during the Pennsylvanian as the Pedernal uplift rose out of the shallow Pennsylvanian sea. During most of the Pennsylvanian, central New Mexico was covered by a shallow marine shelf. As the Pedernal uplift rose, its exposed Precambrian core was eroded, shedding sedimentary debris to the east and the west. The resulting sedimentary rocks were sandstones, conglomerates, and shales deposited off the flanks of the uplift. Further away on shelf areas, thick sequences of marine limestones were deposited and became interbedded with the clastic sediments derived from the uplift.

Deep fault-bounded grabens referred to as elevator basins formed adjacent to many of the Ancestral Rocky Mountain uplifts (Broadhead, 2001a). The Perro sub-basin is an elevator basin within the Estancia Basin that formed along the western flank of the Pedernal uplift during the Early Pennsylvanian (Fig. 43; Barrow and Keller, 1994; Broadhead, 1997). As the Perro sub-basin subsided, it was infilled with a thick section of shales and feldspathic sandstones derived from erosion of the Pedernal uplift. The basin fill consists of dark-gray, organic-rich shales, organic-poor red shales, white to gray sandstones and minor coals (Fig. 44; Broadhead, 1997). The basin fill is mostly Morrowan to Atokan (Early Pennsylvanian). Morrowan (earliest Pennsylvanian) strata are absent from the shelf to the west. A maximum of 300 ft of Atokan strata are present on the western shelf. Pennsylvanian strata on the shelf to the west consist of cyclically deposited marine limestones, gray shales, red shales, sandstones,

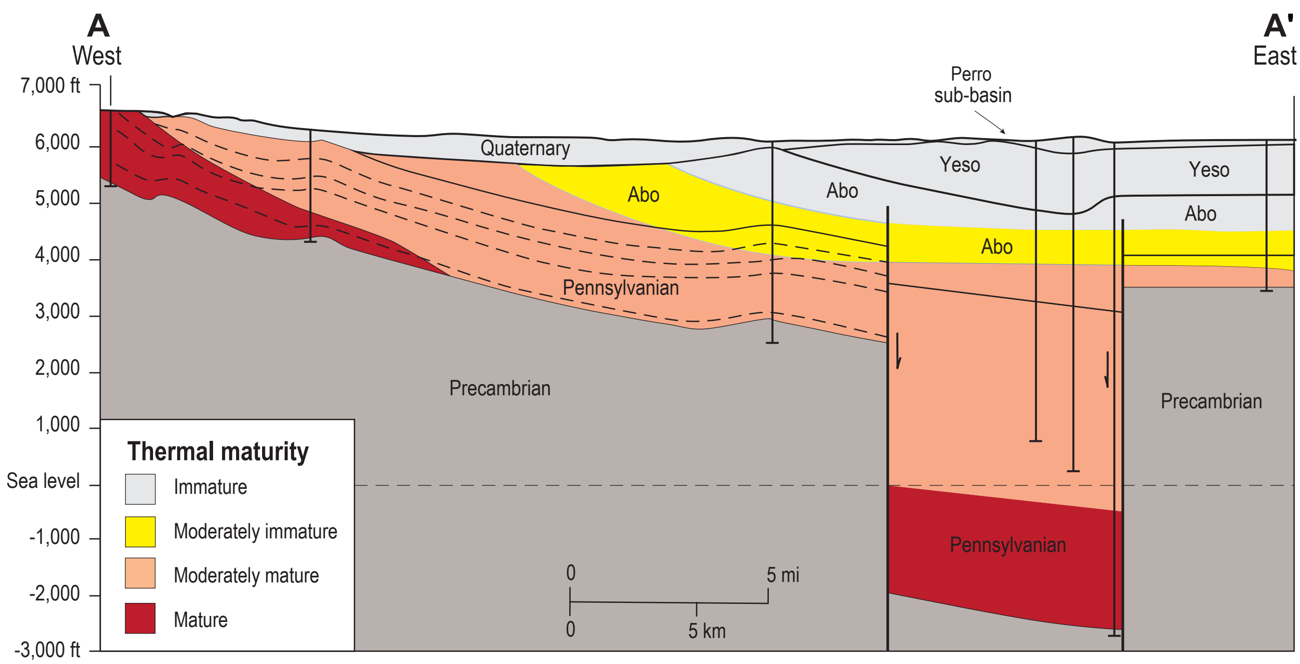


Figure 43. West-east structural cross section through Estancia Basin showing thermal maturity windows. See Figure 44 for location. After Broadhead (1997).

conglomerates, and minor coal. Apparently, the rapidly subsiding Perro sub-basin acted as a trap for sediment washed off the Pedernal uplift. The present form of the Estancia Basin was acquired during the Tertiary when, along with the formation of the Rio Grande rift, the Manzano Mountains were formed and Paleozoic strata on the western flank of the basin were turned upward to the west where they are truncated at the outcrop in the Manzano Mountains (see Karlstrom and Pazzaglia, 1999).

The dark-gray, organic-rich Pennsylvanian shales are petroleum source rocks in the Estancia Basin. Source rocks are not present in post-Pennsylvanian strata (Broadhead, 1997). Total organic carbon (TOC) is highest within the dark-gray shales in the Perro sub-basin, exceeding 2.5% in some stratigraphic intervals. Elevated TOC was associated with anoxic bottom conditions that existed in bathymetrically low areas within the Perro sub-basin (Broadhead, 2001b). Interbedded coals will have generated gas upon maturation. Kerogens in Pennsylvanian shales within the Perro sub-basin are woody gas-prone types, and kerogens on the shelf to the west of the sub-basin are a mixture of herbaceous and amorphous-sapropelic oil-prone and woody gas-prone types. The kerogens are mature and have generated gas within the deeper parts of the Perro sub-basin (Fig. 43). On the eastern deeper part of the shelf, maturation is insufficient for major petroleum generation. Maturation increases westward on the shelf and the lower part of the Pennsylvanian section is within the oil window on the eastern flank of the Manzano Mountains despite the shallower burial depths. The westward increase in maturation may be associated with proximity to higher heat flows within the rift (see Reiter et al., 1975).

Hydrocarbons shows are well documented within the Pennsylvanian section in the Estancia Basin. Most shows are within the Perro sub-basin in association with the mature shales. On the shelf, shows of CO_2 are common.

Two small accumulations of CO_2 gas are formed by small anticlines near the town of Estancia (Fig. 44; Anderson, 1959; Broadhead, 1997). These were produced from 1934 until 1942; the CO_2 was converted to dry ice and bottled liquid. The source of the CO_2 is enigmatic. It may be associated with liberation of CO_2 when influent fresh groundwater dissolves the limestone aquifers on the eastern flank of the Manzano Mountains. Alternatively, the CO_2 may have originated from the degassing of rising magmas

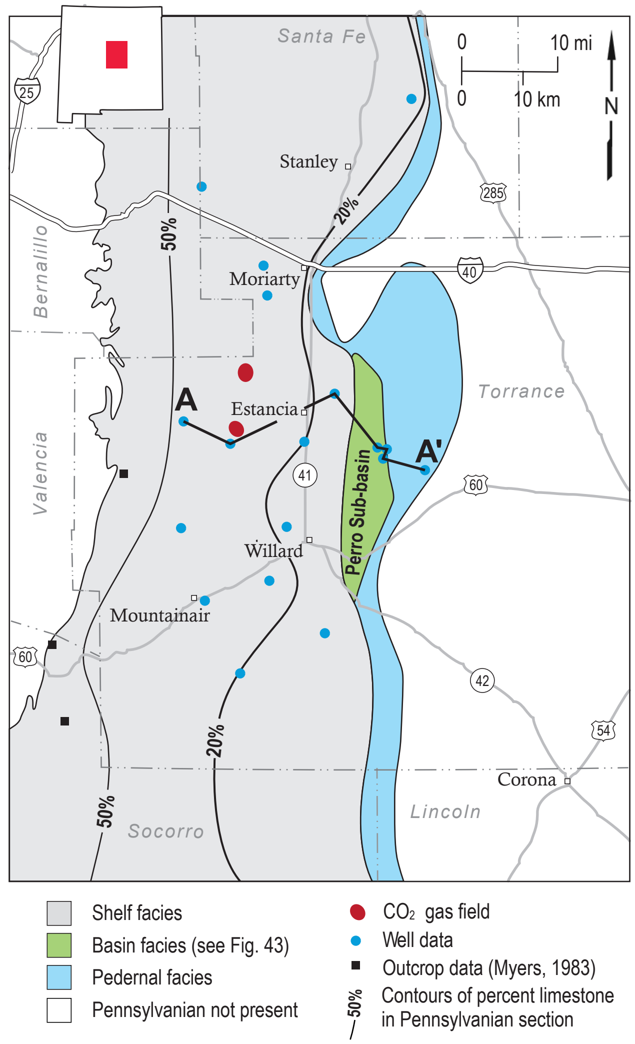


Figure 44. Map of Estancia Basin showing lithofacies of Pennsylvanian strata and location of CO_2 gas fields. Cross section A-A' is shown in Figure 43. After Broadhead (1997).

that form Tertiary dikes and sills that are found in the basin. These igneous bodies crop out in the southern part of the basin (Bates et al., 1947).

Primary petroleum potential in the Estancia Basin is for hydrocarbon gas in the Perro sub-basin. The sandstones that are interbedded with the shale and coal source rocks are attractive targets (Broadhead, 1997). The thick shale sections with their load of gas-prone kerogen may have shale-gas possibilities. The shelf area to the west with its lower thermal maturity appears to be characterized by CO_2 in a water-saturated system. Pennsylvanian shales enter the oil window on the western margin of the basin. In this area, reservoirs are flushed with recharge of fresh water from outcrops in the mountains.

XII. CHUPADERA MESA AND SIERRA BLANCA BASIN

The Chupadera Mesa region encompasses several diverse geomorphic elements including Chupadera Mesa, the Oscura Mountains, and the Sierra Blanca Basin (Fig. 45). Several isolated mountain ranges in the eastern part of the area were formed principally by exhumed Tertiary-age igneous bodies. Chupadera Mesa is a broad upland bordered on the west by the northern part of the Jornada del Muerto Basin. The upper Paleozoic stratigraphic section thins eastward as Permian strata onlap the Pedernal uplift, a north-south trending tectonic highland that was part of the Ancestral Rocky Mountains (Fig. 46). Pennsylvanian strata thin eastward and are erosionally truncated by an unconformity at the base of the Permian. On the Pedernal uplift, the Pennsylvanian is absent, and the Abo Formation (Permian: Wolfcampian) rests on Precambrian basement.

Several petroleum exploration wells have been drilled in the region, principally to test surface anticlines (Fig. 45). The nature of the Prairie Springs and Oscura anticlines and the Torres syncline is in doubt due to the absence of wells in the synclinal areas; the geometry of these structural features is known from surface geology. Cather (2009) concluded that much of the structural relief on the Prairie Springs and Oscura anticlines is due to intraformational tectonic thickening of the Yeso Formation related to detachment faulting along evaporate beds. If this is the case, then the two anticlines and the intervening syncline may be rootless and the structures so prevalent at the surface may not be present in sub-Yeso rocks.

Oil and gas shows were recorded in exploratory wells drilled on the Oscura anticline, a north-plunging extension of the Oscura mountain block. Note that Cather (2009) refers to the Oscura anticline as the Chupadera anticline. These shows indicate that oil and gas migrated through the area. Unfortunately, the structure has been breached by Cenozoic erosion on its southern up-plunge part. Source rocks on Chupadera Mesa are restricted to dark-gray marine shales in the Lower Pennsylvanian. These rocks contain more than 1% TOC and more than 2%

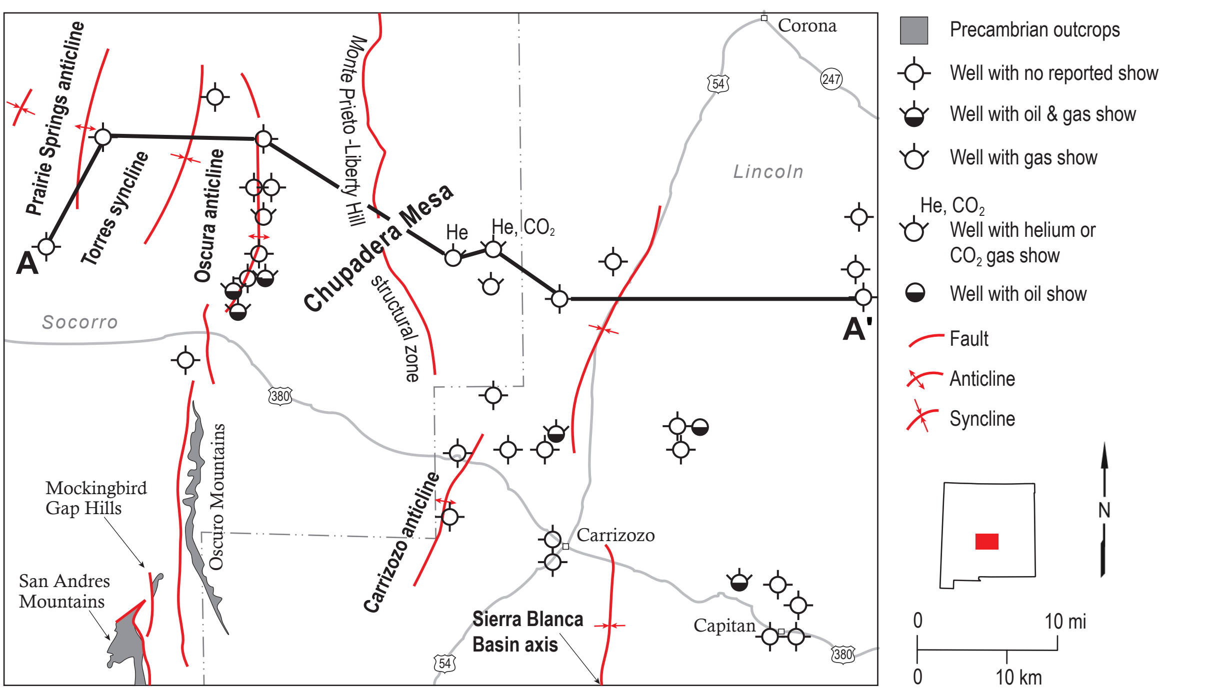


Figure 45. Chupadera Mesa area showing major structural features visible at the surface and exploratory wells with oil, natural gas, CO_2 and helium shows. Cross section A-A' is shown in Figure 46. After Broadhead (2009d).

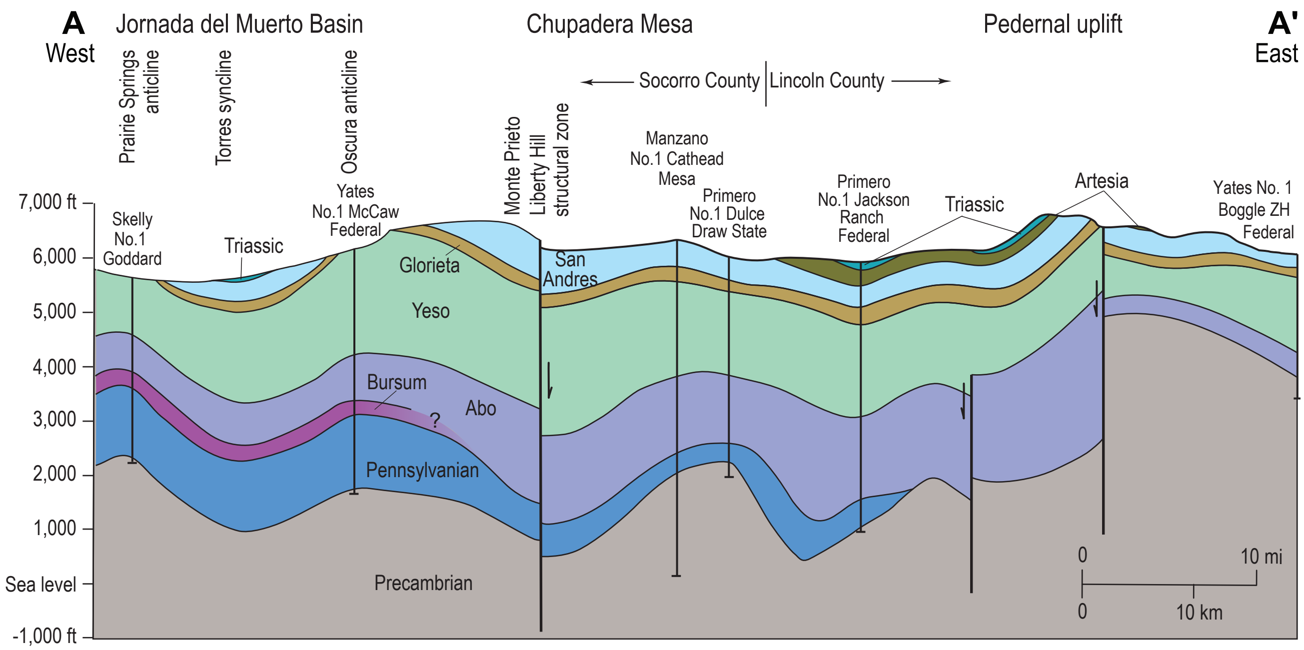


Figure 46. West-east structural cross section through Chupadera Mesa region, showing major tectonic elements and eastward truncation and pinchout of Pennsylvanian strata. From Broadhead (2009d).

TOC in some stratigraphic intervals (Broadhead and Jones, 2004; Broadhead, 2009d), amounts sufficient for petroleum generation. Other shallower, younger parts of the stratigraphic section do not contain sufficient organic matter for petroleum generation except perhaps in thin, discontinuous stratigraphic intervals. Thermal maturity is marginal in the vicinity of the Oscura anticline, but increases into the upper part of the oil window to the east and to the west of the anticline (Broadhead, 2009d). The maturity increase to the east may be due to high paleo-heatflows associated with the numerous, large Tertiary intrusive bodies. The maturity increase to the west may be due to higher paleo-heatflows associated with the Rio Grande rift.

There is modest coalbed methane potential in the Sierra Blanca Basin. A maximum of approximately 2,000 ft of Upper Cretaceous strata have been preserved in this Laramide downwarp. The Crevasse Canyon Formation in the upper part of the Cretaceous section contains lenticular coals, most of which are less than 2 ft thick. In general, the thin, discontinuous nature of the coals and low thermal maturity within the biogenic gas window limits coalbed methane potential (Broadhead and Jones, 2004). However, coal rank increases near igneous intrusive bodies (Sidwell, 1946), suggesting that areas of thermogenic gas generation may be present near the larger intrusive bodies.

Chupadera Mesa is a favorable setting for helium gas. Although production has not been established, helium-rich and CO_2-rich gases have been recovered from Permian reservoirs by recently drilled wells (Fig. 45). The gases are mostly N_2 and CO_2, contain almost no hydrocarbons, and have helium contents between 2.5–3.4%. These gases have the highest known concentrations of helium in New Mexico, except for the mostly depleted helium fields on the Four Corners Platform (see Broadhead and Gillard, 2004). Isotopic composition of the helium suggests a mixed crustal and mantle genesis (Broadhead, 2009d). The transport mechanism for the mantle-derived fraction is enigmatic, but the helium may have migrated into the shallow crust via the Liberty Hill–Monte Prieto structural zone (Fig. 45; note that Cather, 2009, refers to this structural feature as the Chupadera fault). Alternatively, the mantle fraction of the helium may have been transported to the shallow crust by the magmas that formed the Tertiary-age igneous rocks in the region. The crustal fraction of the helium came from radiogenic decay of uranium, thorium, and radium-bearing minerals in granitic rocks of the Precambrian basement and also possibly from the arkosic sandstones that are present in the Abo and Yeso Formations. The CO_2 may have come from degassing of the rising magmas that formed the large igneous intrusive bodies in the region.

XIII. SOUTHERN RIFT BASINS

The Palomas and Mesilla Basins sit astride the southern part of the Rio Grande River in south-central New Mexico. They formed as a result of Tertiary extension that also formed other basins in the Rio Grande rift system. Both basins are bounded on their east and west sides by high-angle normal faults that separate the basins from adjoining uplifts. To the east lie the Jornada del Muerto (Spanish for "Journey of Death") and Tularosa Basins, also formed as a result of Tertiary extension and faulting associated with the Rio Grande rift (Hawley and Seager, 1978).

Palomas Basin

The Palomas Basin is a half graben that dips eastward and is bordered on its eastern side by a west-dipping listric normal fault (Fig. 47; Lozinsky, 1987; Adams and Keller, 1994). For purposes of this discussion, the Engle Basin is considered to be a part of the Palomas Basin. The basin has been sparsely drilled with only five wells, mostly located on uplifted blocks. Wells have encountered 1,000–2,500 ft of Tertiary sands, gravels and clays unconformably overlying 200–1,600 ft of Cretaceous marine to nonmarine shales and sandstones. The Cretaceous section rests on 300–700 ft of San Andres Limestone (Upper Permian) which is, in turn, underlain by 800–1,600 ft of shallow-marine Yeso Formation (Permian: Leonardian) and 900–1,200 ft of terrestrial Abo red beds (Permian: Wolfcampian). The Abo rests on 1,500–3,000 ft of Pennsylvanian marine strata, which, in turn, unconformably overlie 800 ft of Montoya and El Paso (Ordovician) shallow-marine carbonates. The Ordovician rests unconformably on Precambrian basement. Possible petroleum source rocks are dark-gray to black Mancos shales (Upper Cretaceous), fetid dark-gray deeper-water limestones in the San Andres, and dark-gray carbonaceous marine to deltaic shales within the Pennsylvanian. Sparse petroleum source rock analyses indicate that the Cretaceous is within the oil window. Therefore, underlying Paleozoic source beds should also be mature. Thick Tertiary monzonite dikes and sills penetrated by wells probably provided local enhancement of thermal maturity. Reservoir targets include Cretaceous, Permian and Pennsylvanian sandstones as well as Permian, Pennsylvanian and Ordovician carbonates. Potential is tempered by the extensional rift-related deformation which may have resulted in the fracturing of seals, especially in the brittle carbonate sections.

Jornada del Muerto Basin

The Jornada del Muerto Basin (Fig. 1) lies east of the Palomas Basin. The two basins are separated by the Fra Cristobal and Caballo Mountains, uplifted and east-tilted upthrown fault blocks bordered on their west sides by normal faults. The east-side of the Jornada del Muerto Basin is formed by the west-tilted upthrown fault block of the San Andres Mountains, although along the northeastern flank the structure changes to the east-tilted fault block that forms the Oscura Mountains. The northern limit of the basin is formed by a gentle south-plunging syncline that gently rises northward onto Chupadera Mesa. As a whole, the basin takes on the form of a doubly plunging syncline (Gilmer et al., 1986). The basin has been only sparsely drilled because of its remote location and difficult access. The eastern half of the basin became part of White Sands Proving Ground (now Missile Range) during World War II, and leasing and exploration are not permitted in this area.

Within the Jornada del Muerto Basin, maximum thickness of Cenozoic fill varies from almost 12,000 ft in the south to less than 4,500 ft in the north (Harder et al., 1986). Maximum drilled depth to Precambrian is 11,604 ft in the south-central part of the basin in the Exxon No. 1 Prisor Federal well of southern Sierra County (Sec. 20, T16S, R1E). Precambrian marks the base of the prospective section and consists mostly of crystalline rocks with a veneer of schists, quartzites, and meta-arkose locally present (Foster, 1978). The Precambrian is overlain by 15–110 ft of Bliss Sandstone (Cambrian–Ordovician); 300–1,100 ft of dolostones, limestones, and minor sandstones of the El Paso and Montoya Formations (Ordovician);

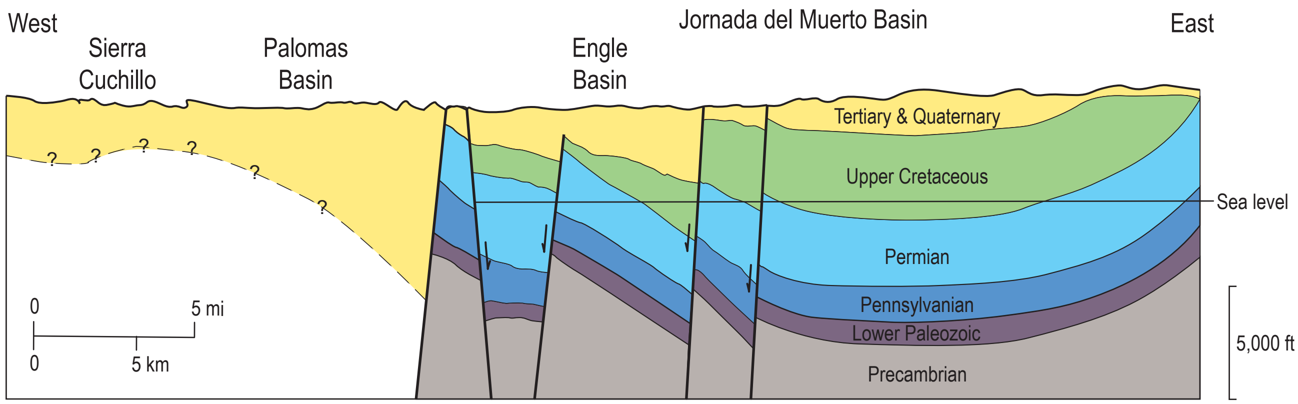


Figure 47. West-east structural cross section of Palomas and Jornada del Muerto Basins. Simplified from Lozinsky (1987).

0–300 ft of Fusselman dolostones (Silurian); and 70–150 ft of Middle to Upper Devonian brown to black marine shales and minor sandstones that are, in turn, overlain by up to 100 ft of Mississippian limestones and marine shales.

A thick Pennsylvanian section rests unconformably on the Mississippian limestones. In the Jornada del Muerto Basin, the Pennsylvanian section is 1,700–2,500 ft thick and ranges in age from Morrowan (Early Pennsylvanian) to Virgilian (Late Pennsylvanian; Foster, 1978). Pennsylvanian strata consist of complexly interbedded sandstones, conglomerates, shales, limestones, and minor anhydrite. They represent a synorogenic record of the uplift of the Ancestral Rocky Mountains and subsidence of adjacent basins. The limestones locally bear bioherms.

The Pennsylvanian is overlain by 2,500–3,000 ft of Lower Permian strata composed of (ascending): Bursum Formation, Abo Formation, Yeso Formation. The Bursum Formation is a transitional sedimentary package between the dominantly marine Pennsylvanian section and the overlying fluvial red sandstones and shales of the Abo Formation. In the southern part of the basin, the Abo intertongues with marine limestones of the Hueco Formation, which are in places representative of high-energy environments and were deposited in reefal settings. The Abo and Hueco Formations are overlain by the Yeso Formation, which is 1,200–1,500 ft thick. The Yeso is composed of orange to red sandstone and shale, limestone, dolostone and anhydrite deposited in shallow marine and marginal marine environments. The Yeso is overlain by 500–800 ft of San Andres dolostones and dolomitic limestones. In the northern part of the basin, 25–80 ft of marginal marine to shallow marine Glorieta Sandstone separates the San Andres and Yeso formations.

Triassic strata consist of the fluvial Santa Rosa Sandstone and the overlying red lacustrine shales of the Chinle Group. They are present only in the northern part of the Jornada del Muerto Basin where they have a maximum thickness of 200 ft.

Cretaceous strata unconformably overlie the Chinle shales. The Cretaceous section is 900–3,600 ft thick (Foster, 1978). The Cretaceous thins to the north as it rises out of the basin and is beveled by overlying Tertiary valley fill deposits. The Cretaceous section consists of the basal sandstones and shales of the Dakota Sandstone, the overlying dark-gray marine Mancos shales, and on top, the Mesaverde Group that consists of up to 450 ft of paralic marine to nonmarine sandstones, marine to nonmarine shales, and minor thin coals.

The Jornada del Muerto Basin is overall a simple synclinal feature (Gilmer et al., 1986). In the southern part of the basin, the intrabasinal Rio Grande uplift is buried underneath the Tertiary basin fill (Keller et al., 1986). This uplift is a Laramide-age basement-cored feature formed by a north-directed thrust fault (Seager et al., 1986). Although Mesozoic and Paleozoic strata appear to have been eroded from the top of the uplift, they are present in the downthrown block north of the thrust fault.

The Jornada del Muerto Basin has thus far been nonproductive. Shows of oil and gas have been encountered in Middle Pennsylvanian and Upper Cretaceous strata in wells drilled on the western flank of the basin. In addition, other wells have had drill-stem tests run on the Glorieta Sandstone, Pennsylvanian sandstones, and Montoya carbonates, which suggests that shows were encountered but not described in those wells.

The uncomplicated synclinal form of the basin suggests that primary targets will be updip pinchouts in Cretaceous and Paleozoic strata. Subthrust truncations associated with the thrust fault that forms the Rio Grande uplift are also exploratory possibilities. Reconnaissance source rock analyses indicate that stratigraphic units with sufficient organic matter for petroleum generation may include the Mancos Shale (Upper Cretaceous), some of the more organic-rich strata in the Yeso Formation (Lower Permian), and the Upper Devonian shales. Sparse data indicate that a large portion of the pre-Tertiary stratigraphic section is within the thermogenic oil window throughout the Jornada del Muerto and perhaps within the thermogenic gas window along the deeper parts of the basin axis. The marine Mancos shales merit consideration as targets for unconventional oil. In addition, Ordovician dolostones and Cambrian sandstones are truncated by the unconformity at the base of the Pennsylvanian in the northern part of the basin, raising the possibility that hydrocarbons could be trapped in favorable updip locations under the unconformity (Broadhead, 2009c).

Tularosa Basin

The Tularosa Basin (Fig. 1) is the easternmost of the Rio Grande rift basins in southern New Mexico. Similar to the Jornada del Muerto Basin, the Tularosa Basin has been sparsely drilled because all, but a narrow strip a few miles wide on the eastern flank, has been occupied by the White Sands Missile Range since World War II. The Tularosa Basin is bordered on the west by the San Andres Mountains and, to the south of the San Andres Mountains, by the Organ Mountains with their extensive outcrops of Tertiary intrusive rocks. These mountain ranges are formed by west-tilted fault blocks with large, basin-bounding normal faults on their eastern sides. On the northeast the Oscura Mountains, an east-tilted fault block, forms the basin boundary. The east side of the basin is formed by the east-tilted fault block of the Sacramento Mountains. On the southeast, the Tularosa Basin is bordered by Otero Mesa, an uplifted highland separated from the Tularosa Basin by normal faults (Seager et al., 1987). The Tularosa Basin extends southward into Texas where it is known as the Hueco Basin. Tertiary and Quaternary sands and gravels that fill the Tularosa Basin are thought to have a maximum thickness of 9,500 ft in the deepest parts of the basin (Healy et al., 1978). Depth to Precambrian may exceed 18,000 ft along the basin axis.

The Precambrian is overlain by 300–400 ft of Cambro-Ordovician strata consisting of the basal Bliss Sandstone, dolostones of the El Paso Formation, and dolostones and sandstones of the Montoya Formation. The Ordovician is overlain by dark cherty dolostones of the Fusselman Formation (Silurian). Fusselman strata are absent from the northern part of the Tularosa Basin where they were eroded prior to deposition of Devonian sediments but attain a thickness of 470 ft in the southern part of the basin. The Devonian section is 40–120 ft thick and pinches out in the northern part of the basin. It consists of (ascending): sandstones of the Onate Formation; calcareous shales and nodular limestones of the Sly Gap Formation; and the dark-gray to brown, organic-rich Percha Shale. Marine limestones and calcareous shales of the Mississippian System overlie the Percha (King and Harder, 1985). Mississippian limestones include crinoidal grainstones as well as bioherms (Bowsher, 1986). The Mississippian pinches out in the northern part of the basin where it and the Devonian section are erosionally truncated by the unconformity at the base of the Pennsylvanian.

Pennsylvanian strata are 1,500–3,000 ft thick in the Tularosa Basin. Pennsylvanian strata are a sequence of complexly interbedded and cyclic sandstones, conglomerates, shales, and marine limestones that reflect synorogenic deposition associated with uplift of the Ancestral Rocky Mountains, subsidence of associated basins, and eustatic sea level fluctuations. The Tularosa Basin area was occupied by the Orogrande Basin during the Pennsylvanian, and its facies represent deposition of a clastic belt in the east derived by erosion of the Precambrian core of the Pedernal uplift, passing westward into a facies dominated by marine limestones (Kottlowski, 1960a). Phylloid-algal bioherms are evident as well as massive carbonate banks along uplifted fault blocks on the eastern side of the basin (Bowsher, 1986).

Overlying these strata are 2,000–2,500 ft of latest Pennsylvanian to Permian strata consisting of (ascending) Bursum Formation, Abo Formation, Yeso Formation, and San Andres Limestone. The Bursum Formation is Late Pennsylvanian to Early Permian and marks a transition from the dominantly marine environments of the Pennsylvanian to the overlying fluvial red sandstones and red shales of the Abo Formation (Permian: Wolfcampian). The Abo intertongues southward with the marine limestones that constitute the Hueco Formation (Kottlowski, 1965). The Abo and Hueco Formations are overlain by the Yeso Formation (Permian: Leonardian). The Yeso was deposited under shallow marine to marginal marine evaporitic conditions and consists of complexly interbedded fine-grained sandstones, siltstones, red to yellow to gray shales, limestones, dolostones, anhydrite, and minor halite (King and Harder, 1985). Carbonate facies are prevalent in the southern part of the Tularosa Basin.

The San Andres Limestone (Permian:Leonardian to Guadalupian?) overlies the Yeso Formation. These are the youngest Permian strata known to be preserved in the Tularosa Basin. The San Andres is composed of 100–800 ft of marine limestones and dolostones.

Triassic strata unconformably overlie the Permian section. The Triassic is 200–300 ft thick and consists of fluvial to lacustrine sandstones and red shales.

Upper Cretaceous strata overlie Triassic strata. The distribution of Cretaceous strata is poorly understood, but available data indicate they are absent from most of the basin (King and Harder, 1985). The Cretaceous section consists of (ascending) Dakota Sandstone, Mancos Shale, and Mesaverde Group. Laramide (latest Cretaceous to Early Tertiary) upwarping over the area now occupied by the Tularosa Basin resulted in erosion of the Cretaceous section from a large part of the region (Black, 1973). Sparse drilling indicates approximately 1,000 ft of Upper Cretaceous strata are present in the north-eastern part of the Tularosa Basin (see King and Harder, 1985). No wells have been drilled in the western half of the basin to test for the presence of the Cretaceous.

There is significant potential for oil and gas in the Tularosa Basin. Numerous oil and gas shows encountered by the few exploratory wells in the basin indicate that hydrocarbons were generated and migrated into reservoirs in Lower and Upper Paleozoic strata (Foster, 1978; King and Harder, 1985). Significant volumes of gas were tested from Middle Pennsylvanian limestone in the Houston Oil and Minerals No. 1 Lewelling well along the eastern margin of the basin in northernmost Otero County (Sec. 12, T12S, R9E; Foster, 1978; King and Harder, 1985). Possible source rocks with sufficient organic carbon for petroleum generation are the Percha Shale, dark-gray Pennsylvanian shales, and, with their uncertain but limited distribution, Mancos shales. Limestones in the San Andres Formation have a fetid organic-rich facies that may also have suitable source rock characteristics. Reservoir targets include Ordovician and Silurian dolostones with vugular and karsted porosity, and Pennsylvanian sandstones and reefal limestones. Limited data suggest that source rocks are either in the oil window or in the thermogenic gas window throughout a large portion of the basin.

Mesilla Basin

The Mesilla Basin (Fig. 1) is the southernmost rift basin in New Mexico. It straddles the Rio Grande River and is offset to the east from the Palomas Basin. The Robledo and Dona Ana Mountains separate the Mesilla Basin from the Jornada del Muerto Basin to the north. On the east, the basin is separated from the Tularosa Basin by the Organ Mountains in New Mexico and the Franklin Mountains in Texas. To the south, the Mesilla Basin stretches into Mexico.

The Mesilla Basin is formed by a west-tilted graben bounded on its east and west sides by normal faults (Seager et al., 1987). Basin fill consists of up to 15,000 ft of Tertiary sands, conglomerates, clays, and volcanic rocks (Seager et al., 1987). Depth to Precambrian exceeds 22,000 ft in the deeper parts of the basin. Pre-Tertiary strata include up to 1,700 ft of Ordovician dolostones; 300–700 ft of Fusselman (Silurian) dolostones; 200 ft of Upper Devonian Percha shale; 150 ft of Mississippian limestones and shales; and 1,500 ft of Pennsylvanian limestones, shales, and sandstones. Permian strata (ascending) are 3,500 ft of dark-gray marine shales and micritic limestones of the Wolfcampian Hueco Formation, terrestrial red shales and sandstones of the Abo Formation; and shallow-marine dolostones, sandstones, variegated shales, anhydrites and salts of the Yeso Formation. Lower Cretaceous strata overlie Permian strata. These are 1,800–2,700 ft of shales, siltstones, sandstones, and lime mudstones and wackestones of the Hell-to-Finish and U-Bar Formations. Tertiary basin fill rests on the Lower Cretaceous. Details of subsurface stratigraphy are found in Thompson (1982), Thompson and Bieberman (1975), Clemons (1993) and Uphoff (1978).

Considerable petroleum potential exists in the Mesilla Basin despite its complex structure. The sparse exploratory wells have encountered oil and gas shows in Ordovician, Pennsylvanian, and Permian strata. Strata favorable for source rocks include Percha shales, Pennsylvanian and Lower Permian dark-gray shales and micritic basinal limestones, and Lower Cretaceous shales. Favorable units for reservoirs include Ordovician and Silurian dolostones, Pennsylvanian and Permian reefal limestones and sandstones, and Lower Cretaceous sandstones.

XIV. OTERO PLATFORM

The Otero Platform of south-central New Mexico is a wide tectonic upland bordered on the west by the Tularosa Basin, on the north by the Sacramento Mountains, and on the east by the Salt Basin Graben (Fig. 48). To the south in Texas lies the Diablo Platform, an essentially flat and undeformed extension of the Otero Platform (Black, 1976). The western boundary with the Tularosa Basin is formed by a system of north-trending normal faults that are downthrown to the west. The northern part of the Otero Platform is essentially an extension of the Sacramento Mountains, and strata in this area dip gently to the east (Black, 1976). On the east, the Salt basin graben separates the Otero Platform from the uplifted blocks of the Brokeoff Mountains and the Guadalupe Mountains. The Cornudas Mountains, formed by exhumed Tertiary intrusive bodies, sit astride the south-central part of the platform just north of the Texas state line. The Otero Platform has been sparsely drilled, and production has not been established. The western part of the Platform is part of the McGregor Artillery Range, and drilling is restricted in this area, the last well having been drilled in 1954.

The most prominent structural features on the surface of the Otero Platform are en echelon systems of north to northwest trending anticlines (Black, 1973, 1976). Axial fold lengths are 5–20 miles. The folds are thought to have formed during Laramide compression but may also have experienced post-Laramide movement (Black, 1973, 1976).

The subsurface is more complex than the gently folded strata at the surface (Broadhead, 2002). The Laramide surface folds are superimposed on large-scale faulting of Ancestral Rocky Mountain (Pennsylvanian to Early Permian) age. The Ancestral Rocky Mountain structures are dominated by north- to northwest-trending blocks bounded by high-angle

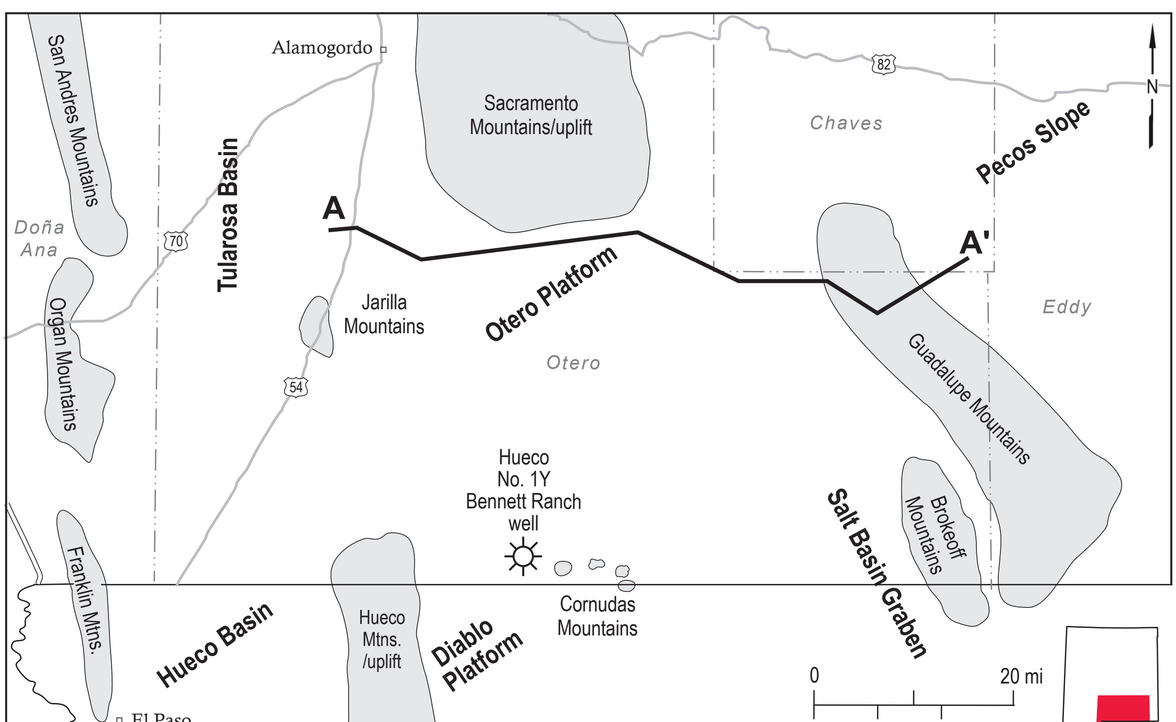


Figure 48. Major tectonic elements at the surface of the Otero Platform and surrounding areas. Cross section A-A' is shown in Figure 49. Modified from Broadhead (2002).

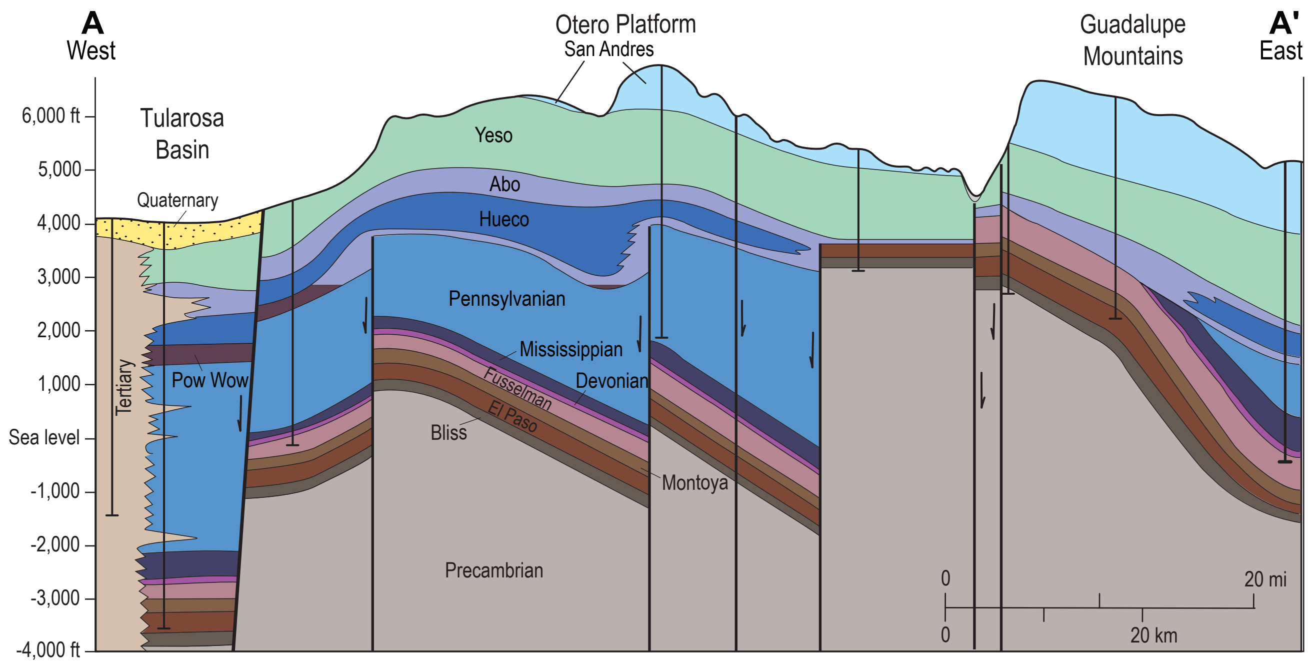


Figure 49. West-east structural cross section through Otero Platform showing complex pre-Permian Ancestral Rocky Mountains structures. See Figure 48 for location. From Broadhead (2002).

normal faults (Fig. 49). These are buried beneath Lower Permian strata of the Hueco, Abo, and Yeso Formations. Distribution of the strata are indicative of fault movement. Ordovician strata are present on all of the horsts as well as in all of the grabens. Silurian, Devonian, and Mississippian strata are present in all of the grabens but eroded from large parts of the horst blocks. Syntectonic Pennsylvanian strata are present within the grabens.

Pennsylvanian strata consist primarily of black, organic-rich lime mudstones of the Panther Seep Formation. They are within the oil window in the grabens where they are mature oil-prone source rocks and contain up to 1.6% TOC. Mississippian marine shales contain up to 3% oil-prone TOC and are within the oil window in the grabens. In the grabens, Devonian black marine shales and black cherts contain up to 3.9% organic carbon and are thermally mature. Source units are thermally immature where preserved over the horst blocks.

Reservoir rocks include Ordovician and Silurian dolostones with vugular porosity, Mississippian limestones, and fractured igneous sills of Tertiary age. The Pennsylvanian section contains mostly basinal limestones, mudstones with minor arkosic sandstones, and carbonate grainstones. Algal bioherms are also present in the Panther Seep Formation (Soreghan and Giles, 2001) and may be preferentially located on intrabasinal positive structural elements. Other possibilities for Pennsylvanian reservoirs include debris flows off the flanks of intrabasinal structures.

Panther Seep limestones are permeable. Exploratory wells have encountered oil and gas shows and have recovered water with drill-stem tests. Cores indicate permeability is provided by dissolution-enhanced vertical to near vertical fractures and not by matrix porosity (Broadhead, 2002).

Natural gas was discovered on the Otero Platform in 1997 by the Heyco No. 1Y Bennett Ranch well (Fig. 48). The primary reservoir is a fractured Tertiary-age igneous sill that intruded Mississippian strata. The enveloping black Mississippian shales apparently provide the source rock and the seals for the sill reservoir. Development and further drilling were inhibited by concerns related to surface occupancy of desert grasslands and by possibilities of contaminating fresh groundwater in naturally fractured Paleozoic aquifers.

XV. SOUTHWESTERN NEW MEXICO

Southwestern New Mexico and adjoining parts of Arizona and Mexico (Fig. 1) have seen four major tectonic episodes (Mack and Clemons, 1988; Clemons and Mack, 1988) that exerted major influence on the petroleum geology of the region. The first episode was Pennsylvanian to Early Permian deformation associated with formation of the Ancestral Rocky Mountains and associated basins. This stage of deformation resulted in subsidence that created the Pedregosa Basin to the south and the Burro, Florida and Moyotes uplifts to the north (Figs. 1, 50). The second episode was Laramide (latest Cretaceous to earliest Tertiary) compressional northeast-directed thrust faulting that resulted in the northwest-southeast trending Burro uplift as well as similarly-oriented thrust sheets separated by Laramide basins. The third episode was Middle Tertiary volcanism and the formation of multiple cauldrons. The fourth episode was Late Tertiary basin-and-range extensional faulting that formed the north-south trending mountain ranges and intermountain basins that dominate the landscape today.

Strata in the region pertinent to petroleum exploration range in age from Cambrian to Early Cretaceous. Paleozoic and Mesozoic strata were once continuous over the entire area but have been eroded from late Paleozoic, Laramide, and Tertiary basin-and-range uplifts. Kottlowski (1963) described Paleozoic and Mesozoic strata in the region, and it is his work that is the basis for most of the following discussion of the stratigraphy of southwestern New Mexico. At the base of the sedimentary section is the Cambro-Ordovician Bliss Sandstone, derived from weathering and erosion of the underlying

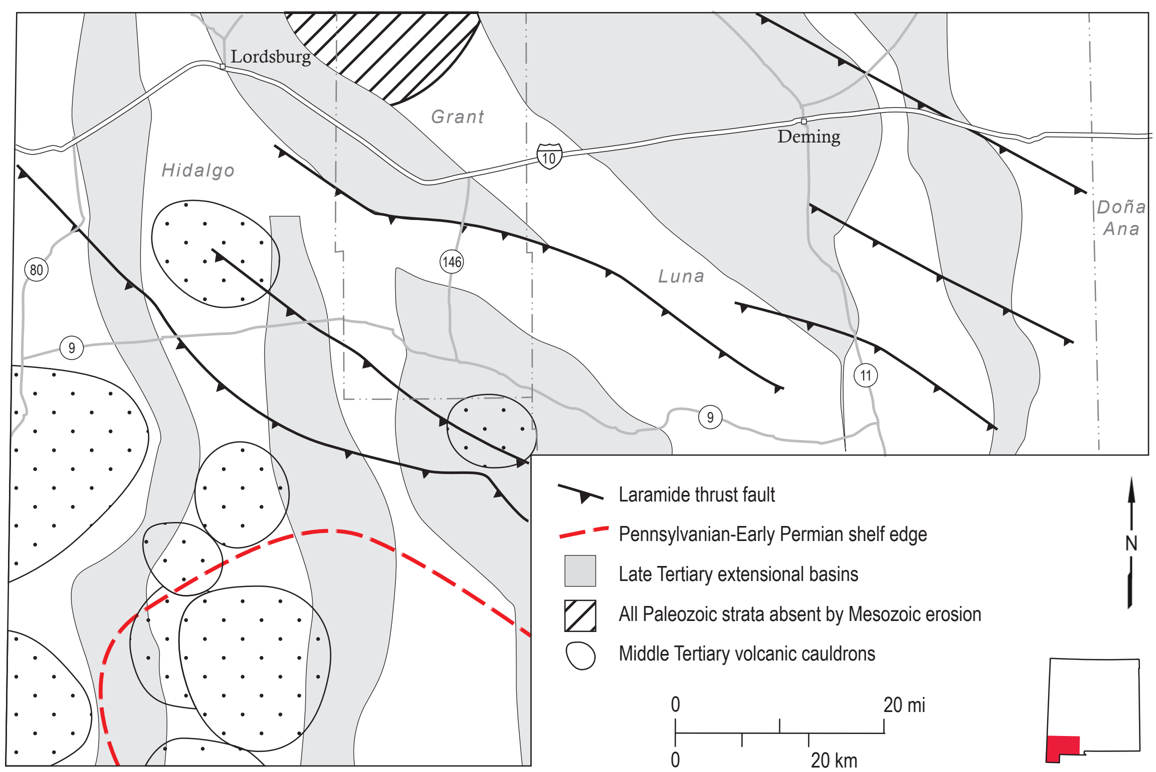


Figure 50. Late Paleozoic, Laramide and Late Tertiary tectonic elements and Middle Tertiary volcanic cauldrons in southwestern New Mexico. Pennsylvanian-Early Permian shelf margin from Thompson and Jacka (1981). Laramide thrust faults from Lawton and Clemons (1992) and Thompson (1981). Volcanic cauldrons from Clemons and Mack (1988). Pinchout of Paleozoic strata from Kottlowski (1963).

Precambrian. The Bliss is 300–400 ft thick but is not present on the higher parts of the Burro uplift. Ordovician strata are composed of 600–800 ft of marine limestones and dolostones of the El Paso Formation and overlying dolostones of the shallow-marine Montoya Formation. Up to 1,000 ft of Fusselman (Silurian) dolostones overlie the Ordovician. Again, the Ordovician and Silurian are absent from large parts of the Burro uplift, apparently the victims of Early to Middle Jurassic erosion. The Fusselman is also absent from most of Hidalgo County. Elsewhere, Upper Devonian strata of the Percha Shale are 250–400 ft thick and consist of dark-gray to black shales, minor fine-grained limestones, and thin nodular limestones. Mississippian limestones of the Escabrosa Limestone and Paradise Formation are 900 ft thick and thicken to more than 1,300 ft in southern Hidalgo County. Like underlying Paleozoic strata, they are absent from most of the Burro uplift.

Pennsylvanian strata are 1,000–3,500 ft thick in southwestern New Mexico and are assigned to the Horquilla Limestone. During the Pennsylvanian, subsidence occurred in southern Hidalgo County, adjoining areas of Arizona, and to the south in Chihuahua, Mexico, as the Pedregosa Basin formed. Southwestern New Mexico became differentiated into three bathymetric regimes. In the deep Pedregosa Basin, dark shales and thinly bedded black limestones were deposited (Zeller, 1965; Thompson and Jacka, 1981). To the north, thinly bedded bioclastic limestones were deposited on the shelf. Partially dolomitized fringing reefs formed at the shelf margin. Further north, the Burro, Florida, and Moyotes uplifts rose out of the Pennsylvanian sea and shed their clastic sands and gravels southward where they intertongued with the shelf limestones (Kottlowski, 1963; Greenwood et al., 1977).

Permian strata are more than 5,000 ft thick in the Pedregosa Basin and pinchout to the north on the flanks of the uplifts. These strata consist of (ascending) siltstones and light-gray shales of the Earp Formation, thinly bedded black limestones of the Colina Limestone, light- to dark-gray dolostones of the Epitaph Dolomite, and cherty dolomitic limestones of the Concha Limestone (Zeller, 1965). Permian strata buried the Burro, Florida, and Moyotes uplifts (Fig. 1) but were subsequently eroded after Laramide renewal of the Burro uplift (Greenwood et al., 1977).

Lower Cretaceous strata overlie Permian sedimentary rocks in the Pedregosa Basin. The Lower Cretaceous section is more than 15,000 ft thick in southeastern Hidalgo County but thins depositionally and erosionally northward to less than 1,000 ft over the Burro uplift. It pinches out north of the Burro uplift in northern Grant and central Sierra Counties. The Lower Cretaceous section consists of the following stratigraphic units (ascending; Zeller, 1965): red arkosic sandstones, siltstones, and shales of the Hell-to-Finish Formation; bioclastic and biohermal limestones and thin gray shales of the U-Bar Formation; and interbedded shallow-marine sandstones and dark-organic-rich shales of the Mojado Formation.

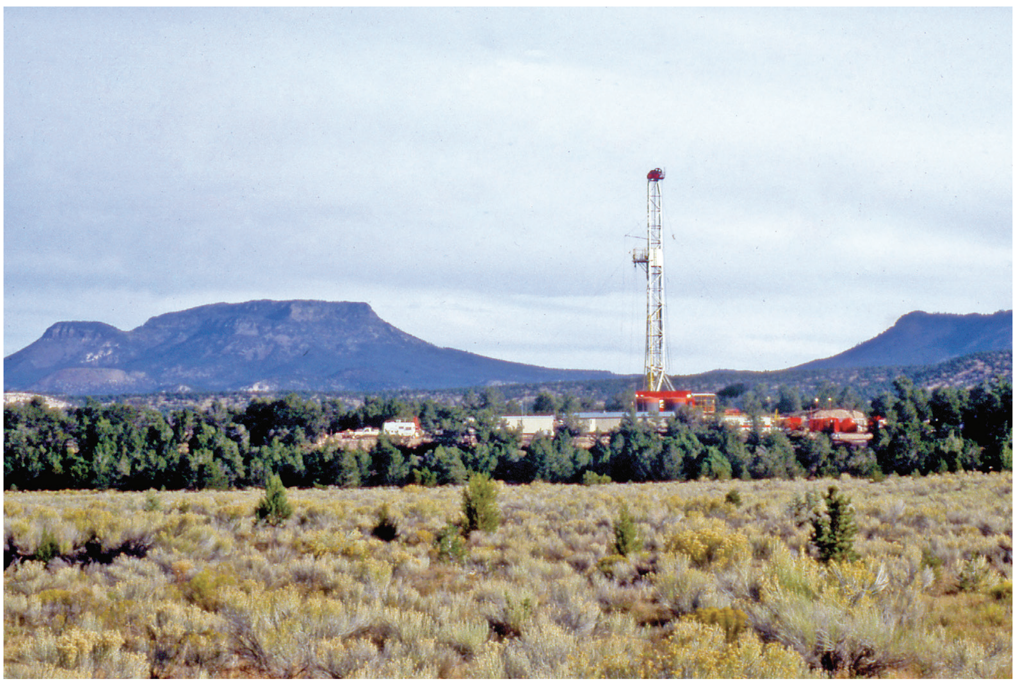
Upper Cretaceous strata are absent from most of southwestern New Mexico, having been removed by erosion following Laramide uplift. However, in northern Grant and Luna Counties along the northern part of the Burro uplift, as much as 2,000 ft of Upper Cretaceous sandstones and marine shales of the Mesaverde Group overlain by volcaniclastic sediments are present (Kottlowski, 1963). In places, remnants of the Ringbone Formation (latest Cretaceous to earliest Tertiary) are present at the top of the Cretaceous section. The Ringbone consists of gray to black bituminous nonmarine shale with volcanic flows in the upper third (Zeller, 1970).

Post-Ringbone Tertiary rocks consist mostly of rhyolitic to dacitic volcanic rocks and volcaniclastic sedimentary rocks. These dominate most of the outcrops in the uplifted Tertiary-age fault blocks that form the rugged mountain ranges of southwestern New Mexico. In the north-south aligned Tertiary basins, volcanic flows, sills, and dikes are interbedded with volcaniclastic sands, conglomerates, and clays. Thickness of the Tertiary basin fill is locally more than 10,000 ft but appears to be only a few thousand feet in most places.

Petroleum source rocks in southwestern New Mexico have been described by Thompson (1981). Primary organic-rich source units include shales of the Mojado Formation (Lower Cretaceous), dark-colored dolostones of the Epitaph Formation (Lower Permian), dark-colored basinal limestones of the Horquilla Formation (Pennsylvanian), and limestones and shales of the Paradise Formation (Mississippian). Despite their dark-gray to black color, Percha (Upper Devonian) shales contain surprisingly low percentages of TOC, generally less than 1% in Hidalgo and Grant Counties and increasing to 1–2% eastward into Luna County (Raatz, 2005). The poorly understood and poorly documented black, nonmarine shales of the Ringbone Formation may also provide a suitable source facies. Although TOC contents are generally less than 2% in most source units in southwestern New Mexico, most source rocks are mature to overmature (Thompson, 1981) so that pre-maturation organic content was substantially higher than present-day organic content. Kerogen populations are generally gas prone or a mixture of oil-prone and gas-prone types that would have generated either gas or gas mixed with oil upon maturation. In thermally overmature areas, reservoired hydrocarbons will be dry gas. Factors affecting thermal maturity in southwestern New Mexico include burial depth within deeper parts of the Tertiary basins and proximity to the large Tertiary volcanic intrusions, especially the Middle Tertiary volcanic cauldrons (Fig. 50). Contact metamorphism of carbonate rocks extends to more than 2,000 ft above the main intrusive bodies (Budding and Broadhead, 1977) with kerogen maturation into the dry gas window much farther into the country rock (Cernock and Bayliss, 1977).

Southwestern New Mexico has been sparsely drilled. Less than one dozen wells have penetrated Precambrian basement. Shows of oil and gas have been encountered in several exploratory wells (Thompson, 1981). Shows are primarily gas and have been encountered in the Mojado Formation (Lower Cretaceous), the Epitaph Dolomite (Lower Permian), and dolostones of the Montoya and El Paso Formations (Ordovician). Primary reservoir targets (Thompson, 1981) are Mojado sandstones; rudistid bioherms in the U-Bar Formation; Epitaph dolostones, shelf limestones, and shelf-margin reef complexes in the Horquilla Formation (Pennsylvanian); and dolostones in the Fusselman Formation (Silurian), and the Montoya Group and El Paso Formation (Ordovician).

The complex, multi-stage structural deformation in southwestern New Mexico renders exploration challenging. In addition to stratigraphic aspects of reservoirs, north-directed Laramide thrust faults provide opportunities for structural traps as do normal block faults associated with Late Tertiary basin-and-range deformation (Fig. 50). These are buried deep beneath Tertiary basin fill that largely post-dates movement of trap-forming structures. Therefore, structural traps are buried by a thick blanket of Tertiary sediment interlayered with volcanic rocks. With multiple stages of intense deformation, seal integrity is a major consideration, especially in the Paleozoic section which is dominated by brittle carbonate rocks. Seismic acquisition will also be a challenge. Furthermore, Tertiary sills and laccoliths may be confused with carbonate buildups on seismic lines.



Hunt Oil Company No. 1–16 State well drilling in Catron County, November, 1989. *Photo by Ron Broadhead*.

XVI. WEST-CENTRAL NEW MEXICO

West-central New Mexico is a geologically diverse region. It contains buried elements of the Late Paleozoic Ancestral Rocky Mountains, Laramide downwarped basins and compressional uplifts, and Late Tertiary extensional tectonic features associated with basin and range deformation. Above all, much of the landscape is dominated by rugged mountains formed from extensive mid-Tertiary volcanism.

Mississippian strata are the oldest Paleozoic rocks in the region. They were deposited on a peneplained surface of Precambrian igneous, metamorphic, and volcanic rocks (Armstrong, 1959). The Mississippian section is known to be present as erosional remnants in central and eastern Socorro County, where it is 20–135 ft thick and consists of a basal sandstone a few feet thick that is overlain by shallow-marine limestones. It pinches out to the west and is not known from subsurface data to be present in Catron County (Foster, 1964), although Armstrong (1962) inferred from regional distribution that it may be present in the southern part of the county where no exploratory wells have been drilled through the thick volcanic cover.

Pennsylvanian strata unconformably overlie the Mississippian and are composed of (ascending) the Sandia Formation and the Madera Group. Maximum thickness of Pennsylvanian strata is approximately 2,700 ft on the Lucero uplift. From the Lucero uplift, Pennsylvanian strata thin to the west and pinchout as they rise up onto the Pennsylvanian Zuni uplift (Fig. 51; Kottlowski, 1959; Armstrong and Chamberlin, 1994).

Pennsylvanian strata are composed of interbedded sandstones, conglomerates, shales, and marine limestones. The Lucero uplift, which now forms the rugged upland with west-dipping outcrops of Pennsylvanian strata west of the Albuquerque Basin, was a basin during the Pennsylvanian. Pennsylvanian strata thin onto the shelf areas that surround the basin. They are dominantly marine shales of variegated dark-gray, olive, and reddish colors. Many of the limestones are biostromal (Kottlowski, 1960b). The more favorable sandstones in the Sandia Formation have porosities in the 10–20% range (Reese, 1975). To the west as the Pennsylvanian section thins, the clastic ratio increases, and the shales become red (Foster, 1964; Kottlowski, 1960b) and organically leaner, therefore losing their source-rock potential.

Pennsylvanian strata grade upward into the nonmarine red beds of the Abo Formation (Permian: Wolfcampian). To the west where the Pennsylvanian is absent, the Abo rests on Precambrian basement. Abo thickness varies from 850 ft on the Lucero uplift/Lucero Basin to approximately 400 ft on the higher parts of the Zuni uplift. The Yeso Formation (Permian: Leonardian) overlies the Abo and is 1,000–1,300 ft thick on the Lucero uplift and 600–1,500 ft thick over the ancestral Zuni uplift in Catron County. The Yeso is composed of interbedded white to orange, shallow-marine to coastal sandstones, orange to brown shales, brown dolostones, and anhydrite. The Glorieta Sandstone, some 100–300 ft thick, overlies the Yeso Formation and is composed of white, fine- to medium-grained shallow marine sandstones, and minor finely crystalline dolostones. The sandstones and dolostones are visibly porous in cuttings from many of the exploratory wells drilled in the region. The San Andres Formation (Permian: Leonardian) overlies and intertongues with the Glorieta Sandstone. The San Andres is 100–400 ft thick in west-central New Mexico. It typically is fractured, karsted, in places cavernous, and exhibits very high permeability. The San Andres Formation and Glorieta Sandstone form a major aquifer in the region with recharge derived from outcrops on the flanks of the Zuni Mountains in Cibola County (White and Kelly, 1989).

Triassic strata unconformably overlie the San Andres Formation. The Triassic section is 0–1,500 ft thick (Woodward and Grant, 1986) and consists of a northward thickening wedge of red to purple nonmarine shales and minor fluvial sandstones of the Chinle Group (Upper Triassic) that overlie reddish-brown nonmarine shales, sandstones, and conglomerates of the Moenkopi Formation (Middle Triassic). Thickness variations are due largely to erosion associated with the unconformity at the top of the Triassic. The Jurassic System is absent except in the Cibola and McKinley Counties where it is represented by (ascending) Entrada Sandstone, Todilto Limestone, and Morrison Formation. These are planed off to the south by the unconformity at the base of the Cretaceous System. The eolian Entrada Sandstone is 100–450 ft thick and is overlain by 50–90 ft of dark fetid limestones and anhydrite of the lacustrine Todilto Formation. The fluviatile Morrison Formation overlies the Todilto and consists of 800–1,200 ft of sandstones and variegated shales.

Cretaceous strata blanket much of west-central New Mexico except for the Zuni Mountains, the Lucero uplift, the Defiance uplift, and other localized uplifts in eastern Cibola and western Socorro Counties such as the Magdalena Mountains. Throughout most of the region only the Gallup Sandstone and pre-Gallup Cretaceous is preserved, with younger strata having been removed by Laramide through Holocene erosion.

San Agustin Basin

The San Agustin Basin (Fig. 51) is a northeast-trending graben of Late Tertiary age. The sole exploratory well is Sun Oil Co. No. 1 Plains of San Agustin well which was drilled in 1966 and penetrated (descending) 230 ft of Quaternary alluvium and lake deposits; 4,290 ft of Tertiary volcanic rocks and interbedded volcaniclastic sediments; and 2,100 ft of Tertiary sandstones, conglomerates, and minor pyroclastic rocks. Underneath the Cenozoic section are Upper Cretaceous strata. The uppermost Cretaceous unit is the Gallup Sandstone underlain by 320 ft of Lower Mancos Shale with 95 ft of Dakota Sandstone at the base. The Cretaceous is underlain by a 95 ft thick erosional remnant of Upper Triassic red shales. San Andres (Permian: Leonardian) limestones and dolostones underneath the Triassic extend to a depth of 8,524 ft followed by 1,600 ft of fine-grained shallow marine to paralic sandstones and minor dolostones of the Yeso Formation. The terrestrial red beds of the Abo Formation from depths of 10,180 to 12,146 ft were intruded by a Tertiary aplite laccolith from 10,310 to 11,780 ft; gas shows were encountered in the sill. A 360 ft thick section of Pennsylvanian marine limestones and sandstones is present beneath the Abo and rests unconformably on Precambrian granite gneiss. Despite the presence of thick Tertiary volcanic rocks in the well, the Upper Cretaceous shales are within the oil window, but they contain mostly gas-prone kerogens. San Andres and Yeso carbonates, although organically lean, are within the lower part of the oil window and contain a mixture of oil-prone and gas-prone kerogens (see Bayliss and Schwarzer, 1987). Pennsylvanian limestones in the well contain insufficient kerogen to merit consideration as major source rocks.

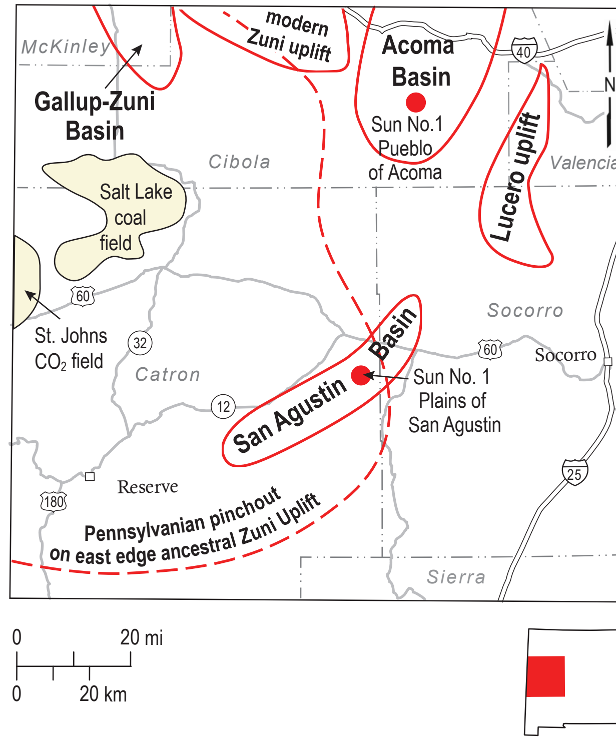


Figure 51. West-central New Mexico showing major tectonic elements, the St. Johns CO_2 field, and the locations of two exploration wells discussed in the text. Solid red lines indicate boundaries of basins and uplifts. Dashed red line indicates western pinchout of Pennsylvanian strata on the ancestral Zuni uplift. Yellow areas are known economic deposits of the Salt Lake coal field and the St. Johns CO_2 field.

Acoma Basin

The Acoma Basin (Fig. 51) has extensive outcrops of the lower part of the Cretaceous section preserved along the basin axis. Outcrops of Jurassic and Triassic strata are present along the northwestern and southeastern flanks of the basin. Although the basin axis has not been drilled to Precambrian basement, data from shallow wells along the basin axis and from deep wells that penetrated Precambrian on the basin flanks combined with gravity data suggest that the Precambrian may be at depths of 8,000 ft or more along the axis. Possible petroleum source rocks are dark-gray, kerogen-rich Pennsylvanian marine shales matured to the oil window or wet gas window, depending on burial depth (Broadhead and Black, 1989). The shallower San Andres dolostones are only marginally mature but contain sufficient percentages of oil-prone kerogen to have generated heavy oils.

The Todilto Limestone (Jurassic) is present in the northeastern part of the basin and may have generated oil as it has done on the southern flank of the San Juan Basin (see Vincelette and Chittum, 1981). Major objectives in the Acoma Basin are the shallow Mesaverde, Gallup, and Dakota sandstones (Upper Cretaceous), which may be flushed by fresh water near their outcrops; the Entrada Sandstone (Jurassic); San Andres (Permian) limestones and dolostones; the Glorieta Sandstone (Permian); and Pennsylvanian sandstones and limestones.

Shows of oil and gas in the Acoma Basin have been reported from the Upper Cretaceous, the Permian Glorieta and Yeso formations, and the Pennsylvanian (Woodward and Grant, 1986; Broadhead and Black, 1989). The Sun Oil Company No. 1 Pueblo of Acoma well (Fig. 51) was drilled on the southeastern flank of the Acoma Basin to a total depth of 4,794 ft in Precambrian basement. Gas recovered from a drill-stem test in the 750 ft thick Pennsylvanian section was composed of 95% CO_2 and carried 0.13% helium. The CO_2 may have originated from degassing of magmas that formed a large Tertiary dike that crops out near the well. The presence of elevated levels of helium, which may have originated from radiogenic decay of Precambrian granitic basement, indicates potential for this valuable resource in the Acoma Basin.

Gallup-Zuni Basin

The Gallup-Zuni Basin (Fig. 51) is a north-trending Laramide structural depression sandwiched between the Zuni Mountains on the east and the Defiance uplift on the west. The fifteen exploratory wells drilled in the basin (Broadhead and Black, 1989) have largely targeted surface anticlines. Cretaceous strata are present only at shallow depths and only in the eastern part of the basin, so they are not a major objective. Maximum depth to Precambrian is approximately 2,500 ft. Abo terrestrial red beds (Permian: Wolfcampian) rest on Precambrian granite. No marine Pennsylvanian section is present. Oil shows have been reported from the sparse exploratory wells in the San Andres Formation and in the Yeso Formation (Permian: Leonardian). The only identified petroleum source rocks are thin Yeso carbonates that are in the oil window and bear mostly oil-prone kerogens (see Bayliss and Schwarzer, 1988).

Elsewhere in west-central New Mexico the Upper Cretaceous section contains shallow coal beds of the Moreno Hill Formation in the Salt Lake coal field (Fig. 51). Coals have maximum thicknesses of 14 ft and have maximum lateral continuity of 15 mi (Hoffman, 1994). However, vitrinite reflectance is less than 0.5% (Hoffman, 1994), placing the coals within the biogenic rather than the thermogenic gas window. This, combined with shallow burial depth that limits the volume of methane that may be adsorbed onto the coals, restricts the gas resource potential.

The wide area south of the Zuni and Acoma Basins has significant petroleum potential (Foster, 1964; Woodward and Grant, 1986). A large portion of the area is covered by Middle Tertiary volcanic rocks, rendering the location of favorable structures difficult (Foster, 1964). Woodward and Grant (1986) identified and mapped several anticlines in areas where Mesozoic rocks are exposed. Overall, potential will decrease to the west with the thinning and, ultimately, the absence of the Pennsylvanian section and its source and reservoir facies.

The St. Johns CO_2 field of Apache County, Arizona pokes its nose into westernmost Catron County (Fig. 51; Rauzi, 1999; Broadhead et al., 2009). Primary reservoirs are sandstones in the lower part of the Yeso Formation (Lower Permian). The CO_2 appears to have been derived from the degassing of rising Middle Tertiary magmas that form the volcanic rocks so prevalent throughout Catron County (Gilfillan et al., 2008; Broadhead et al., 2009). CO_2 is the dominant gas encountered in both oil exploration wells and water wells throughout the region (Broadhead et al., 2009). With abundant Middle Tertiary magmas, and absence of Pennsylvanian source rocks, and a paucity of source rocks within the Permian section, the potential in Catron County may be primarily for CO_2 rather than oil or hydrocarbon gas. Limited data indicate helium content of the gases is approximately 0.20% (Broadhead and Gillard, 2004), increasing westward into Arizona where concentrations as high as 8% have been documented (Rauzi, 2003).

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GLOSSARY

Allochthonous (sedimentary rocks)— Sedimentary rocks whose dominant constituents were formed elsewhere and were transported from another area to the site of deposition.

Anhydritic dolostones—These are sedimentary rocks composed mostly of dolomite - CaMg $(CO_3)_2$ - with secondary amounts of anhydrite - $CaSO_4$.

API gravity—A measure of the density of crude oil. API gravity is inversely proportional to density so that very dense, viscous oil (heavy crude) will have a very low API gravity (perhaps in the range of 10–20° API) and less dense, less-viscous oil (light crude) will have a high API gravity (perhaps in the range of 40–45° API). Units of API gravity are degrees API.

Aplite—A finely crystalline, light-colored igneous rock of granitic composition.

Arkosic sandstone—A sandstone whose constituent grains are at least 10% feldspar.

Autochthonous (sedimentary rocks)— Sedimentary rocks whose dominant constituents were formed at the site of deposition, most commonly limestones, dolostones, gypsum, anhydrite, salt and coal.

Authigenic—Minerals that were formed in a sediment (or rock formed from the sediment after burial) by chemical or biochemical processes after the deposition of the sediment.

Back reef—Where a barrier reef is present, the back reef is the area on the landward or shelf side of the barrier reef.

Bafflestone—A limestone formed by sediment with abundant stalk-shaped fossil remains that acted to form a sediment trap (or baffle) for lime mud, which was deposited in the areas between the baffles. The lime mud is volumetrically dominant.

Barrier reef—A long, narrow reef that is located offshore and is generally elongate parallel to the shoreline. On the landward side the barrier reef is separated from the land by a shallow-water shelf or lagoon. The barrier reef separates the shallow shelf/lagoon from a deep marine basin located on the seaward side of the reef.

Basinal sandstones—Sandstones deposited in a deep-water marine basin as opposed to being deposited on a shallow-water marine shelf or on an exposed uplift above sea level.

Biogenic gas—Natural gas generated by microbes in the shallow subsurface. Biogenic gas (also sometimes referred to as swamp gas) can accumulate in traps and therefore can be produced by wells. Almost all biogenic gas accumulations are small and have low reserves when compared to thermogenic gas. Moreover, biogenically derived gases often have high concentrations of inert gases such as nitrogen which decreases the quality of the gas.

Bioherm—A mound like mass of sediment built mainly by organisms that secrete a calcium carbonate shells or exoskeletons. Usually formed by animals such as corals, but in the geologic past some bioherms were formed by calcite-secreting plants such as phylloid algae.

Biostratigraphy—The age-related subdivision and correlation of rock units based on the types of fossils they contain.

Boundstone—A type of limestone with dominant components that were bound or cemented together (by calcite) during deposition of the sediment that the limestone was formed from. Most often the components are shells of organisms that formed a reef.

Brecciated—This refers to a rock whose components are very angular and large in size and are fragments of a pre-existing rock.

Bryozoan—A type of very small marine animal that secretes a calcite exoskeleton.

Bubble point—The natural pressure in an oil reservoir above which only liquid oil (which contains dissolved natural gas) is present. Below the bubble point pressure, both liquid oil and a separate phase of natural gas are present within the pore system of the reservoir rock.

Chester (Chesterian)—Rocks of Mississippian age are divided into the Lower (or Early) Mississippian and the Upper (or Late) Mississippian. Chesterian strata constitute the upper part of the Upper Mississippian section.

Cleats—Natural fractures that occur in coal beds.

Combination solution gas – water drive—In reservoirs with a combination drive, the natural reservoir energy required to produce oil is derived from both a solution-gas drive and a water drive.

Combination trap—An oil or gas trap that is formed by both deformation and structural tilting of the reservoir rock and a lateral transition of the reservoir rock into a seal (for example, the lateral transition of a sandstone into a shale).

Conodonts—The teeth of extinct organisms that resembled modern eels. These were the only hard parts of the animals and except in rare circumstances are the only part of the organism that survives as a fossil. rapid evolution of the conodont animals resulted in distinctive changes in conodonts through time. This has left conodonts as one of the most useful fossils for age dating and biostratigraphically correlating sedimentary rocks.

Coralgal—Refers to limestones where the dominant constituents are a type of algae that secretes a calcium-carbonate skeleton (coralline algae).

Crinoid—Marine animals that have several arms that are attached to a short body (or calyx) that is, in turn, attached to a stalk. They contain an internal skeleton of disk-like calcium carbonate fragments. In most cases, the disks separate after death of the animal and are incorporated into the underlying sediment. While most modern crinoids are free swimming, many ancient and extinct types of crinoids were attached to the bottom sediment by their stalk.

Crinoidal grainstone—A limestone that is a grainstone, the grains of which are almost entirely skeletal pieces of crinoids.

Depocenter—The area of a basin where the sedimentary rocks that fill in the basin are thickest.

Diagenetic changes (diagenesis)—Physical and chemical changes that happen to sediment after deposition of the sediment. Diagenetic changes can happen a few days after deposition or they can happen millions of years after deposition when the sediment has been buried deeply in the earth's crust. Typical diagenetic changes include cementation of the mineral grains that form the rock which results in decreased porosity and dissolution of selective more soluble minerals which results in increased porosity.

Drive mechanisms (reservoir drive mechanisms)—The natural sources of energy that allow oil or natural gas to be naturally expelled from a reservoir rock into a well and from the well to the land surface.

Facies (reservoir facies)—The rock types that are present in an oil or natural gas reservoir.

Foraminifera—Single cell animals, usually microscopic in size, that secrete calcium carbonate skeletons. Most live in the water column in a marine environment but some types of foraminifera live in fresh water lakes.

Fore reef—Where a barrier reef is present, the fore reef is the deep marine setting immediately seaward of the barrier reef.

Frontier basins—From a petroleum perspective, these are basins without established petroleum production or with only small volumes of established petroleum production obtained from only a few, usually small, oil or natural gas fields.

Gas-cap assisted water drive—In oil reservoirs with a gas-cap assisted water drive, the natural reservoir energy required to produce oil is derived from both a separate gas cap above the oil-saturated part of the reservoir and a water drive provided by the water-saturated part of the reservoir below oil-saturated portion. The water drive provides more energy than the gas cap.

Gas-cap drive—When free gas is present in reservoirs with pressures below the bubble point, it accumulates as a layer or within the pore system in the upper part of a trap. This gas layer (called a gas cap) is present above a layer of oil within the trap. When a well is drilled into the reservoir, the gas in the gas cap pushes down on the gas-oil contact, pushing the oil toward the well so that it can be produced.

Graben—A structural block that is longer than wide and is bounded on its long sides by faults. The rock layers within the graben are lower than the same rock layers on either side of the graben. Contrast with half graben.

Grainstone—A limestone formed by sand-size calcite particles (or grains) with no lime mud matrix. The grains may be fragments of calcium-carbonate secreting organisms such as clams or snails or may be ooids. A grainstone is essentially the limestone equivalent of a sandstone.

Granite—A coarse-grained igneous rock composed primarily of alkali feldspar and quartz with lesser amounts of plagioclase feldspar, mica and hornblende.

Granite gneiss—A coarse-grained, banded metamorphic rock of granitic composition.

Half graben—A structural block that is longer than wide and is bounded on one of the long sides by a fault. On the other long side of the half graben, the rock layers tilt downward into the half graben. The rock layers within the half graben are lower than the same rock layers on either side of the graben. Contrast with graben.

Hubbert's peak—The maximum possible oil production from the world, a country or state, or a basin preceded by a period of increasing production and followed by a period of declining production. Also known as peak oil.

Hydrozoan—A simple marine animal with a branched structure that attaches itself to a substrate and secretes a calcium-carbonate skeleton that is left as a fossil in limestones.

Kerogen—Organic matter in sedimentary rocks (mostly shales and lime mudstones) that was deposited along with the minerals that make up the rock.

Kinderhook (Kinderhookian)—Rocks of Mississippian age are divided into the Lower (or Early) Mississippian and the Upper (or Late) Mississippian. Kinderhookian strata constitute the lower part of the Lower Mississippian section.

Laccolith—A lense-shaped body of intrusive igneous rock that has dome up overlying rocks as a result of the intrusion.

Lacustrine anhydrites—Anhydrite is a soft mineral made of calcium sulfate ($CaSO_4$). It is deposited most often as gypsum (hydrous $CaSO_4$ or $CaSO_4 \cdot H_2O$) in hot arid conditions as standing water is evaporated until Ca^{++} and SO_4= is sufficiently concentrated that gypsum is precipitated from solution and accumulates on the sea floor or lake floor. After burial of the sediment, the gypsum loses its water content and is turned into anhydrite. Lacustrine anhydrite refers to anhydrite whose gypsum precursor was deposited in a lake rather than in a marine setting.

Laramide orogeny—A period of mountain building in western North America that began in the latest part of the Cretaceous Period and ended in the early part of the Tertiary Period.

Lenticular sandstones—Sandstone beds that change thickness laterally and pinchout in all directions from a place of maximum thickness. Lenticular sandstones are encased in another rock type, usually shales but sometimes limestones.

Lime mud—Microscopic particles of calcium carbonate that are present in most limestones and are the dominant components of lime mudstones and wackestones. Most lime mud originates as the microscopic components of some types of algae and falls to the sea floor after the algae dies and decays.

Listric normal fault—A fault that dips very steeply (or is nearly vertical) near the earth's surface and curves to be almost horizontal (or flat) at depth. Rocks on the side toward which the fault is curved are down-dropped (or deeper) than rocks on the other side of the fault.

Meramec (Meramecian)—Rocks of Mississippian age are divided into the Lower (or Early) Mississippian and the Upper (or Late) Mississippian. Meramecian strata constitute the lower part of the Upper Mississippian section.

Micritic limestone—A limestone that is composed almost entirely of lime mud.

Offset wells—Oil or natural gas wells that are drilled near an exploratory well for the purpose of either confirming an oil or gas discovery or developing the oil or gas reservoir found by the exploratory well so that it can be produced.

Ooid (or oolite)—In this context, sand-sized spherical or egg-shaped calcite grains in limestones. Ooids internally are formed of concentric layers at a microscopic scale. They are formed in turbulent nearshore marine waters by non-biologic processes. The concentric layers coat a smaller core particle that is most often a very small fossil fragment or a grain of sand. Some grainstones and packstones are composed primarily of ooids.

Osage (Osagean)—Rocks of Mississippian age are divided into the Lower (or Early) Mississippian and the Upper (or Late) Mississippian. Osagean strata constitute the upper part of the Lower Mississippian section.

Packstone—A limestone that is similar to a grainstone but where a minor amount of lime mud is present between the grains. The grains support the structure of the rock. Contrast with wackestone.

Paleobathymetry—for rocks that were deposited in a marine (sea) environment, this term refers to the water depth when the sediments that formed the rock were deposited.

Paleoslope—Refers to the direction in which the upper surface of the sediments is inclined at the bottom of the sea when the sediments were being deposited. It may be different from present-day slope because tectonic movements that took place after deposition of the sediment may have tilted the sediment in a different direction.

Paleostructure—The geologic structures (anticlines, synclines, faults, etc.) present in an area in the geologic past. Different from present-day structure because the structural configuration of an area may change with time as a result of changing tectonic forces.

Paleotectonic—This refers to the deformation of rocks by folding and/or faulting in the geologic past.

Paludal—Refers to sediment deposited in a swamp.

Paralic—This refers to sediments at or near the shoreline.

Peloid—Small sand-size spherical or elliptical grains in limestones that consist of lime mud. Most were formed as excrement by animals that live on or just under the surface of the sea floor and eat the lime mud for its organic content. Peloids are present as grains in grainstones, packstones and wackestones.

Pelmatazoan—Extinct primitive crinoids that were attached to the sea floor by a stalk. Pelmatazoans resembled plants but were actually animals.

Peneplain—A land surface that has been worn by erosion to a nearly flat surface (or plain).

Petroleum source rock—See source rock.

Phylloid algae—An extinct form of algae that lived in marine settings and grew upward from the sea floor as one or more broad fronds.

Pinchout—This refers to the place where a rock layer (or stratum) laterally thins to zero thickness.

Play—A group of oil or natural gas fields in an area that have similar geologic parameters such as reservoir rock type, reservoir depositional environment, structural setting or rock type.

Pressure depletion drive—A natural gas reservoir in which the dominant source of energy that produces the gas is expansion of the gas that is present within the pore spaces of the reservoir rock. As the gas expands, it moves in the only direction possible, toward the well.

Progradation—A seaward advance of a marine shelf or delta into the deep basin.

Ramp (carbonate ramp)—A ramp refers to a marine depositional setting where there is a gradual, uniform transition from shallow water to deep water. If the rocks deposited on the sea floor are mostly limestones and dolostones, then it is a carbonate ramp.

Recompleted uphole—This refers to a producing oil or gas well that initially produced from a deeper reservoir, often in the lowest part of the well. After the oil or gas in the deeper reservoir was depleted and the deep reservoir abandoned, new production was established "uphole" in a shallower reservoir.

Reef—In this context a mound-like or ridge-like feature made of calcium carbonate that is present just below the surface of the ocean. It consists of a core of organisms with calcium carbonate shells or skeletons that were bound together during growth and grew upward as a colony to just beneath the water surface. The core is flanked by grainstones composed of particles that were derived from erosion (by waves) of the shells or skeletons that form the core. After burial, pressure of overlying sediments turn the reef into a limestone that is encased laterally and vertically by non-reef rocks such as shales or lime mudstones.

Reefal—This term refers to limestones that were deposited on or near a reef.

Rudists (rudistid)—Extinct marine mollusk with a lower cone-shaped valve and an upper, flatter valve. The lower conical valve was usually attached to the sediment on the sea floor or another rudist. Important reef-building organisms. A rudistid reef is a reef in which rudists are the dominant organisms in the reef core.

Rudstone—A limestone that is either a grainstone or a packstone but with grains that are more than 2 mm in diameter.

Seal—An impermeable rock (such as a shale, a lime mudstone, or a salt bed) or other geologic feature (such as a fault) that blocks the natural movement of oil or gas in the subsurface and allows it to accumulate in a trap.

Siliciclastic—Sediments or sedimentary rocks composed dominantly of detrital siliceous materials, especially quartz, feldspars, and clay minerals. Most siliciclastic rocks are either sandstones or shales.

Solution drive assist—This refers to an oil reservoir where the primary source of energy for oil production is derived from either water drive or gas-cap drive, but where a solution-gas drive provides a secondary source of energy for oil production.

Solution gas drive—This natural oil production mechanism utilizes the energy of natural gas that is naturally dissolved within oil in the pore spaces of a reservoir rock. As reservoir pressure drops when the reservoir is penetrated by a well, some of the gas comes out of solution and forms a separate phase of gas bubbles within the pores. These bubbles expand and push the oil in the direction of declining pressure (the well).

Source rock (petroleum source rock)—A unit or body of kerogen-rich sedimentary rock that has generated oil or natural gas in sufficient quantity to form commercial accumulations.

Strandline—The shoreline.

Stromatoporoid—An extinct type of marine organism related to sponges that produced a laminated calcite structure that typically formed reefs.

Stylolite—In this context, an irregular zig-zag appearing surface in a limestone that was formed during deep burial by dissolution of the calcium carbonate that makes up the limestone. Stylolites are most often recognized by insoluble minerals such as clays that line the surface of dissolution and are a different, usually darker color than the limestone.

Synorogenic—This refers to sediments that are deposited at the same time that structural movements deform the landscape. The structural features that are formed from the deformation affect the thickness of synorogenic sediments (they are thicker in structurally low areas and thinner in structurally high areas) and also affect the distribution of sediment types.

Thermogenic gas—Natural gas generated by the natural heating of a source rock during deep burial. The heating, usually to at least 150°C causes chemical breakdown of kerogen in the source rock and natural gas is formed. Thermogenic gas can also be formed by the natural heating of oil that is present in reservoir rocks at great burial depths; this heating leads to the natural refining of the reservoired oil. The oil has been previously generated from a source rock. Contrast with biogenic gas.

Tight gas—Natural gas that is produced from reservoirs of very low permeability.

Trap—The geologic arrangement of a reservoir rock and one or more seals in such a manner that has allowed the accumulation of oil or natural gas.

Turbidite—A sedimentary rock (usually sandstone) deposited by underwater currents formed by a dense mixture of sediment and water. Most turbidites are deposited in deep marine settings but also sometimes occur in lakes. Loose sediment that was deposited in shallow water can become dislodged by storms or earthquakes, mix with water, and flow downslope as a turbidity current into deeper waters in the basin where it is deposited as a turbidite, usually as widespread thin sandstone beds.

Updip—When strata have been naturally tilted by tectonic movements, updip refers to the direction where strata are higher,

Vuggy (porosity)—This refers to pores in a limestone or dolostone that are formed by dissolution of the rock.

Vugular—Describes porosity that is vuggy.

Wackestone—A limestone that contains both lime mud and sand-size carbonate grains (ooids or fragments of shells). The lime mud is dominant and the grains are isolated in a matrix of lime mud. Contrast with packstones and grainstones.

Water drive—A natural oil production mechanism. Most oil reservoirs contain oil in the pore spaces that rests above a system of pore spaces that are filled with saline water. If the reservoir is regional in nature (i.e. it covers a large geographic area) and saline water can enter the reservoir from beyond the boundaries of the trap, the water will exert an upward pressure on the oil-water contact which pushes the oil toward and into the wells. As the oil is produced from the reservoir, it is displaced by water.

ABBREVIATIONS

Ag—silver
A-S—acid-sulfate
Au—gold
Be—beryllium
Bbls—barrels
BBO—billion bbls oil
BCF—billion cubic feet (ft3)
BHP—Broken Hill Proprietary or bottom hole pressure if one is discussing geothermal, oil and gas wells
BHT—Bottom hole temperature (in a well)
BLM—U.S. Bureau of Land Management
Btu/lb—British thermal units per pound of fluid
CPD—Carlsbad potash district
CSDP—Continental Scientific Drilling Program
CO_2—Carbon dioxide
Cu—copper
D—Derivative waters (geothermal)
DPA—Designated Potash Area
DG—Deep geothermal waters
EMNRD—Energy, Mineral, and Natural Resources Department (New Mexico)
GCC—Grupo Cementos de Chihuahua (cement)
GPM—Great Plains Margin
HDR—hot dry rock (geothermal)
I/S—illite/smectite clays
JPSB—Jemez Pueblo-San Juan Basin type
ka—thousand years ago
KCl—potassium chloride
km—kilometers
LANL—Los Alamos National Laboratory
LBL—Lawrence Berkeley Laboratory
lbs—pounds
Li—lithium
m—meters
Ma—million years ago
Myr—Million years old
MBO—thousand bbls oil
mi—miles
MOP—muriate of potash
MORB—mid-ocean ridge basalt
MRI—Magnetic resonance imaging
MVT—Mississippi Valley-type
MWe—Megawatts (electrical)
NMBMMR—New Mexico Bureau of Mines and Mineral Resources
NMBGMR—New Mexico Bureau of Geology and Mineral Resources
NMMMD—New Mexico Mining and Mineral Division
NMIMT—New Mexico Institute of Mining and Technology
NURE—National Uranium Resource and Evaluation
OSHA—Occupational Safety and Health Administration
oz—ounces
oz/short ton—ounces per short ton
P & A'd—plugged and abandoned (well)
PGE—platinum group elements (platinum, Pt; palladium, Pl; osmium, Os; ruthenium, R; iridium, I; and rhodium, Rh)
Pb—lead
PNM—Public Service Company of New Mexico
ppb—parts per billion
ppm—parts per million
REE—rare earth elements
RGR—Rio Grande Rift
SMCRA—Surface Mine Control and Reclamation Act
Th—thorium
TCF—trillion cubic feet (ft^3)
U—uranium
µm—micrometers
UNOCAL—Union Oil Company of California
USDOE—U.S. Department of Energy
USGS—U.S. Geological Survey
USBM—U.S. Bureau of Mines
VCNP—Valles Caldera National Preserve
VMS—Volcanogenic massive sulfide
WIPP—Waste Isolation Pilot Plant
Wt%—weight per cent
Y—yttrium
Zn—zinc
Zr—zirconium
δ—delta value used in isotope measurements
°C—degrees centigrade

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