Carbon Dioxide in New Mexico: Geologic Distribution of Natural Occurrences

By

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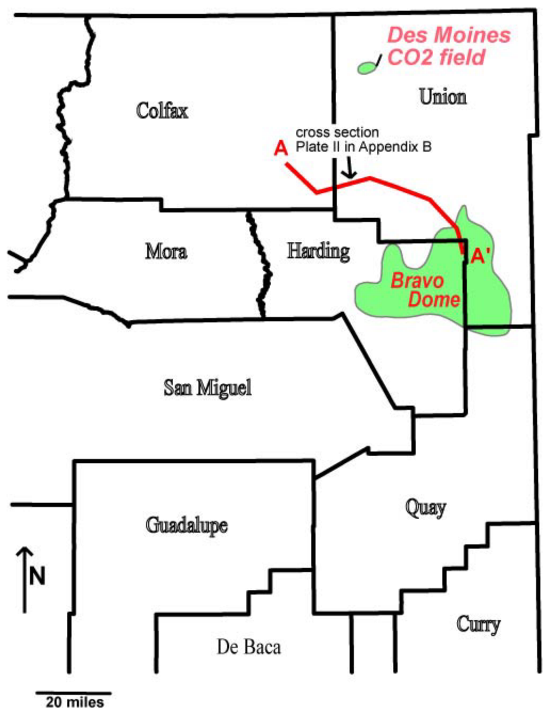

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Abstract

Carbon dioxide (CO_2) occurs as a common component of natural gases throughout New Mexico. In most gases, CO_2 is a minor constituent and comprises less than 1 percent of the gas. More rarely, CO_2 is the dominant component of the gases and may constitute more than 99 percent of the gas. Some accumulations of this nearly pure CO_2 have been produced commercially for their CO_2 content.

Most gases in the Permian Basin of southeastern New Mexico contain less than 1 percent CO_2. In general, stratigraphic units comprised predominantly of carbonate rocks harbor gases that contain higher percentages of CO_2 than units comprised predominantly of siliciclastic sedimentary rocks.

In the San Juan Basin of northwestern New Mexico, most gases in Cretaceous reservoirs contain less than 1 percent CO_2. Cretaceous gases contain more than 1 percent CO_2 in the deep northern part of the basin. Gases in Pennsylvanian reservoirs contain more than 10 percent CO_2 along trends on the Four Corners platform and in the deeper parts of the San Juan Basin. Gases in Mississippian reservoirs are comprised of more than 90 percent CO_2 over large areas.

Widespread accumulations of gases that are nearly pure CO_2 are present over large parts of the Bravo Dome and Sierra Grande uplift of northeastern New Mexico. CO_2 has been produced commercially from the Bravo Dome field that has yielded a cumulative production of more than 1.2 trillion ft^3 CO_2 gas. Triassic sandstones are secondary reservoirs at Bravo Dome. CO_2 has also been produced from the much smaller, now-abandoned Des Moines field on the Sierra Grande uplift. Significant potential remains for undiscovered CO_2 resources on the Sierra Grande uplift and Bravo Dome.

In north-central New Mexico, CO_2-rich gases are present within Pennsylvanian and Lower Permian sandstones in the vicinity of large igneous intrusions in the Las Vegas Basin. In the Raton Basin, gases composed primarily of CO_2 occur in Triassic sandstones and in the Glorieta Sandstone (Permian).

In central New Mexico, CO_2-rich gases are present in the Estancia Basin, in the Chupadera Mesa area, and in the Albuquerque Basin. CO_2 has been produced from two small, now-abandoned accumulations in Lower Pennsylvanian sandstones in the Estancia

Basin. Potential for additional CO_2 resources is limited. On Chupadera Mesa, recent exploratory drilling has revealed the presence of CO_2 in Lower Permian sandstones. CO_2 has been encountered in Tertiary-age sandstone aquifers in the Albuquerque Basin.

CO_2 has been encountered by exploratory wells drilled in west-central New Mexico. The St. Johns CO_2 field of Arizona extends into westernmost Catron County. Sparse exploratory drilling elsewhere has revealed the presence of CO_2-rich gases in Pennsylvanian and Permian reservoirs in eastern Catron and Cibola Counties.

No gas analyses are available for the smattering of exploratory tests drilled in southwestern New Mexico. Pervasive Tertiary-age volcanism and reservoirs in thick sections of strata of Cambrian through Tertiary age are favorable for CO_2 accumulations, but extensive Tertiary-age volcanism and tectonism may have breached traps and seals.

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Introduction and Purpose

Carbon dioxide (CO_2) is a common constituent of natural gases. CO_2 is a minor component of most natural gases and constitutes less than 1 mole percent of the gas, with either hydrocarbons or nitrogen being the dominant components. In other less common gases CO_2 is the dominant component and may constitute more than 99 percent of the gas. Some of these gases that are almost pure CO_2 have been produced commercially for their CO_2 content (Figure IN 1). Prior to 1980, the main use of produced CO_2 was as a feedstock for the manufacture of dry ice or it was converted to liquid CO_2 and used in the carbonation of beverages among other applications. The volume of CO_2 needed for these purposes was small and less than twenty wells in the state produced CO_2 for these purposes. As a result, most wells that encountered CO_2 rich gases were plugged and abandoned because the gas had no commercial value at the time, with hydrocarbon gases or oil being the usual targets of exploratory drilling.

During the 1970's, however, a new use for CO_2 emerged. Injection of this gas into old oil fields could mobilize oil that has been left behind by primary or secondary recovery techniques. Old oil fields could be revitalized and oil could be produced that otherwise would be left in the reservoir. This new use substantially increased demand for CO_2. As a result, the long-neglected CO_2 accumulations at Bravo Dome in northeastern New Mexico and at McElmo Dome and Sheep Mountain in southern Colorado were explored, drilled, developed and produced and the extracted CO_2 was shipped via underground pipeline to the Permian Basin of west Texas and southeastern New Mexico where it was sold and injected into old fields, increasing total recovery of oil. For the twenty years from 1980 until 2000, the supplies of CO_2 at Bravo Dome, McElmo Dome and Sheep Mountain were sufficient to meet demand. However, the combination of increasing age of oil fields in the Permian Basin and the rise of oil prices from less than $25/bb in 2000 to more than $140/bbl in 2008 led to increased interest in instituting new CO_2 floods in previously unflooded fields. In addition, reserves of CO_2 at existing, discovered CO_2 fields were gradually being depleted. The result was that existing natural supplies of CO_2 were inadequate to meet the opportunities for CO_2 injection. The interest in exploration for new and unproduced CO_2 accumulations increased. The project that resulted in this report was prepared in order to obtain a better understanding of the distribution of CO_2 in the subsurface of New Mexico, thereby providing basic information that could be used in leasing as well as in exploration.

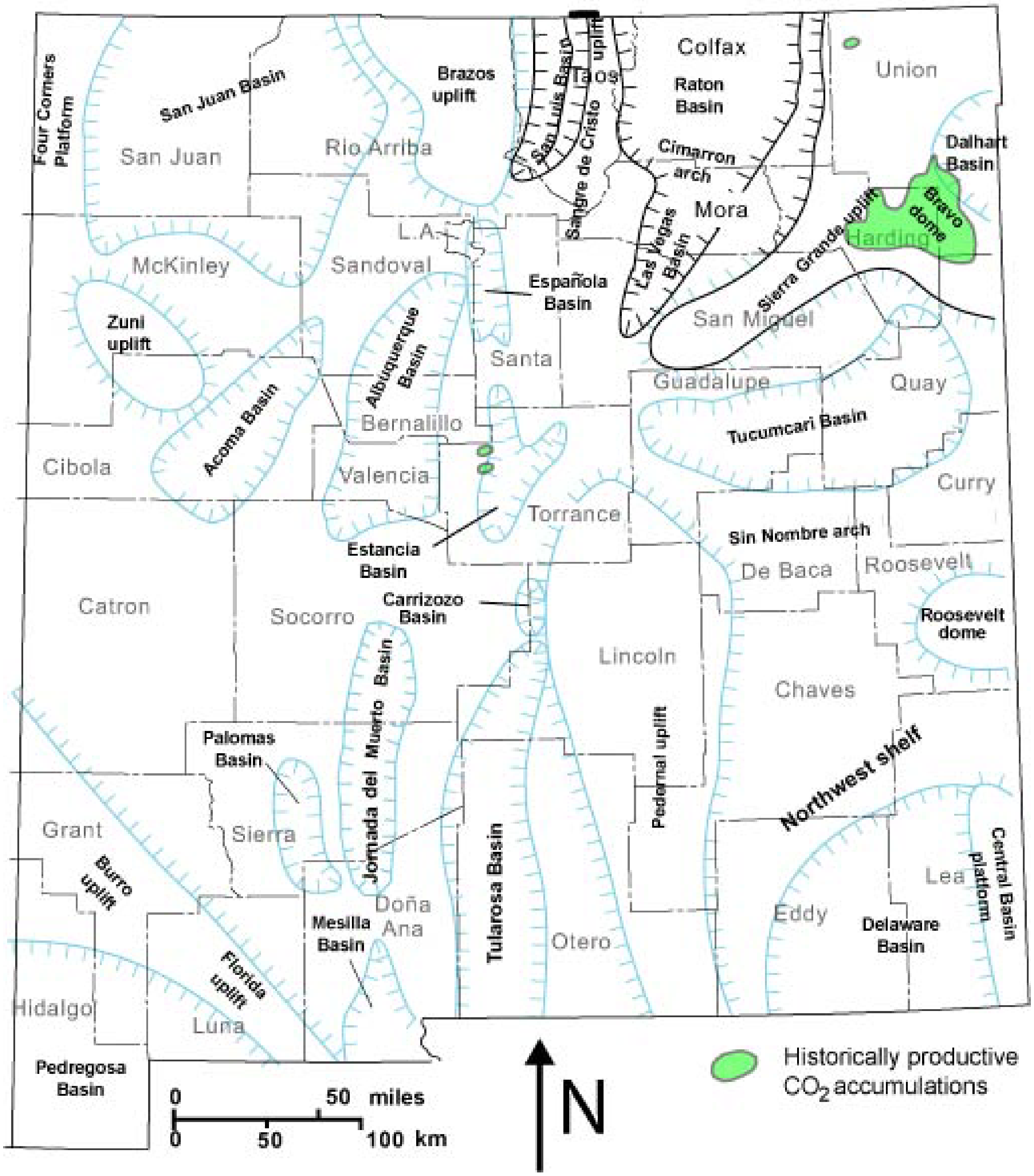

Figure IN 1. Basins and uplifts in New Mexico and locations of CO_2 accumulations that have been commercially produced.

The rising interest in sequestering man-made CO_2 may result in man-made CO_2 being separated from exhaust streams of power plants and other emitters. These man-made sources could eventually be used for enhanced oil recovery supplanting or even eventually totally replacing naturally-sourced CO_2. Thus, the man-made CO_2 could be sequestered in oil fields and also aid in producing more energy. CO_2 can also be injected into coalbed methane reservoirs to increase natural gas production.

There is also rising interest in sequestering anthropogenically derived CO_2 in underground reservoirs that are not associated with oil and gas fields. The data and maps presented in this report could play a part in CO_2 sequestration in that they would help identify reservoirs where natural gases are largely or even dominantly CO_2. These reservoirs may be favorable for CO_2 sequestration because they are likely in at least partial chemical equilibrium with CO_2. Also, it would be desirable to avoid sequestration into reservoirs that contain hydrocarbon gases in order to avoid diluting the hydrocarbons with injected CO_2 and thereby reducing their usefulness.

The purpose of this report is therefore to provide basic geological data and information relevant to the occurrence and distribution of CO_2-rich gases in New Mexico.

This report is organized into four parts. ***The first part of this report*** is this pdf document that present key data, maps and analyses of CO_2 distribution in New Mexico and also summarizes CO_2 geology and uses, some of which are presented for historical information only. ***The second part of this report*** is contained in Appendix A and is a database of gas analyses (***NM gases CO2 project.xls)*** in Excel format. This database, further described below in the section on Appendices, includes parameters on 975 gas analyses including well/sample location, sample depth, reservoir stratigraphy and and a variety of data on gas composition. ***The third part of this report,*** contained in Appendix B, is a series of oversized plates in pdf format. These plates include a structure contour map on top of the Precambrian, several cross sections made with well logs, and several state-wide contour maps of the CO_2 content of stratigraphic units ranging in age from Ordovician though Upper Cretaceous. The various smaller contour maps of CO_2 content that appear in the main body of this report were excerpted from the statewide maps that appear in Appendix B. ***The fourth part of this report*** is a Geographic Information

System (GIS) project that allows the user to overlay the various maps that are presented in Appendix B The GIS project is presented in Appendix C.

The senior author of this report prepared the database, the maps, the cross sections, and the written text. The junior authors digitized the maps and prepared the GIS project. The data and ideas expressed in this report are the responsibility of the senior author.

Acknowledgments

This project was funded by the New Mexico State Land Office (The Honorable Patrick H. Lyons, Commissioner of Public Lands) through contract 09-539-P615-8825 to the New Mexico Institute of Mining and Technology. John Bemis, Jami Bailey and Joe Mraz of the State Land Office were instrumental in securing funding for this project. Joe Mraz acted as project liason for the Land Office. As always, the staff of the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources, Amy Trivitt Kracke and Annabelle Lopez, contributed through their meticulous organization of our vast collections of data.

Appendix A - The New Mexico Carbon-Dioxide Gases Database

A major part of this report is the database of gas analyses in Excel format (see database ***Nmgases CO2 project.xls*** in Appendix A on this CD). This database contains analyses of the composition of 975 gas samples from New Mexico. Most of the gas samples came from oil and gas exploration and production wells, but a minor amount are from water wells, springs, and surface seeps that emit gas. Most of the analyses presented in this report were performed under the U.S. Bureau of Mines gas analyses program, which is now administered by the U.S. Bureau of Land Management. This program is designed to provide publicly accessible analyses of the helium content of natural gases throughout the United States as well as other parts of the world. The analyses available in the U.S. Bureau of Mines/Bureau of Land Management database were supplemented by data provided by the private sector for use in this report or by data previously donated to the New Mexico Bureau of Geology by the private sector. Other analyses reported in published literature were also incorporated into the database. In addition, our Subsurface Library has records have information from exploratory wells throughout New Mexico. For several of these wells, gas was recovered either on drill-stem tests or by production testing. Although chemical analyses of the gases may not be available, they are often described as being either "nonflammable" or as being comprised mostly of CO_2 or N_2. These gas descriptions were added to the database and are utilized at various points in this report. Although there are relatively few non-U.S. Bureau of Mines analyses, many of these are from regions where little if any data are present in the U.S. Bureau of Mines database so they help fill in large gaps in geographic and geologic coverage.

The U.S. Bureau of Mines/Bureau of Land Management database is available to the public on CD-ROM in an ASCII delimited file as National Technical Information Service (NTIS) order number PB2004-500040. For this report, the data from the Bureau of Mines/Bureau of Land Management database was extensively modified. First, the ASCII delimited file was translated into Microsoft Excel format to make it easier to search and use. Second, all data from places other than New Mexico was deleted. Third, significant amount of data were either added to the database or corrected based upon records available at the New Mexico Bureau of Geology and Mineral Resources. Added data include gas analyses donated for this project by the private sector. Other gas analyses were obtained from the published literature.

Many samples in the U.S. Bureau of Mines database have incomplete data entries. Data fields that were not complete for many samples include the name of the stratigraphic unit from which the gas sample was obtained. For samples without this entry, or with an entry that was thought to be suspect upon examination, the name of the stratigraphic unit was obtained by crosschecking the depth of the sample with well records in the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology. Other data were added or verified as time permitted. Other data fields were added are calculations based upon existing data; these include *Total Gas Liquids* and *Total Hydrocarbons*.

Relatively few wells in the U.S. Bureau of Mines/Bureau of Land Management database have locations given in terms of latitude and longitude, but instead have locations given in terms of section, township, range, and footage from section boundaries. Latitude and longitude are needed to plot well locations in the Arc/GIS mapping system. For wells without latitude and longitude coordinates, latitude and longitude were calculated at the New Mexico Bureau of Geology and Mineral Resources using the Geographix Exploration System (a product of Landmark Graphics) and the Whitestar Corporation digital land grid of New Mexico; this method allows translation of section-township-range coordinates to latitude-longitude coordinates based on the 1927 North American datum.

Latitude and longitude cannot be calculated with the Whitestar land grid for unsurveyed areas of New Mexico principally Spanish land grants and Native American reservations. In these unsurveyed areas, latitude and longitude were obtained from the U.S. Geological Survey gas analyses database, formerly available online at http://energy.cr.usgs.gov/prov/org. The locations in the U.S. Geological Survey database are not exact, but rather mark the centers of ¼ mi^2 grid points; they are calculated to two decimal places instead of the five decimal places of the New Mexico Bureau of Geology and Mineral Resources and the U.S. Bureau of Mines data. Mapping of data points using latitude and longitude calculated by different methods is not considered a problem because of the low density of data points (sample locations) across New Mexico. Latitude-longitude locations for other wells in unsurveyed areas were derived by plotting the described well locations on U.S. Geological Survey 1:250,000 scale topographic maps and manually calculating the latitude and longitude coordinates.

Data fields

The following data fields are present in the database on this CD-ROM.

Sample Number: This is a numeric sample number from the U.S. Bureau of Mines/Bureau of Land Management database (e.g. 11152), an alphanumeric number for analyses donated to the New Mexico Bureau of Geology and Mineral Resources (e.g. NMBGMR 7), or an alphanumeric code referring to analyses obtained from published literature (FCGS = Four Corners Geological Society, 1978, 1983; FOS = Foster and Jensen, 1972; MONT = Montgomery, 1986). Although there are relatively few non-U.S.

Bureau of Mines analyses, many of these are from regions where little if any data are present in the U.S. Bureau of Mines database so they help fill in large gaps in geographic and geologic coverage.

County: The county from which the sample is from.

Field: For oil and gas wells, this is the name of the oil or gas field which the well was drilled in.

Operator: The company or organization that drilled the well.

Well name and number: The lease name and number of the well.

Location S-T-R: The location of the well in terms of section, township and range.

Footage location: The location of the well in feet from section boundaries.

Latitude: The latitude of the well, in decimal degrees. Samples in white have values of latitude calculated at the New Mexico Bureau of Geology and Mineral Resources. Samples in yellow have latitude obtained from the U.S. Bureau of Mines/Bureau of Land Management database. Samples in blue have latitude obtained from the U.S. Geological Survey database.

Longitude: The longitude of the well, in decimal degrees. Samples in white have values of longitude calculated at the New Mexico Bureau of Geology and Mineral Resources. Samples in yellow have longitude obtained from the U.S. Bureau of Mines/Bureau of Land Management database. Samples in blue have longitude obtained from the U.S. Geological Survey database.

Gas sample date: The date the gas sample was taken in the following format: year/month/day/.

Reservoir age: The geologic system of the reservoir rock from which the gas sample was obtained.

Reservoir name: The stratigraphic name of the reservoir rock from which the sample was obtained.

Depth: The depth in the well from which the sample was obtained, in feet.

Elevation: The surface elevation of the well or sample, in feet.

Elevation datum: The datum at which the surface elevation was measured. KB= Kelly bushing; GL = ground level.

SIWHP: The shut-in pressure measured at the well head, in pounds per in^2.

Flow rate: The rate of flow of gas as measured at the well, in thousand ft^3 (MCF) per day, unless otherwise noted.

Methane: The mole percentage of methane in the gas.

Total gas liquids: The mole percentage of gas liquids in the gas. Gas liquids range from C_2 (ethane) to C_{6+} (hexanes and heavier liquids).

Total hydrocarbons: The mole percentage of hydrocarbons in the gas. This is the sum of *Methane* and *Total gas liquids*.

Helium: The mole percentage of helium in the gas. TR = trace, generally less than 0.01 percent.

Oxygen: The mole percentage of oxygen in the gas. A significant percentage of oxygen in the gas may indicate the sample was contaminated by air.

Argon: The mole percentage of argon in the gas.

Hydrogen: The mole percentage of hydrogen in the gas, as H_2.

Nitrogen: The mole percentage of nitrogen in the gas.

CO_2: The mole percentage of carbon dioxide in the gas.

Hydrogen: The mole percentage of hydrogen in the gas.

Heating value: The heating value of the gas in British Thermal Units (BTU) per ft^3.

Comments: additional comments concerning gas composition.

Appendix B – Oversized Plates

Appendix B contains oversized plates whose format is too large to be placed into the main text of this report. They are in pdf format and are designed to be plotted or printed on oversized paper. The plates are listed below. Most show contours of CO_2 content of gases recovered from wells and are based on the CO_2 gases database in Appendix A. Plate I is a structure contour map on the Precambrian surface and is described in more detail above. Other plates are cross sections in northeastern, north-central, and west-central New Mexico that are discussed in appropriate sections of this report. The cross sections are based on well logs and show the well logs. The plates showing contours of CO_2 content are numbered in stratigraphic sequence rather than in the order they are cited in the text of this report.

Plate I – Structure contours on Precambrian surface
Plate IA - Structure contours on Precambrian surface and New Mexico State Trust Lands
Plate II – Cross section A-A' on Sierra Grande uplift in northeastern New Mexico
Plate III – Cross section B-B' in north-central New Mexico
Plate IV – Cross section C-C' in north-central New Mexico
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Plate VII – CO_2 content of Ordovician gases
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Plate IX – CO_2 content of Devonian gases
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Plate XII – CO_2 content of Lower Permian gases
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Plate XIV – CO_2 content of Triassic gases

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Plate XVI – CO_2 content of gases in Dakota Group (Upper Cretaceous)

Plate XVII – CO_2 content of gases in Mesaverde Group (Upper Cretaceous)

Plate XVIII – CO_2 content of gases in Pictured Cliffs Sandstone (Upper Cretaceous)

Plate XIX – CO_2 content of gases in Fruitland Formation

Appendix C – Geographic Information System (GIS) Project

Appendix C contains the Geographic Information System (GIS) projects associated with this report. The GIS project contains the contour maps of CO_2 content for the various stratigraphic intervals presented as oversized plates in Appendix B as well as the structure contour map on top of the Precambrian surface. Two folders are present In Appendix C. The ArcMap GIS project is presented in ArcMap format and ArcMap (a product of ESRI Corp.) or compatible software will be needed to open the project. The files are written for use with ArcMap version 9.3.1. The ArcReader GIS project allows the user to view the different maps presented in this report as layers that can be turned on and off, but does not allow the user to manipulate or add to the data presented in Appendix A. ArcReader is free GIS map viewer software provided by ESRI Corp. and a copy is presented in Appendix C that can be installed on your computer. To install ArcReader, open folder ArcReader GIS project in Appendix C and then open the ArcReader setup folder – double click on "setup" to install ArcReader. To view the maps in ArcReader, go back to the ArcReader GIS project folder and double click on the file ***NM CO2 Content Map***, an ESRI published map.

Precambrian Structure Contour Map

A structure contour map on top of the Precambrian (Plate I in Appendix B) was prepared as part of this project. An understanding of the structure of the Precambrian and the structural relief on top of the Precambrian is necessary to understanding the locations and boundaries of basins and uplifts in the state. Distribution and structure of basins and uplifts controls the distribution and thickness of stratigraphic units and are also integral to understanding the distributions and trends of major tectonic elements in the state. These, in turn, exert control over the occurrence and distribution of CO_2 in natural gases.

Foster (1961) had previously published an excellent structural relief map of the Precambrian surface of New Mexico. However, in the 48 years since that map was published, hundreds of deep exploratory wells have been drilled that have helped to better define the Precambrian surface and statewide Bouguer gravity anomaly and aeromagnetic anomaly maps (Cordell, 1983; Keller and Cordell, 1983) have been produced that are indispensable in defining relief on the top of the Precambrian. In addition, several detailed basinal studies have been completed that offered detailed structure maps of several basins and adjoining uplifts.

The Precambrian structure contour map presented as Plate I combines detailed maps of studied basins with less detailed but new work in intervening areas. The Precambrian structure of the Tucumcari Basin was adapted from Broadhead and others (2002), the Sin Nombre area from Broadhead and Jones (2002), Bravo Dome and Dalhart Basin from Broadhead (1990), Estancia Basin from Broadhead (1997), and the Chupadera Mesa area from Broadhead and Jones (2004). The structure of the Raton and Las Vegas Basins is from Broadhead (2008). The structure contours of the Jornada del Muerto Basin are from Foster (1978).

Precambrian structure contours in the Permian basin of southeastern New Mexico are based upon correlations of the Precambrian top in wells but contour shape and form used structure contours maps on shallower Lower, Middle and Upper Paleozoic stratigraphic units (Kelley, 1971; Haigler and Cunningham, 1972; Broadhead 2005, 2006) as guides to help shape and form the contours on the top of the Precambrian where well control is less dense. In the San Juan Basin, the excellent structure contour map of the base of the Dakota Sandstone (Thaden and Zech, 1984) was used as a guide to help shape and form contours on the much deeper Precambrian surface. Other areas represent new work based upon well data with the state gravity anomaly and aeromagnetic anomaly maps (Cordell, 1983; Keller and Cordell, 1983) as well as surface geology (New Mexico Bureau of Geology and Mineral Resources, 2003) used to help interpret subsurface structure and guide and shape contour form. Foster's (1961) map proved an invaluable starting point in these areas.

The Precambrian structure contour map is based primarily on the subsea elevation of 1114 wells drilled throughout the state. In each of these wells, depth to top of Precambrian was obtained from the published basinal studies listed above or was correlated on geophysical well logs or sample logs for this study. Tops were obtained from scout cards for less than 100 wells. Faults were mapped as indicated by the previous studies or as indicated on the surface geologic map of the state (New Mexico Bureau of Geology and Mineral Resources, 2003).

The contour interval varies from basin to basin because the magnitude of structural relief varies so greatly from basin to basin. For example, structural relief on the Precambrian surface exceeds 30,000 ft over a distance of less than 20 miles in the Albuquerque Basin whereas 20,000 ft of structural relief in the Permian Basin occurs over a distance of 150 miles. Contour intervals were selected for each basin so that basin geometry, relief, and shape could be depicted in an easy-to-read manner in each basin. In addition, contour intervals that are too small can imply a false sense of accuracy in basins where well control is sparse.

Origin of CO_2 in Natural Gases

Carbon dioxide (CO_2) is a common constituent of natural gases. Most natural gases contain less than 1 mole percent CO_2, but some rare natural gases, such as those found on the Bravo Dome of northeastern New Mexico, are almost pure CO_2. The CO_2 in natural gases has been ascribed to many origins and the CO_2 in any one reservoir system may be derived from multiple sources, although a single source is usually dominant. The following mechanisms are currently thought to be the more common sources for most of the CO_2 found in natural gases (Wycherly, 1999; Whiticar, 1994; Hunt, 1996).

1. *Mantle/magmatic degassing*. With this mechanism, CO_2 originates in the mantle and is presumably primordial. This mantle-derived carbon appears to be transported to the crust primarily through rising magmas that carry the CO_2 upward as a dissolved gas phase. In some areas migration of CO_2 through deep-seated faults is thought to be the main transport mechanism. For the magmatic-derived CO_2, confining pressure on the magmas decreases as they rise upward from the mantle and up through the crust and CO_2 is exsolved as a separate phase. If the magma rises to the surface to form an extrusive volcanic rock, much of the CO_2 may eventually be lost to the atmosphere. Gases emitted from active volcanoes are primarily water vapor and CO_2 gas (e.g. see MacDonald, 1972; Baubron et al., 1990; Giggenbach, 1996; Giggenbach et al., 1991). If the magma does not escape to the surface and forms an intrusive body such as a sill, dike or laccolith, the CO_2 gas will migrate into reservoirs that are pierced by the magma. Once in the reservoirs, it may be redissolved into the water system and migrate in water solution.
2. *Regional metamorphism*. Regional metamorphism of basement rocks releases CO_2 gas. Presumably this is most effective when the basement rocks contain large amounts of calcium carbonate, either in the form of carbonate rocks or as carbonate cement.
3. *Contact metamorphism of carbonate rocks*. When magmas intrude a sedimentary section of carbonate rocks, they heat them and at sufficiently high temperatures the carbonates decompose and form calcium and CO_2 as products, similar to a lime kiln. Earlier investigators (e.g. Lang, 1959) concluded that this was a major

source for CO_2 found in many reservoirs, but more recent studies seldom mention this mechanism as the main source for CO_2 accumulations.

4. *Dissolution of carbonate rocks*. When groundwater undersaturated with respect to $CaCO_3$ moves through a limestone, it will dissolve some of the rock, leaving behind void spaces and producing CO_2 as a dissolved component of the water.
5. *Thermal degradation of organic matter*. This happens as a result of maturation of organic material in sedimentary rocks that accompanies temperatures increases that take place as a function of burial. CO_2 is formed relatively early in the maturation process along with methane. Humic nonmarine organic matter produces more CO_2 than sapropelic marine organic matter. Peak CO_2 production is attained before peak methane production, but both methane and CO_2 should be present in the system if this process is the major method for CO_2 production in a sedimentary basin.
6. *Microbial degradation or oxidation of hydrocarbons*. CO_2 can be produced from oil in an oil reservoir where sufficient oxygen is present.
7. *Contact metamorphism of coals*. When magmas intrude a coal-bearing sedimentary section, CO_2 can be produced as a result of thermal maturation of the humic organic matter in the coals.

It is beyond the scope of this report to determine the sources of CO_2 encountered in New Mexico gases. However, possible sources are mentioned, particularly when they have been determined or discussed in the literature. The source of the CO_2 has a bearing on determination of CO_2 potential or prediction of the distribution of CO_2-bearing gases in undrilled or sparsely drilled areas. In general, the source of CO_2 in gases is best determined by the isotopic composition of the CO_2 and other gases in the reservoir, especially the Noble gases. The geologic setting is also an important factor when considering the origin of CO_2 in natural gases and can be used to determine which of the mechanisms discussed above are plausible sources for a CO_2 accumulation.

Uses of CO_2

With the rising concerns about the atmospheric emissions of anthropogenic CO_2 as a cause of global warming, it may be surprising to learn that a number of commercial uses have been discovered for CO_2 within the last century. Some of these utilize this compound in solid form (dry ice), others in liquid form, and yet others in gaseous form. The following list of some of these uses was obtained from the late Augustus Hayoz of Ross Carbonics of Mosquero, New Mexico. Some are historical uses and may not be presently active.

1. Enhanced oil recovery
2. Refrigeration with dry ice
3. Carbonation of beverages
4. Noncombustble gas in fire extinguishers
5. Shredding of old tires
6. Stripping of insulation from scrap wire
7. Removal of corn kernels from the cob during food processing
8. Removal of hair from hogs in slaughterhouses
9. Cooling of metal cutting tools
10. Stripping of paints
11. Noncombustible atmosphere that can be introduced into grain silos to prevent grain dust explosions
12. Inert, noncombustible atmosphere for welding
13. Nontoxic aerosol propellant
14. Branding of livestock
15. Stimulation of plant growth in greenhouses
16. Excellent solvent when in the supercritical state

More than 99 percent of the CO_2 produced from natural accumulations in New Mexico is used for enhanced oil recovery. In this use, the CO_2 is transported to an old oil field through a pipeline and is then injected into the oil reservoir. When pressure becomes sufficiently high, the CO_2 becomes miscible in the oil and reduces the oil viscosity, allowing the oil to move more easily through the reservoir rock. With this method, oil can be produced that would otherwise remain in the reservoir. It is this methodology and the need for nearly pure CO_2 gas that has spurred interest in the exploration for additional CO_2 accumulations in the state. Before introduction of usage in enhanced oil recovery in the 1980's, the primary uses for CO_2 were for conversion into dry ice and into a bottled liquid. A small amount of New Mexico CO_2 is still converted into these forms.

In the future, CO_2 may likely be collected from waste gases emitted from coal-fired generating facilities in the San Juan Basin of northwestern New Mexico and from other industrial facilities as well. This CO_2 would then supplement or even eventually replace the natural CO_2 that is used for enhanced oil recovery. This would not only provide additional sources for enhanced oil recovery but would also help control CO_2 emissions.

CO_2 in Permian Basin, southeastern New Mexico

Gases in the Permian Basin and its constituent elements (the deep Delaware Basin, the Central Basin Platform and the Northwest Shelf) contain low levels of CO_2. Average CO_2 concentrations range from a low of 0.11 percent in reservoirs of the Abo (Lower Permian) redbeds in Chaves County to a high of 4.11 percent in Silurian carbonates (Figures PB 1a, PB 1b). In general, stratigraphic units comprised predominantly of carbonate rocks (Ordovician and Silurian strata, San Andres Formation) have gases that contain higher concentrations of CO_2 than stratigraphic units comprised predominantly of siliciclastic sediments. Notable exceptions to this are gases in Hueco ("Wolfcamp") carbonate reservoirs where CO_2 content averages only 0.26 percent with a maximum value of 0.67 percent.

Upper Permian strata

Gases in Upper Permian stratigraphic units (San Andres Formation, Artesia Group, Rustler and Salado Formations) contain the highest concentrations of CO_2 in the Permian of southeastern New Mexico (Figures PB 1a, PB 1b). In general, most gases in Upper Permian reservoirs have CO_2 concentrations of less than 1 percent (Figure PB 2; Plate XIII in Appendix B). Maximum CO_2 content exceeds 1 percent, and in places exceeds 5 percent, along an east-west trend centered on central Chaves County and the Lea-Roosevelt County line. Gases along this trend are from oil reservoirs in the San Andres Formation and are comprised dominantly of hydrocarbons with 60 to 75 percent methane and 10 to 25 percent hydrocarbon gas liquids (C_{2+}). This trend of gases with enhanced CO_2 concentrations is coincident with an east-west trend of Tertiary igneous dikes that have been mapped at the surface (Figure PB 2; New Mexico Bureau of Geology and Mineral Resources, 1993). The spatial relationship between the dikes and the elevated CO_2 concentrations may be spurious or it may be that the dikes have introduced CO_2 into the reservoirs either by causing thermal decomposition of the carbonates or by exsolution of juvenile CO_2 from rising magmas. Isotopic studies of the carbon and oxygen in the CO_2 as well as study of related noble gases in the reservoirs are needed to confirm an origin.

A second trend of Upper Permian gases with high CO_2 concentrations is located on the Central Basin platform (Figure PB 2). Along this trend the CO_2 content of Upper Permian gases exceeds 1 percent and locally exceeds 5 percent. Reservoirs with increased levels of CO_2 are present in the Grayburg Formation, Queen Formation, and the Seven Rivers Formation. Igneous rocks of post-Precambrian age are not known to be present on the surface in this area (see Nicholson and Clebsch, 1961; Barnes, 1976) and have not been reported from the subsurface. This indicates a non-igneous origin for the CO_2.

Although data are sparse, it appears that gases in the Yates and Seven Rivers Formations which contain more than 1 percent CO_2 are found in reservoirs deeper than 3000 ft; gases with less than 1 percent CO_2 occur in reservoirs deeper than 3000 ft as well as reservoirs shallower than 3000 ft (Figure PB 3). Similarly, gases with more than 2 percent CO_2 are found at depths below 3000 ft in the Queen Formation (Figure PB 4) and 3400 ft in the Grayburg Formation (Figure PB 5) and more than 4 percent CO_2 below 4000 ft in the San Andres Formation (Figure PB 6).

Gases in the uppermost part of the Permian section, the Rustler and Salado Formations, average 0.43 percent CO_2 (Figure PB 1a). The few analyses available indicate maximum CO_2 content is 0.6 percent. The gases are predominantly nitrogen. Hydrocarbon content of Rustler and Salado gases is low, averaging only 2.15 percent. All hydrocarbons are gas liquids; methane is absent.

Upper Permian basinal sediments of the Delaware Mountain Group are restricted to the Delaware Basin (Garber and others, 1989; Bachman, 1984). Oil and associated gases are produced from sandstone reservoirs in submarine fan and channel settings (Broadhead et al, 1998). Although data are sparse, CO_2 contents of gases in the sandstone reservoirs of the Delaware Mountain Group are low, averaging 0.23 percent and ranging from 0.04 to 0.6 percent. Gases are wet, containing an average of 67 percent methane and 17 percent natural gas liquids. Nitrogen content is relatively high at an average 15.3 percent and ranging from 3.8 to 26.9 percent.

PERMIAN BASIN

Age		Strata		CO2 average	CO2	N2	CH4	C2+	No. of samples
Triassic		Chinle		No samples					
		Santa Rosa							
Permian	Ochoan	Dewey Lake		No samples					
		Rustler		0.43	0.2 - 0.6	97.15	0	2.16	
		Salado							
	Guadalupian	Artesia Group	Tansill	No samples					
			Yates	0.88	0.17 - 5.55	10.07	71.60	17.23	21
			Seven Rivers						
			Queen	1.15	0 - 6.36	34.78	49.86	13.42	24
			Grayburg	1.05	Tr - 4.63	11.94	60.73	25.84	10
		San Andres		3.93	0.1 - 10.6	14.44	61.73	19.35	14
	Leonardian	Glorieta		1.5		2.3	76.9	19.2	1
		Yeso	Paddock	0.48	0 - 2.12	3.31	79.78	16.11	12
			Blinebry						
			Tubb						
			Drinkard						
	Wolfcampian	Abo	red beds	0.11	0 - 0.31	6.44	85.32	7.46	51
			carbonates	2.3	1.3 - 3.3	1.8	69.1	26.9	2
		Hueco ("Wolfcamp")		0.26	0.07 - 0.67	2.21	84.17	13.26	17
Pennsylvanian	Virgilian	Cisco		0.47	0.08 - 1.06	2.75	80.73	15.73	19
	Missourian	Canyon							
	Des Moinesian	Strawn		0.37	0.1 - 0.8	1.27	84.17	13.93	21
	Atokan	Atoka		0.41	0 - 1.42	2.36	85.76	11.11	45
	Morrowan	Morrow		0.70	0.3 - 1.49	1.06	90.39	7.67	111
Miss.		undivided		1.3		0.8	86	11.9	1
Dev.	Upper	Woodford		No samples					
	Middle								
	Lower	Thirtyone							
Sil.	Upper	Wristen		4.11	0.9 - 16	3.47	78.71	13.26	18
	Middle								
	Lower	Fusselman							
Ord.	Upper	Montoya		1.45	0.1 - 5.1	4.61	82.6	10.92	5
	Middle	Simpson							
	Lower	Ellenburger							
Cambrian		Bliss		No samples					
Precambrian									

Figure PB 1a. Stratigraphic column of Permian Basin and composition of gases in stratigraphic units. Values are averages except for the right CO_2 column which is the range of values.

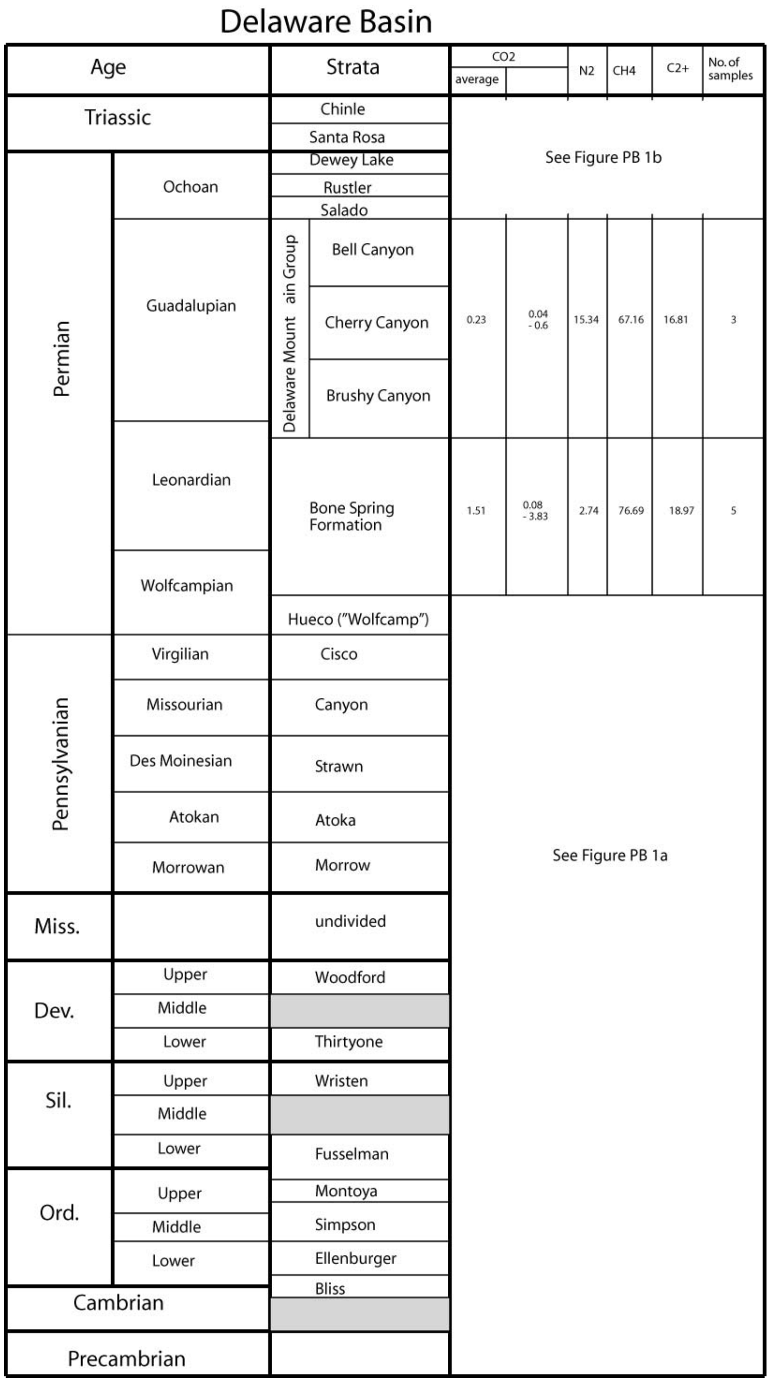

Figure PB 1b. Stratigraphic column of Delaware Basin and composition of gases in stratigraphic units. Values are averages except for the right CO_2 column which is the range of values.

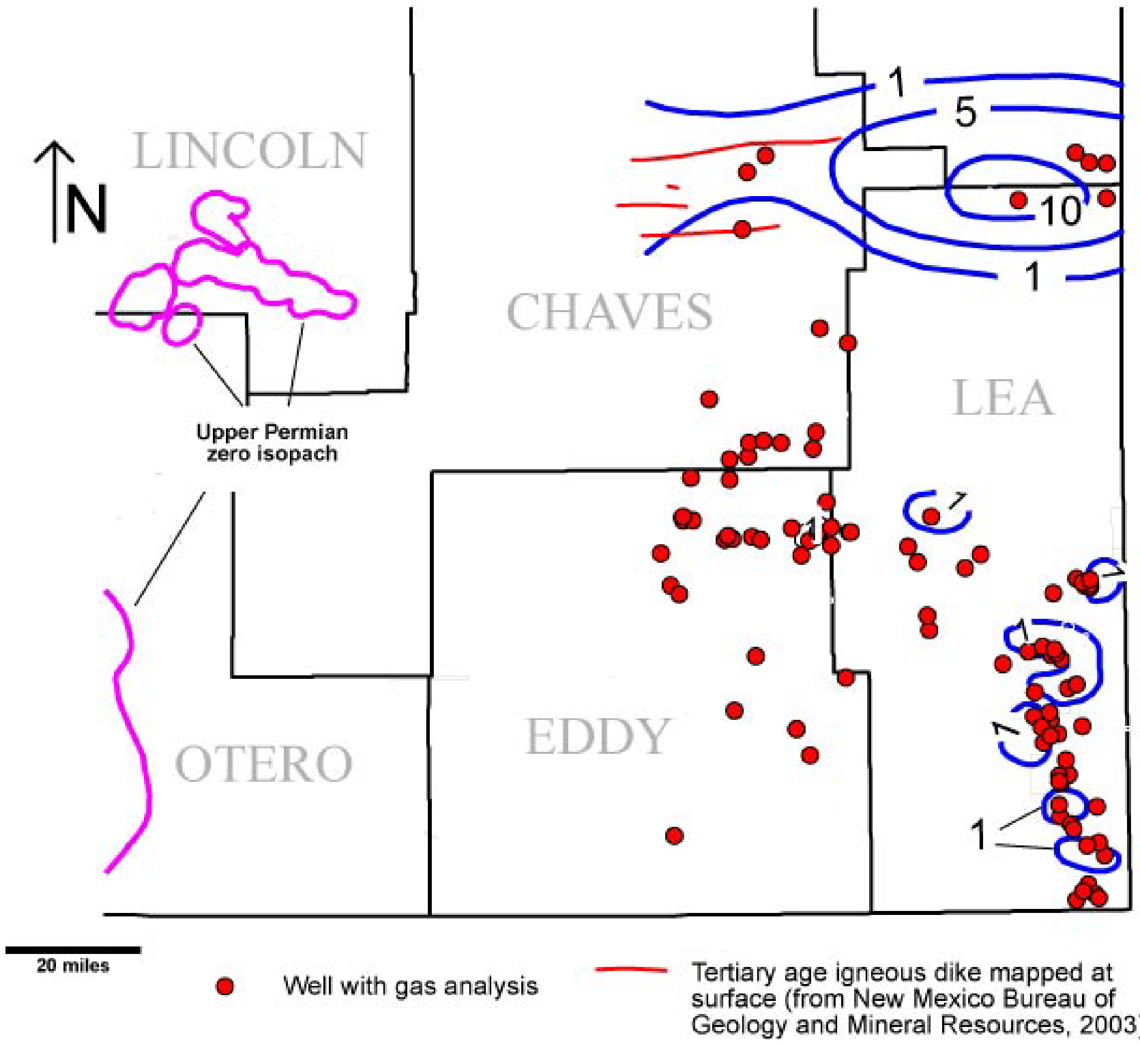

Figure PB 2. CO_2 content of gases in Upper Permian reservoirs in southeastern New Mexico. Upper Permian zero isopach line adapted from New Mexico Bureau of Geology and Mineral Resources (2003).

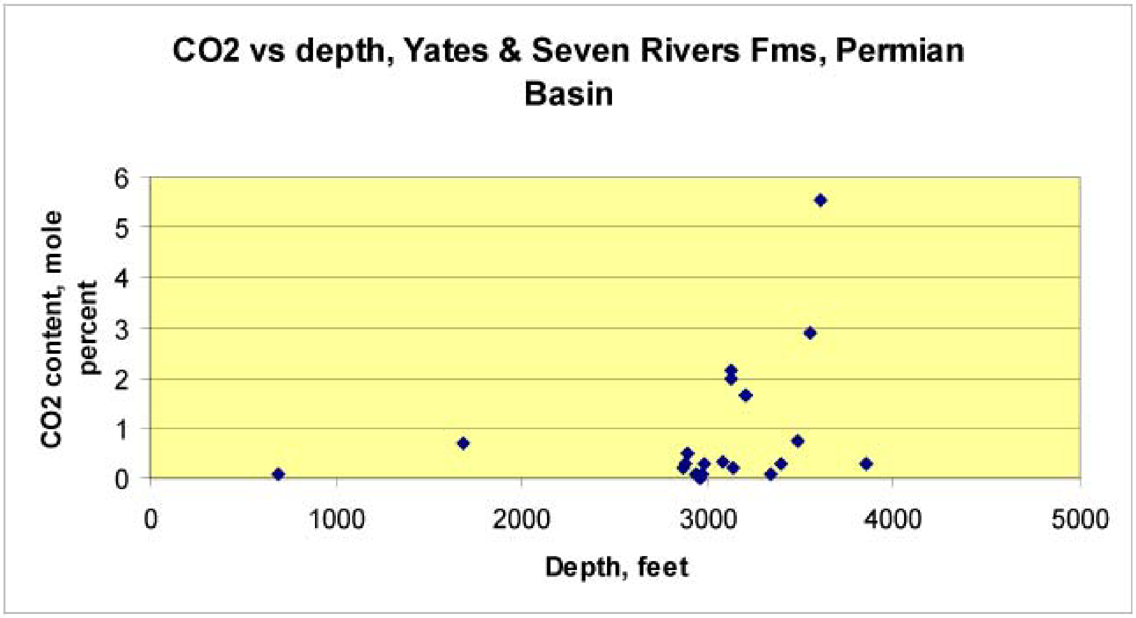

Figure PB 3. CO_2 content of Yates and Seven Rivers gases vs reservoir depth, Permian Basin.

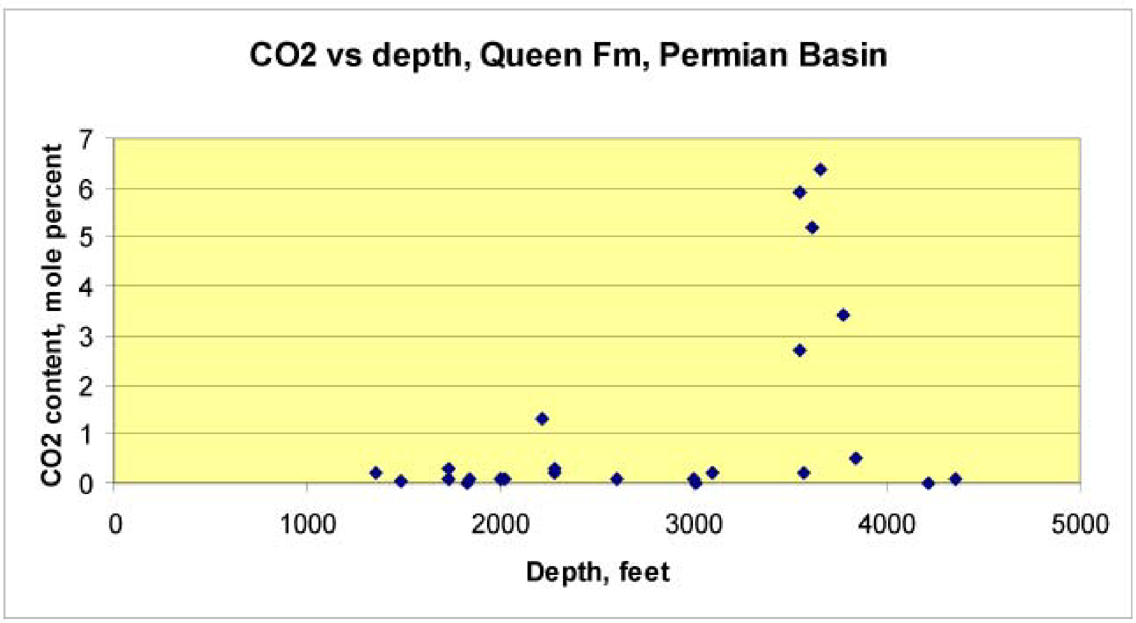

Figure PB 4. CO_2 content of Queen gases vs reservoir depth, Permian Basin.

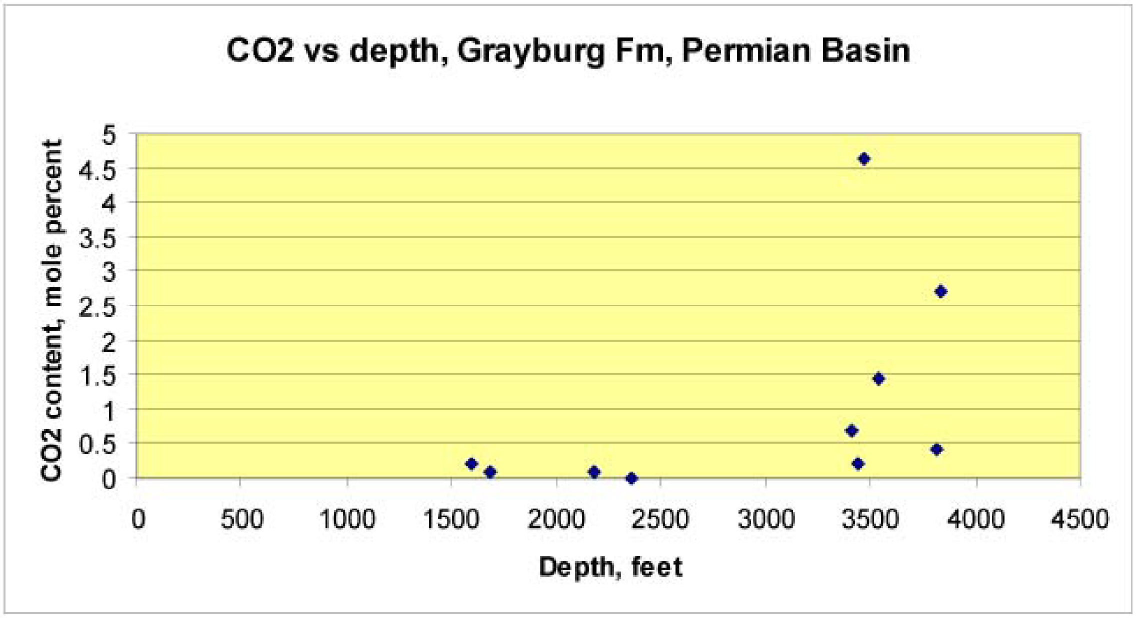

Figure PB 5. CO_2 content of Grayburg gases vs reservoir depth, Permian Basin.

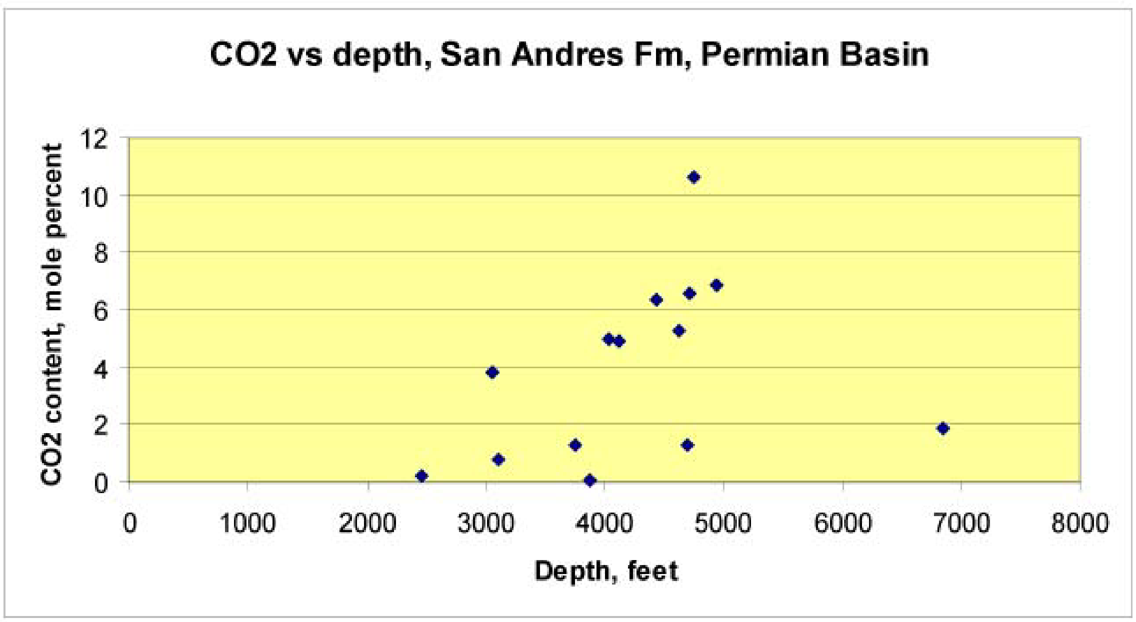

Figure PB 6. CO_2 content of San Andres gases vs reservoir depth, Permian Basin.

Lower Permian strata

Gases in Lower Permian reservoirs (Hueco Group, Abo Formation, Yeso Formation, Glorieta Formation, Bone Spring Formation) contain less than 1 percent in most places (Figure PB 7; Plate XII in Appendix B). Yeso reservoirs, which are predominantly dolostones, contain gases with an average CO_2 content of 0.48 percent.

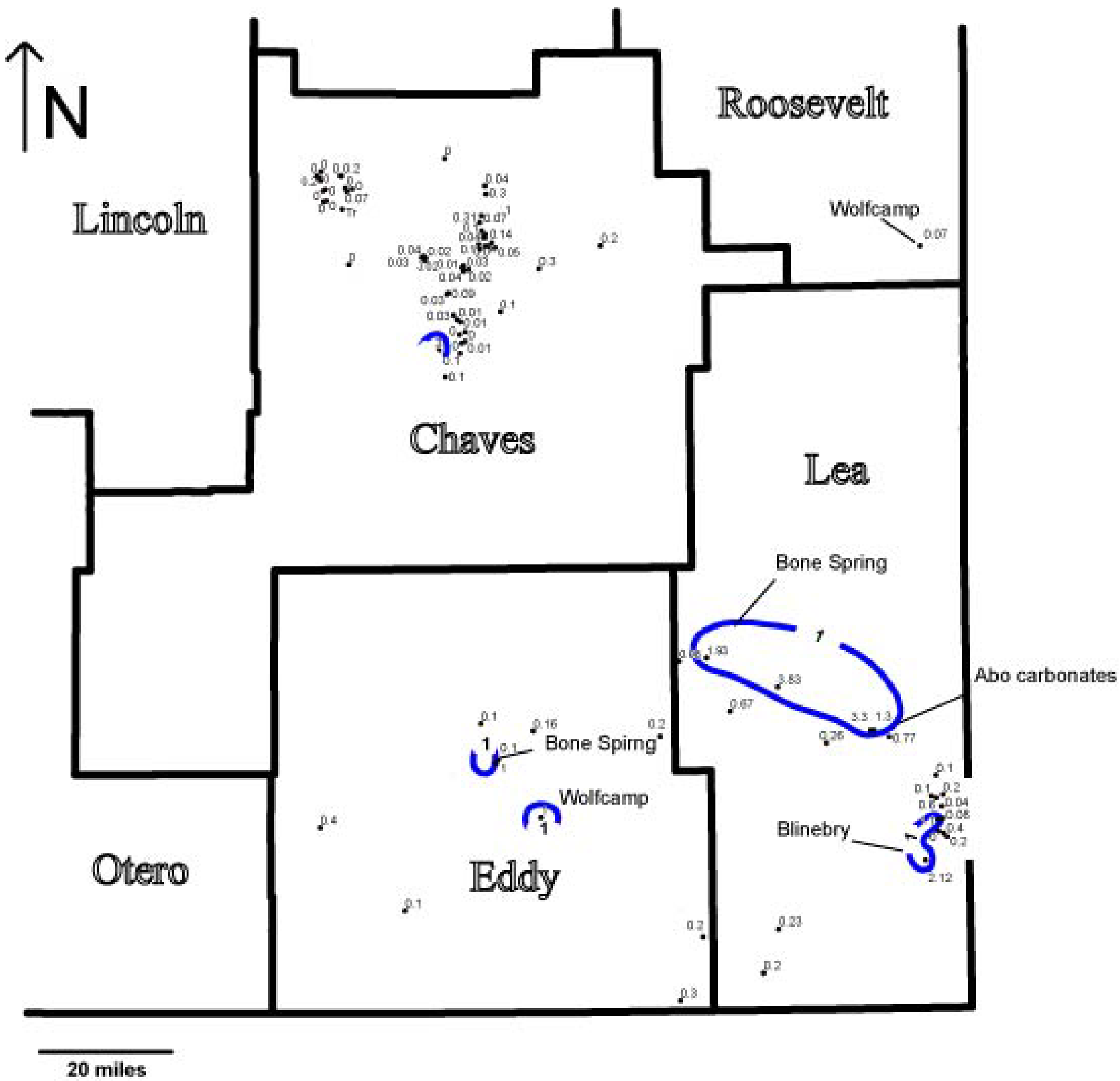

Figure PB 7. CO_2 content of gases in Lower Permian reservoirs in the Permian Basin of southeastern New Mexico.

Most Yeso reservoirs bear gases with less than 1 percent CO_2 (Figure PB 8). From available data, there does not appear to be a relationship between reservoir depth and CO_2 concentration. Locally, dolostones reservoirs in the Blinebry member bear gases that have as much as 2.12 percent CO_2 (Figure PB 1a).

Gases from two wells in Abo shallow-marine carbonate reservoirs on the Central Basin platform have CO_2 concentrations ranging from 1.3 to 3.3 percent. Gases in Abo fluvial-deltaic red bed sandstones of central and northern Chaves County have low CO_2 concentrations, averaging 0.11 percent with a maximum value of 3.1 percent; most of the gases obtained from Abo red bed reservoirs contain less than 0.1 percent CO_2 (Figure PB 9). There is no apparent relationship between CO_2 content and reservoir depth within the Abo. Hueco (or "Wolfcamp") reservoirs contain gases with an average CO_2 content of 0.26 percent and a maximum CO_2 content of 1 percent (Figure PB 10).

Lower Permian sandstones, dolostones, and shales deposited in the Delaware Basin belong to the Bone Spring Formation. The Bone Spring reservoirs in the northern part of the basin are dolomitized limestone debris flows that were derived from the Abo shelf-margin carbonate complex. Gases are associated with crude oil in the reservoirs and are comprised of more than 95 percent hydrocarbons; CO_2 varies from 0.08 to 3.83 percent (Figure PB 1b). Further to the south, Bone Spring reservoirs are primarily fine-grained siliciclastic turbidites for which little is known about gas composition except that hydrocarbons predominate. These gases are produced for fuel gas.

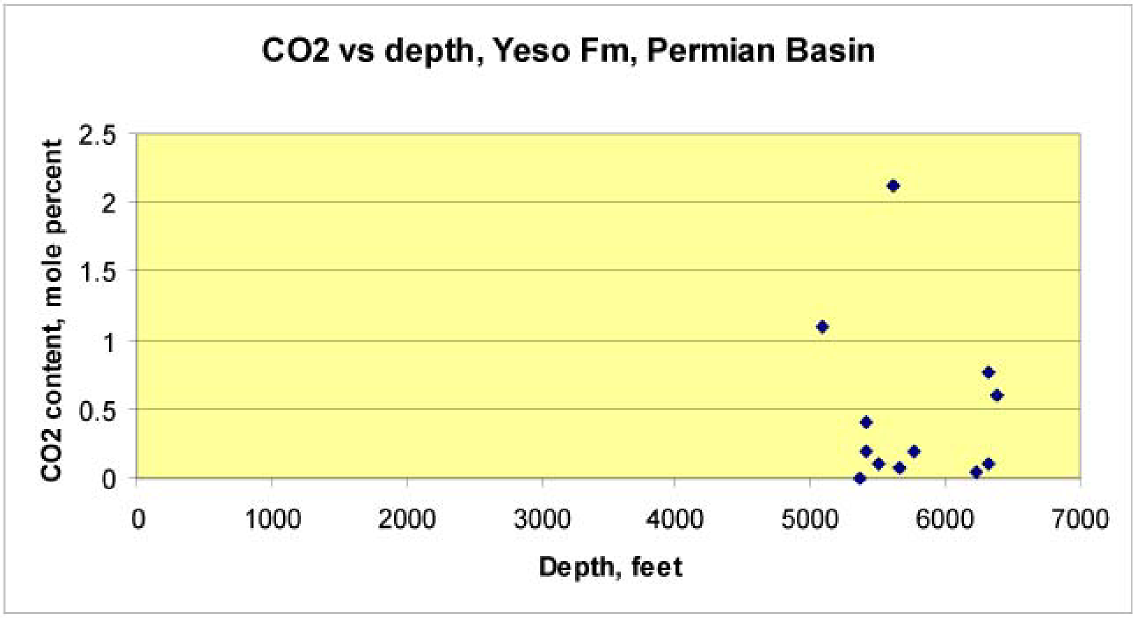

Figure PB 8. CO_2 content of Yeso gases vs reservoir depth, Permian Basin.

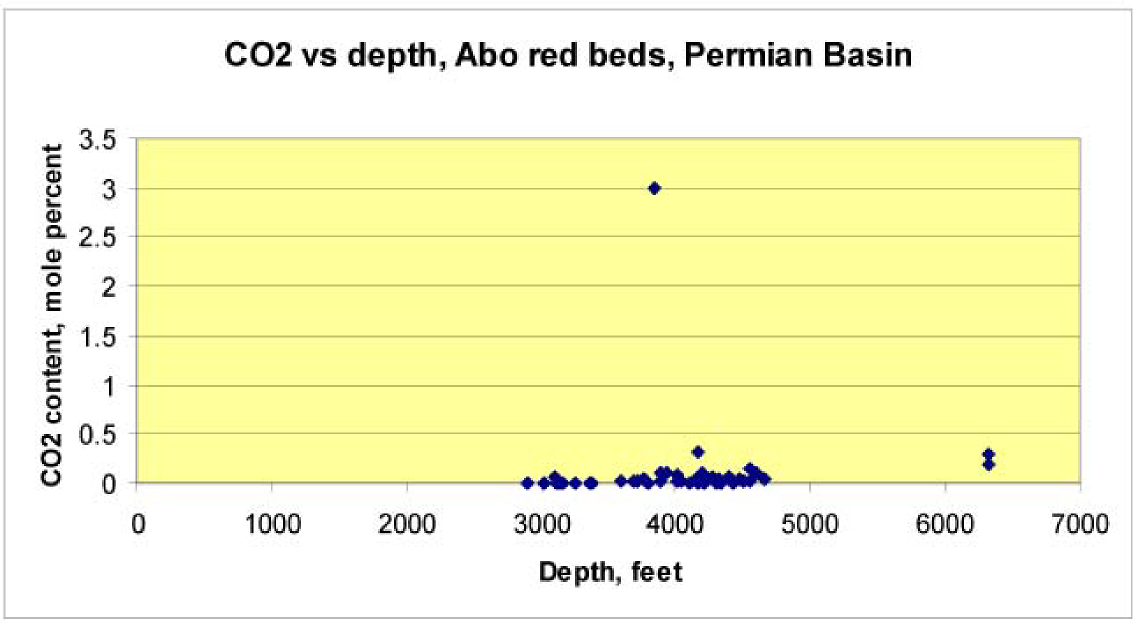

Figure PB 9. CO_2 content of gases in the Abo red beds vs reservoir depth, Permian Basin.

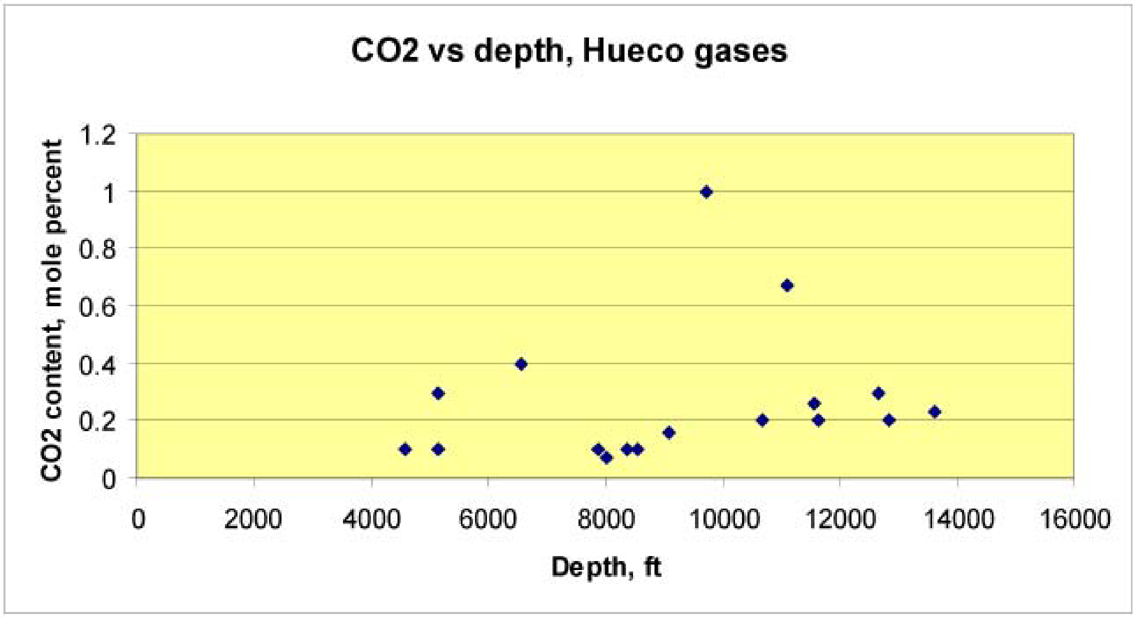

Figure PB 10. CO_2 content of Hueco ("Wolfcamp") gases vs reservoir depth, Permian Basin.

Pennsylvanian System

Upper Pennsylvanian reservoirs in the Permian Basin belong to the Cisco and Canyon Groups. The reservoirs are predominantly carbonates deposited as phylloid algal mounds and associated flanking carbonate sand bodies. Productive reservoirs are located on the Northwest Shelf and as a shelf-margin carbonate complex on the rim of the Delaware Basin. Partial to complete dolomitization is common (Cox et al., 1998; Sharp, 2008). CO_2 content of gases is low with an average value of 0.47 percent and a maximum value of 3.2 percent (Figures PB 1a, PB 11; Plate XI in Appendix B). Gases are predominantly hydrocarbons with average methane content of 81 percent and an average gas liquids content of approximately 16 percent. There are insufficient data to determine whether or not there is a relationship between CO_2 content of Upper Pennsylvanian gases and reservoir depth. The few data available suggest that gases with more than 1 percent CO_2 are present only in reservoirs below 3500 ft (Figure PB 11).

Middle Pennsylvanian reservoirs in the Permian Basin belong to the Strawn Group. Productive reservoirs are primarily patch reefs that grew on positive tectonic features. Strawn production is dominated by accumulations of gas and gas liquids in the western part of the Delaware Basin and accumulations of oil and associated gas in the eastern part of the basin (Broadhead et al., 2004; Dutton et al., 2005). Gases are predominantly hydrocarbons with an average methane concentration of 84 percent; gas liquids constitute approximately 14 percent of the Strawn gases. CO_2 concentrations are low with an average value of 0.37 percent; maximum CO_2 concentration is 0.8 percent (Figure PB12).

Lower Pennsylvanian reservoirs in the Permian Basin are fluvial to deltaic to shallow-marine sandstones in the Atoka and Morrow Groups. Production is mostly nonassociated gas and hydrocarbon gas liquids. Gases in Atoka reservoirs contain an average of only 0.41 percent CO_2 (Figure PB 1a). Gases in Morrow reservoirs contain somewhat more CO_2, an average of 0.70 percent (Figure PB 1a). There is no apparent relationship between reservoir depth and CO_2 content for Lower Pennsylvania gases. Except where noted otherwise, the trends of Pennsylvanian gases with more than 1 percent CO_2 shown on Figure PB 14 are in Atokan and Morrowan reservoirs.

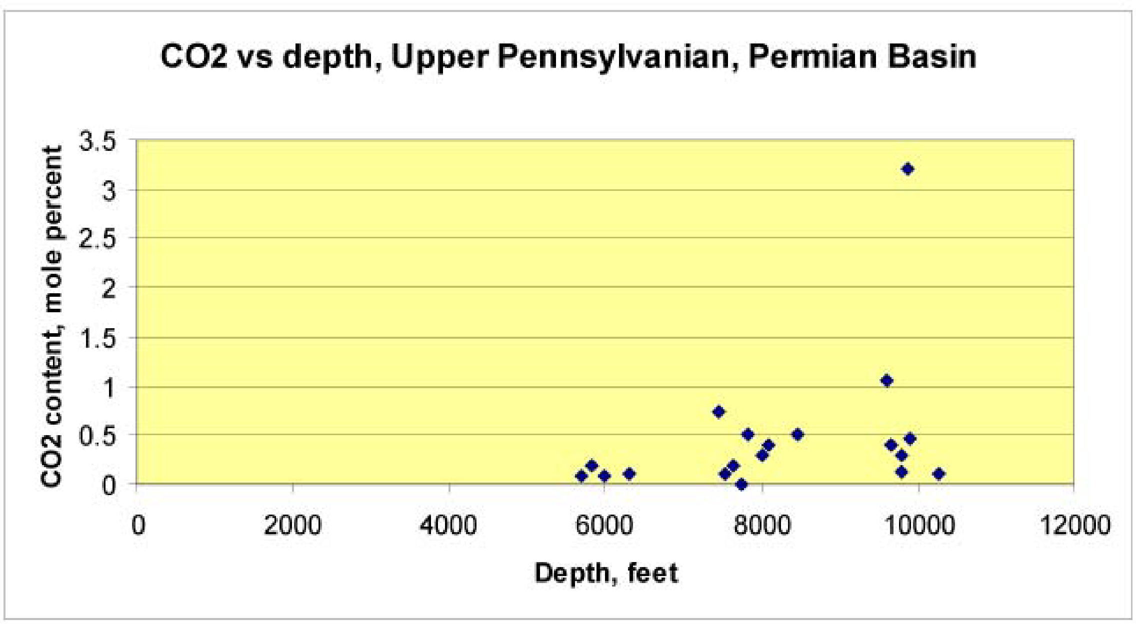

Figure PB 11. CO_2 content of Upper Pennsylvanian gases vs reservoir depth, Permian Basin.

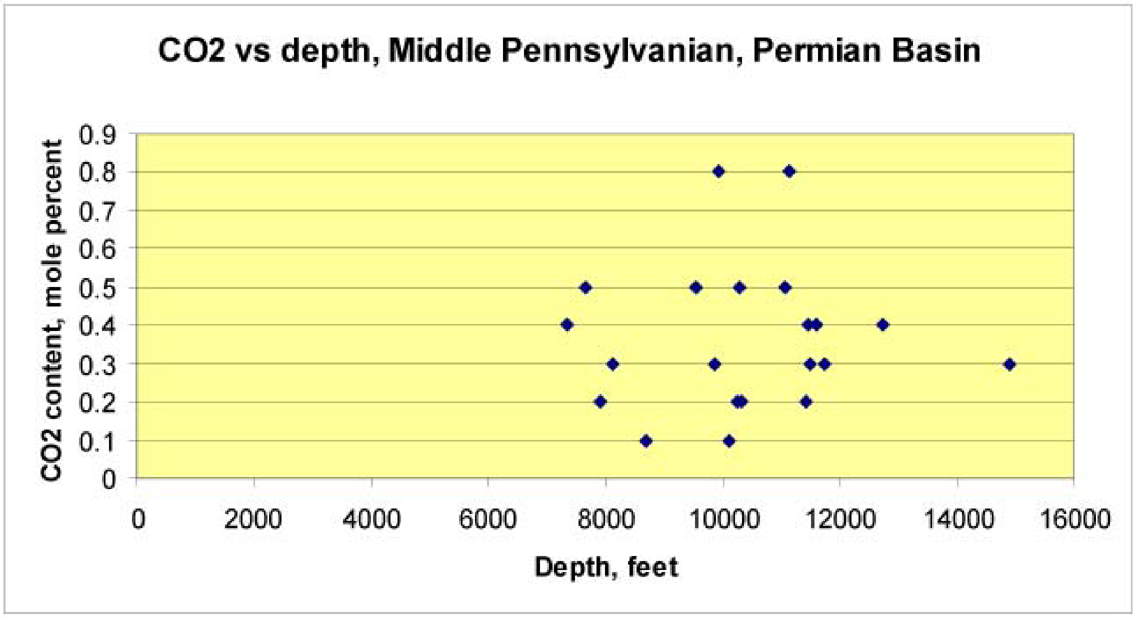

Figure PB 12. CO_2 content of Middle Pennsylvanian gases vs reservoir depth, Permian Basin.

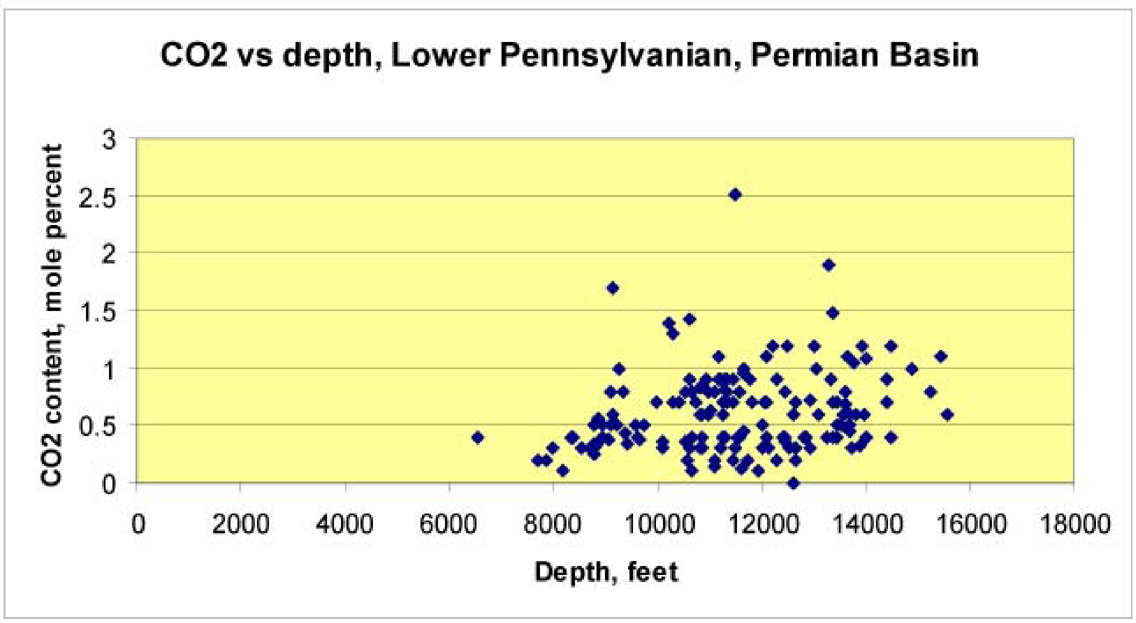

Figure PB 13. CO_2 content of Lower Pennsylvanian gases vs reservoir depth, Permian Basin.

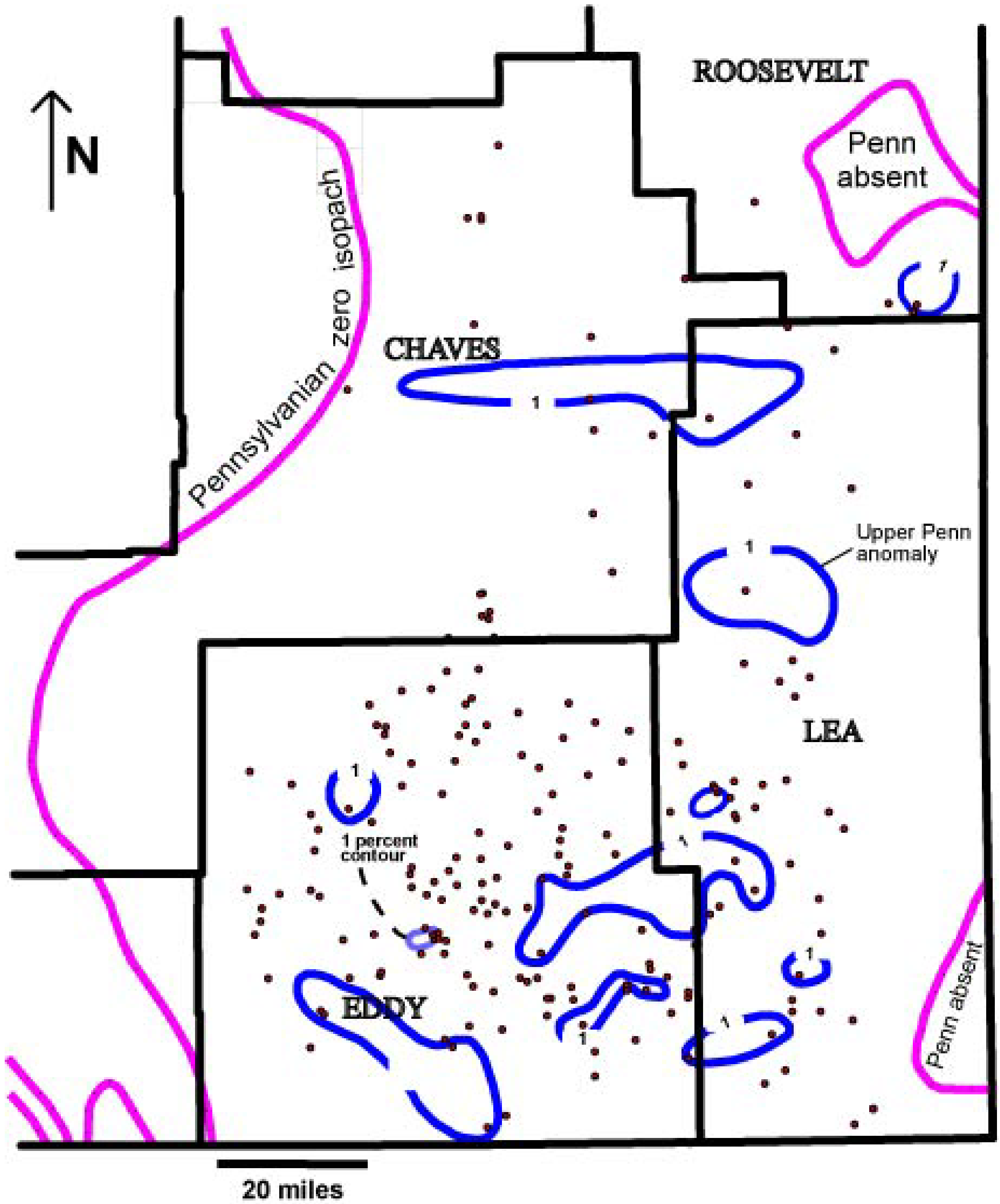

Figure PB 14. CO_2 content of gases in Pennsylvanian reservoirs in the Permian Basin of southeastern New Mexico. Pennsylvanian zero isopach lines modified from Meyer (1966).

Mississippian System

Mississippian limestones are productive of hydrocarbon gases on the Northwest Shelf, in the Tatum Basin, and in the northernmost part of the Delaware Basin (Broadhead, 2006, in press). Production is primarily gas with associated oil. Only one gas analysis is available and that is from a well productive from the Austin pool in T14S R36E, northern Lea County (Plate X in Appendix B). In that well, the gas is comprised of 86 percent methane, 11.9 percent hydrocarbon gas liquids, and only 1.3 percent CO_2. Because gases from other Mississippian reservoirs have been produced primarily for their fuel gas content, it is probable that all Mississippian gases in southeastern New Mexico consist primarily of hydrocarbons and have very low concentrations of CO_2.

Devonian and Silurian Systems

Silurian and Devonian carbonates of the Thirtyone, Wristen, and Fusselman Formations are productive of oil and natural gas in southeastern New Mexico. Forty-eight reservoirs have produced more than 1 million bbls oil and associated gas with more than 80 percent of the production obtained from the Wristen Formation (Broadhead, 2005). Gases are predominantly hydrocarbons with an average methane content of 79 percent and an average gas liquids content of 13 percent. CO_2 content is high for Permian Basin gases, averaging 4.11 percent. CO_2 content is less than 4 percent everywhere except in the Bagley reservoir where it varies from 14 to 16 percent (Figure PB 15; Plate VIII in Appendix B), skewing the overall average of these gases. The gases produced from Bagley contain higher concentrations of CO_2 than identified in any other reservoir of any age in southeastern New Mexico. There is no apparent relationship between reservoir depth and CO_2 concentration in Silurian gases except for the cluster of points at 10,500 ft in the Bagley reservoir (Figures PB 15, PB 16).

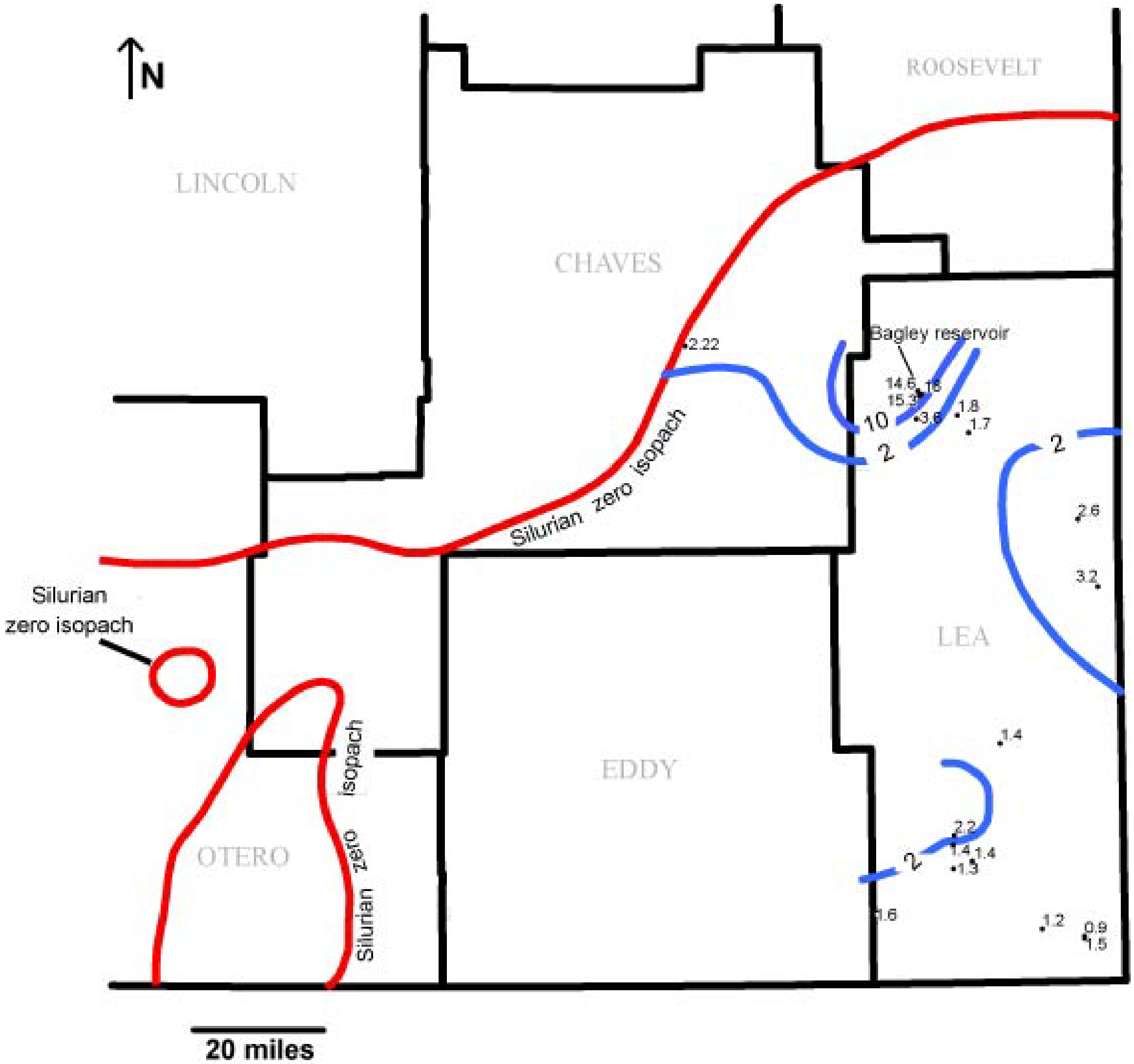

Figure PB 15. CO_2 content of gases in Silurian reservoirs in northeastern New Mexico. Silurian zero isopach modified from Grant and Foster (1989) and Broadhead (2005).

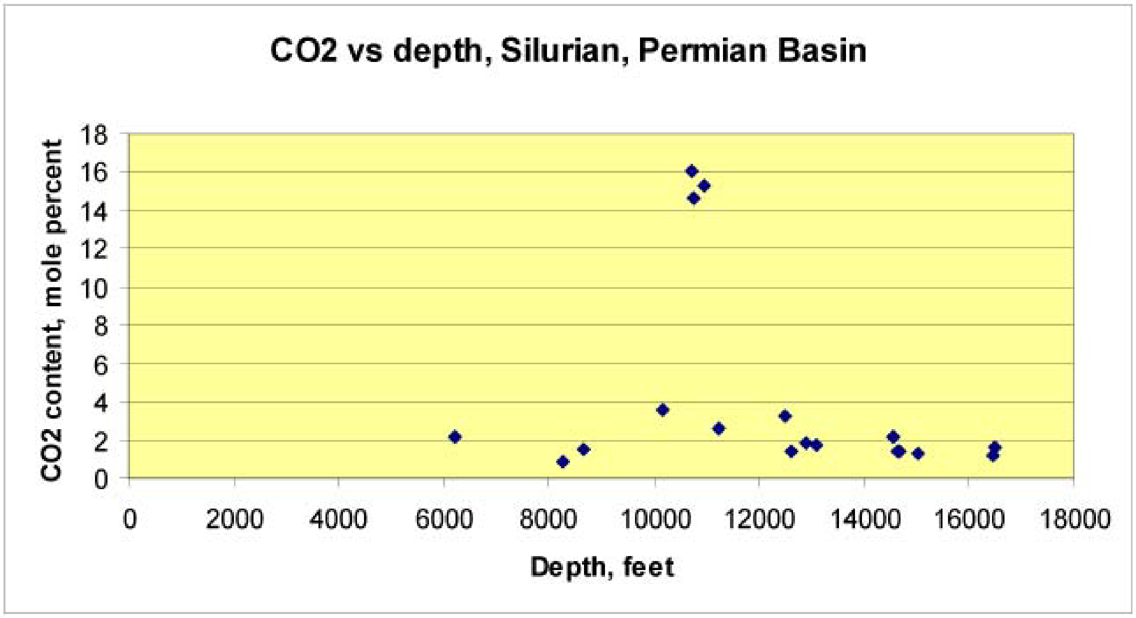

Figure PB 16. CO_2 content of Silurian gases vs reservoir depth, Permian Basin.

Ordovician System

Ordovician reservoirs of the Ellenburger, Simpson, and Montoya Groups are productive of oil and natural gas in southeastern New Mexico (Speer, 1993). Most production has been obtained from reservoirs on the Central Basin platform. But scattered reservoirs that are productive of either oil and associated gas or nonassociated gas and gas liquids are present in the Delaware Basin and on the Northwest Shelf and in the Tatum Basin. The Montoya has been productive from isolated reservoirs as far north as the Foor Ranch gas field in central Chaves County and the Tule gas field in west-central Roosevelt County. Simpson reservoirs are shallow marine sandstones. Montoya and Ellenburger reservoirs are dolostones. Although data are sparse, it appears that CO_2 concentrations in Ordovician gases are low, averaging only 1.45 percent. The highest concentration is 5.1 percent at the Lightcap West field in east-central Chaves County (Fig. PB 17; Plate VII in Appendix B). Sparse data suggest there is no apparent relationship between reservoir depth and CO_2 concentration in Ordovician gases (Figure PB 18). Ordovician gases are produced as fuel and have an average methane content of 83 percent and an average gas liquids content of almost 11 percent.

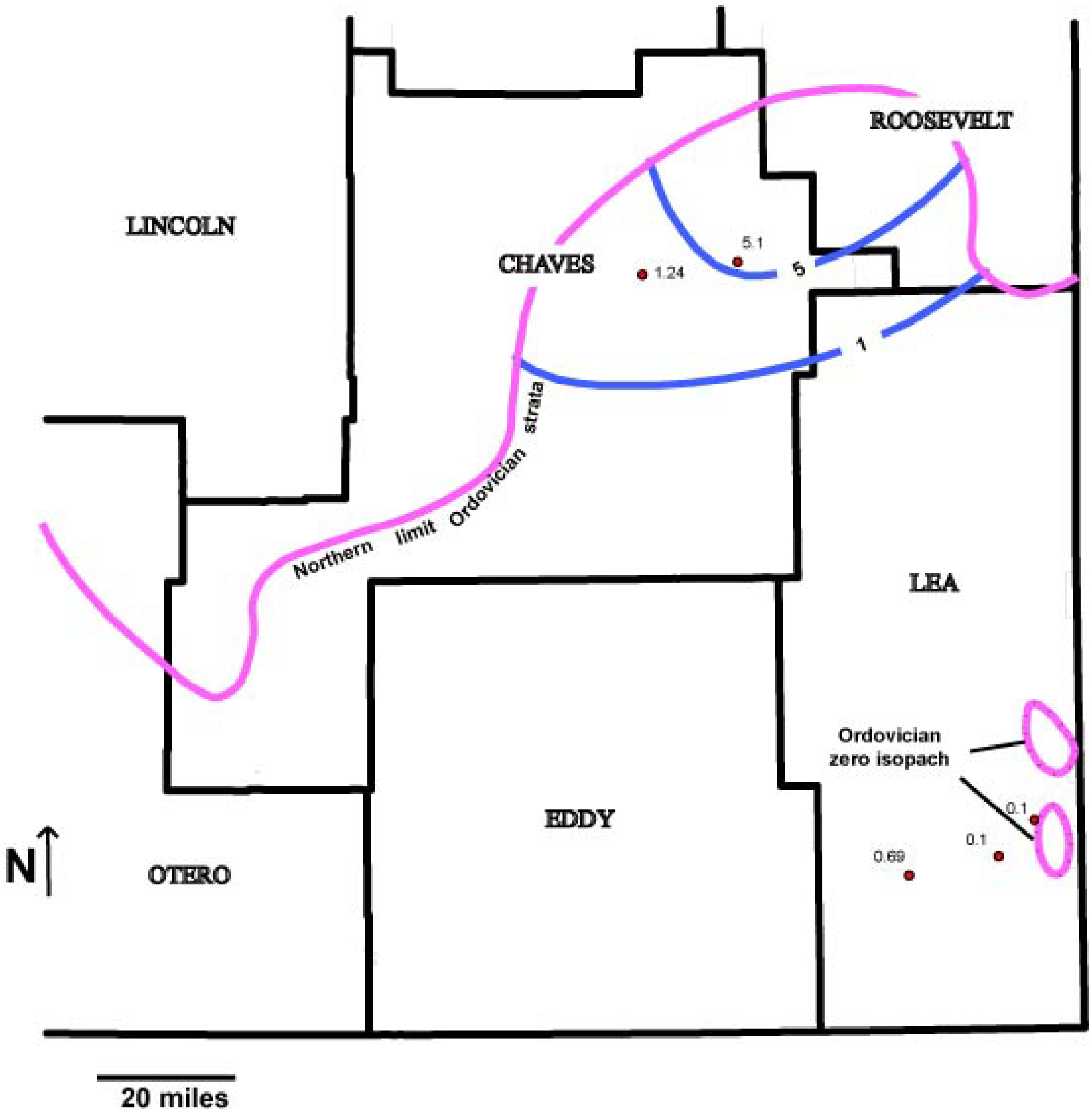

Figure PB 17. CO_2 content of gases in Ordovician reservoirs of southeastern New Mexico. Northern limit Ordovician strata and Ordovician zero isopach from Grant and Foster (1989).

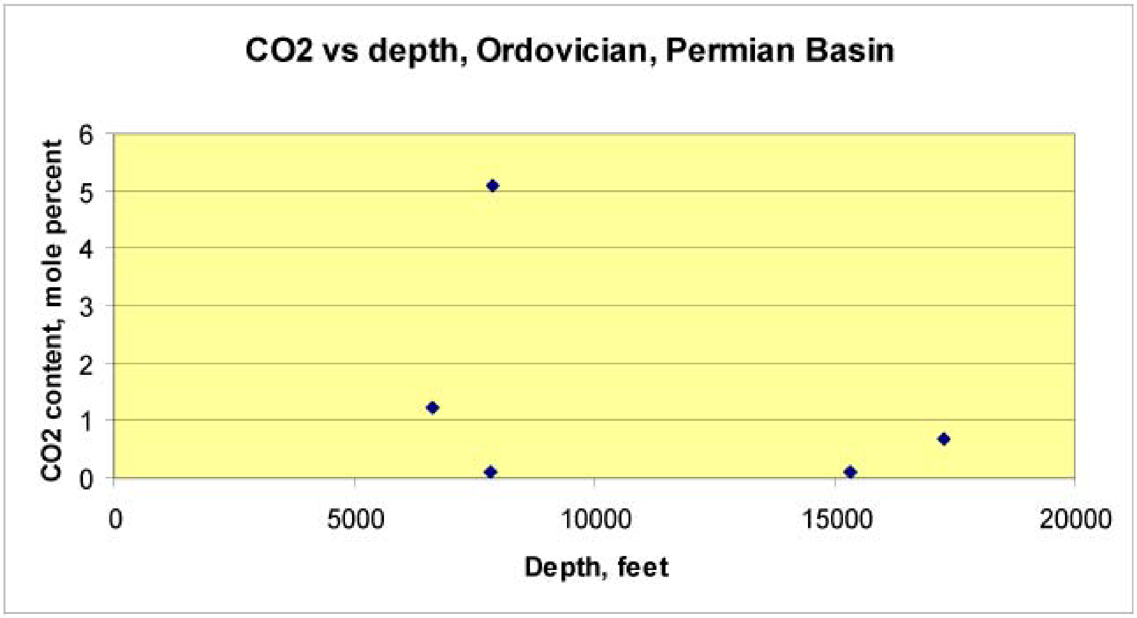

Figure PB 18. CO_2 content of Ordovician gases vs reservoir depth, Permian Basin.

CO_2 in San Juan Basin, northwestern New Mexico

Most gases in the San Juan Basin have relatively low concentrations of CO_2 (Figure SJ 1). Most gases in Cretaceous reservoirs contain less than 1 percent CO_2, but gases in coal reservoirs of the Fruitland Formation and sandstone reservoirs of the Pictured Cliffs Sandstone, the Mesaverde Group and the Dakota Group contain more than 1 percent CO_2 along trends in the deep northern portion of the New Mexico part of the basin. Although data are sparse, gases in Triassic and Permian reservoirs contain less than 1 percent CO_2. Gases in Pennsylvanian reservoirs contain contain more than 10 percent CO_2 along trends on the Four Corners platform and in deeper parts of the San Juan Basin. Mississippian gases contain more than 50 percent CO_2 throughout most of the basin and appear to have more than 90 percent CO_2 in large areas. Devonian reservoirs bear gases with less than 1 percent CO_2 on the Four Corners platform but may contain CO_2-rich gases in the deep San Juan Basin. Fractured basement rocks may locally contain CO_2-rich gases.

Tertiary System

Only three analyses were available for gases recovered from Tertiary reservoirs (Figure SJ 1). These were for gases obtained from sandstones in the Nacimiento Formation and Ojo Alamo Sandstone. CO_2 content of these gases is low, averaging 0.33 percent with a maximum of 0.50 percent. These gases consist mostly of hydrocarbons with an average methane content of 82.3 percent and gas liquids ranging from 2 to 20 percent. Nitrogen content is low but variable, ranging from 1 to 12 percent.

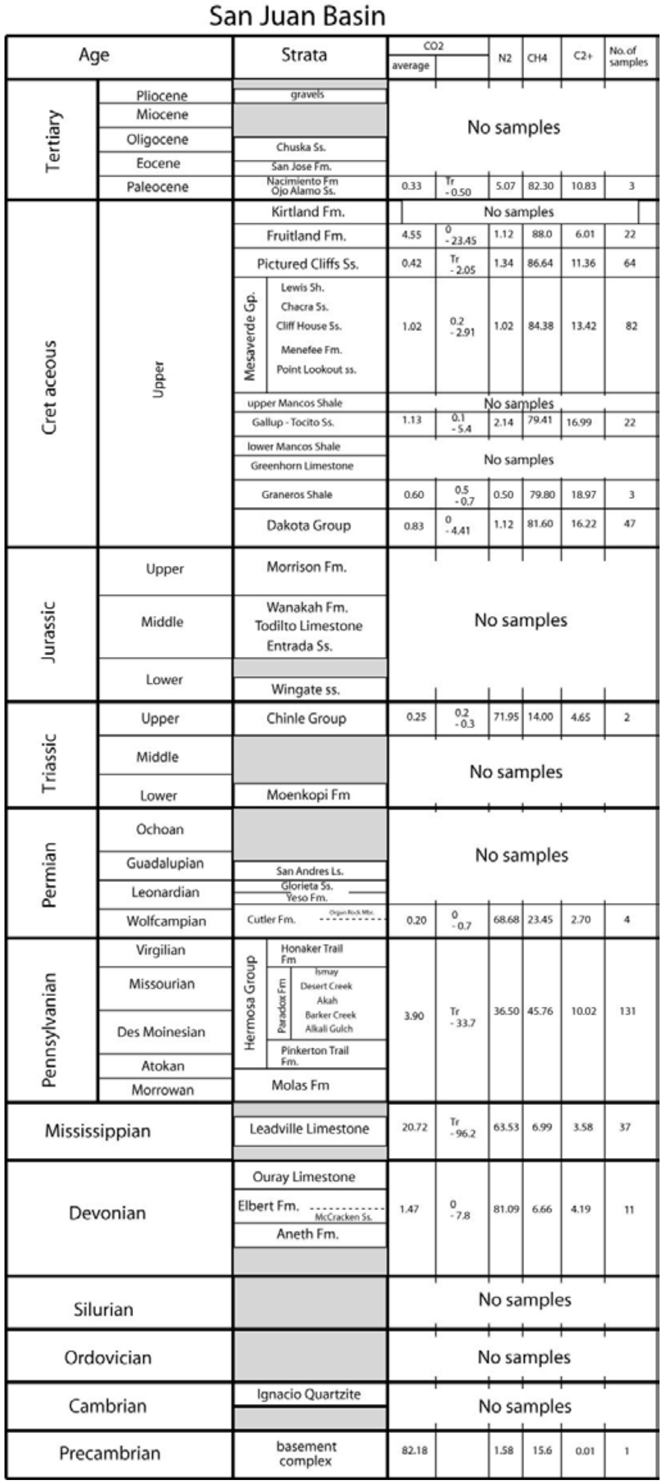

Figure SJ 1. Stratigraphic column of San Juan Basin and composition of gases in stratigraphic units. Values are averages except for the right CO_2 column which is the range of values.

Cretaceous System

Fruitland Formation

Coalbeds of the Fruitland Formation are significant gas reservoirs in the San Juan Basin (Kaiser and Ayers, 1994; Figure SJ 2). Gases from these reservoirs are produced for their hydrocarbon content. In 2007, the Fruitland coalbed reservoirs produced 470 BCF gas, 48 percent of the gas produced from the New Mexico part of the San Juan Basin and 31 percent of all gas produced from New Mexico. Stratigraphically associated sandstones in the Fruitland Formation produce additional volumes of gas.

CO_2 content of Fruitland gases ranges from a trace to more than 20 percent (Figure SJ 3; Plate XIX in Appendix B). Gases with higher CO_2 contents occur in Fruitland coalbeds and not in the stratigraphically associated Fruitland sandstones. Gases obtained from the Fruitland sandstone reservoirs generally contain less than 1 percent CO_2 in the southern part of the San Juan Basin; in the northern part of the basin gases in Fruitland sandstones average 2.2 percent CO_2 with a maximum CO_2 content of 3.4 percent (Scott and others, 1994).

Fruitland coalbeds in the deep northern parts of the basin are overpressured while Fruitland coalbeds in the southern part of the basin are underpressured (Kaiser et al, 1994). Within the Fruitland coalbeds, gases in overpressured areas in the northern part of the basin contain more CO_2 than gases in underpressured areas in the southern part of the basin; the overpressured areas are generally characterized by CO_2 contents of more than 3 percent (Scott and others, 1994). Gases with more than 5 percent CO_2 occur at burial depths of more than 2600 ft (Figure SJ 4). However, several gases from depths of more than 2600 ft contain less than 1 percent CO_2. All Fruitland gases from depths shallower than 2600 ft contain less than 1 percent CO_2.

Scott and others related the distribution of CO_2 in Fruitland gases to the thermal maturity of the coals (coal rank) and to basin hydrology. They concluded that some of the CO_2 has a thermogenic origin and was generated from the coals. The remainder of the CO_2 was thought by Scott and others to have been generated bacterially in the shallower parts of the basin as a byproduct of biogenic methane gas generation and subsequently transported in solution to deeper parts of the basin by movement of formation waters where it was released as a separate gas phase during production-related pressure decline.

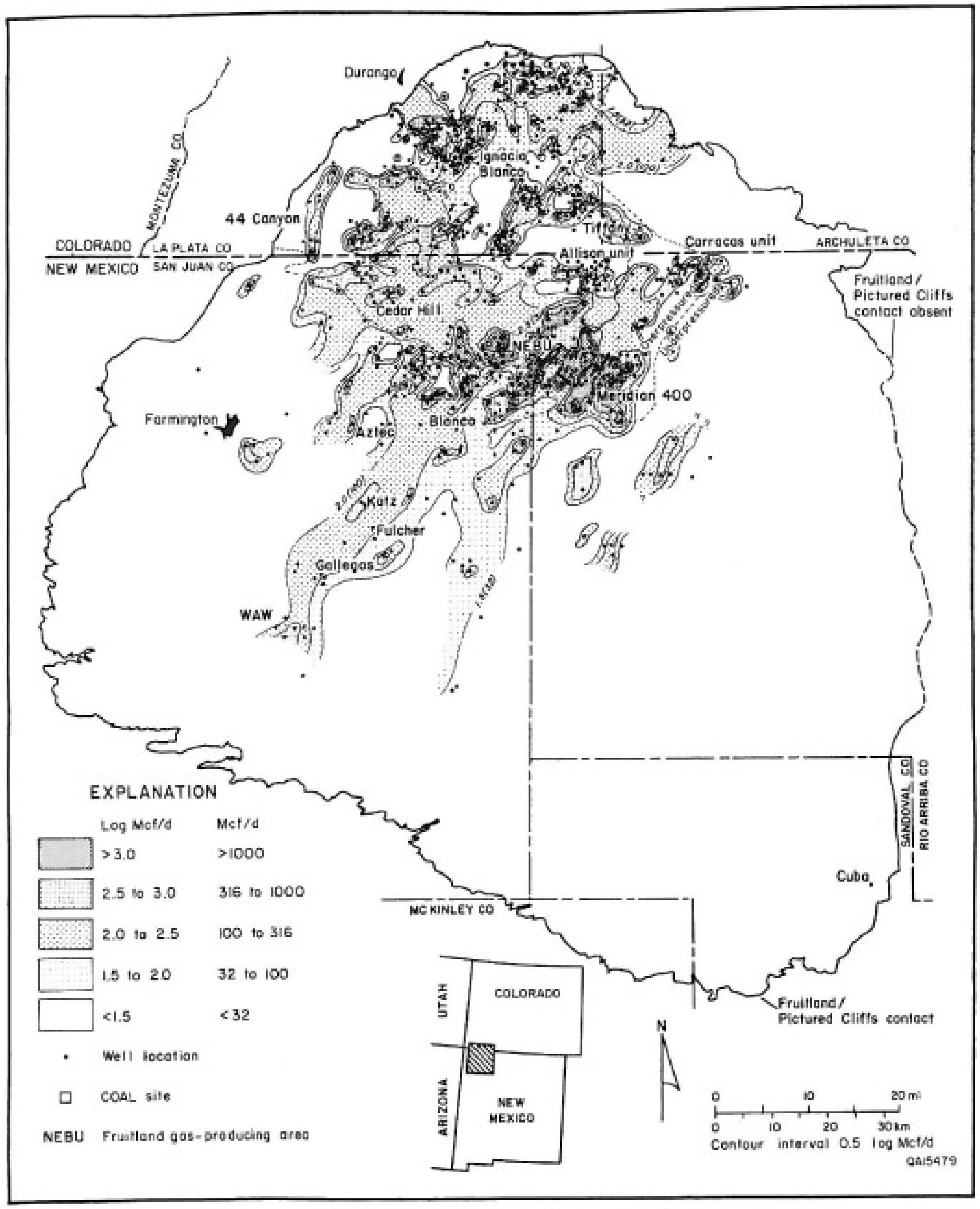

Figure SJ 2. Map of initial gas potential in Fruitland coalbed methane wells, San Juan Basin of New Mexico and Colorado. From Kaiser and Ayers (1994).

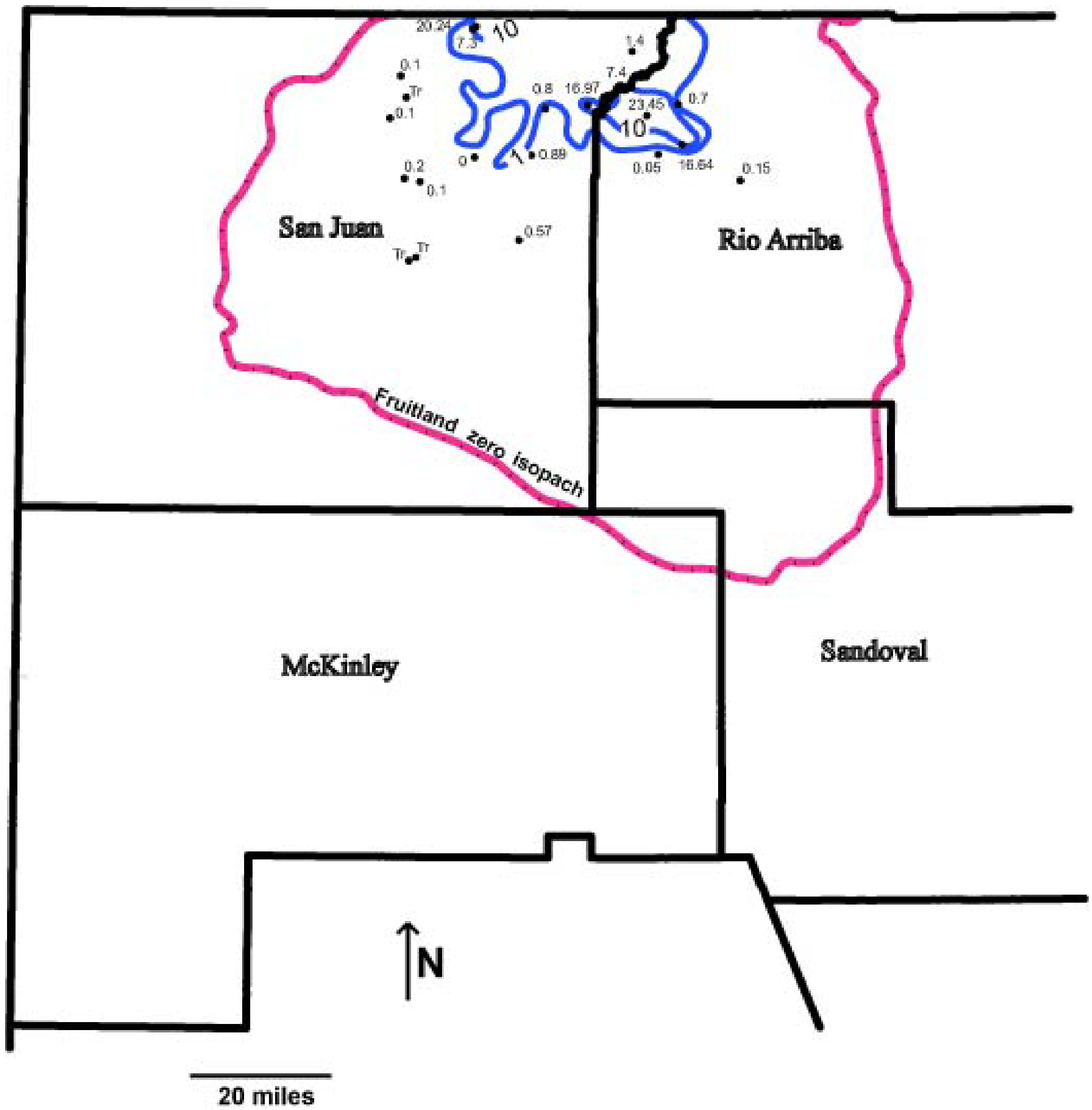

Figure SJ 3. CO_2 content in gases of the Fruitland Formation in the San Juan Basin. Fruitland zero isopach line from New Mexico Bureau of Geology and Mineral Resources (2003).

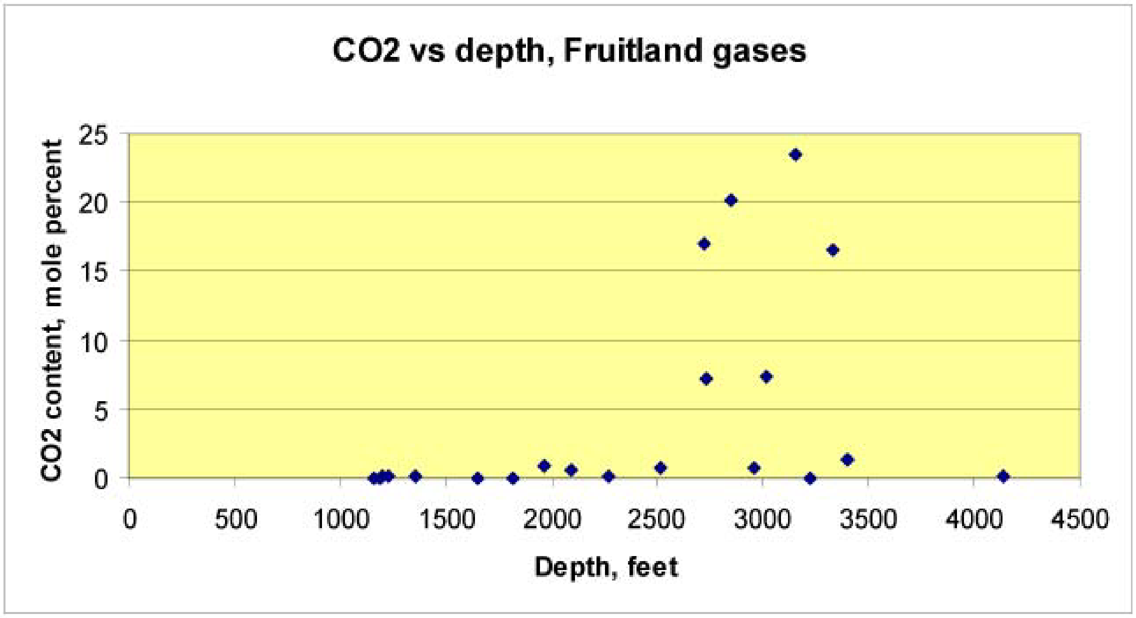

Figure SJ 4. CO_2 content of Fruitland gases vs reservoir depth, San Juan Basin.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone, which underlies and intertongues with the Fruitland Formation, is a major natural gas reservoir in the San Juan Basin (Whitehead, 1993a; Figure SJ 5). CO_2 content of Pictured Cliffs gases averages 0.42 percent and ranges from a trace to 2.8 percent. In general, CO_2 content increases to the north (Figure SJ 6; Plate XVIII in Appendix B; Whitehead, 1993a). Pictured Cliffs gases with more than 1 percent CO_2 occur only at depths below 2800 ft (Figure SJ 7). Pictured Cliffs gases with less than 1 percent CO_2 are present at depths above 2800 ft as at depths below 2800 ft. Scott and others (1994) indicated that the Pictured Cliffs has two small areas, perhaps defined by solitary wells, that may be characterized by gases with CO_2 contents as high as 10 percent in the deeper, northern parts of the basin. Scott and others (1994) hypothesized that Pictured Cliffs gases have higher CO_2 content in places where there is communication with the overlying Fruitland coals; in these areas, the Fruitland acts as a partial source for the gases in Pictured Cliffs reservoirs although the Lewis Shale is also a source of gases in the Pictured Cliffs based upon analyses of gas wetness/dryness and nitrogen content. Alternatively, Scott and others (1994) hypothesized that well completions that straddle the Fruitland-Pictured Cliffs boundary may be responsible for elevated levels of CO_2, presumably acting to

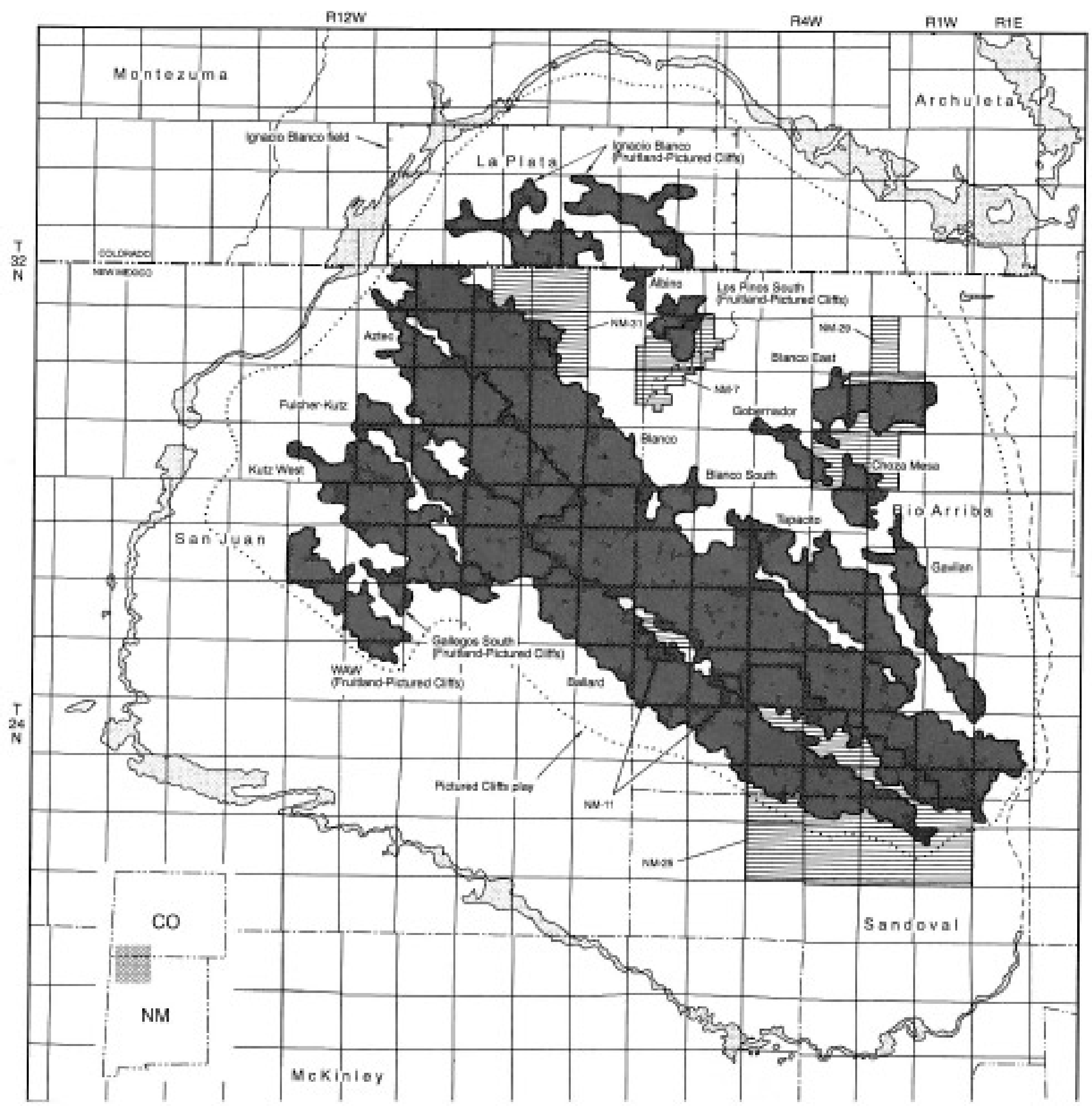

Figure SJ 5. Gas reservoirs in the Pictured Cliffs Formation of the San Juan Basin. Areas with horizontal line patterns are designated tight gas areas. From Whitehead (1993a).

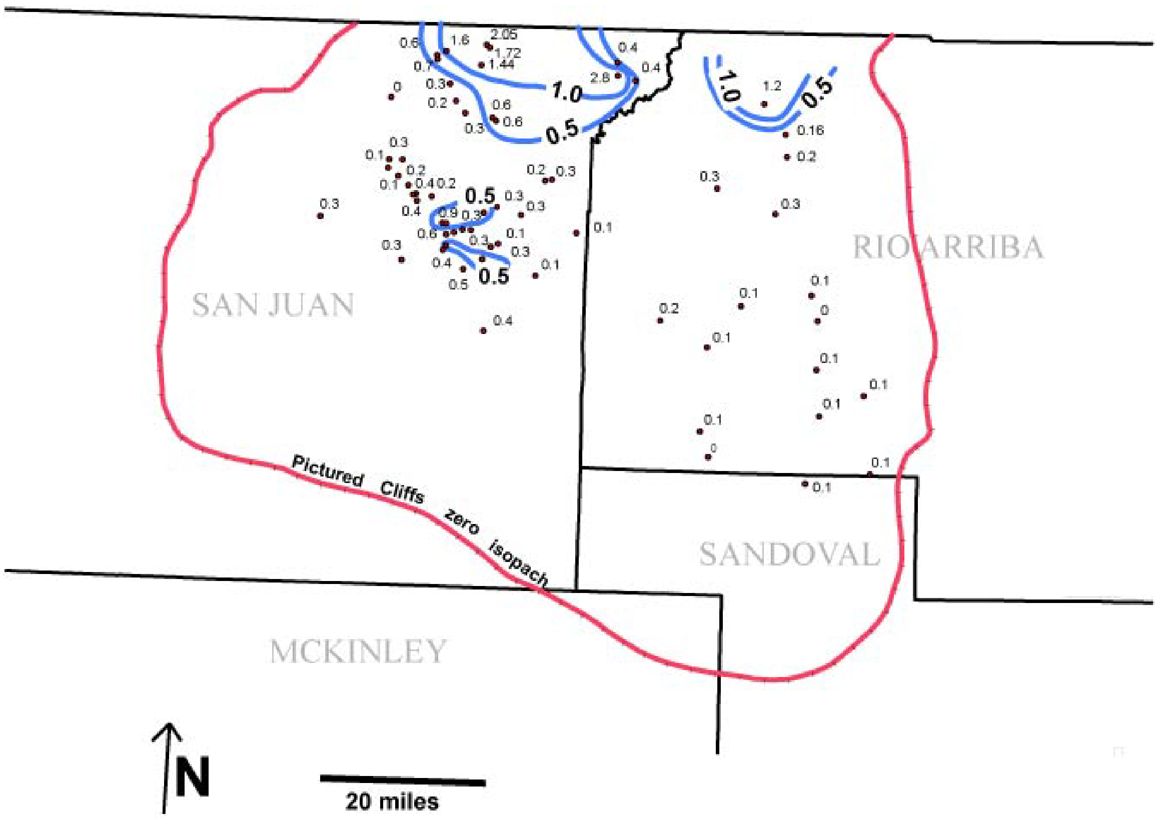

Figure SJ 6. CO_2 content in gases of the Pictured Cliffs Sandstone in the San Juan Basin. Pictured Cliffs zero isopach lines from New Mexico Bureau of Geology and Mineral Resources (2003).

commingle CO_2-rich Fruitland gases with CO_2-poor Pictured Cliffs gases. Other workers conclude that the Fruitland coals were the main sources of the gas in the Pictured Cliffs. Rice (1983) utilized gas composition data and carbon isotopic analyses to conclude that Pictured Cliffs gases were derived from the Fruitland coals. Choate and others (1984) also concluded on the basis of gas composition that the Fruitland coals were the main source of Pictured Cliffs gases. As there appears to be some doubt of the source of the Pictured Cliffs gases, there will also be uncertainty about the source of the CO_2 in the Pictured Cliffs reservoirs. What is certain is that areas of Pictured Cliffs gases with the highest CO_2 concentrations are roughly coincident with areas of highest CO_2 concentration in Fruitland gases.

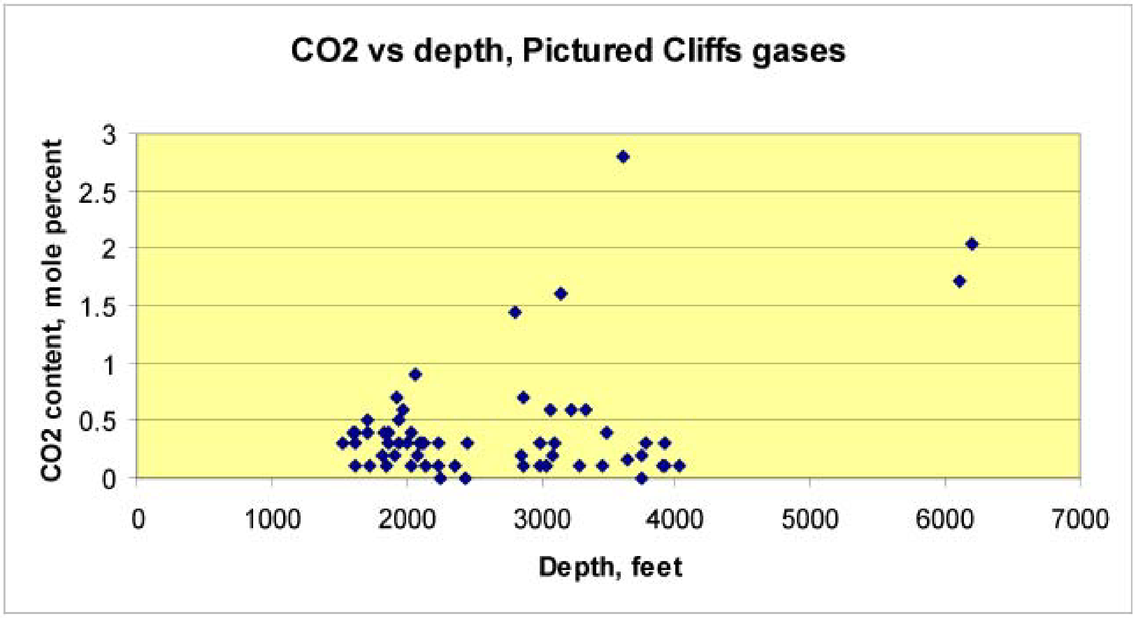

Figure SJ 7. CO_2 content of Pictured Cliffs gases vs reservoir depth, San Juan Basin.

Mesaverde Group

The Mesaverde Group consists of several nonmarine, parallic, and shallow-marine sandstone stratal units that intertongue northward with the marine Mancos and Lewis Shales (Figure SJ 8). Although most of the sandstone units are productive of gas, most of the production is obtained from the Point Lookout Sandstone. The regional trap in the Point Lookout Sandstone forms one of the largest natural gas accumulations in the San Juan Basin (Whitehead, 1993b; Figure SJ 9). In many wells, production from the Point Lookout is commingled with production from other reservoirs in the Mesaverde Group. For this report, CO_2 content of gases is mapped for the Mesaverde Group as a whole (Figure SJ 10; Plate XVII in Appendix B). CO_2 content of Mesaverde gases averages 1.02 percent and ranges from 0.2 to 2.91 percent (Figure SJ 1). CO_2 concentrations of more than 1 percent are found in the northern, deeper parts of the basin (Figure SJ 10). Only reservoirs with a present day burial depth of more than 5000 ft have gases with CO_2 concentrations more than 1.5 percent (Figure SJ 11), although numerous reservoirs at depths of more than 5000 ft also have gases with less than 1.1 percent CO_2. All reservoirs with present-day burial depths less than 5000 ft contain gases with less than 1.1 percent CO_2. There are no Mesaverde gases that have CO_2 concentrations between 1.1 and 1.5 percent, suggesting that there are two families of gases – those with more than 1.5 percent CO_2 and those with less than 1.1 percent CO_2. Areas of higher CO_2 concentrations in Mesaverde gases are approximately coincident with areas of higher CO_2 concentrations in the overlying Pictured Cliffs and Fruitland Formations (Figures SJ 3, SJ 6).

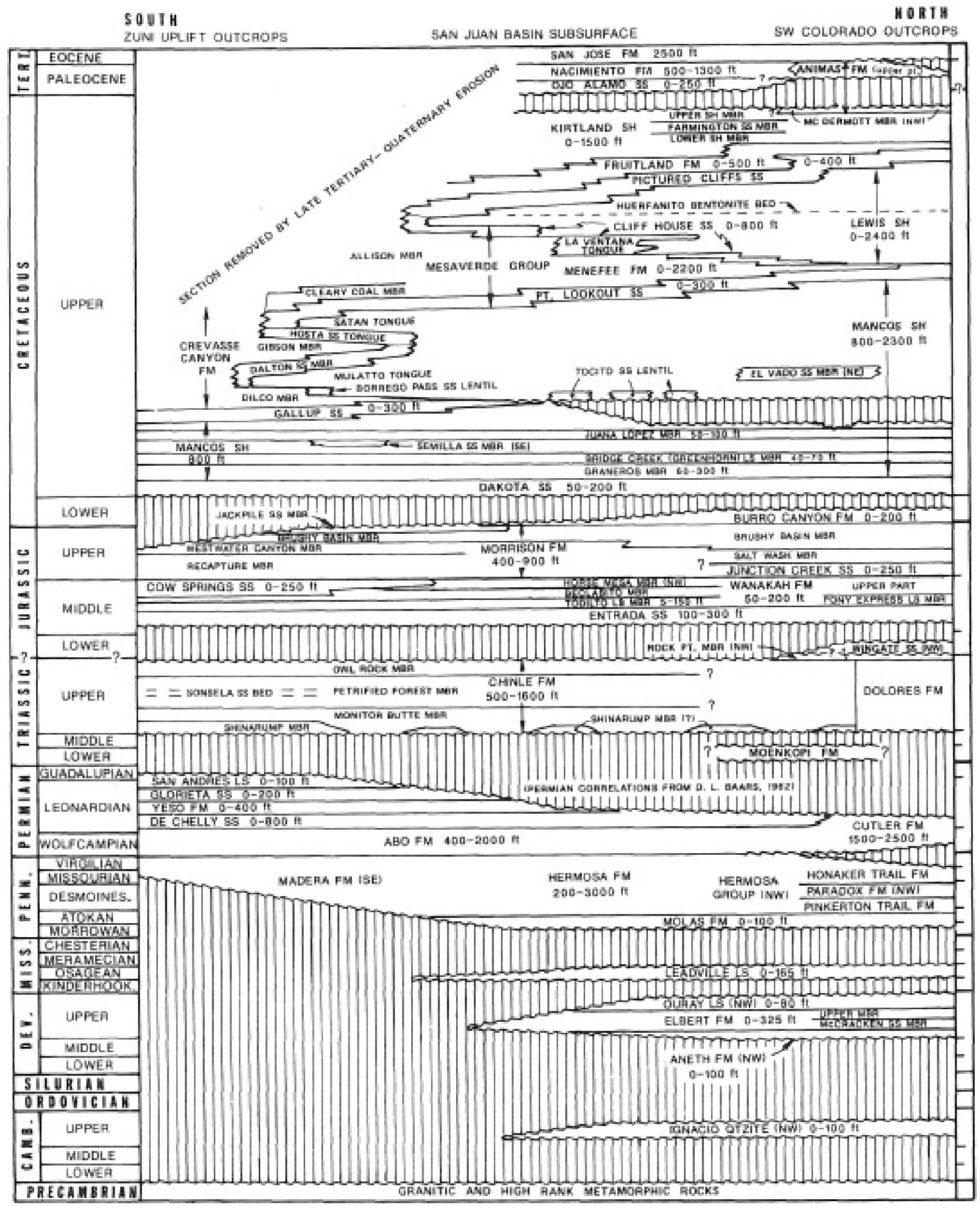

Figure SJ 8. San Juan Basin stratigraphic correlation chart. From Molenaar (1991).

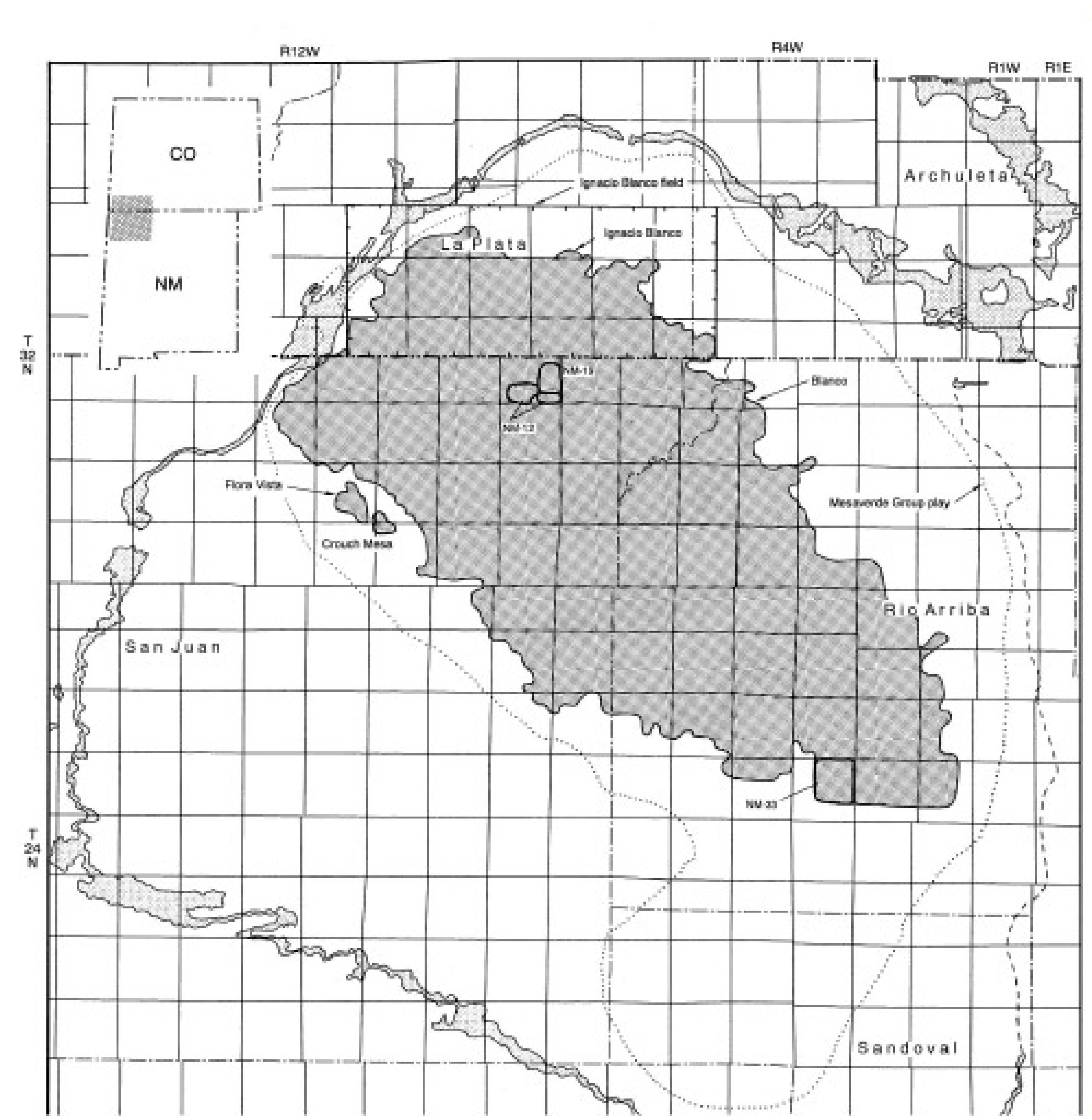

Figure SJ 9. Gas reservoirs productive from Mesaverde sandstone reservoirs in San Juan Basin. From Whitehead (1993b).

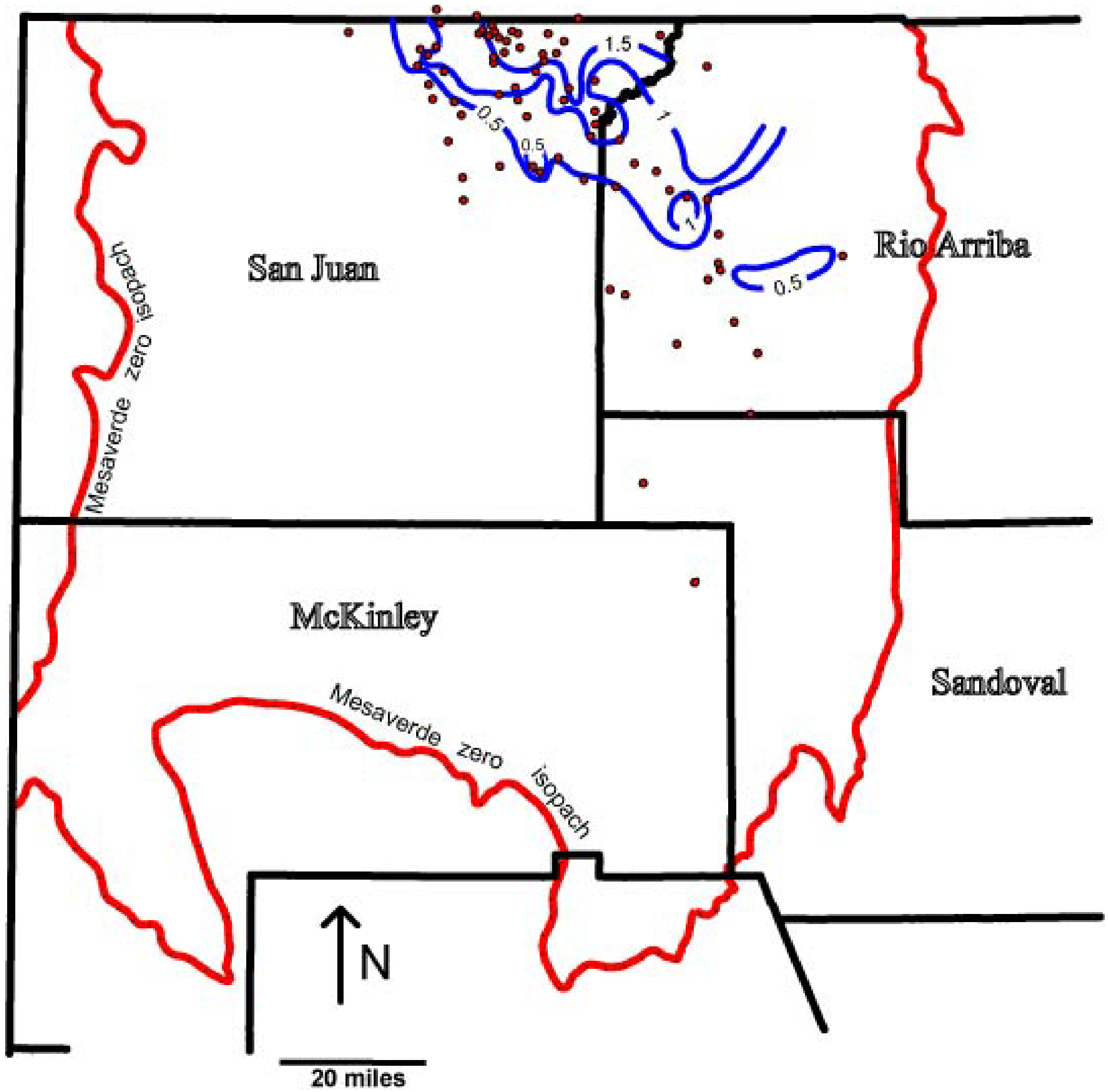

Figure SJ 10. CO_2 content in gases of the Mesaverde Group in the San Juan Basin. Mesaverde zero isopach lines from New Mexico Bureau of Geology and Mineral Resources (2003).

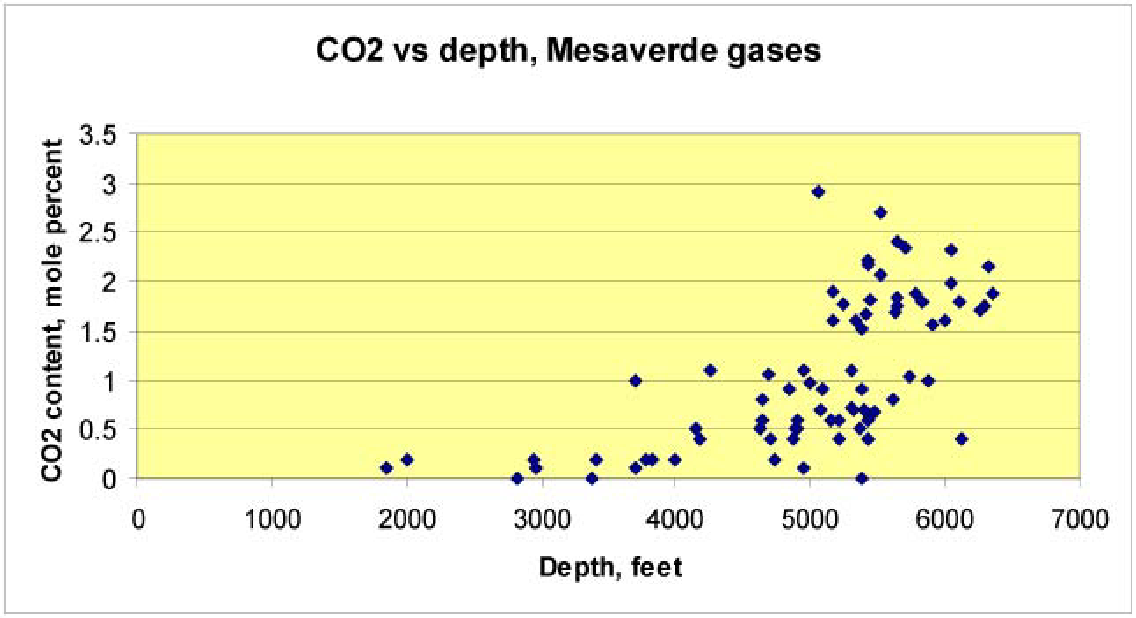

Figure SJ 11. CO_2 content of Mesaverde gases vs reservoir depth, San Juan Basin.

Gallup-Tocito sandstones

Most of the oil and gas reservoirs in the San Juan Basin that have traditionally been assigned to the "Gallup Sandstone" actually are in the Tocito Sandstone and lateral equivalents in the lower part of the Upper Mancos Shale (see Figure SJ 8). The Tocito and equivalent sandstones are separated from the true Gallup Sandstone by a regional unconformity. Reservoirs in the Tocito sandstones were formed by northwest-southeast trending shoestring sandstones that were deposited as offshore bars (Figure SJ 12; Sabins, 1963; Molenaar, 1973). These reservoirs are productive of oil and associated gas and are among the largest oil reservoirs in the basin. CO_2 concentrations of Gallup-Tocito gases averages 1.13 percent and ranges from 0.1 to 5.4 percent (Figure SJ 1). Most Gallup-Tocito gases contain less than 0.5 percent CO_2. Unlike other Upper Cretaceous reservoirs in the San Juan Basin, there does not appear to be a relationship between depth and CO_2 content of gases (Figure SJ 13).

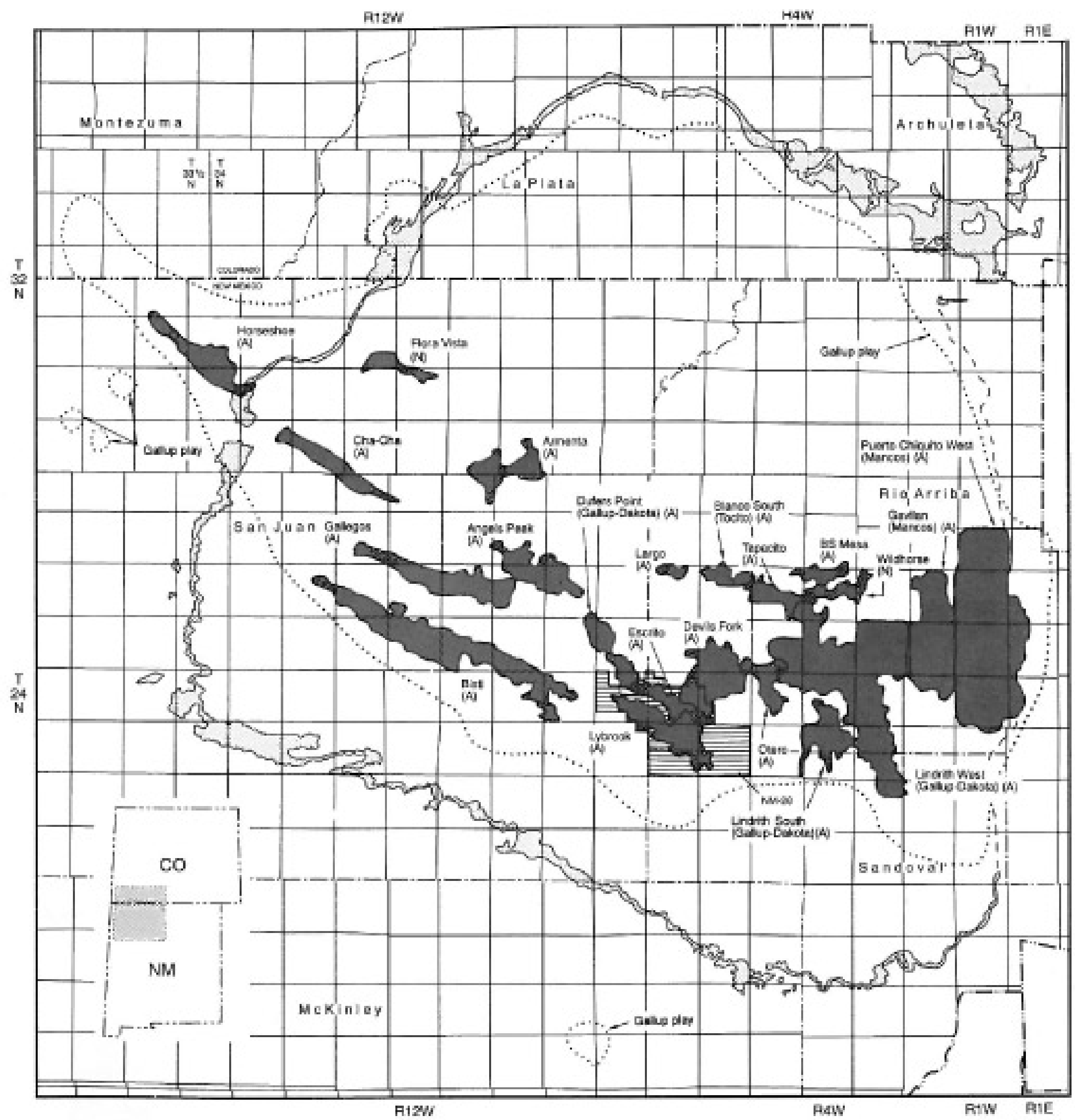

Figure SJ 12. Reservoirs productive from Gallup-Tocito sandstones in San Juan Basin. Areas with horizontal line patterns are designated tight gas areas. From Whitehead (1993c).

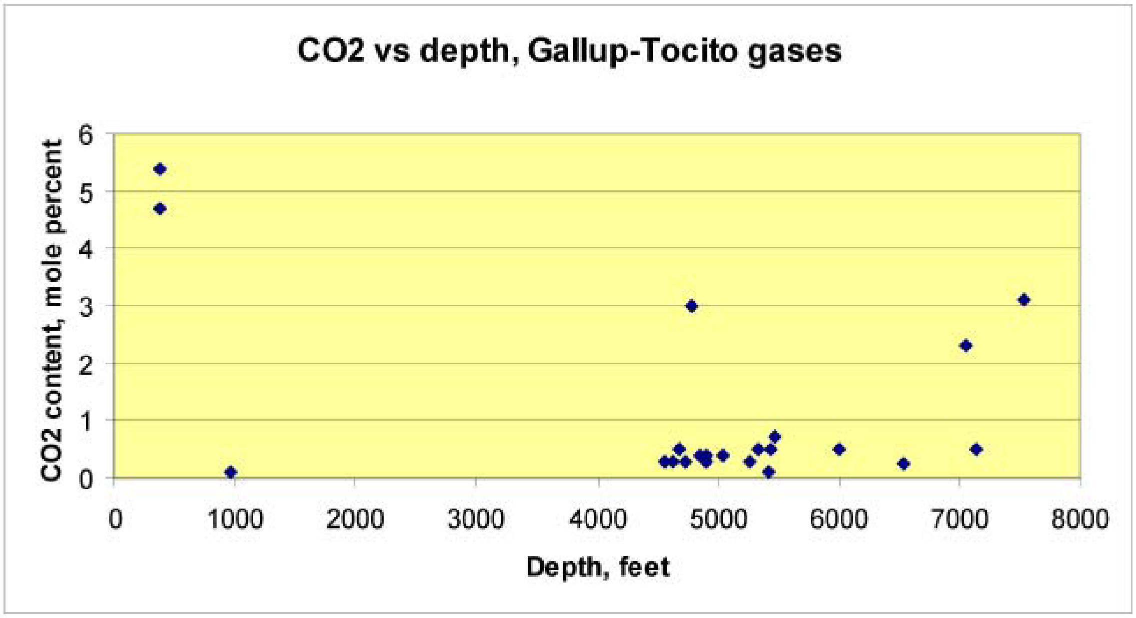

Figure SJ 13. CO_2 content of Gallup-Tocito gases vs reservoir depth, San Juan Basin.

Dakota Group

Sandstones of the Dakota Group form the base of the Cretaceous section in the San Juan Basin (Figure SJ 8). Dakota sandstones are productive across large areas of the San Juan Basin (Figure SJ 14; Whitehead, 1993d). CO_2 content of gases in Dakota reservoirs is low, averaging 0.83 percent and ranging from 0 to 4.41 percent (Figure SJ 1). As with the other blanket-type Cretaceous reservoirs in the San Juan Basin, CO_2 content of gases increases northward into the deeper, axial parts of the basin (Figure SJ 15; Plate XVI in Appendix B). Similar to the other blanket-type reservoirs, there appears to be a relationship between CO_2 content and reservoir depth (Figure SJ 16).

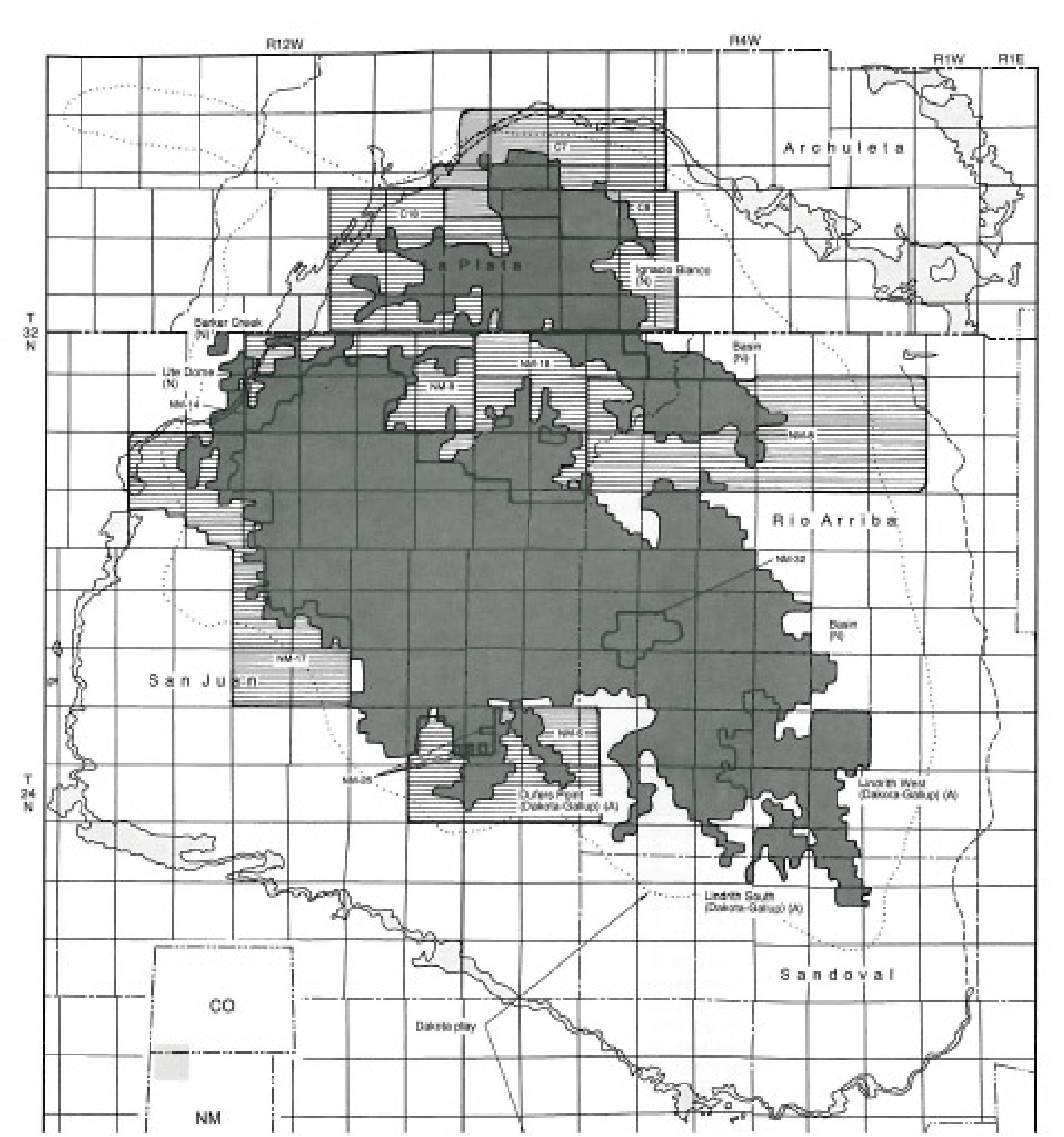

Figure SJ 14. Reservoirs productive from Dakota sandstones of the San Juan Basin. Areas with horizontal line patterns are designated tight gas areas. From Whitehead (1993d).

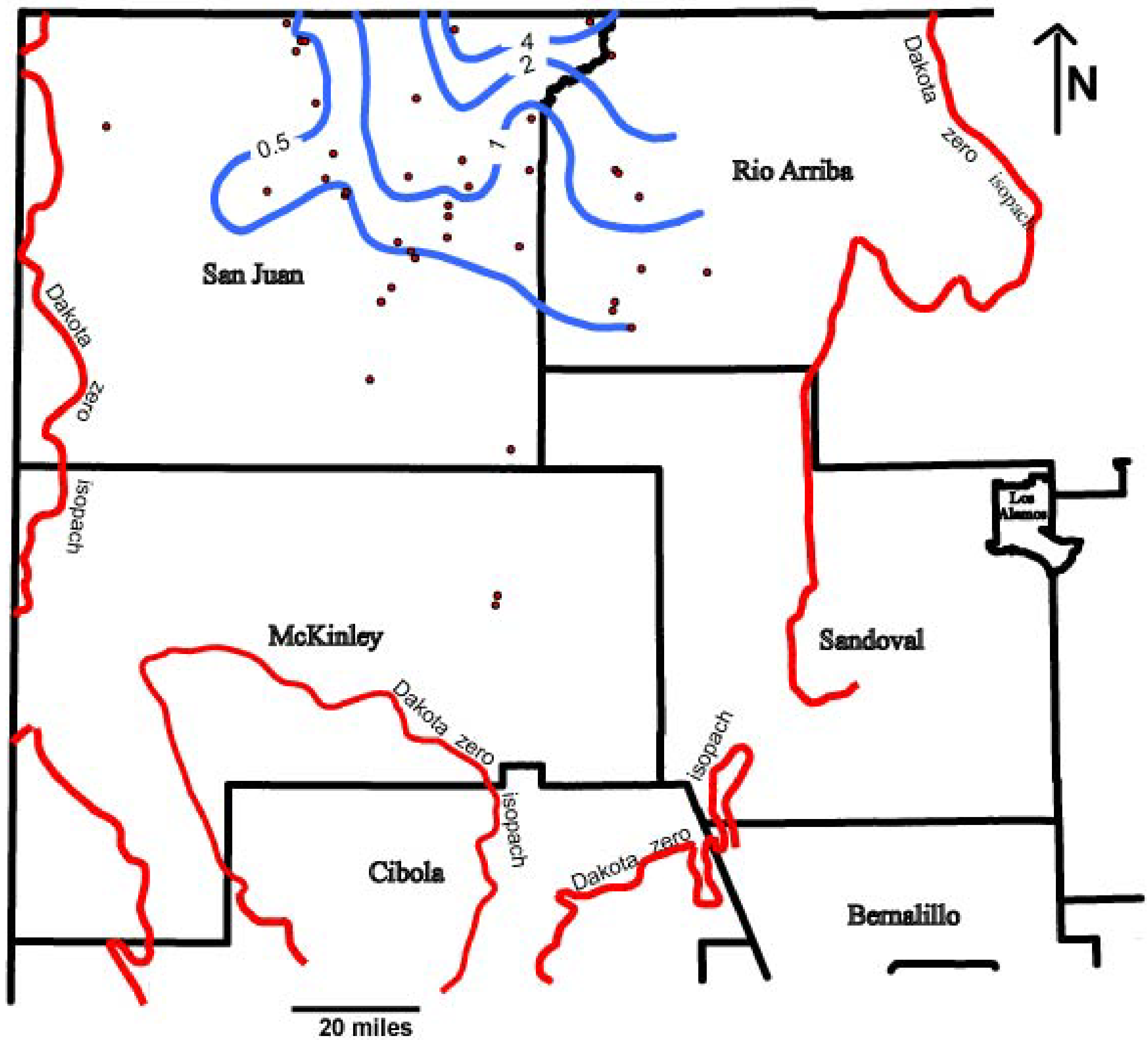

Figure SJ 15. CO_2 content in gases of the Dakota Group in the San Juan Basin. Dakota zero isopach lines from New Mexico Bureau of Geology and Mineral Resources (2003).

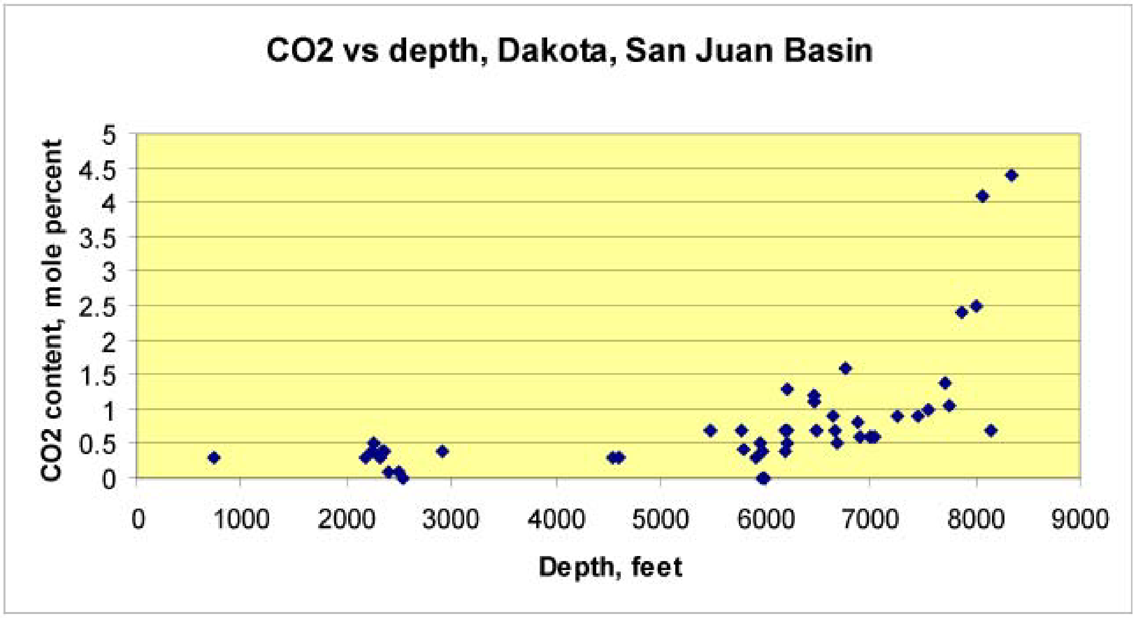

Figure SJ 16. CO_2 content of Dakota gases vs reservoir depth, San Juan Basin.

Jurassic System

Relatively modest volumes of oil are produced from a few isolated, small reservoirs in the Entrada Sandstone in southeastern San Juan, northeastern McKinley, and northwestern Sandoval Counties (Vincelette and Chittum, 1981). No analyses of natural gases recovered from Jurassic reservoirs in the San Juan Basin were available for this study.

Triassic System

The nonmarine Triassic redbeds of the San Juan basin are comprised primarily of fluvial to lacustrine shales and interbedded sandstones. Only two analyses of Triassic natural gases were available. The analyses represent different sample dates of a reservoir in the Chinle Formation on the Four Corners platform. They indicate low CO_2 concentrations, with a maximum value of 0.3 percent (Figure SJ 1; Plate XIV in Appendix B). The gas is dominantly nitrogen and helium is present in anomalously high amounts of 8.9 and 9.1 percent.

Permian System

Four analyses were available for gases obtained from Permian reservoirs. All samples came from reservoirs in the Cutler Formation (Figure SJ 1, Figure SJ 17; Plate XII in Appendix B). All four of the samples are from wells on the Four Corners platform. Average CO_2 content is 0.20 percent. CO_2 content ranges from 0 to 0.7 percent. Nitrogen content is high in three of the four wells, ranging from 88 to 91 percent and helium content is anomalously high, ranging from 4.17 to 5.65 percent. Gas from the northeastern most of the four wells contains 82.8 percent methane, 9 percent hydrogen, and only 0.52 percent helium.

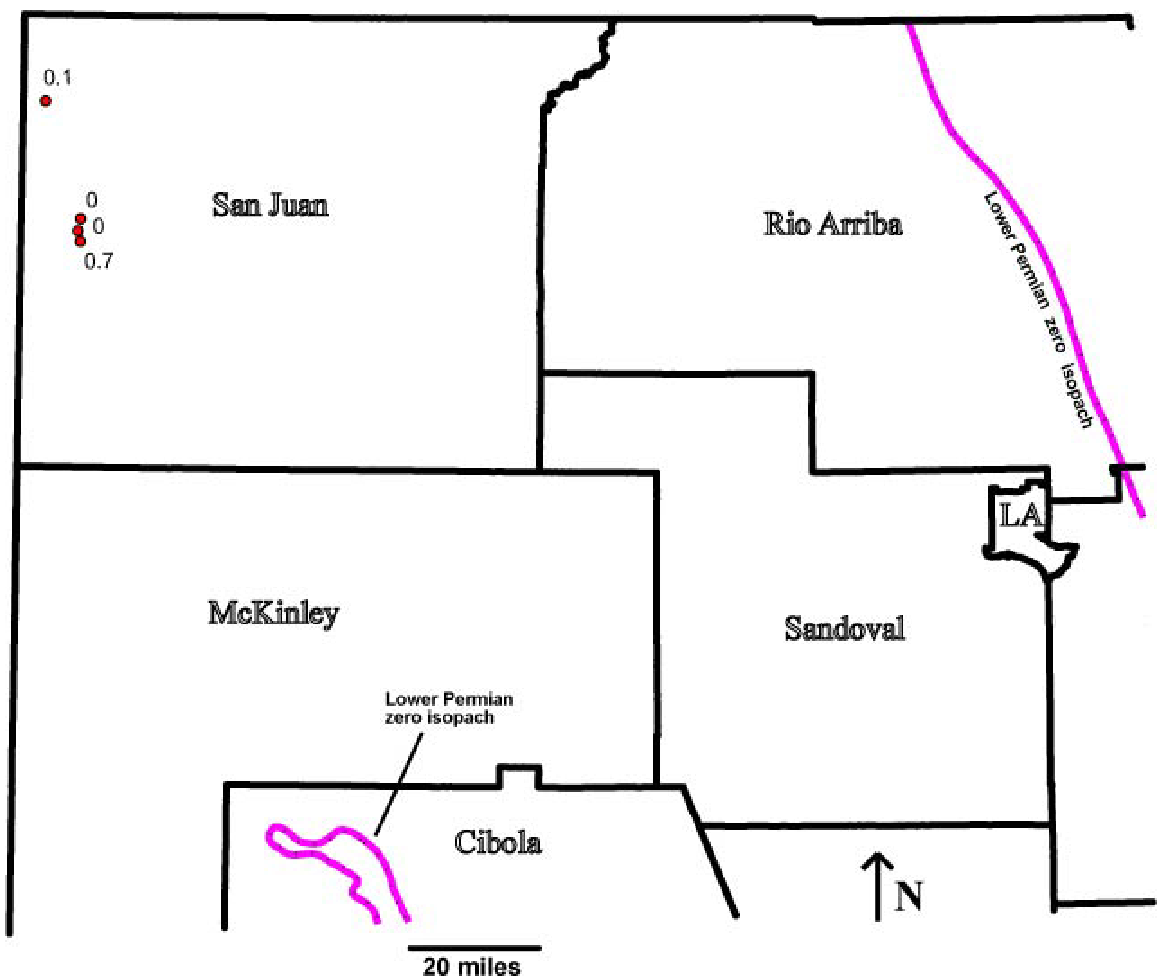

Figure SJ 17. CO_2 content in gases of the Lower Permian reservoirs in the San Juan Basin. Lower Permian zero isopach lines from Baars (1962) and New Mexico Bureau of Geology and Mineral Resources (2003).

Pennsylvanian System

Gases within Pennsylvanian reservoirs in the San Juan Basin contain relatively high concentrations of CO_2. The average CO_2 content is 3.90 percent (Figure SJ 1). CO_2 content ranges from a trace to 33.7 percent. Most of the gas analyses are from wells drilled on the Four Corners platform (Figure SJ 18; Plate XI in Appendix B). In general, the CO_2 content of Pennsylvanian gases increases toward the northeast on the Four Corners platform. CO_2 concentrations of more than 25 percent are associated with Ute Dome, located in T31-32N, R13-14W (Figure SJ 18; Figure SJ 19). Ute Dome is a faulted anticline that acts as a trap in strata of Mississippian, Pennsylvanian and Cretaceous age (Tezak, 1978 a, b).

Only four analyses were available for the deep San Juan Basin. These indicate CO_2 concentrations ranging from 1.12 to 13.17 percent. Three of the samples are from different Pennsylvanian reservoirs in one well, the Burlington Resources No. 2 Vasaly located in Sec. 22 T30N R11W. In that well, CO_2 content was 1.12 percent at a depth of 11,876 ft in the Ismay member of the Paradox Formation, 13.17 percent at a depth of 12,136 ft in the Akah Member of the Paradox Formation, and 4.99 percent at a depth of 12,685 ft in the Alkali Gulch member of the Paradox Formation. For the basin as a whole, there is no evident correlation between reservoir depth and CO_2 concentration in Pennsylvanian gases apart from the cluster of gases with CO_2 content more than 25 percent between 8000 and 9500 ft (Figure SJ 19).

Pennsylvanian gases in the San Juan Basin are dominated either by a hydrocarbon component, a nitrogen component, or a mixed hydrocarbon-nitrogen component (Figure SJ 20). Average methane content is 45.76 percent. Average content of gas liquids is 10.02 percent. Average nitrogen content is 36.50 percent. Because nitrogen and the hydrocarbon gases are the dominant constituents of Pennsylvanian gases in the basin, there is a strong correlation between nitrogen content and hydrocarbon content (Figure SJ 20). There is an associated negative correlation between heating value of the gases and nitrogen content (Figure SJ 21) and a positive correlation between heating value and hydrocarbon content (Figure SJ 22). The data points that fall significantly above the trend lines in Figures SJ 21 and SJ 22 represent gases that have enhanced concentrations of gas liquids (C_{2+}). The data points that fall below the trend line on the N_2 vs hydrocarbon plot (Figure SJ 20) represent gases with relatively high CO_2 content.

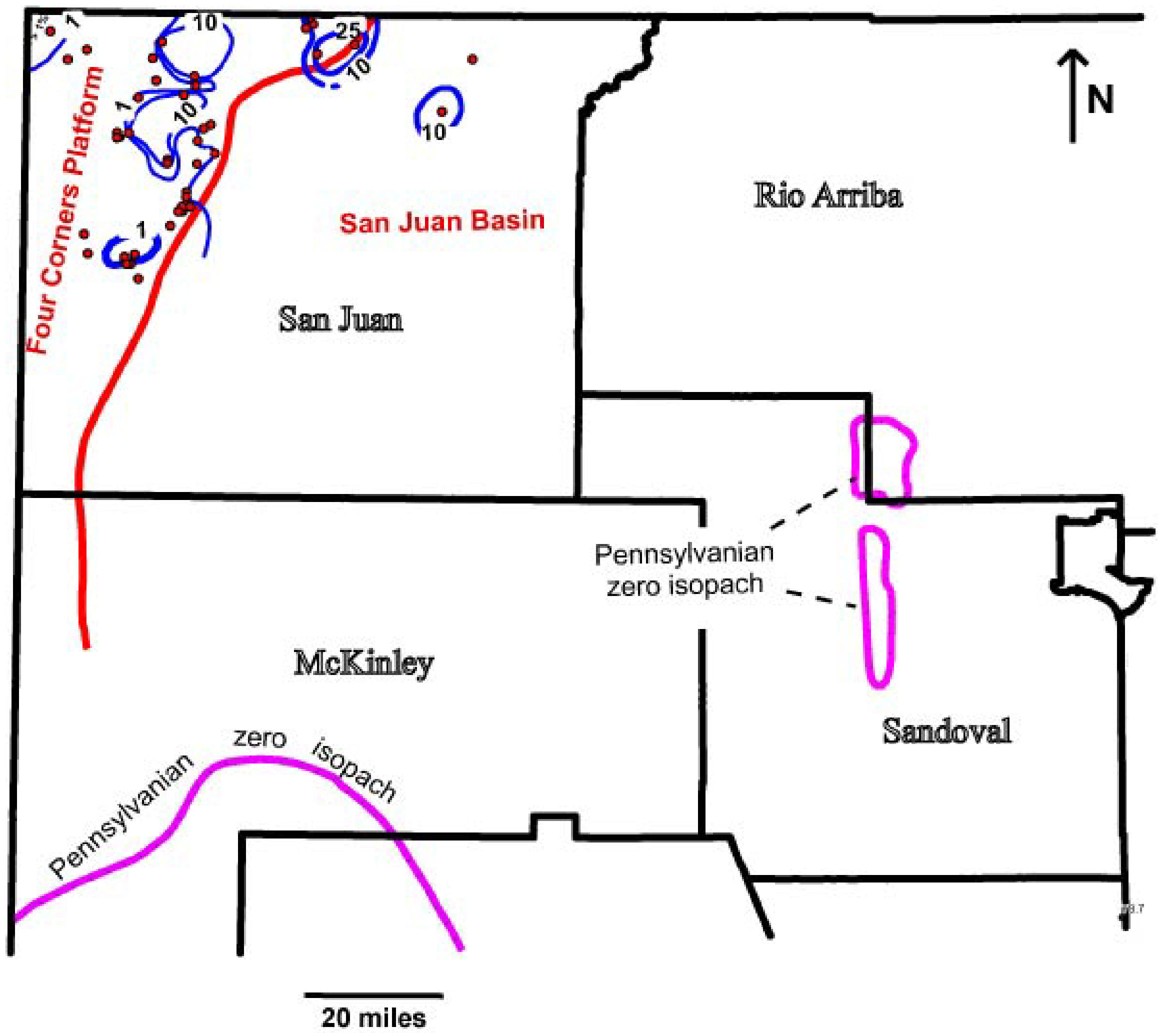

Figure SJ 18. CO_2 content in gases of Pennsylvanian reservoirs in the San Juan Basin. Pennsylvanian zero isopach lines from New Mexico Bureau of Geology and Mineral Resources (2003).

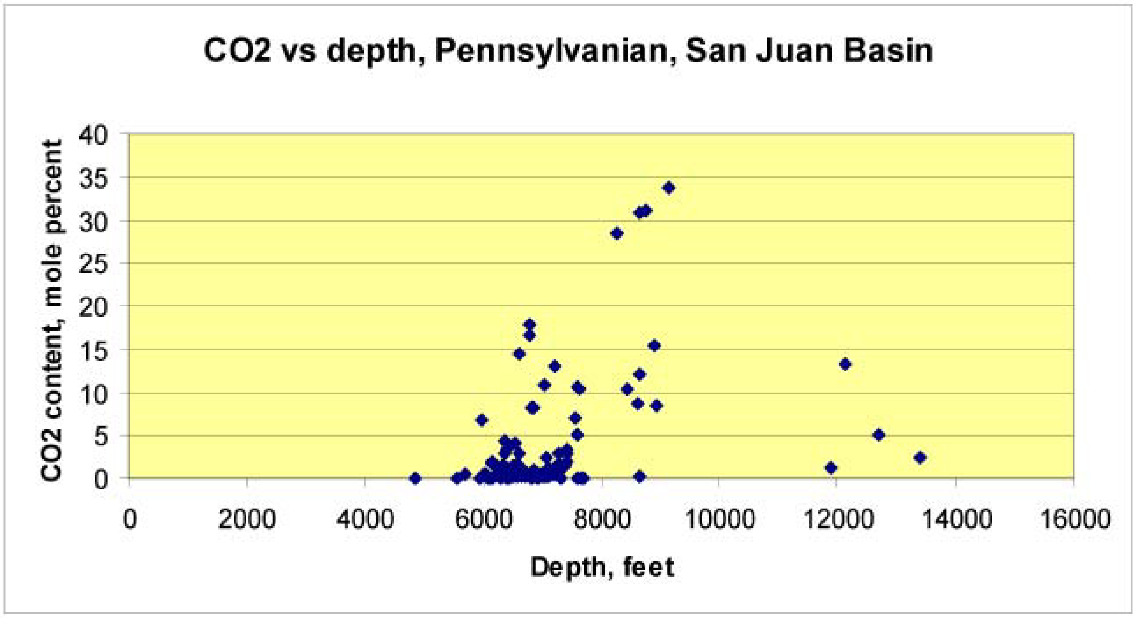

Figure SJ 19. CO_2 content of Pennsylvanian gases vs reservoir depth, San Juan Basin.

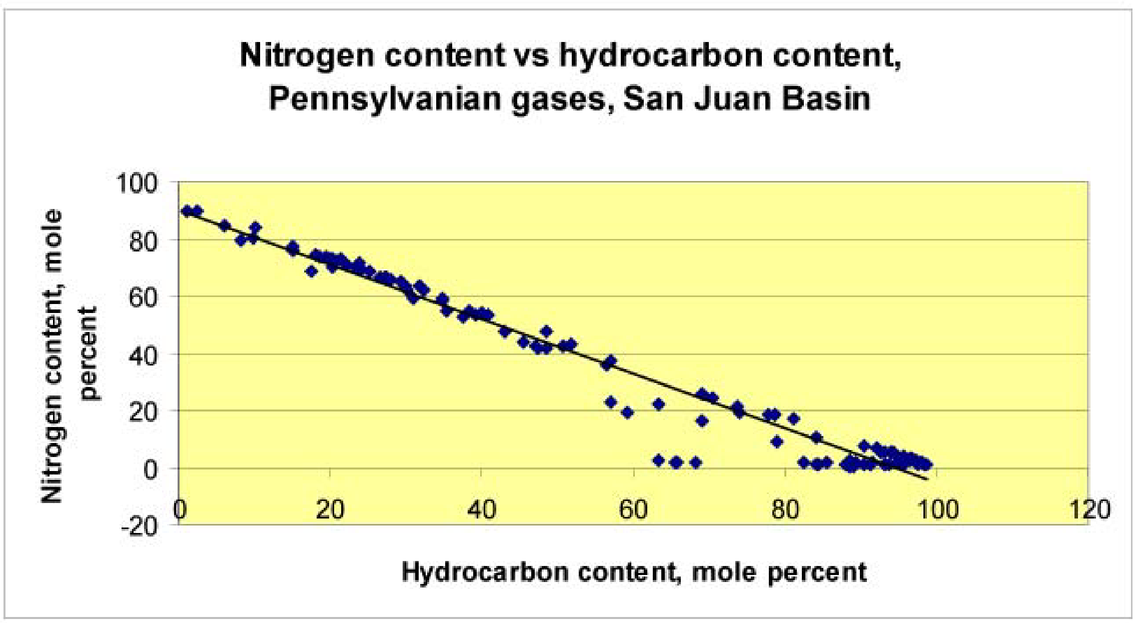

Figure SJ 20. N_2 content of Pennsylvanian gases vs hydrocarbon content, San Juan Basin.

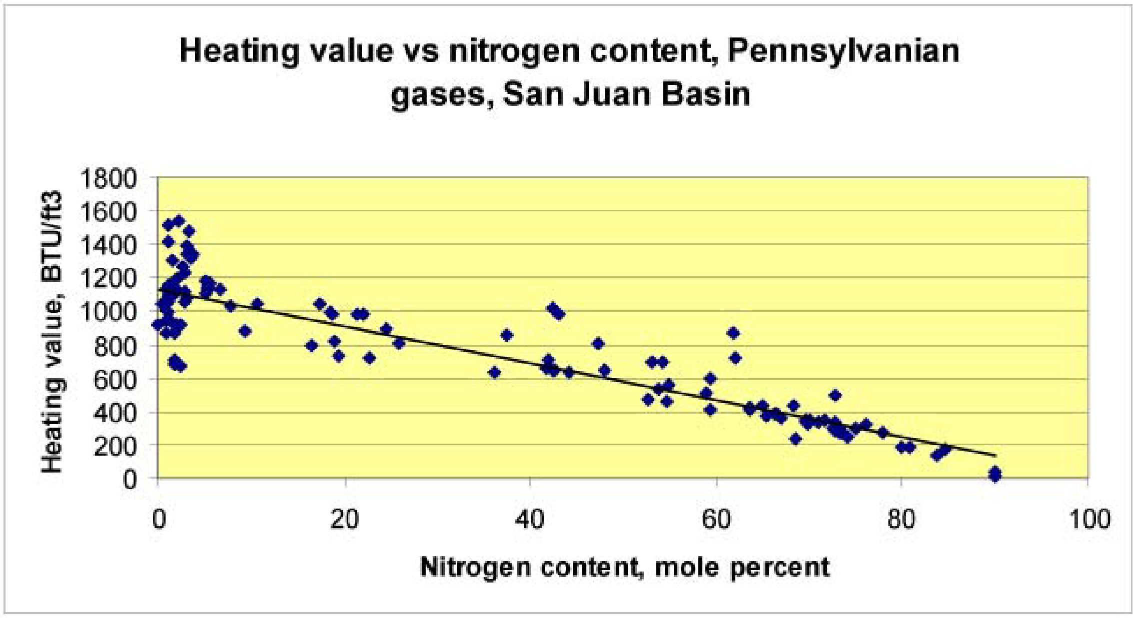

Figure SJ 21. Heating value of Pennsylvanian gases vs N_2 content, San Juan Basin.

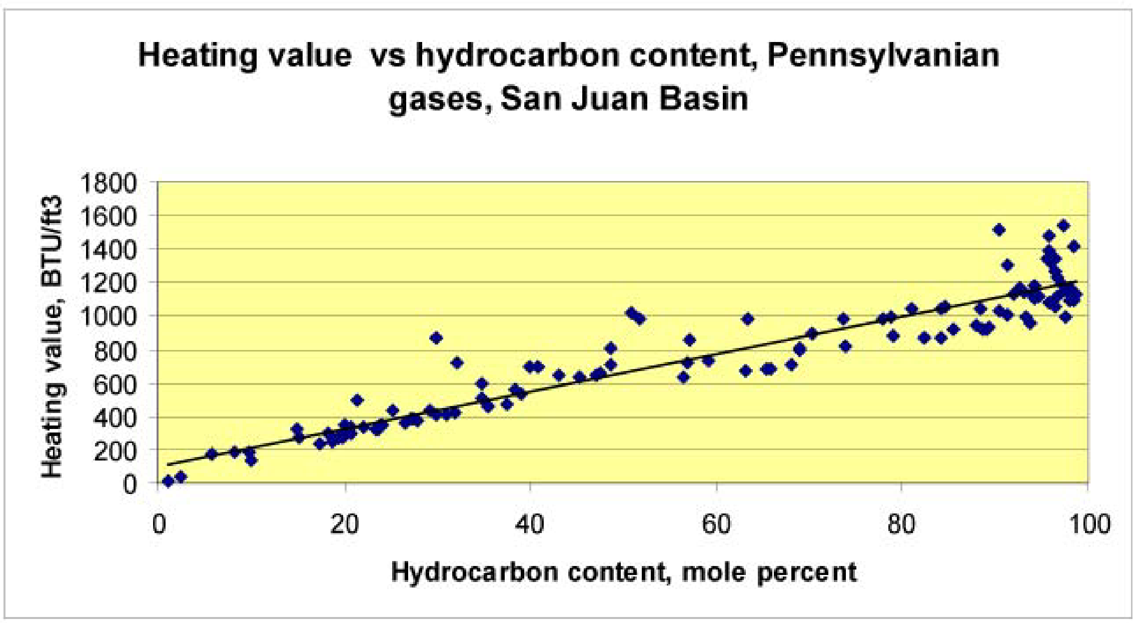

Figure SJ 22. Heating value of Fruitland gases vs hydrocarbon content, San Juan Basin.

Mississippian System

Mississippian carbonate reservoirs of the Leadville Formation contain gases with an average CO_2 content of 20.72 percent (Figure SJ 1). CO_2 content in Mississippian gases ranges from a trace to 96.2 percent. Mississippian gases in the deep part of the San Juan Basin (i.e. that part of the basin east of the Four Corners platform) contain 65 to 96 percent CO_2 (Figure SJ 23; Plate X in Appendix B). The very limited data available indicates that CO_2 constitutes more than 90 percent of Mississippian gases throughout most of the deep part of the basin.

On the central and southern parts of the Four Corners platform, Mississippian gases contain less than 1 percent CO_2 (Figure SJ 23). The non-CO_2 component of the gases in this area is mostly nitrogen. The hydrocarbon fraction is less than 15 percent in most wells. Gases in these wells are characterized by high helium concentrations, generally in the 5 to 7 percent range. CO_2 concentrations increase to more than 80 percent on the northern part of the Four Corners platform. In this area, the hydrocarbon fraction is less than 10 percent and nitrogen content constitutes only 2 to 6 percent of the gases, significantly lower than on the central and southern parts of the Four Corners platform. On the northern part of the platform, helium attains a maximum concentration of 1.4 percent and is less than 1 percent in most places.

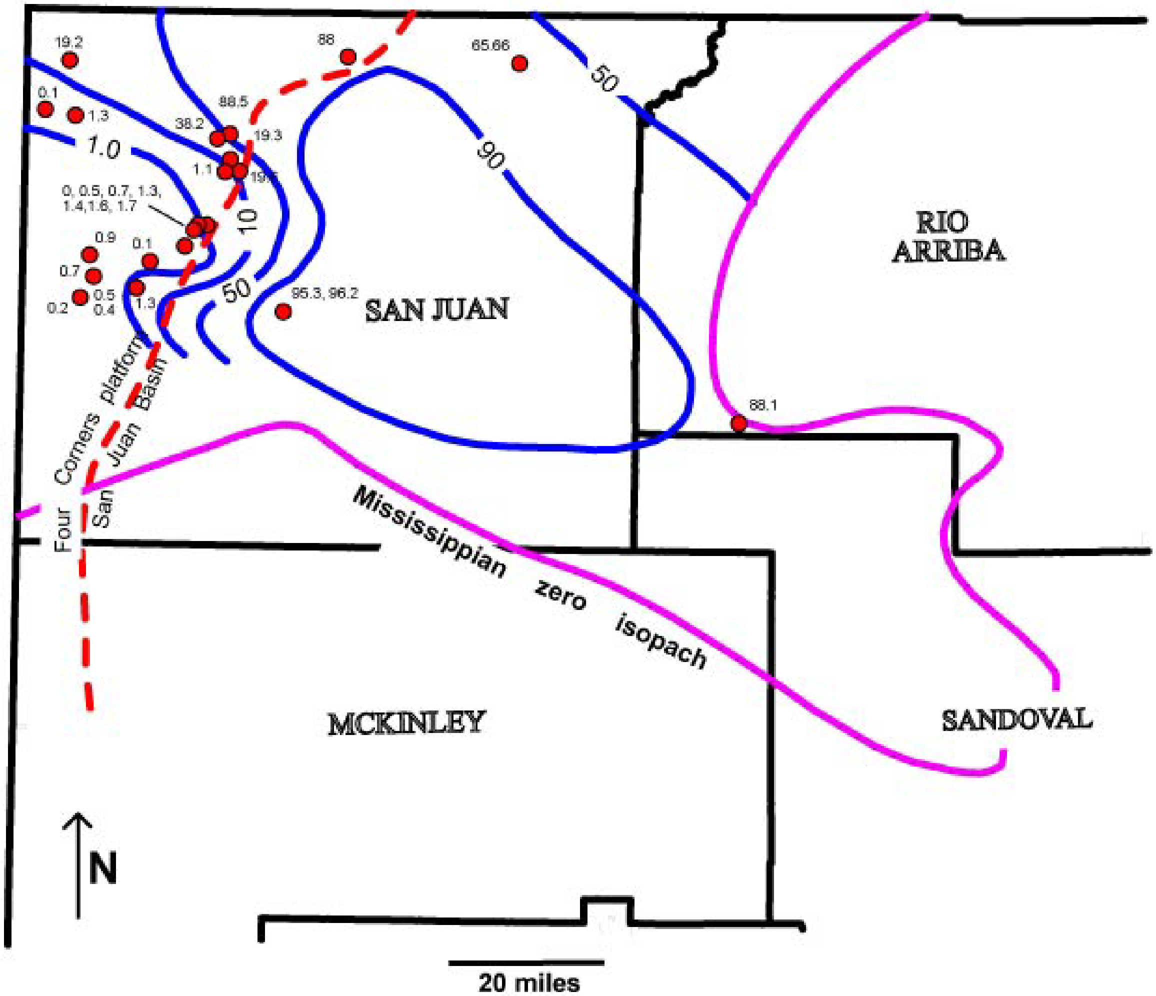

Figure SJ 23. CO_2 content in gases of Mississippian reservoirs in the San Juan Basin. Mississippian zero isopach line from Armstrong and Mamet (1977).

Devonian System

Devonian reservoirs of the Ouray Limestone, Elbert Formation, and Aneth Formation rest unconformably on Precambrian basement or on a thin layer of Cambrian-age Ignacio Quartzite. The Ignacio has a maximum thickness of approximately 100 ft.

Average CO_2 content of Devonian gases is 1.47 percent and CO_2 content ranges from 0 to 7.8 percent Figures SJ 1, SJ 24; Plate IX in Appendix B). Nitrogen is the most abundant constituent of Devonian gases, averaging 81 percent and ranging from 48 to 93 percent. The hydrocarbon fraction is low, averaging 10.85 percent with a maximum of

40.8 percent. Helium content is in the 4 to 8 percent range in most of the Devonian gases. Because of the low hydrocarbon content, Devonian gases in the San Juan Basin have low heating values and therefore have limited use as fuel gases.

Analyses of Devonian gases are available only from wells on the central and southern parts of the Four Corners platform. Because CO_2 content of gases in the overlying Mississippian section increases to the north on the Four Corners platform and to the east into the deep San Juan Basin (Figure SJ 23), it is likely that a similar distribution of gas composition in Devonian reservoirs is present, although data are not available to verify this.

Precambrian basement

Precambrian basement in the San Juan Basin is comprised predominantly of granitic and high-grade metamorphic rocks. These rocks contain little, if any, matrix porosity. However, fractured reservoirs may be present in the upper part of the Precambrian, especially in areas close to the high-angle faults that form the Four Corners platform or are present in the deep San Juan Basin to the east of the platform (see Taylor and Huffman, 1998).

One analysis was available for a gas recovered from a Precambrian reservoir in the San Juan Basin. A diorite near the top of the Precambrian at a depth of 13,890 ft in the Burlington Resources No. 2 Marcotte well, located in Sec. 8 T31N R10W, yielded gas composed of 15.6 percent methane, 0.013 hydrocarbon gas liquids, 0.11 percent helium, 1.58 percent nitrogen, and 82.18 percent CO_2 with the remainder consisting of oxygen, argon, and hydrogen.

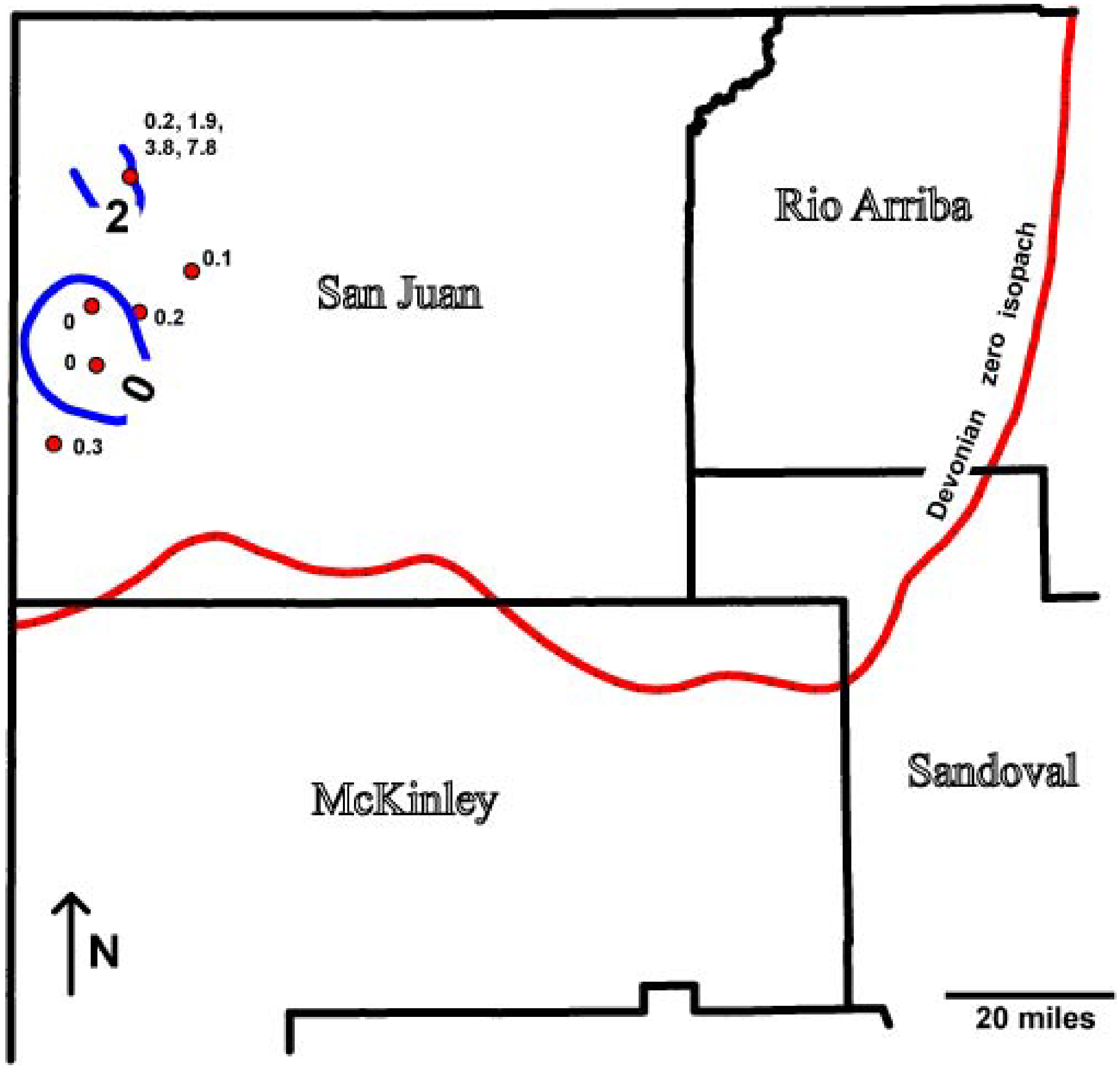

Figure SJ 24. CO_2 content in gases of Devonian reservoirs in the San Juan Basin. Devonian zero isopach line from Stevenson and Baars (1977).

CO_2 in Northeastern New Mexico

Northeastern New Mexico has been known to contain accumulations of nearly pure CO_2 since 1916. Two CO_2 gas fields, Bravo Dome and Des Moines, have been discovered and produced (Figure NE 1). More than 2.1 trillion ft^3 CO_2 gas have been produced from northeastern New Mexico. Most of the CO_2 has been used for enhanced oil recovery in the Permian Basin of southeastern New Mexico and west Texas. A relatively small amount has been converted to dry ice and bottled liquid CO_2.

The Bravo Dome field was originally known as the Bueyeros field. It was discovered in 1916 by the American Production Corporation No. 1 Bueyeros well, located in Sec. 32 T20N R31E. The well was drilled on a surface anticline as an oil exploration well but encountered CO_2 gas at a depth of 2000 ft in the Tubb sandstone member of the Yeso Formation (Permian). The well blew open at a reported rate of 25 million ft^3 (MMCF) gas per day and was plugged after one year (Anderson, 1959). At the time, there was no market for CO_2 in the region. The main uses at that time for CO_2 were as dry ice for refrigeration and as liquid CO_2 that was used to make carbonated beverages.

The Bravo Dome (nee Bueyeros) accumulation remained undeveloped and unproduced until 1931 when a new exploration well, the Southern Dry Ice Company No. 1 Kerlin, located in Sec. 34 T21N R30E, was drilled on the Baca anticline, a relatively small surface structure, in search of CO_2 gas. By this time, markets for dry ice and bottled liquid CO_2 had developed in the region. In the Kerlin well, gas was encountered at a depth of 940 ft in the Santa Rosa Sandstone (Triassic). Some CO_2 was also encountered in sandstones of the Chinle Formation (Triassic) at depths of 287 and 870 ft. Two additional wells were subsequently drilled and completed successfully as CO_2 gas wells. The gas was converted into dry ice and liquid forms by a plant erected near the wells. The dry ice was used for refrigeration purposes mostly in Denver and Amarillo (Anderson, 1959). The liquid CO_2 was bottled and sold to manufacturers of carbonated beverages in west Texas, Oklahoma and Kansas (Anderson, 1959). As a response to increased demand for dry ice and liquid CO_2, additional wells were drilled in the Bueyeros field and additional plants for conversion of the gas to liquid and solid forms were erected. Production of dry ice for use as a refrigerant continues to the present from four wells.

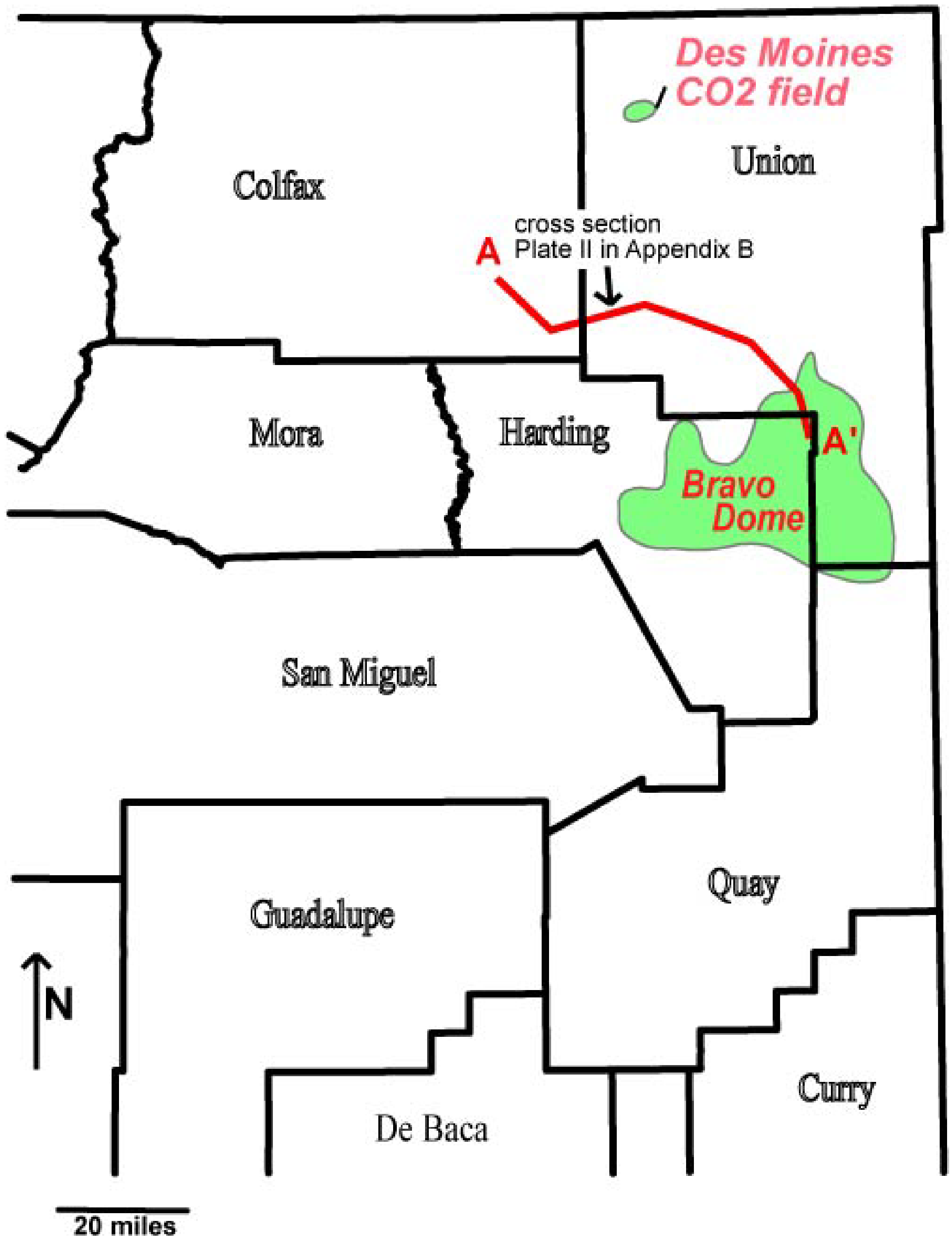

Figure NE 1. Location of CO_2 fields in northeastern New Mexico that have produced CO_2 for commercial purposes. See Plate II in Appendix B for cross section A-A'.

Main development of the Bravo Dome CO_2 field occurred during the early to middle 1980's. The number of CO_2 wells increased from 16 during 1982 to 258 at the end of 1985 (Broadhead, 1990). It was during this period of expansion that the field name was changed from Bueyeros to Bravo Dome. Production increased as wells were drilled, peaking at 145 billion ft^3 per year during 1996 and subsequently declining to the present rate of approximately 100 BCF per year (Figure NE 2). The primary reservoir is the Tubb sandstone member of the Yeso Formation (Figure NE 3), which has yielded more than 99 percent of the production from the field. The gas brought into production since 1980 is transported via pipeline to the Permian Basin of southeastern New Mexico and west Texas where it is used in enhanced oil recovery. Production from the Triassic section has been limited to few older wells drilled in the western part of the field; the Triassic gas has been used to manufacture dry ice and liquid CO_2. The trap in the Triassic is formed by an anticline that covers only a small part of the Bravo Dome.

The trap in the Tubb sandstone at Bravo Dome is a combination structural-stratigraphic trap. The northwestern, updip limit of the trap is stratigraphic and is formed by regional thinning of the Tubb to less than 100 ft and an associated facies change from porous permeable reservoir sandstones in the southeast to impermeable muddy sediments in the northwest (Figures NE 4, Plate II in Appendix B; Broadhead, 1993). Trapping to the northeast, southeast and northwest is structural and is associated with the southeast-plunging Bravo Dome (Figure NE 4).

The Des Moines field (Anderson, 1959; Foster and Jensen, 1972) is located near the axial crest of the Sierra Grande uplift (see Plate I). The field was discovered in 1935 by the Sierra Grande No. 1 Rogers well, located in Sec. 4 T29N R29E. Four additional productive wells were drilled during the 1950's and a processing plant was built to convert the CO_2 into liquid carbon dioxide and dry ice (Anderson, 1959; Foster and Jensen, 1972). The field was produced until 1966 when it was abandoned because of problems related to gas processing and not because reserves were depleted (Foster and Jensen, 1972). Annual and cumulative production from the Des Moines field is unknown.

The primary reservoirs at the Des Moines field are lenticular arkosic conglomerates and conglomeratic sandstones of the Abo Formation (Permian). The Abo rests unconformably on Precambrian basement in the area. Interbedded red shales act as seals. Depth to production rages from 2,060 ft to 2,600 ft and original reservoir pressures varied from 64 to 210 psi. Minor shallow production was obtained from a dolostone in the Bernal Formation (Foster and Jensen, 1972); this shallow reservoir had an initial pressure of only 5 psi. The areal and vertical extent of the field has not been defined by drilling and remains unknown.

CO_2 gas is widespread in Paleozoic and Mesozoic strata of northeastern New Mexico. Apart from the Bravo Dome and Des Moines fields, CO_2 has been encountered in wells penetrating the Abo and Yeso Formations (Lower Permian), the Glorieta Sandstone (Upper Permian), the San Andres Formation (Upper Permian), and Triassic strata on the Sierra Grande uplift (Figures NE 5, NE 6, NE 7, and NE 8; Plates XII, XIII, and XIV in Appendix B). Where compositional analyses are available, the gases in this area are comprised of more than 90 percent CO_2 although nitrogen-rich gases are known to be present locally within sandstone reservoirs of the Chinle Formation (Triassic; Figure NE 5). Although CO_2-rich gases may be nearly ubiquitous on the Sierra Grande uplift, little is known of pressure regimes in the subsurface outside of the Bravo Dome (Broadhead, 1993) and Des Moines fields (Foster and Jensen, 1972).

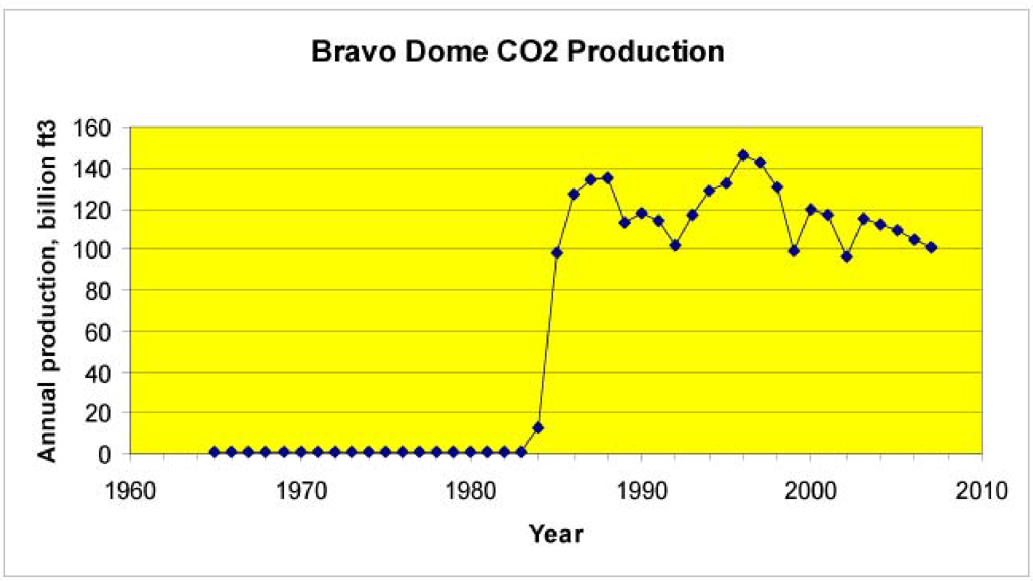

Figure NE 2. Annual production of CO_2 from Bravo Dome field.

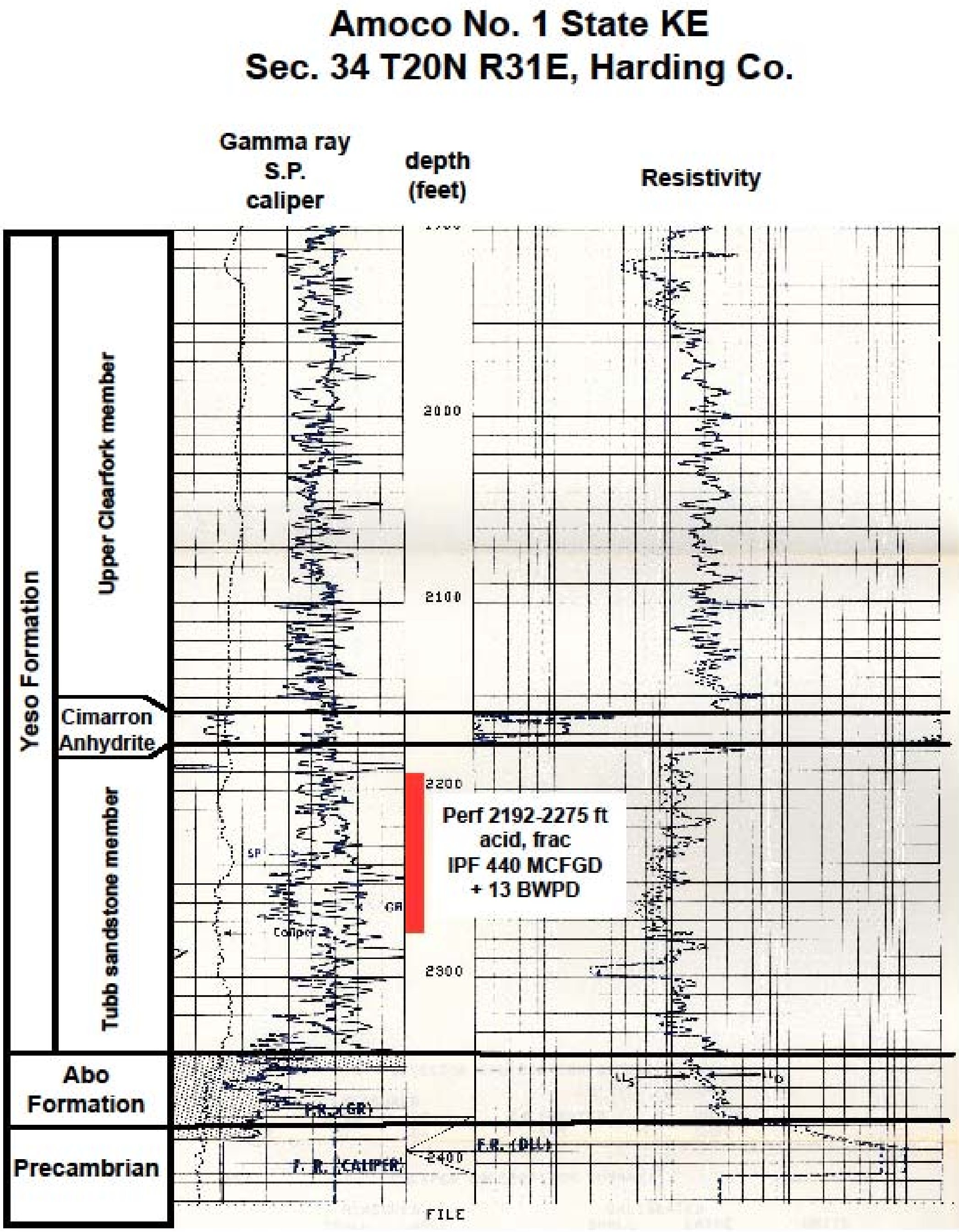

Figure NE 3. Typical gamma ray and resistivity logs from Bravo Dome field.

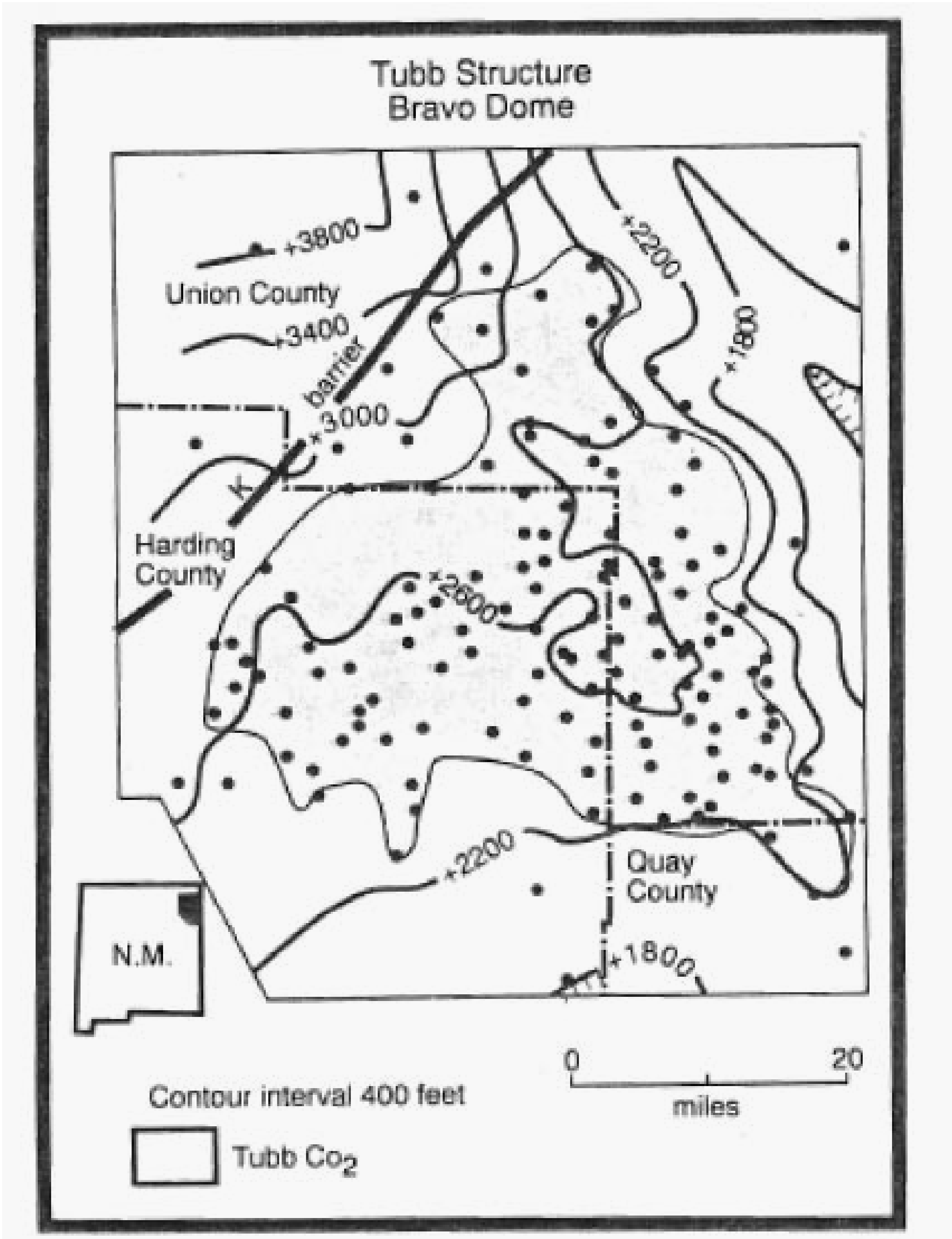

Figure NE 4. Structure contours on top of Tubb sandstone and northwestern, updip permeability barrier within Tubb sandstone, Bravo Dome CO_2 field. From Broadhead (1993).

Pennsylvanian strata are not present on the Sierra Grande uplift or on the Bravo Dome, but are present in adjacent basins (Tucumcari Basin to the south, Dalhart Basin to the east, Las Vegas and Raton Basins to the northwest). Pennsylvanian gases in the adjacent basins generally contain low concentrations of CO_2 because the Pennsylvanian in these basins contain thick sections of generative source rocks that contain hydrocarbon gases (Broadhead et al., 2002; Broadhead, 2001; Broadhead, 2008). Gases in Pennsylvanian reservoirs in these basins consist mostly of hydrocarbons with only minor amounts of CO_2, nitrogen and helium.

The CO_2 at Bravo Dome is considered to have a mantle source, with magmas acting as the transport mechanism to convey the CO_2 from the mantle to the upper part of the crust. Isotopic analyses of the CO_2 and associated noble gases at Bravo Dome indicate a mantle source for the gas (Gilfillan and others, 2008). Staudacher (1987) concluded that the noble gases present in small percentages in Bravo Dome gas (generally less than 0.1 percent) have an upper mantle isotopic signature that is exactly the same as gases recovered from mid-ocean ridge basalts. Gilfillan and others (2008) used the ^{20}Ne concentration gradient in Bravo Dome gases to conclude that the reservoir filled from west to east. This concept is supported by the distribution of pressure regimes and pressure compartments within the Tubb sandstone reservoir; the western side of the field is normally pressured and compartments on the eastern side are progressively more underpressured in an easterly direction (see Broadhead, 1993).

The age of most basaltic volcanic rocks that crop out in Union County is 1.2 to 3.4 ma (see Wilks and Chapin, 1997; Trauger, 1987). However, the volcanic rocks that form Capulin Mountain in T29N R28E were formed 4500 to 10,00 years before present (Hunt and others, 1997). Introduction of most of the CO_2 in the region can therefore be dated to the age of most of the volcanism (1.2 to 3.4 ma) with perhaps a relatively minor volume of CO_2 associated with the relatively recent Capulin eruptions or temporally related intrusive events.

Considerable potential is present for undiscovered CO_2 accumulations on the Bravo Dome and Sierra Grande uplift. Hess Corporation has drilled almost 60 wells to expand production on the western side of the Bravo Dome field during the past two years. Most completed wells have an initial production rate of between 3 and 6 MMCFGD. This is the higher pressure part of the field (see Broadhead, 1993). The new wells demonstrate that significant potential for undeveloped resources remains on the western side of the field.

To the north, Kodiak Petroleum drilled three exploratory wells on the Sierra Grande uplift during 2008 (Figure NE 5). All three wells were completed as CO_2 gas wells but initial production rates, reservoir pressures, and gas composition data have not yet been released. At present, the gas is stranded without a pipeline. Perforated zones in the three wells are within the Santa Rosa Sandstone (Triassic) at depths of 1076 to 1704 ft, the Glorieta Sandstone (Permian) at depths of 1600 to 1970 ft, and the Yeso Formation (Permian) at depths of 1740 to 2132 ft. These wells in addition to other wells with shows in the Triassic, Upper Permian and Lower Permian (Figures NE5, NE6, NE7) indicate potential for additional CO_2-rich gases on the Sierra Grande uplift.

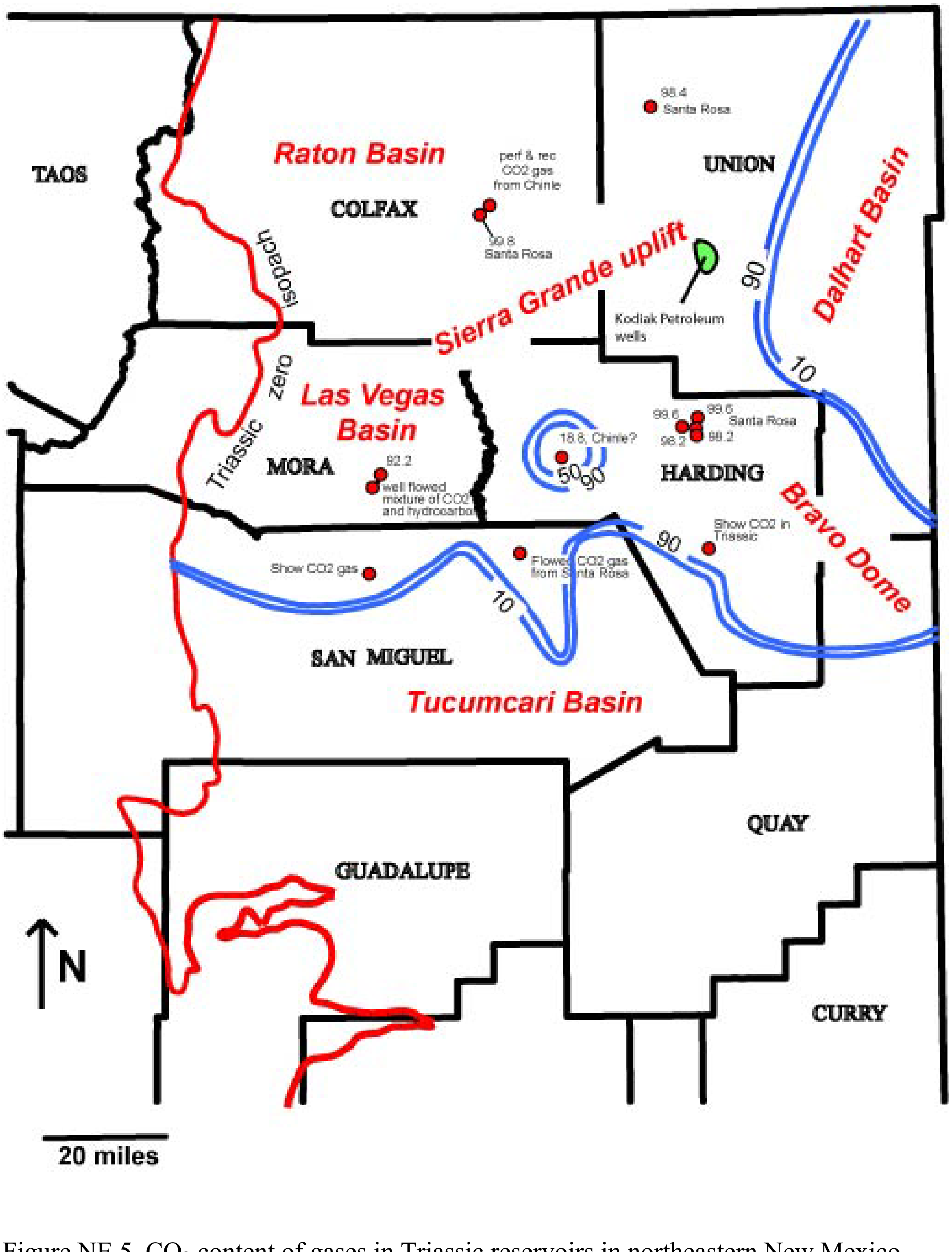

Figure NE 5. CO_2 content of gases in Triassic reservoirs in northeastern New Mexico. Triassic zero isopach line adapted from New Mexico Bureau of Geology and Mineral Resources (2003).

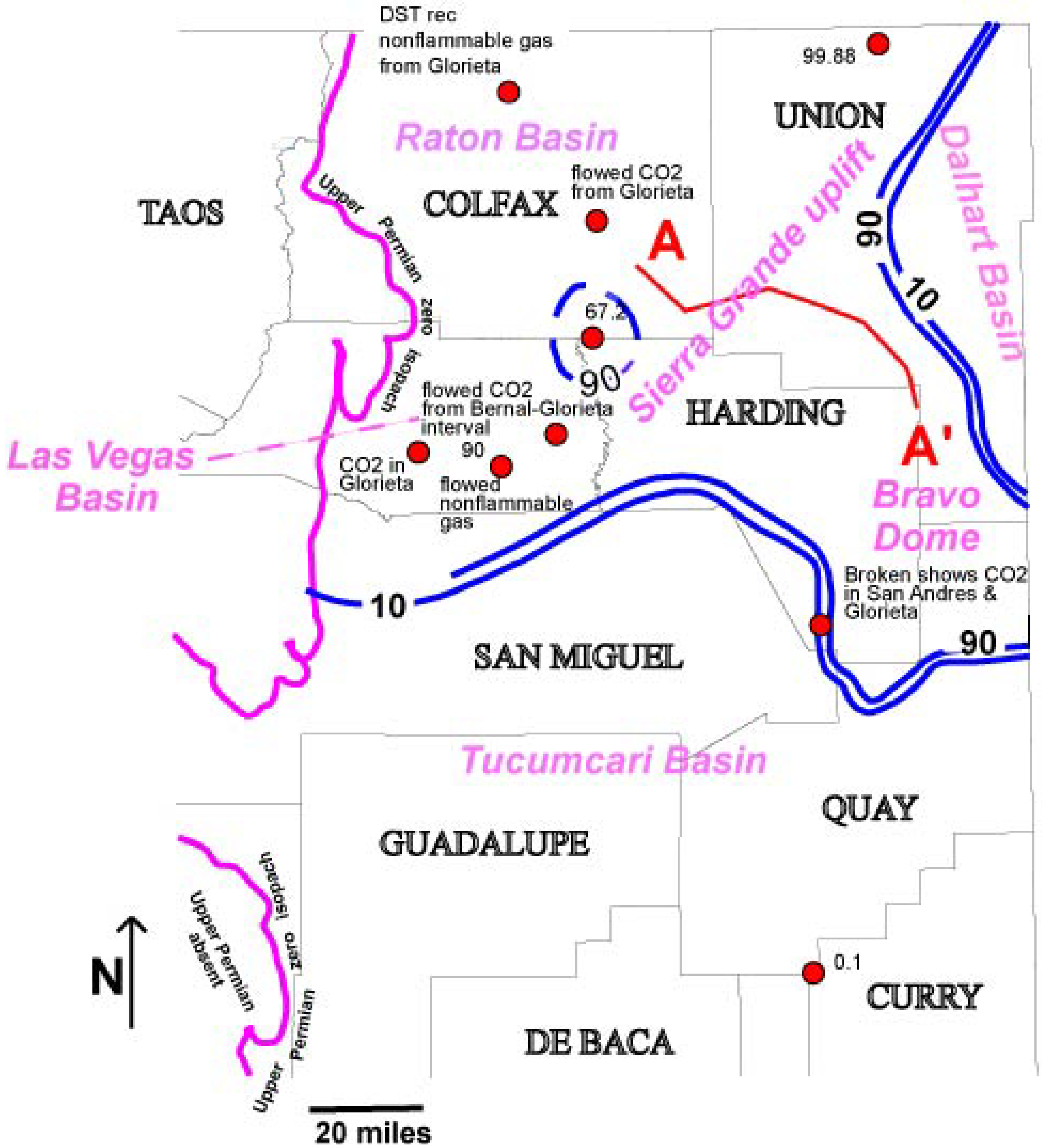

Figure NE 6. CO_2 content of gases in Upper Permian reservoirs in northeastern New Mexico. See Plate II in Appendix B for cross section A-A'. Upper Permian zero isopach line adapted from Broadhead (1997) and New Mexico Bureau of Geology and Mineral Resources (2003).

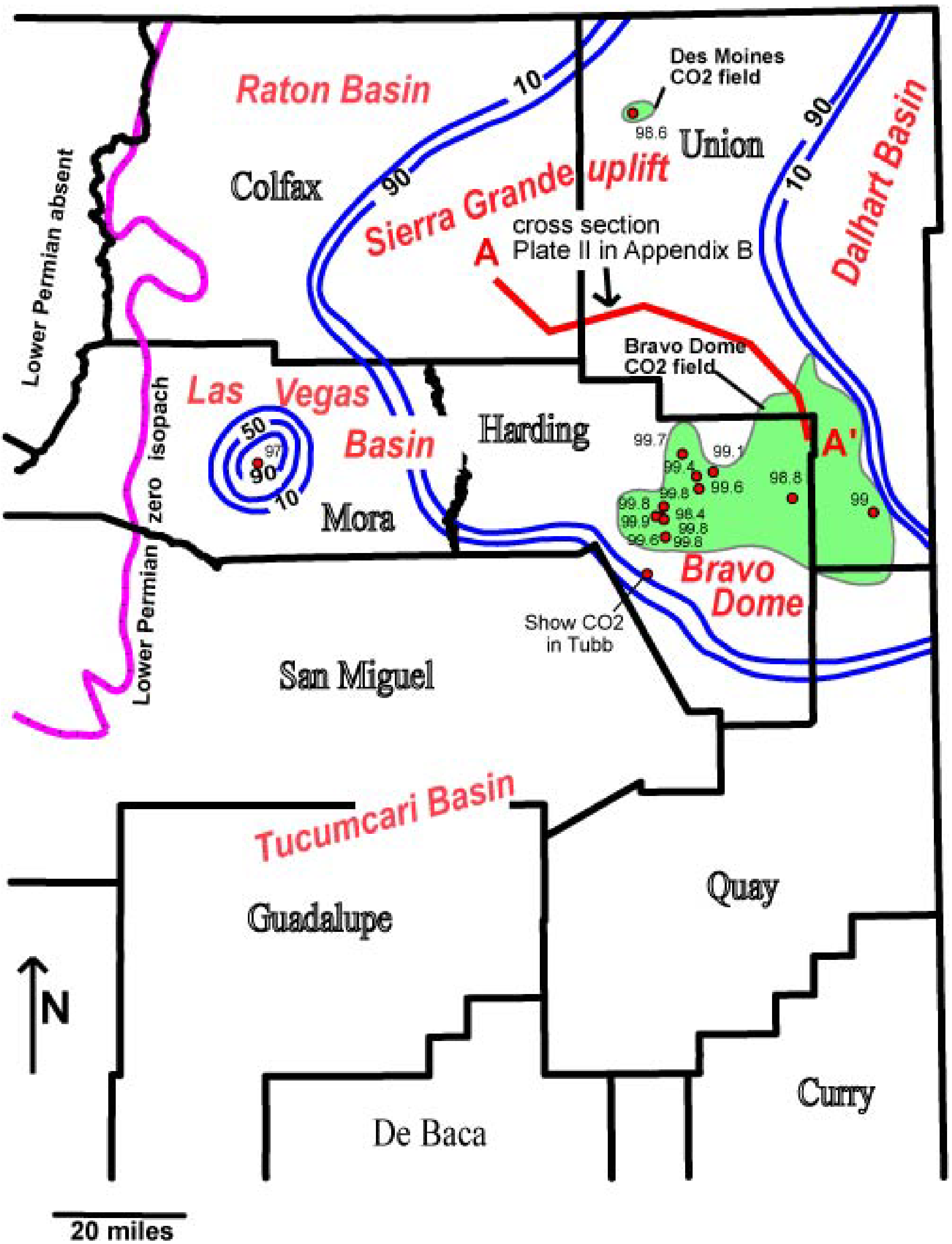

Figure NE 7. CO_2 content of gases in Lower Permian reservoirs in northeastern New Mexico. See Plate II in Appendix B for cross section A-A'. Lower Permian zero isopach line adapted from New Mexico Bureau of Geology and Mineral Resources (2003).

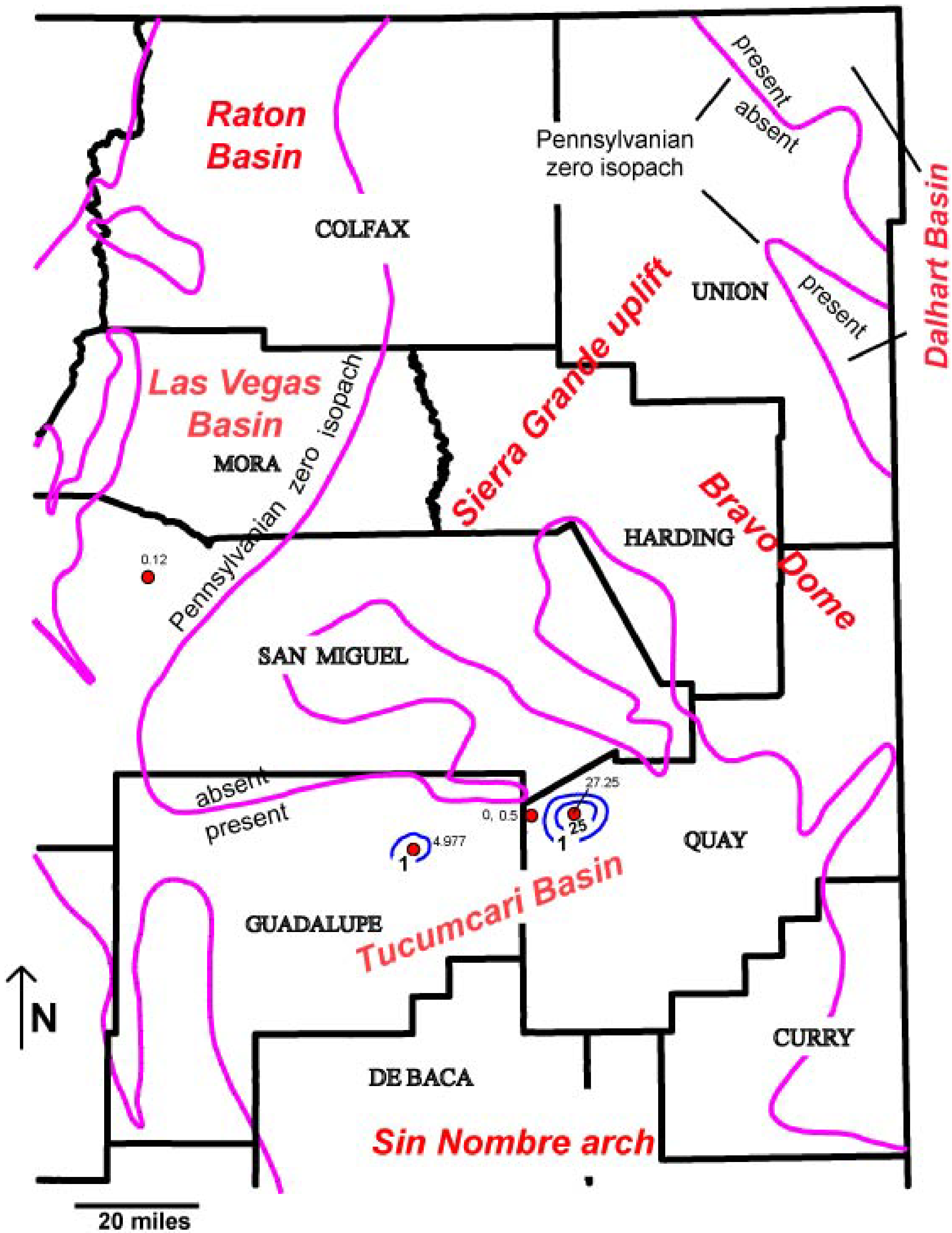

Figure NE 8. CO_2 content of gases in Pennsylvanian reservoirs in northeastern New Mexico. Pennsylvanian zero isopach line adapted from Broadhead and King (1988) and Broadhead (1997, 2008).

CO_2 in North-central New Mexico

North-central New Mexico consists of three basins (Raton, Las Vegas and San Luis Basins) and two uplifts (Cimarron and Sangre de Cristo uplifts) that separate the basins from each other (Figure NC 1; Plates I, III, IV and V in Appendix B). The Cimarron uplift separates the Raton Basin from the Las Vegas Basin. The Sangre de Cristo uplift, which forms the Sangre de Cristo Mountains, separates the Raton and Las Vegas Basins from the San Luis Basin. The eastern boundary of the Sangre de Cristo uplift is formed by Laramide age (latest Cretaceous to Early Tertiary) reverse and thrust faults that bring the Precambrian basement of the uplift over the Paleozoic and Mesozoic strata that fill the two basins (see Baltz and Myers, 1999; New Mexico Bureau of Geology and Mineral Resources, 2003). Structural relief on Precambrian basement is more than 13,000 ft (Broadhead, 2008). On the east, the strata that infill the Raton and Las Vegas Basins gradually rise upward on the gently west-tilted Precambrian basement. The boundary between these basins and the Sangre de Cristo uplift is gradational (see Plate I in Appendix B).

The Las Vegas Basin is filled primarily with strata of Pennsylvanian and Early Permian age (Sandia, Madera and Sangre de Cristo Formations) that form a sequence 9000 ft thick along the basin axis (see Plates III, IV in Appendix B). Although the present-day configuration of these basins resulted from Laramide tectonism, both have a late Paleozoic (Pennsylvanian through Early Permian) ancestry. The Sandia, Madera and Sangre de Cristo Formations are synorogenic and their internal facies variations reflect the Pennsylvanian and Early Permian tectonism. In the Las Vegas Basin, Sangre de Cristo strata are overlain by as much as 900 ft of Lower to Upper Permian strata of the Yeso Formation, Glorieta Sandstone and Bernal Formation, 1100 ft of Triassic strata of the Moenkopi Formation, Santa Rosa Sandstone and Chinle Group, and 300 to 400 ft of Jurassic strata of the Entrada Sandstone and the Morrison Formation. The Jurassic section is overlain by 300 to 900 ft of Cretaceous strata of the Dakota Group, Graneros Shale, Greenhorn Limestone, Carlile Shale, Fort Hays Limestone, and Niobrara Shale. Cretaceous strata form the surface exposures over most of the basin; in most places only erosional remnants less than 500 ft thick of the Cretaceous remain. Tertiary and Quaternary intrusive and extrusive igneous rocks are present in many parts of the Las

Vegas Basin (O'Neill and Mehnert, 1988; Hayes, 1957; Boyd, 1983; New Mexico Bureau of Geology and Mineral Resources, 2003; Broadhead, 2008).

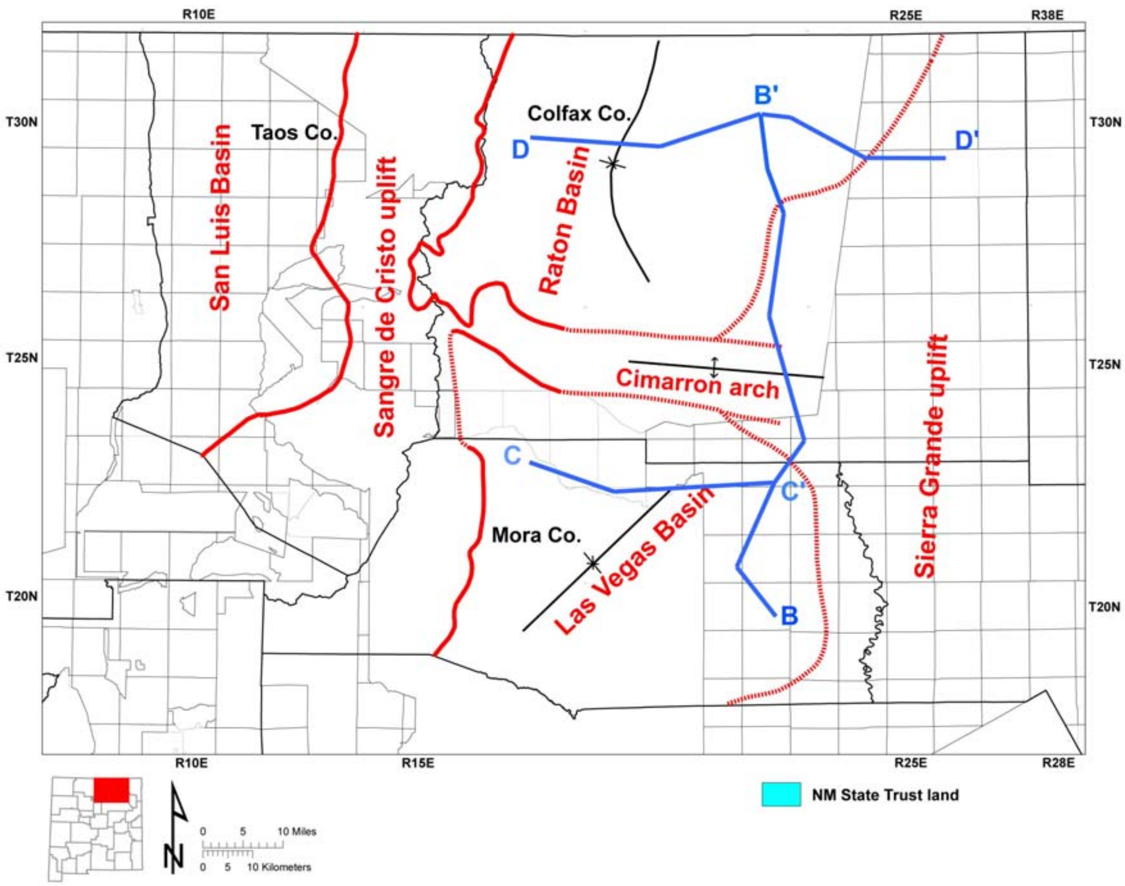

Figure NC 1. Tectonic elements of north-central New Mexico, from Broadhead (2008), modified from Baltz and Myers (1999). See Plates II, Iv and V in Appendix B for cross sections B-B', C-C' and D-D'.

The Raton Basin is filled with strata of Pennsylvanian through Tertiary age (Plates III and V in Appendix B). Pennsylvanian and Lower Permian strata are projected to attain a maximum thickness of 3000 ft along the axis of the basin where they remain undrilled (Broadhead, 2008). The Lower Permian section is overlain by 400 ft of Lower to Upper Permian strata of the Yeso Formation, Glorieta Sandstone, and Bernal Formation, 300 to 600 ft of Triassic strata of the Moenkopi Formation, Santa Rosa

Sandstone and Chinle Group (see Plates III and V in Appendix B). Above the Triassic are 400 to 500 ft of strata of the Entrada Sandstone and Morrison Formation and 1000 to 4000 ft of Cretaceous strata belonging to the Dakota Group, Graneros Shale, Greenhorn Limestone, Carlile Shale, Fort Hays Limestone, Niobrara Shale, Pierre Shale, Trinidad Sandstone and Vermejo Formation. These are, in turn, overlain by 0 to 2000 ft of the Raton and Poison Canyon Formations, Laramide synorogenic, often conglomeratic, clastic deposits derived from the rising Sangre de Cristo uplift and deposited as and eastward-thinning clastic wedge. Intrusive and extrusive igneous rocks of Tertiary age are widespread in the Raton Basin (New Mexico Bureau of Geology and Mineral Resources, 2003; Scott and Pillmore, 1993; Scott and others, 1990; Broadhead, 2008). The intrusive rocks form sills, dikes, laccoliths and volcanic plugs and stocks.

Gases in the Las Vegas Basin consist primarily of hydrocarbons (Broadhead, 2008). Gases in the vicinity of large igneous intrusives may be dominantly CO_2 as a result of gases exsolved from the rising magmas that formed the intrusives. A documented example of this are Lower Permian gases recovered by a well drilled on the Turkey Mountains uplift. The Turkey Mountains uplift is a dome that was formed by uplift over an intrusive laccolith of Tertiary age. A well drilled on the uplift, the Union land and Grazing No. 1 Fort Union, located in Sec. 2 T20N R19E, flowed 923 thousand ft^3 gas per day (MCFD) from the Sangre de Cristo Formation (Lower Permian). The gas was 97 percent CO_2 (Figure NE 7; Plate XII in Appendix B). The magma that formed the laccolith was presumably not only the source of the CO_2, but it also acted to form the domal uplift that has trapped the CO_2.

Elsewhere in the Las Vegas Basin, sparse data indicate that gases are mostly hydrocarbons that were sourced by dark-gray to black, organic-rich shales within the Pennsylvanian section (Broadhead, 2008). One well, the James D. Hancock No. 1 Sedberry well that is located in Sec. 25 T17N R16E flowed gas comprised of 98.69 percent methane and only 0.12 percent CO_2 along with 0.94 percent N_2, 0.24 percent C_2H_6, and 0.01 percent C_3 H_8 from a sandstone reservoir in the lower part of the Pennsylvanian section (see Figure NE 8; Plate XI in Appendix B). That well is distant from any identified igneous intrusive bodies.

Gases in Triassic strata and in the Glorieta Sandstone (Permian) are comprised mostly of CO_2 (Broadhead, 2008). Although few compositional analyses are available for these gases, well records indicate that the Triassic and Glorieta gases are nonflammable and contain large percentages of CO_2 (Figures NC 2, NC 3; Tables NC 1; NC 2).

Two types of gases are present in the Raton Basin. One type is comprised predominantly of hydrocarbons. The other type is noncombustible and is comprised predominantly of CO_2. Most of the gases in the basin are of the first type. Gases in Triassic strata and in the Glorieta Sandstone (Permian) are of the second type (Broadhead, 2008). Although few compositional analyses are available for these gases, well records indicate that the Triassic and Glorieta gases are nonflammable and contain large percentages of CO_2 (Figures NC 2, NC 3; Tables NC 1; NC 2).

The Triassic and Glorieta sandstones also carry fresh water over significant areas of the Raton and Las Vegas Basins. In general, waters recovered from exploratory wells in these strata have been described as fresh (Figures NC 2, NC 3; Tables NC 1, NC 2), indicating that much of the Glorieta and Triassic have been flushed by fresh groundwater over large areas of the two basins.

Gases that are comprised dominantly of hydrocarbons in the Raton and Las Vegas Basins are present in stratigraphic units that contain identified, thermally mature petroleum source rocks (Broadhead, 2008). Gases that are comprised dominantly of CO_2 are present in stratigraphic units that contain few, if any, organic rich sedimentary rocks.

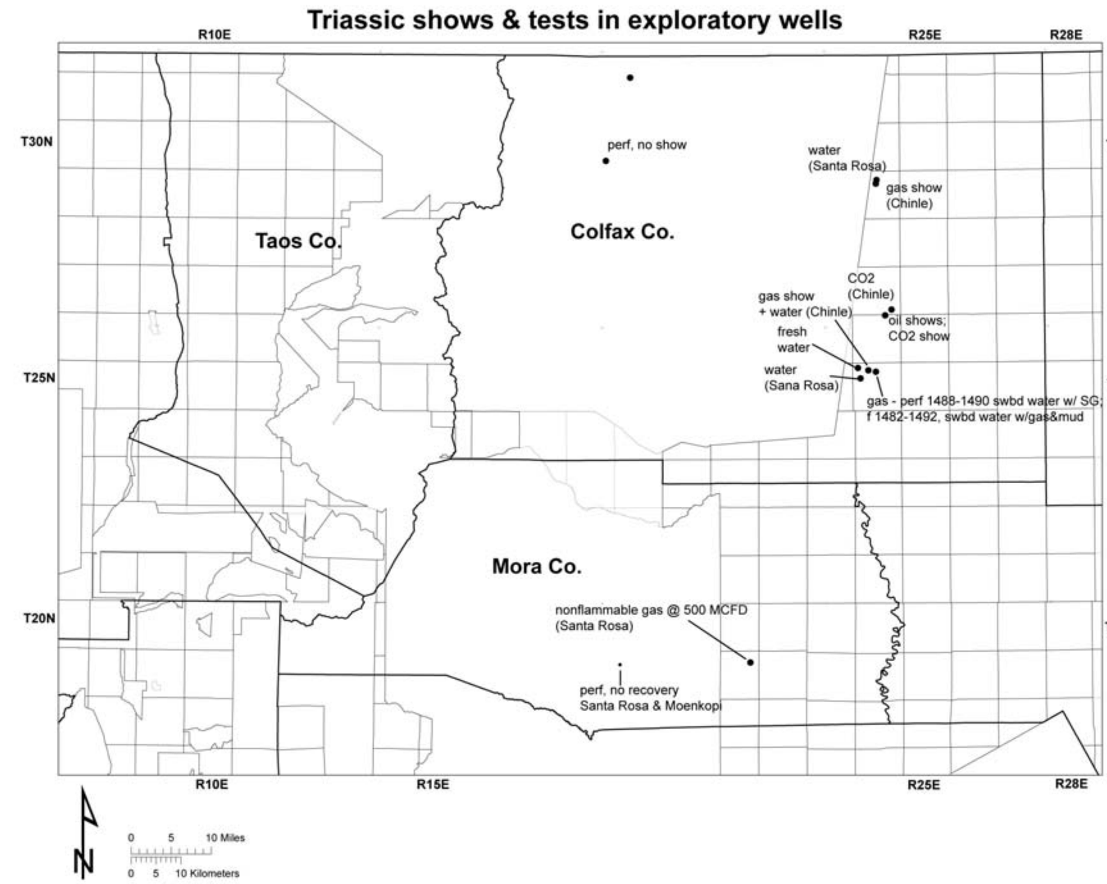

Figure NC 2. Wells with shows and tests in Triassic strata. See Table NC 1 for descriptions of shows. From Broadhead (2008).

Table NC 1. Wells with shows and tests in Triassic strata.

Operator	Well#	Lease name	Twp	N/S	Rng	E/W	Sec	TD	Status	Chinle depth	Santa Rosa depth	Moenkopi depth	Triassic thickness	Remarks	Triassic production or show
Cities Service	2	Fort Union	19	N	19	E	18	2725	water	662	1508	1604	1140	Perf 2056-2068 (Glorieta), swbd 300 BW; Perf 1511-1703 (Santa Rosa-Moenkopi), swbd 100 BFW in 9 hours; Drilled as petroleum exploration well, converted to water well.	perf, no recovery (Santa Rosa-Moenkopi)
Arkansas Fuel Oil	1	Kruse	19	N	21	E	11	2613	D&A					Nonflammable gas @ 12 MMCFD @ 1420-1425 ft (Glorieta?); Nonflammable gas @ 2 MMCFD @ 1670 ft (Glorieta?); Nonflammable gas @ 2 MMCFD @ 1795 ft (Permian); Nonflammable gas @ 10 MMCFD @ 2220-2225 ft (Permian?); 4-6 bbls fresh water per hour @ 2361 ft (Permian?).	nonflammable gas @ 500 MCFD (Santa Rosa)
Winston Marks	1	Sierracita State	25	N	24	E	5	1650	D&A					Water @ 1056 (Chinle) Show gas 1535-1543 (Chinle?)	gas show + water (Chinle)
Kelly Bell	1	State	25	N	24	E	6	1565	water					Drilled as petroleum exploration well. Converted to water well. Pumped 720 BW from open hole 150-1565 (Cretaceous-Triassic).	fresh water
W D Weathers	1		25	N	24	E	7	1097	D&A					water @ 1012 &1078 FT (Santa Rosa)	water (Santa Rosa
HNG Fossil Fuels	1	State	25	N	24	E	9	2664	D&A	1060	1484	absent	538	Perf 1542-1625 (Santa Rosa-Glorieta) no recovery; Perf 1482-1492 (Santa Rosa) swbd water, gas & mud; Perf 1488-1490 (Santa Rosa) swbd water with show gas.	Gas - perf 1488-1490 swbd water w/ SG; f 1482-1492 swbd water w/ gas & mud
York and Denton et al (Amoco/Colfax Carbide)	1	Tex Mex	26	N	24	E	2	1525	D&A	1021	1298	absent	351	IP 250 MCFD, decreased to 153 MCFD; 99.85% CO_2; CO_2 show @ 1147 ft. Show oil @ 1025, 1046, 1092, 1108, 1140, 1245-1286, 1328, 1365 ft.	oil shows; CO_2 show
HNG Fossil Fuels	1	Sauble	27	N	24	E	35	2568	D&A	1070	absent?	absent?		Perf 1634-1646 (Chinle); perf 1538-1558 (Chinle), frac, rec CO_2 + water; perf 1538-1572 (Chinle) no recovery; Perf 1280-1307 (Chinle) acidized, rec acid + drilling mud; Perf 1311-1318 (Chinle) swbd dry.	CO_2 (Chinle)
CO_2 in Action	2	Moore	29	N	24	E	10	4083	D&A	2010	2450	absent		Salt water @ 2345 (Chinle). Show oil @ 2095, 2345 (Chinle).	gas show (Chinle)
CO_2 in Action	1	Moore	29	N	24	E	10	4075	D&A	1946	2310	absent	452	DST 2350-2430 (Santa Rosa-Glorieta) rec 50 water-cut mud + 420 muddy water.	water (Santa Rosa)
El Paso Energy Raton	27	VPR B	30	N	18	E	36	7428	Inj					Perf Chinle (7016-7074).	perf, no show
El Paso Energy Raton	99	VPR E	31	N	19	E	5	7723	Inj	7208	DNP			Disposal Openhole Morrison-Entrada-Chinle (6824-7690 ft)	
El Paso Energy Raton	34	VPR E	31	N	19	E	5	7654	Inj					Disposal Openhole Entrada-Chinle (7133-7614 ft)	

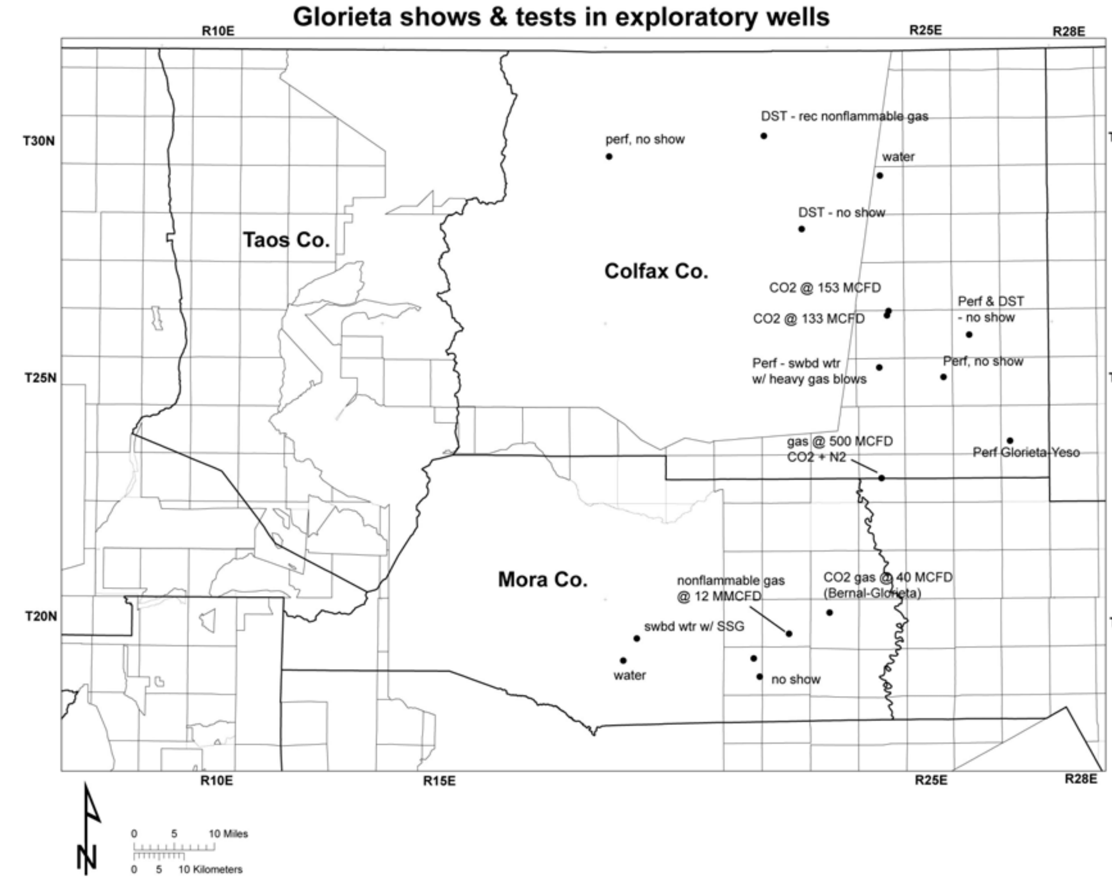

Figure NC 3. Wells with shows and tests in the Glorieta Sandstone. See Table NC 2 for descriptions of shows. From Broadhead (2008).

Table NC 2. Wells with shows and tests in the Glorieta Sandstone.

Operator	Well#	Lease name	Twp	N/S	Rng	E/W	Sec	Elev	Comp	TD	Status	Glorieta depth	Glorieta thickness	Remarks	Glorieta production or show
Cities Service	2	Fort Union	19	N	19	E	18	6675	Jul-78	2725	water	1870	248	Perf 2056-2068 (Glorieta), swbd 300 BW; Perf 1511-1703 (Santa Rosa-Moenkopi), swbd 100 BFW in 9 hours; Drilled as petroleum exploration well, converted to water well.	water
Arkansas Fuel Oil	1	Kruse	19	N	21	E	11	6500	Feb-26	2613	D&A			Nonflammable gas @ 12 MMCFD @ 1420-1425 ft (Glorieta?); Nonflammable gas @ 2 MMCFD @ 1670 ft (Glorieta?); Nonflammable gas @ 2 MMCFD @ 1795 ft (Permian); Nonflammable gas @ 10 MMCFD @ 2220-2225 ft (Permian?); 4-6 bbls fresh water per hour @ 2361 ft (Permian?).	nonflammable gas @ 12 MMCFD
Mobil Producing Texas	1	E C Wiggins	19	N	21	E	24	6265	Oct-77	2697	Gas	1712	374	IP 30 MCFGD; Tested Yeso and Glorieta with no shows.	no show
Cities Service	1	Fort Union	20	N	19	E	33	7321	Feb-78	5836	D&A	1854	316	CO2 encountered above 2000 ft (Permian?)	swbd water w/ SSG (perfs)
Mobil Oil Corp.	1	Wooton & Reardon	20	N	23	E	9	5975	Dec-77	2127	D&A	1246	338	Flowed 175 MCFD @ 1243 ft (Bernal); Perf 1181-1286 ft (Bernal-Glorieta), frac, flowed 40 MCFD (CO2).	CO2 gas @ 40 MCFD (Bernal-Glorieta)
California Company	1	Floersheim State	23	N	24	E	15	5823	Jan-25	2556	D&A	1395	325	Gas at 500 MCFD 1510-1560 (Glorieta) - 67% CO2, 28.7% N2, 4.1% O2, 0.2% He.	gas @ 500 MCFD CO2 + N2
Amoco	1	State FA	24	N	27	E	29	6172	Sep-74	2325	D&A	1760	198	Perf 1766-2039, acidized (Glorieta-Yeso)	Perf Glorieta-Yes
HNG Fossil Fuels	1	State	25	N	24	E	9	6122	May-80	2664	D&A	1598		Perf 1600-1680 (Glorieta) no recovery; perf 1630-1680 (Glorieta) no recovery; Perf 1542-1625 (Santa Rosa-Glorieta) no recovery; Perf 1600-1650 (Glorieta) swbd 70 BW with heavy gas blows.	Gas - Perf, swbd water w/ heavy gas blows
Amoco	1	State EX	25	N	25	E	14	6609	Sep-74	2240	water	1750	236	Drilled as petroleum exploration well. Converted to water well. Perf 586-652 (Dakota), 1771-1810, 1850-1868, 1870-1888, 1902-1920, 1958-1986 (Glorieta)	Perf, no show
York and Denton et al (Amoco/Colfax Carbide)	1	Tex Mex	26	N	24	E	2	6264	Oct-39	1525	D&A			1515-1525 ft (Glorieta?), IP 250 MCFD, decreased to 153 MCFD; 99.85% CO2.	CO2 @ 153 MCFD?
Neill & Steffan	3	Sauble	26	N	24	E	3	6203	Dec-47	1560	water			IP 133 MCFD of CO2; converted to water well	Gas CO2 @ 133 MCFD
Brooks Exploration	1-21	State of New Mexico	26	N	26	E	21	6693	Sep-79	2075	D&A			DST 1322-1384 (Glorieta + supra-Glorieta Permian) no rec; DST 1455-1497 (Glorieta) rec 5 ft mud	Perf & DST, no show
Continental Oil Company	1	Maxwell Land Grant	28	N	22	E	11	6181	Jun-54	2947	D&A	2770	64	DST 2775-2820 (Glorieta) rec 90 mud	DST, no show
CO2 in Action	1	Moore	29	N	24	E	10	6550	Jun-78	4075	D&A	2398	106	DST 2350-2430 (Santa Rosa-Glorieta) rec 50 water-cut mud + 420 muddy water.	water
El Paso Energy Raton	27	VPR B	30	N	18	E	36	8070	Aug-00	7428	Inj			Perf Glorieta (6886-7356)	perf, no show
Continental Oil Company	3	St. Louis, Rocky Mountair	30	N	22	E	18	7972	Sep-54	5500	D&A	5390	58	DST 5327-5477 (Glorieta?) rec 1030 mud, hard blow dies in 50 minutes; DST 5321-5477 (Glorieta?) rec 390 mud + 300 non-inflammable gas-cut mud.	DST rec nonflammable gas

CO_2 in Central New Mexico

CO_2-rich gases have been encountered in three areas of central New Mexico: the Estancia Basin, the Chupadera Mesa area, and the Albuquerque Basin (see Plate I in Appendix B). CO_2 has been produced commercially from the Estancia Basin. Recent exploratory activity on Chupadera Mesa has encountered CO_2-rich gases. Water wells drilled within and on the margins of the Albuquerque Basin have also encountered CO_2. The distribution of CO_2 in each of these areas and the potential for additional CO_2 resources is discussed below and distribution is also shown on Plates XI and XII in Appendix B.

Estancia Basin

Carbon dioxide gas has been produced from two small fields in the Estancia Basin. Both fields are located west of the town of Estancia (Anderson, 1959; Broadhead, 1997; Figure CNM 1). The two fields are known informally as the northern Estancia field and the southern Estancia field. The northern field was discovered in 1931 by the Sinoco (aka Estancia Valley Development Co.) No. 2 DeHart well, located in Sec. 12 T7N R7E (Figure CNM 2). The well was drilled to a total depth of 1440 ft. Production was obtained from a sandstone in the Sandia Formation (Lower Pennsylvanian) at a depth of 1240 ft (Figure CNM 3). Initial potential was a relatively low 140 thousand ft^3 per day (MCFD). Six additional productive wells were drilled between 1934 and 1937 (see Table CNM 1). The reservoirs for the northern Estancia field appear to be sandstones of the Sandia Formation (Foster and Jensen, 1972). The produced gas was converted into dry ice at a nearby processing plant (Anderson, 1959).

The discovery well and all other productive wells were drilled near the crest of the Wilcox anticline (Figure CNM 2). The structure has been mapped at the surface as a doubly plunging anticline with 60 to 80 ft of structural closure (Winchester, 1933). Strata of the Madera Group crop out along the axis of the fold and are faulted along the crest of the structure. The trap appears to be structural, but the downdip boundaries of the field have never been defined by drilling (Figure CNM 2). It is not known if there is a stratigraphic component to trapping.

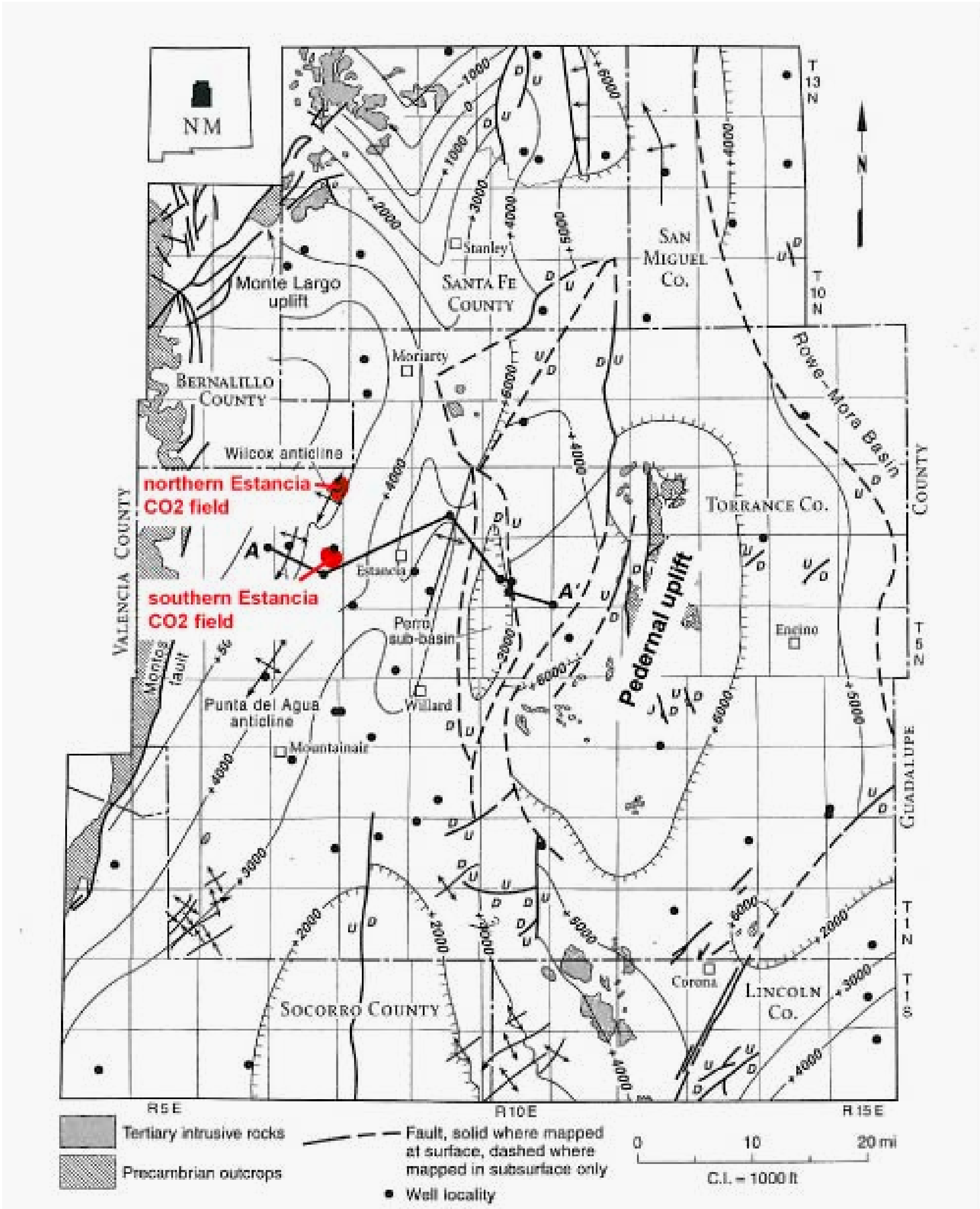

Figure CNM 1. Structure contours on Precambrian basement in Estancia Basin and location of the northern and southern Estancia CO_2 fields. See Figure CNM 5 for cross section A-A'. From Broadhead (1997).

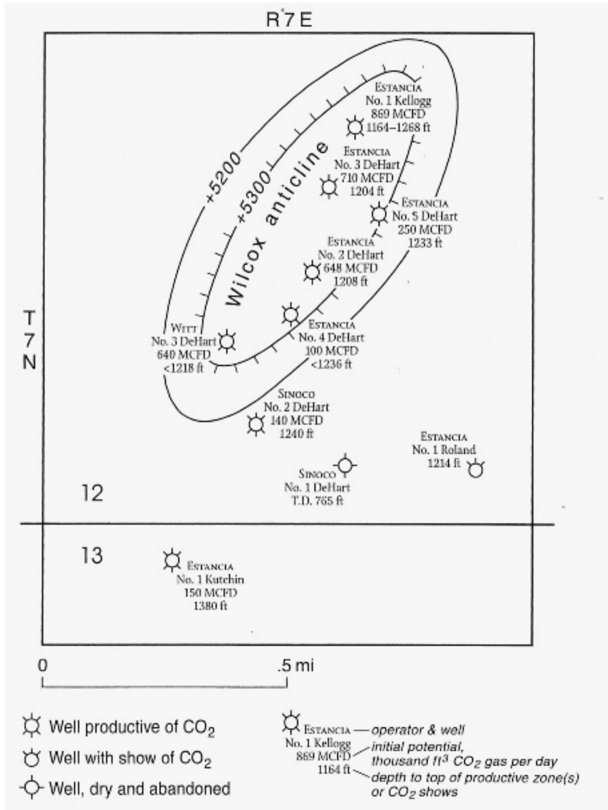

Figure CNM 2. Wells in northern Estancia CO_2 field, depths to production and shows, and structure contours on top of main pay sandstone. Contour interval is 100 ft. datum is sea level. From Broadhead (1997).

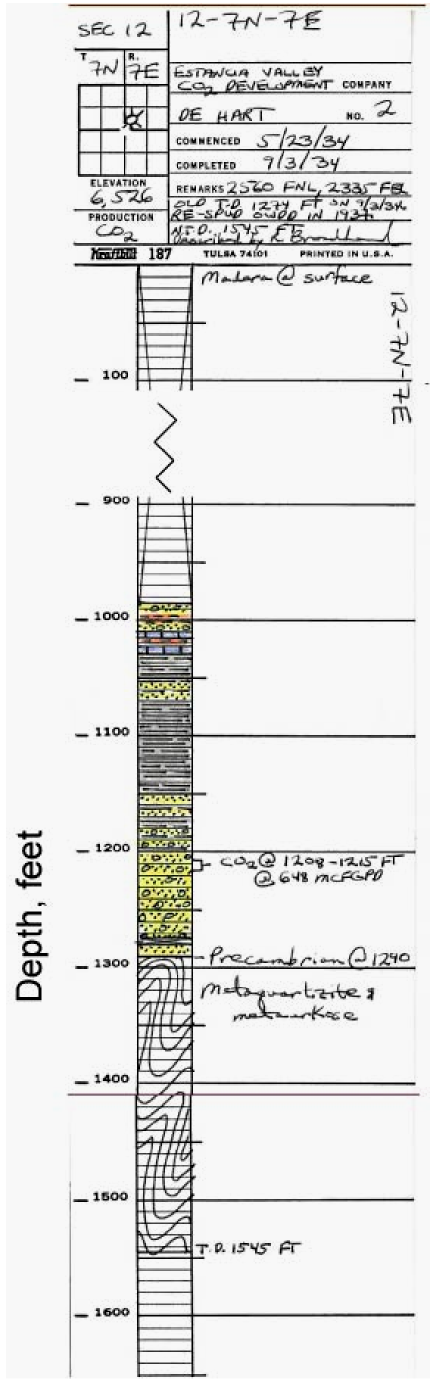

Figure CNM 3. Lithologic log of the lower part of the Estancia Valley Development No. 2 DeHart well, the discovery well in the northern Estancia CO_2 field, showing the productive interval in the conglomeratic sandstone near the base of the Sandia Formation.

The southern Estancia field was discovered in 1928 by the Wilson No. 1A Pace well, located in Sec. 12 T6N R7E (Fig. CNM 4). The well was drilled to a total depth of

2020 ft. Carbon dioxide was encountered between depths of 1645 ft and 1760 ft. Although data are vague, it appears that the gas was obtained from a sandstone in the Sandia Formation (Foster and Jensen, 1972). In all, three wells produced CO_2 from the southern Estancia field (see Table CNM 1).

The trapping mechanism at the southern Estancia field has not been defined. Existing well records are too generalized to construct local subsurface maps with sufficient detail to identify the trapping mechanism. Furthermore, the productive wells are located in an area where Quaternary sediments at the surface obscure the structure of the underlying Pennsylvanian strata.

CO_2 was first produced from the Estancia fields in 1934. In that year, a plant was built to convert the CO_2 gas into dry ice (Anderson, 1959). The plant produced dry ice until 1942. Apparently, water seeped through the well casings and limited the amount of gas that could be produced (Anderson, 1959). Cumulative production from the Estancia fields is unknown. As recently as 1963, two wells, the Meyers No. 1 Milburn and the Meyers No. 1 Smith and Pace, were drilled to develop CO_2 resources in the southern Estancia field (Figure CNM 4). According to Foster and Jensen (1972), both wells discovered additional CO_2 resources but production was never established.

Several water wells that produce from permeable zones in the Madera Group (Pennsylvanian) also produce or effervesce CO_2 gas (Titus, 1980). These wells are located in T6-7N R7E and are structurally updip from the Estancia CO_2 fields. Water is obtained from depths of 100 to 300 ft in these wells, approximately 1000 ft shallower than the reservoir zones in the Estancia fields. Apparently, CO_2-saturated water is characteristic of the Madera in this area. It is not known whether the CO_2 recovered from the water has leaked upward from the reservoirs in the Estancia fields or whether the CO_2 in the water wells is hydraulically isolated from those reservoir strata. It is also not known with certainty whether the CO_2 produced from the water wells occurs as a separate gas phase in the aquifers or is in solution. If the latter, then it desolves from the water as it is produced and rises through the well and essentially “bubbles” out of solution.

There is limited potential for additional CO_2 resources in the Estancia Basin. It is probable that not all of the CO_2 gas was produced from the north and south Estancia fields before they were abandoned. However, the relatively small size of the structures that are thought to act as traps indicates that the overall size of the resource is relatively small. Elsewhere, most of the structure in the basin consists of a simple eastward dip slope that originates on the eastern flank of the Manzano and Sandia Mountains on the west flank of the basin (see Figures CNM 1, CNM 2). Potential reservoir strata are exposed on the east side of the mountain ranges and trap possibilities are limited in the area. However, the large anticlinal feature that runs north-northeast from the town of Willard west of the Perro sub-basin (Figure CNM 1) holds some promise as a trap and covers a substantial area of approximately 4 townships. Potential reservoirs are sandstones in the lower part of the Pennsylvanian section (as at the north and south Estancia fields) or Pennsylvanian limestones, especially if fractured on the crest or limbs of the anticline.

The source of the CO_2 in the Estancia Basin remains unknown. Little information is available to hypothesize the source and therefore guide exploration. In general terms, it could be derived from liberation of carbonate through groundwater interactions in the limestone-rich Pennsylvanian section. Alternatively, it may be juvenile and migrated into the center part of the basin from the northeast-trending igneous dikes (Tertiary) that cut across the southern part of the basin (see Wilpolt and others, 1946 for location and description of these dikes). Perhaps less definite, the CO_2 may have migrated into the Estancia Basin from the Albuquerque Basin that is located west of the mountains that form the western boundary of the Estancia Basin. No isotopic analyses that could be used to help determine an origin are available for either the CO_2 or associated gases that were produced from the Estancia fields.

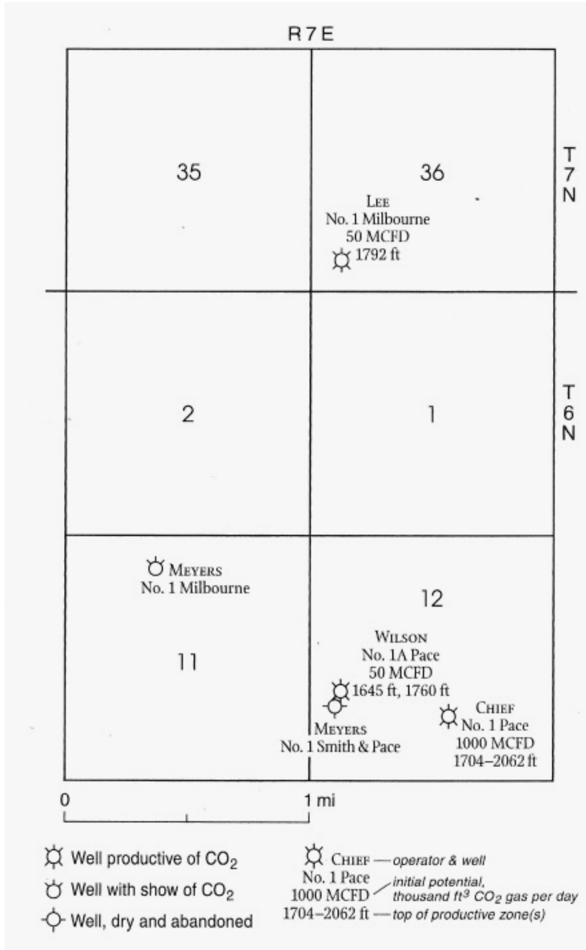

Figure CNM 4. Wells in southern Estancia CO_2 field and depths to production and shows. From Broadhead (1997).

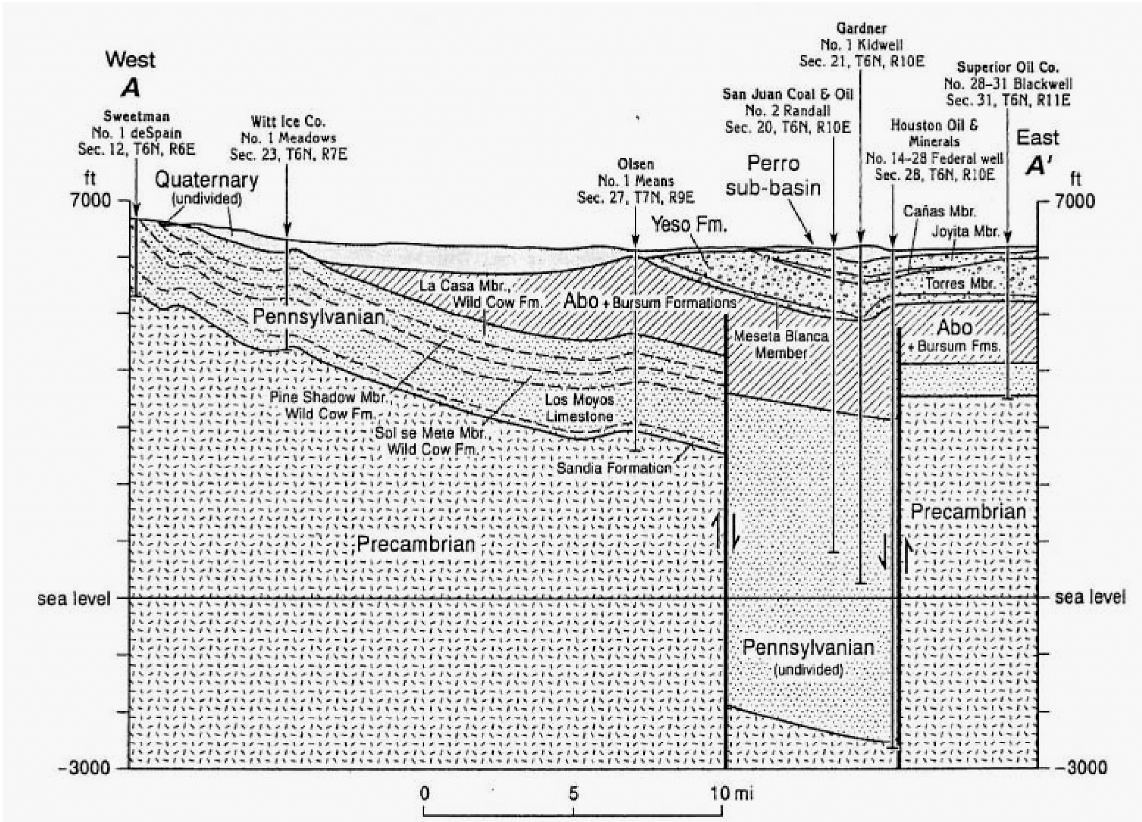

Figure CNM 5. West-east structural cross section A-A' through Estancia Basin. Datum is sea level. See Figure CNM 1 for location. From Broadhead (1997).

Table CNM 1. CO2 fields in the Estancia Basin. Data from Anderson (1959), Foster and Jensen (1972), and well records on file at the New Mexico Bureau of Geology and Mineral Resources.

Field	Location	Number productive wells	Average depth to production (feet)	Reservoir	Gas composition	Field status	Initial potential of individual wells, MCFD
Estancia north	secs. 12 & 13 T7N R 7E	7	1260	Sandia Fm. (Pennsylvanian)	98.4 - 99% CO_2 0.97 - 1.56% N_2 0.03-0.04% He	abandoned	100 - 869 MCFD
Estancia south	sec. 36 T7N R7E sec. 12 T6N R7E	3	1690	schist (Precambrian); Sandia Fm. (Pennsylvanian)	99% CO_2	abandoned	50-1000 MCFD

Chupadera Mesa area

Although no production has been established, several wells drilled on Chupadera Mesa of eastern Socorro and western Lincoln Counties have encountered gases with CO_2 contents ranging from 31 to 91 percent (Figure CNM 6; Table CNM 2). The Abo Formation (Permian) has been the reservoir for most of the CO_2-rich gases encountered thus far (Figures CNM 7, CNM 8).

Exploration in the region was originally for petroleum, but production has not been established (Broadhead and Jones, 2004). Petroleum exploration wells drilled in the 1990's encountered natural gases composed mostly of varying percentages of CO_2 and nitrogen; these gases also contained significant concentrations of helium (Table CNM 2; Broadhead and Jones, 2004). The hydrocarbon component comprised less than 5 percent of these gases. Helium content varied from 2 to almost 3.5 percent, rendering the gases viable as sources of this useful substance providing that the gases have accumulated and can be produced in sufficient quantity.

New Mexico gases commercially produced for CO_2 have been comprised of 98 to 99 percent CO_2, as described in the preceding section on the Estancia Basin and in the section on northeastern New Mexico. Natural gases in the Chupadera Mesa region that have been sampled and analyzed have CO_2 concentrations ranging from 0.73 to 91.43 percent (Table CNM 2), less than the amount present in gases commercially produced for their CO_2 content. However, the presence of significant percentages of helium in natural gases of Chupadera Mesa may render them economic if the gases were produced for either their helium content or produced for both their helium and CO_2. The remainder of the gas is mostly nitrogen.

The source of the CO_2 encountered in the wells drilled on Chupadera Mesa has not been determined. The presence of very large igneous intrusive bodies throughout the eastern part of the region (Figure CNM 9) and the presence of Tertiary-age dikes throughout the Chupadera Mesa area suggests that large volumes of juvenile CO_2 were transported into the area by rising magmas during the Tertiary. If so, one would expect that CO_2 concentration in gases could increase with increasing proximity to major intrusive bodies.

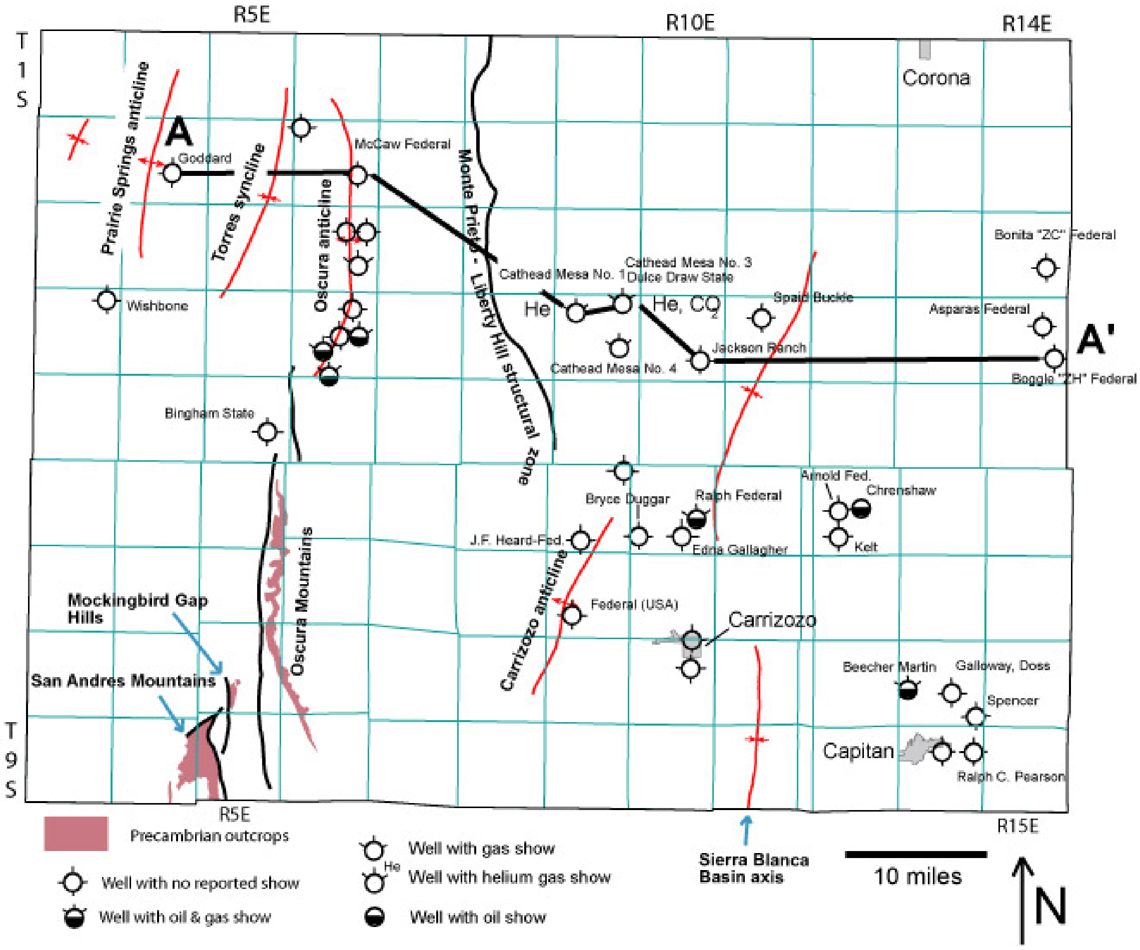

Figure CNM 6. Petroleum exploration wells drilled in the Chupadera Mesa area and shows of oil, natural gas, CO_2 and helium. See Figure CNM 8 for cross section A-A'.

Manzano Oil Co. No 1 Cathead Mesa
Sec. 8 T4S R9E, Socorro County, New Mexico

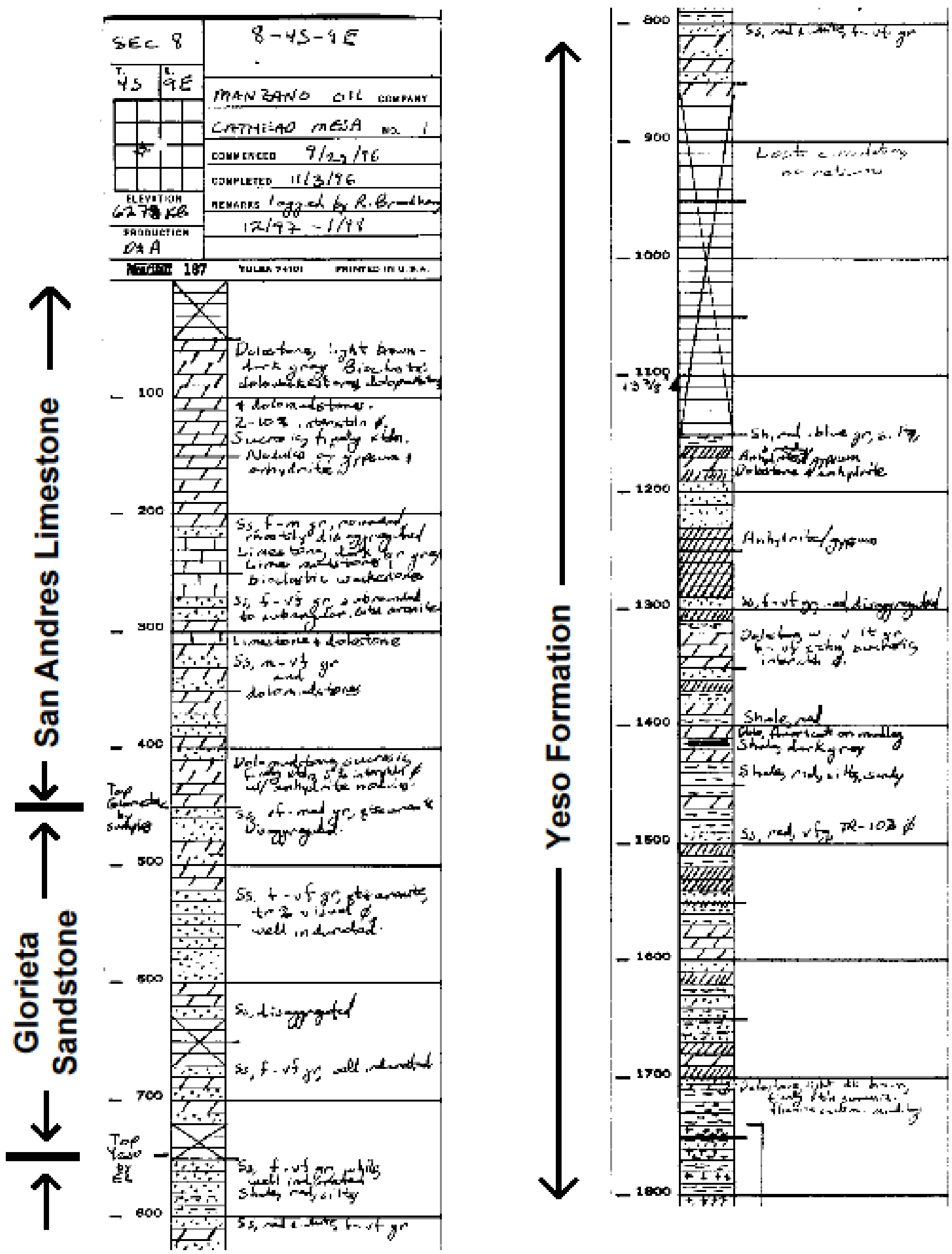

Figure CNM 7. Lithologic log of the Manzano Oil Company No. 1 Cathead Mesa well, located in Sec. 8 T4S R9E. See Figure CNM 6 for location. This well was drilled in the mid-1990's for oil and gas but encountered helium-rich gases instead (see Table CNM 2 for gas analysis).

Manzano Oil Co. No 1 Cathead Mesa
Sec. 8 T4S R9E, Socorro County, New Mexico (continued)

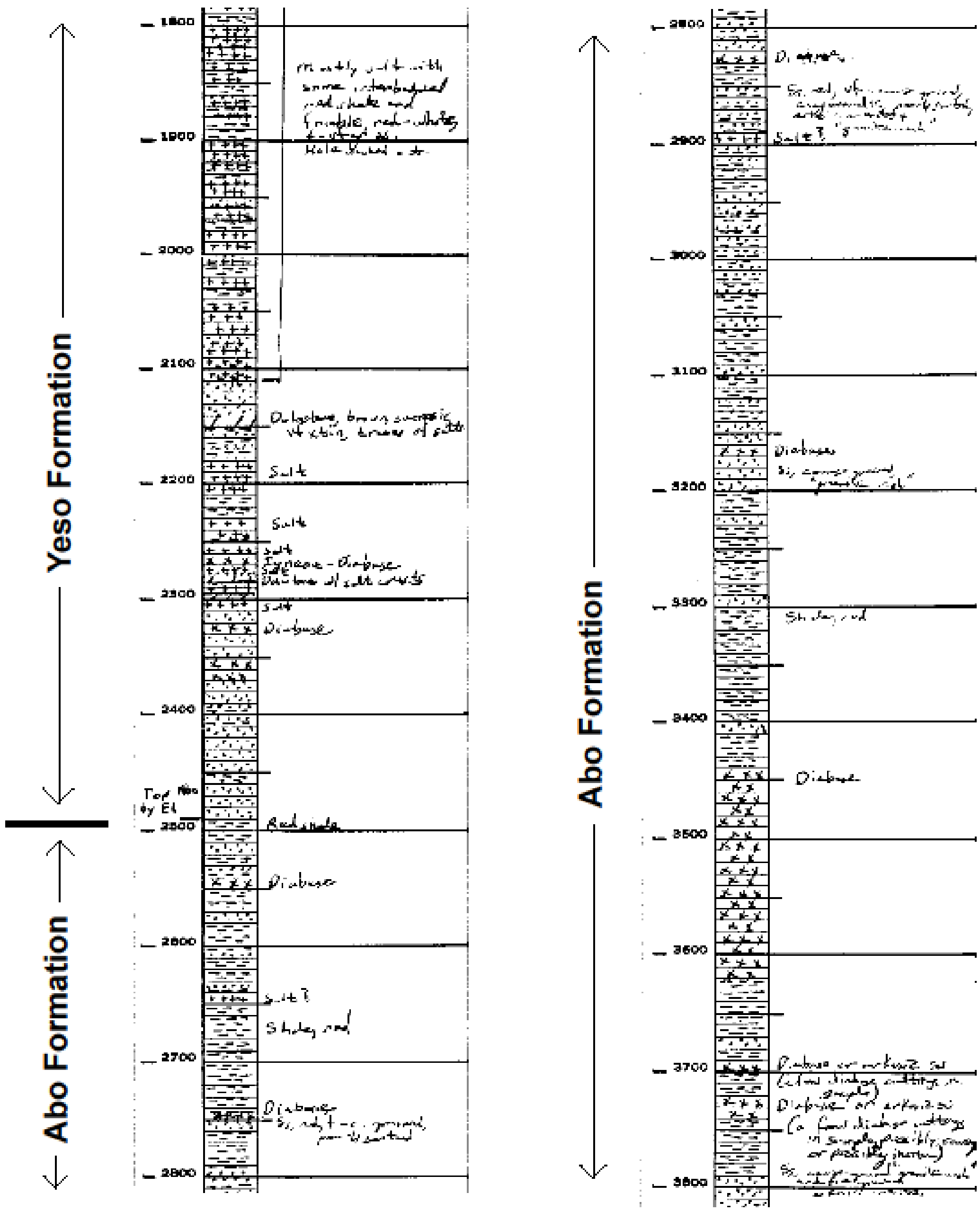

Figure CNM 7 (continued).

Manzano Oil Co. No 1 Cathead Mesa
Sec. 8 T4S R9E, Socorro County, New Mexico (continued)

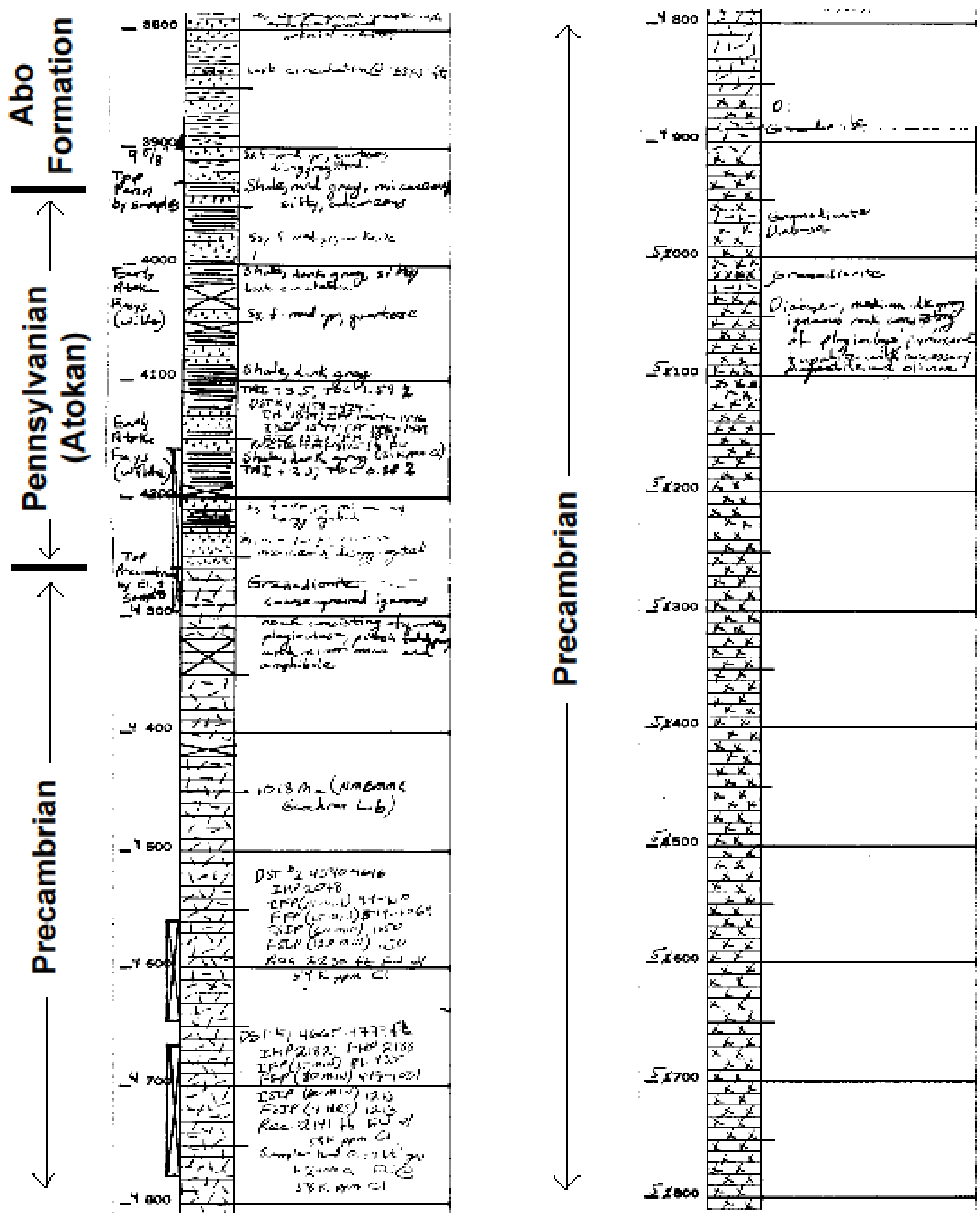

Figure CNM 7 (continued).

Manzano Oil Co. No 1 Cathead Mesa
Sec. 8 T4S R9E, Socorro County, New Mexico (continued)

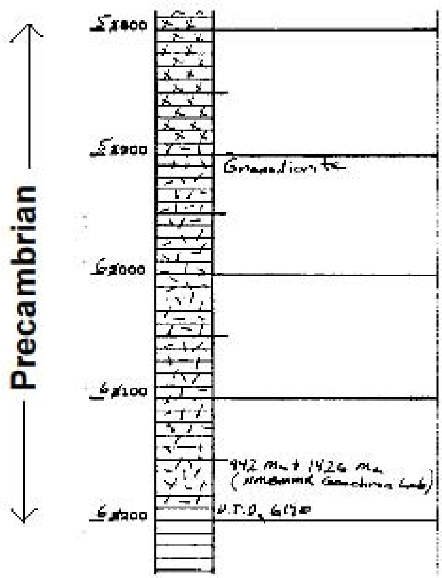

Figure CNM 7 (continued).

Table CNM 2. Composition of gases recovered from wells drilled on Chupadera Mesa.

Well	Location (section -township -range)	Surface elevation (feet)	Sample depth (feet)	Reservoir	Gas composition, mole percent				
					CO_2	CH_4	C_{2+}	N_2	He
Manzano No. 1 Cathead Mesa	8-4S-9E	6278	3900	Abo (Permian) Sandia (Pennsylvanian)	0.73	1.23	0.02	95.26	2.56
Primero No. 1 Dulce Draw State	2-4S-9E	5972	2650	Abo (Permian)	31.1	0.85	0	65.57	2.02
			2846	Abo (Permian)	91.43	0	0	8.3	0.09
Primero No. 3 Cathead Mesa	3-4S-9E	6050	3143-3204	Abo (Permian)	37.81	2.37	0.03	56.93	2.86
			3143-3175	Abo (Permian)	26.32	2.52	0.07	67.64	3.44
Mountain States No. 1 Chupadera	23-3S-6E	5910	4221	Sandia (Pennsylvanian)	flowed 50 MCF nonburnable gas per day				

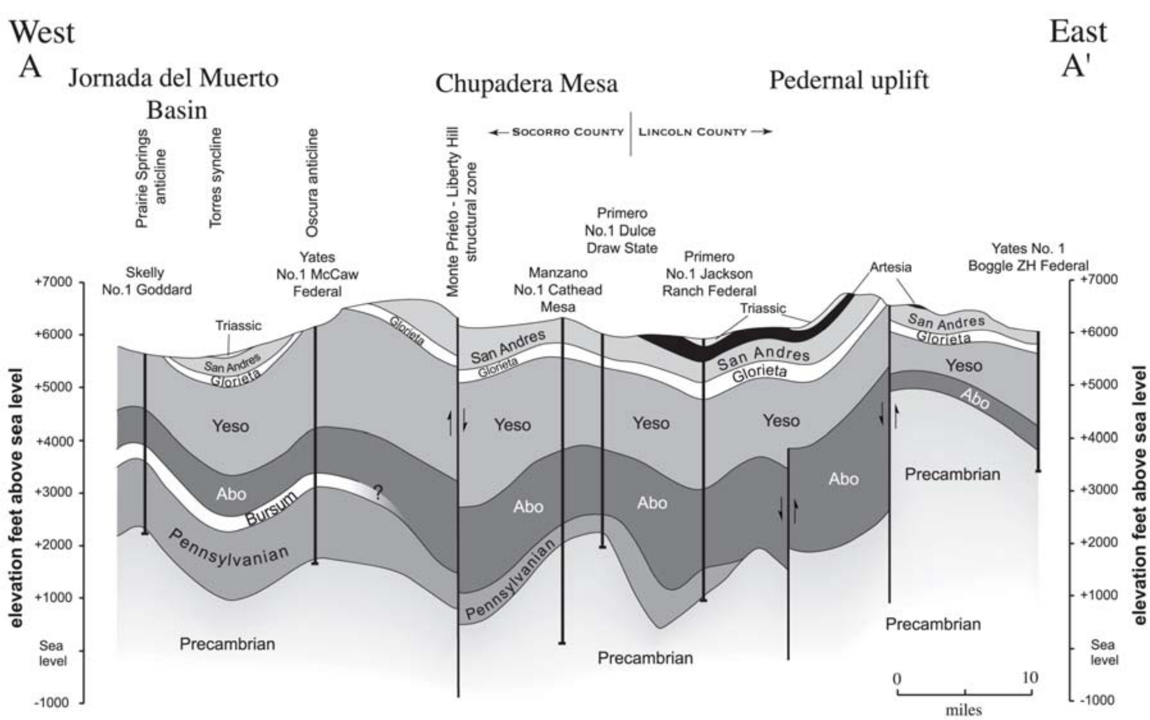

Figure CNM 8. West-east structural across section though Chupadera Mesa area. Datum is sea level.

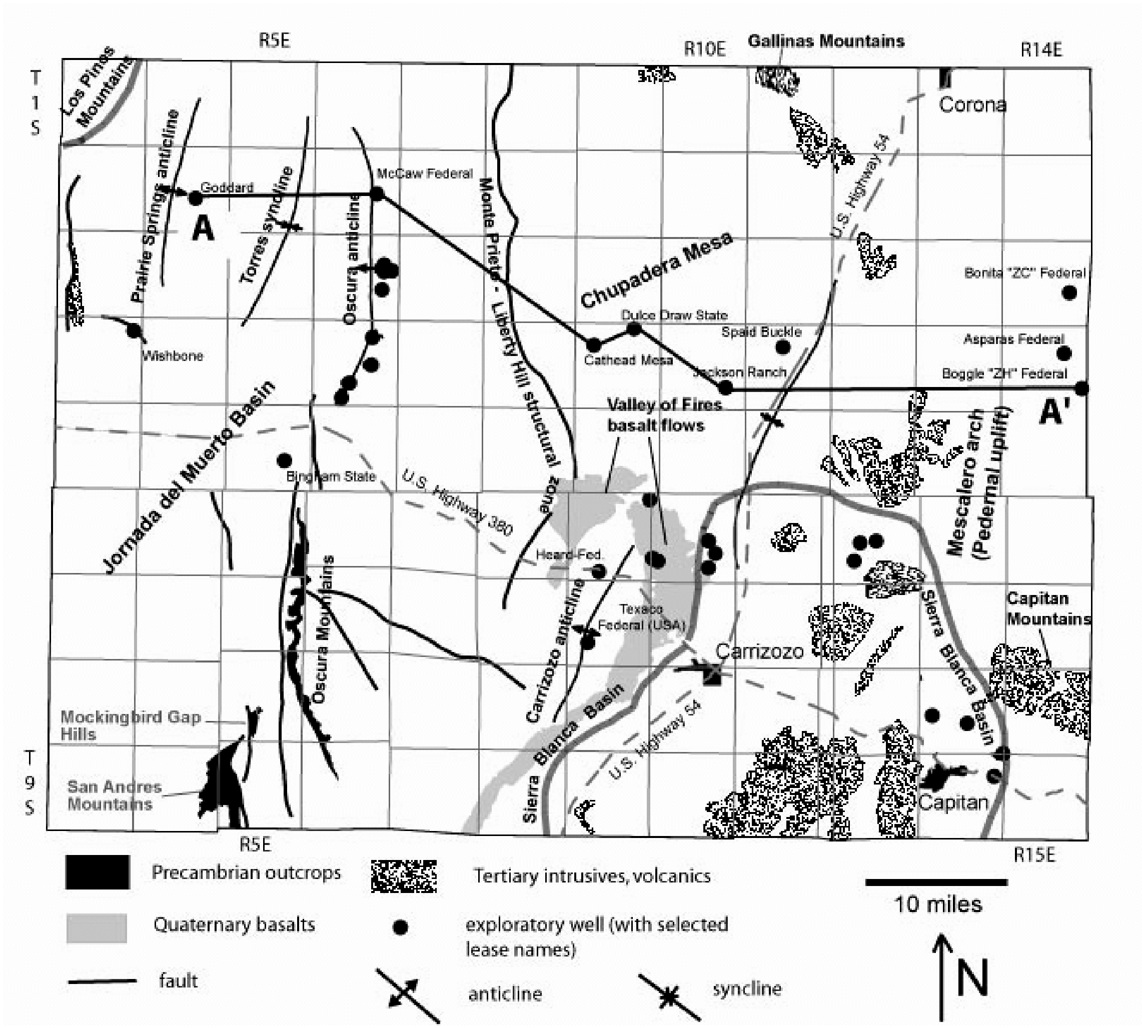

Figure CNM 9. Location of major geologic elements, major structures mapped at the surface, and Tertiary and Cenozoic intrusive and extrusive igneous rocks in the Chupadera Mesa region. See Figure CNM 8 for location of cross section A-A'.

Albuquerque Basin

The Albuquerque Basin (Plate I in Appendix B) is a fault-bounded north-south trending basin. It is one of several such basins that form the Rio Grande rift (Kelley, 1977; Hawley, 1978; Black, 1982, 1999). The basin is bounded on its east and west sides by complex systems of high-angle normal faults. Basin structure is far more complex than portrayed on Plate I. Basin fill of alluvial, fluvial, and lacustrine/playa deposits belongs to the Santa Fe Group (Upper Tertiary) and indicates that structural movement that formed the basin took place during the Late Tertiary. Tertiary-age basin fill exceeds 22,000 ft in the deepest parts of the basin. Maximum structural relief on top of the Precambrian is as large as 33,000 ft between the deepest parts of the basin and the Sandia Mountains on the east side of the basin. At deepest known part of the basin, the top of the Precambrian is projected to be 24,000 ft below sea level. Beneath the Upper Tertiary basin fill are up to 5000 ft of Upper Cretaceous marine strata that are roughly similar to the Upper Cretaceous strata so prolifically productive of natural gas in the San Juan Basin. Beneath the Cretaceous are 2500 ft of nonmarine Jurassic and Triassic strata, 2000 ft of nonmarine and shallow-marine Permian strata, and almost 3000 ft of marine to nonmarine Pennsylvanian sandstones, shales and marine limestones.

The Albuquerque Basin has been the object of oil and natural gas exploration since the first exploratory well was drilled in the basin during 1912 (Black, 1982, 1999; Broadhead, in press). It was not until 1953 that any wells were drilled to a sufficient depth to penetrate Cretaceous strata in the deeper parts of the basin. Most wells before then either reached total depth in Tertiary-age basin fill (which are largely devoid of oil and natural gas possibilities) or went from basin fill into a shallow Permian or Pennsylvanian section on shallow faults blocks near the margins of the basin.

During the 1970's and early 1980's, the first sustained oil and natural gas exploration effort began in the basin. During this period, Shell Oil Company conducted extensive seismic reflection surveys and drilled seven unsuccessful deep (and expensive) exploratory wells, several of which encountered noncommercial volumes or "shows" of oil and natural hydrocarbon gas in Cretaceous strata. As expenses for the exploration program mounted without a return on investment, Shell partnered with other companies to drill an additional two wells. Natural gas was reportedly flowed and flared at the Shell No. 1 West Mesa Federal well located in Sec. 24 T11N R1E, Bernalillo County but large expenses associated with drilling this deep (19,375 ft) well (Black, 1982) combined with the low price of natural gas and apparently limited flow rates contributed to the noncommercial nature of the reservoir encountered by the well. A last well was drilled by UTEX Oil Company in collaboration with Shell and represented the last unsuccessful gasp of the Shell effort. Still, the wells drilled by Shell and its partners provided invaluable geologic information that has helped geologists develop an understanding of basin geology and has provided the foundation for all subsequent exploratory efforts and established that gases in the Cretaceous and pre-Cretaceous sections are hydrocarbon based.

Numerous shows of gas have been reported from wells drilled into Tertiary-age basin fill within the Albuquerque Basin. Although data are sketchy, it appears that the gases have a large CO_2 component. Although quantitative analyses are not available, the gas in at least one well, the Norins No. 2 Albuquerque Acres located in Sec. 19 T11N R4E which was drilled during 1935, was reported to be CO_2 (Table CNM 3). Springs and shallow water wells productive from Pennsylvanian and Permian limestones east and west of the basin emit gas along with water. The gases from these springs and wells are dominantly CO_2 with lesser amounts of nitrogen and hydrogen (Table CNM 3).

Another water well of indefinite location also emits CO_2 gas along with the water it produces. Approximately 15 years ago the senior author and William Haneberg, then a geologist at the New Mexico Bureau of Geology and Mineral Resources, visited a water well located a couple of miles west of the town of Los Lunas. The well was located on the high bench in the Rio Grande valley west of the river. The owner of the well had become concerned because he had started to hear a rapid tapping sound from the well casing. Depth to water was deep, several hundred feet. Haneberg sample the produced well water and found that it contained substantial amounts of CO_2 gas. The gas is dissolved in the water in the aquifer. As the water was produced it rose through the well tubing and pressure was decreased, thereby allowing a portion of the dissolved gas to come out of solution as gas bubbles which rose upward through the water column in the well, causing the tapping sound. In essence, the well produced naturally carbonated water ("Perrier") and demonstrated that at least some of the Tertiary aquifers in the Albuquerque basin contain CO_2 gas in solution.

Whether or not any accumulations of free CO_2 exist in the basin is unknown. It is possible that the CO_2 in the basin is disseminated throughout large parts of the groundwater system in the form of natural soda water. If so, it may not be a viable resource because of low production volumes associated with this type of resource and the large volumes of water that would have to be pumped to the surface and the re-injected, an energy intensive operation. Also, carbonic acid results from solution of CO_2 in water; carbonic acid will corrode (rust) production equipment.

The source of the CO_2 in the Tertiary reservoirs of the Albuquerque Basin has not been established. Isotopic analyses of the CO_2 and related gases have not been acquired or are not available so identification of source must rely on geologic factors.

As mentioned above, CO_2-rich gases appear to be confined to reservoirs in the Tertiary basin fill. Gases in pre-Tertiary sedimentary rock are comprised mostly of hydrocarbons. That indicates the CO_2 in the Tertiary fill did not migrate into it from the pre-Tertiary section. Therefore, it either originated within the Tertiary section or was introduced into it from external sources.

Sedimentary rocks within the Tertiary-age basin fill are light colored and organic poor. Therefore it is unlikely that they served as a CO_2 source in which CO_2 was generated along with methane gas from organic rich petroleum source rocks.

Table CNM 3. Composition of CO2-rich gases recovered from wells drilled adjacent to and within the Albuquerque Basin.

Well	Location (section -township -range)	Reservoir	Gas composition, mole percent				
			CO_2	CH_4	C_{2+}	N_2	He
Jim Crosby water well	36-11N-6E	Madera (Pennsylvanian)	78.7	0.1	0	2.1	0.13
surface spring	35-6N-3W	Madera (Pennsylvanian)	98.4	0	0	1.4	0.01
surface spring	15-8N-3W	San Andres (Permian)	92.1	0	0	7.1	0.6
Norins No. 2 North Albuquerque Acres	19-11N-4E	Santa Fe (Tertiary)	Reported CO2 gas show. Total depth 5024 ft.				

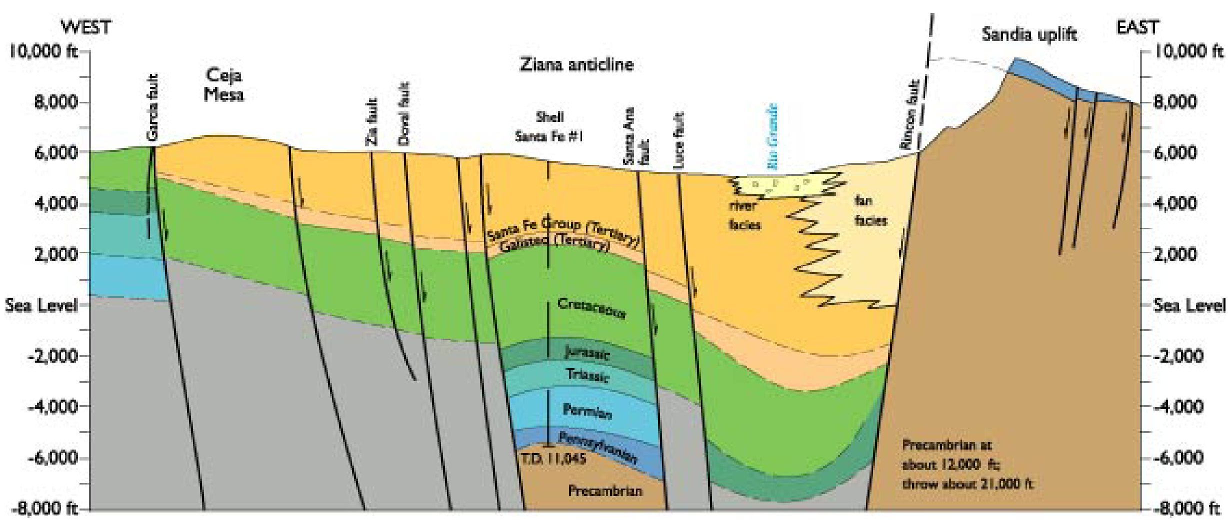

Figure 10. West-east structural cross section across northern part of Albuquerque Basin. Datum is sea level. Modified from Kelley (1977).

Post-rift extrusive and intrusive mafic volcanic rocks are present within the Albuquerque Basin. These form volcanoes and basalt flows at the surface over large portions of the basin (Kelley, 1977; Kelley and Kudo, 1978). Basaltic sills and flows have been encountered within the basin fill in water wells (Titus, 1963). Distribution of volcanic rocks within the subsurface has not been mapped. The magmas that formed these volcanic rocks would have carried dissolved CO_2 which would have exsolved from the rising magmas as a result of decreasing pressure. This may have been the source of the CO_2 in ground waters within Tertiary aquifers. Alternatively, calcite is the main cement for sandstones of the basin fill (Lozinsky and Tedford, 1991) CO_2 is evolved from calcium carbonate when the calcium carbonate is subjected to elevated temperatures and decomposes, either through deep burial or when a calcium-carbonate bearing rock comes into contact with a hot magma (Hunt, 1979, 1996). The CO_2 encountered in the basin could be a mixture of volcanically derived gas and gas derived from the thermal decomposition of calcite cement.

CO_2 in West-central New Mexico

CO_2-rich gases have been encountered by wells drilled in west-central New Mexico (Figure WC 1; Table WC 1) and adjacent areas of Arizona (Rauzi, 1999). The region is characterized by large volumes of intrusive and extrusive Tertiary volcanic rocks that crop out over large areas of the surface (New Mexico Bureau of Geology and Mineral Resources, 2003) but have also been penetrated in the subsurface by exploration wells. Subsurface occurrences of igneous rocks include rhyolitic to andesitic sills and dikes.

The region covered by west-central New Mexico is bounded on the north by the Zuni uplift (see Plate I in Appendix B). East of the area lie the basins of the Rio Grande rift, including the Albuquerque Basin. To the south, the region passes into the rugged volcanic-dominated landscapes of southwestern New Mexico. Subsurface geology and structure of southern Catron County, southwestern Socorro County, and northern Grant and western Sierra Counties remains unknown because no deep exploration wells have been drilled in this area and our knowledge of it is dependent upon the geology at the surface.

In west-central New Mexico, Precambrian basement rises gently westward onto the ancestral (Pennsylvanian to Early Permian) Zuni uplift. In the high areas to the west, the Pennsylvanian section is absent (see Plate VI in Appendix B) and the nonmarine red shales, sandstones and conglomerates of the Abo Formation rest unconformably on Precambrian basement. To the east marine-influenced Pennsylvanian strata are present between the Precambrian and the Abo (Figure WC 2).

The northeast-southwest trending San Agustin Basin (see Plate I in Appendix B), a Tertiary-age graben, cuts across the center of the region. A significant section of Upper Cretaceous marine shales and associated sandstones as well as Tertiary-age sedimentary units are preserved in the graben; 6600 ft of volcaniclastic sediments and tuffs and 1400 ft of Upper Cretaceous strata were penetrated in the San Agustin Basin by the Sun Oil Co. No. 1 Plains of San Agustin well (Figure WC 1). The well reached a total depth of 12,284 ft in Precambrian granite gneiss with top of basement at a depth of 12,146 ft. Aplite intrusives of Tertiary age were encountered in the Cretaceous and Abo (Permian) sections. The intrusive in the Abo is 1440 ft thick and is perhaps best described as a laccolith.

In the eastern part of west-central New Mexico, CO_2-rich gas was encountered in Pennsylvanian strata by the Sun Oil Co. No. 1 Pueblo of Acoma well, located in Sec. 2 T7N R7W, Cibola County (Figures WC 1, WC 2; Table WC 1). Gas-cut mud recovered on a drill-stem test of Pennsylvanian strata from depths of 4486 to 4526 ft; the gas was 95 percent CO_2 and 0.13 percent helium.

Gas samples were recovered from three water wells in Sec. 12 T9N R5W (Table WC 1). The aquifer (or reservoir) in each well is the San Andres Formation. CO_2 content of the gases ranged from 21 to 52 percent with the remainder primarily nitrogen; helium content was 2 to 2.3 percent in these gases.

To the southwest, nonflammable gases were recovered on drill-stem tests in two wells drilled by Shell Oil Co. (Table WC 1; Figure WC 1). Reservoirs were the Yeso Formation (Permian) and the San Andres Limestone (Permian). The chemical composition of the gases is not known but they probably contain CO_2 and/or nitrogen as the principal constituents because the gases are nonflammable.

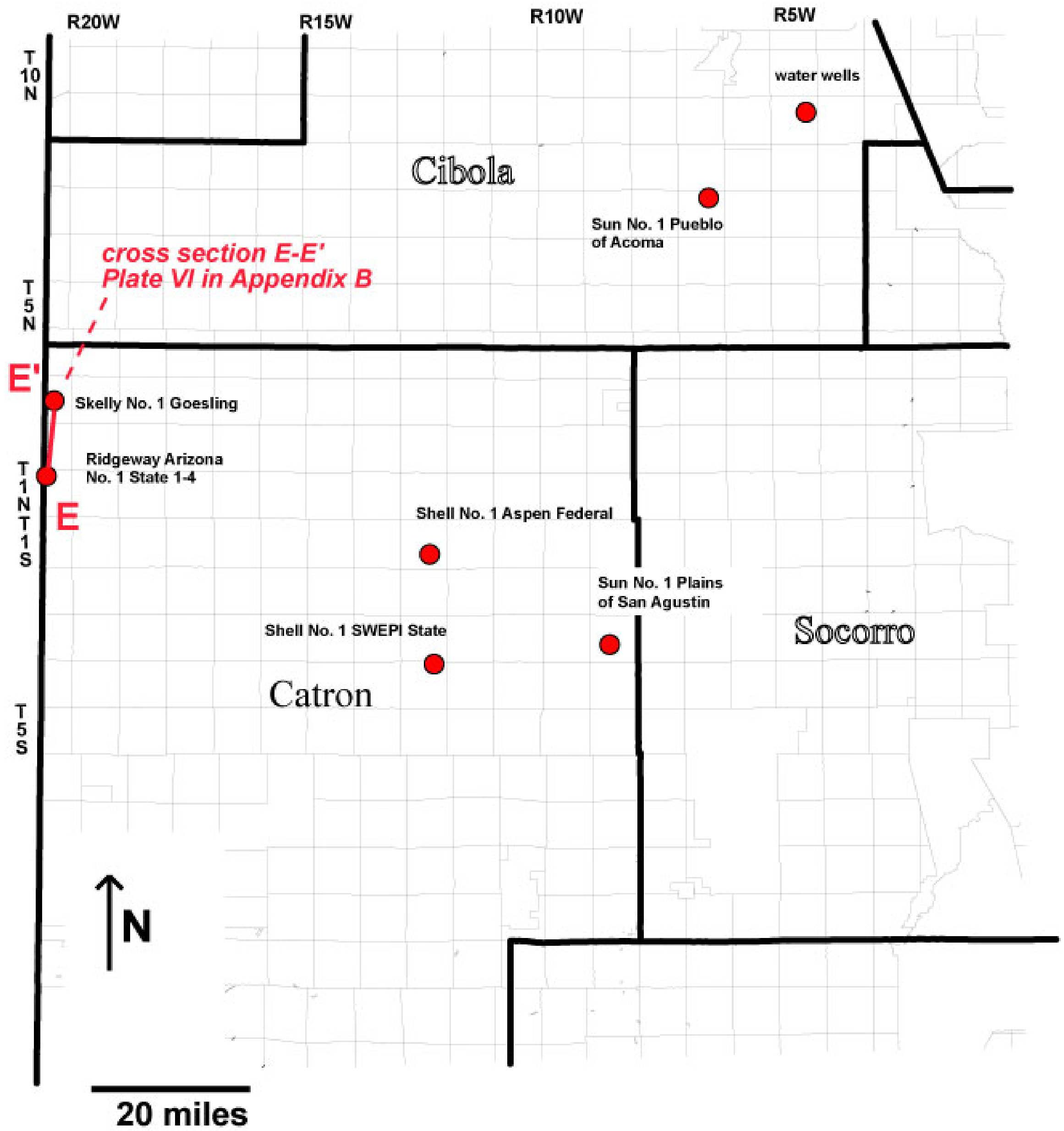

Figure WC 1. Wells in west-central New Mexico discussed in text and in Table WC 1. See Appendix B for cross section E-E'.

Sun Oil Co. No. 1 Pueblo of Acoma
Sec. 2 T7N R7W, Cibola County, NM

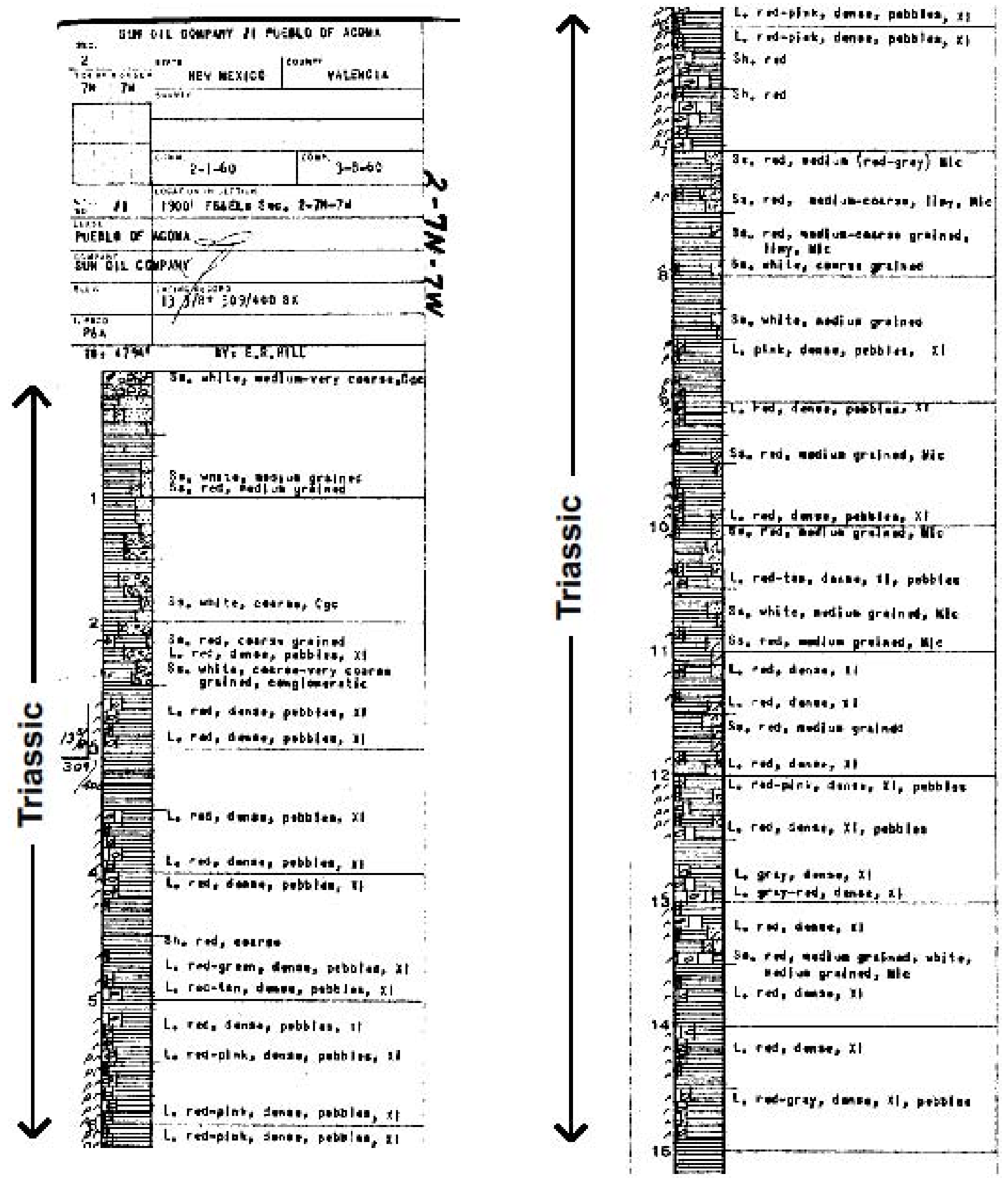

Figure WC 2. Lithologic description of cuttings from Sun Oil Co. No. 1 Pueblo of Acoma well, located in Sec. 2 T7N R7W, Cibola County, New Mexico. Original log by Midland Sample Library, Midland TX.

Sun Oil Co. No. 1 Pueblo of Acoma
Sec. 2 T7N R7W, Cibola County, NM (cont'd)

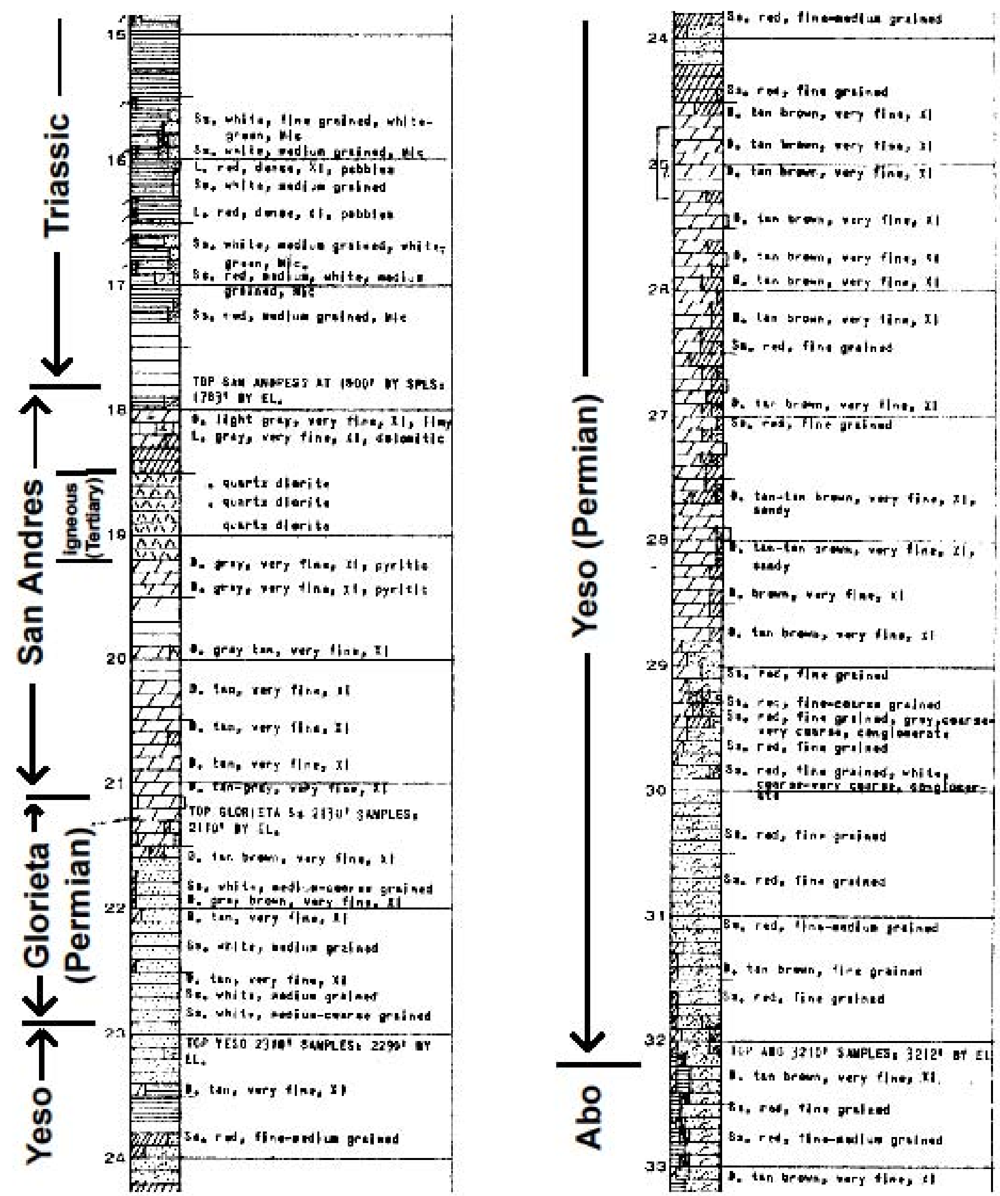

Figure WC 2 (continued). Lithologic description of cuttings from Sun Oil Co. No. 1 Pueblo of Acoma well, located in Sec. 2 T7N R7W, Cibola County, New Mexico.

Sun Oil Co. No. 1 Pueblo of Acoma
Sec. 2 T7N R7W, Cibola County, NM (cont'd)

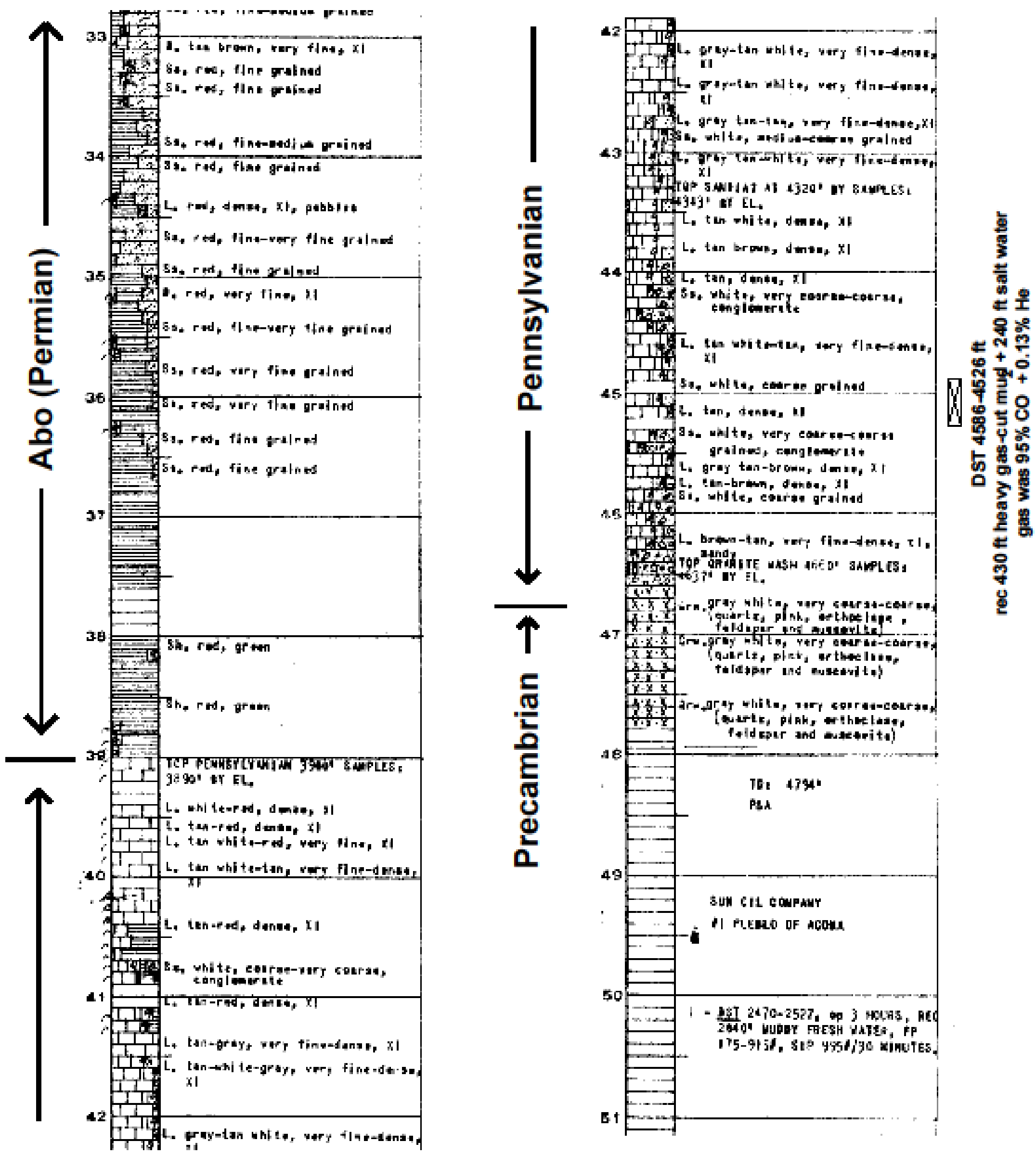

Figure WC 2 (continued). Lithologic description of cuttings from Sun Oil Co. No. 1 Pueblo of Acoma well, located in Sec. 2 T7N R7W, Cibola County, New Mexico.

Table WC 1. Composition of gases recovered from wells drilled in west-central New Mexico.

Well	Location (section -township -range)	Surface elevation (feet)	Sample depth (feet)	Reservoir	Gas composition, mole percent				
					CO_2	CH_4	C_{2+}	N_2	He
Ridgeway Arizona No. 1 State 1-4	4-1N-21W	6845	1783	Yeso (Permian)	99.42	0.13	0.15	0	0.20
Shell No. 1 SWEPI State	2-4S-13W	7650	4834	Yeso (Permian)	recovered nonflammable gas on drill-stem test				
			5270	Yeso (Permian)	recovered nonflammable gas on drill-stem test				
Shell No. 1 Aspen Federal	27-1S-13W	8131	5353	San Andres (Permian)	recovered nonflammable gas on drill-stem test				
			6918	Yeso (Permian)	recovered nonflammable gas on drill-stem test				
Sun Oil Co. No. 1 Pueblo of Acoma	2-7N-7W	6336	4486	Sandia (Pennsylvanian)	95				0.13
water well	12-9n-5W		1665	San Andres (Permian)	42.7	0	0	48	2.3
water well	12-9n-5W		1725	San Andres (Permian)	52.1	0.5	0.1	44.6	2
water well	12-9n-5W		1650	San Andres (Permian)	21.4	Tr	0	44.1	2

Several CO_2 exploration wells were drilled by Ridgeway Arizona Oil Corp. in westernmost Catron County during the late 1990's. The wells are located in R21W between T1S and T2N and are within four miles of the Arizona state line. The purpose of these wells was to extend eastward the St. John's carbon dioxide gas field of Apache County, Arizona. The field was originally discovered during 1959 by the Mae Belcher No. 1 State well. That well, located approximately 3 miles west of where the state line intersects the boundary between T1S and T2S, flowed CO_2 gas at a rate of 25 MMCFD (million ft^3 gas per day) from two reservoirs at depths of 698 ft and 1135 ft (Rauzi, 1999). The well was abandoned because of a lack of a market for the gas. In 1994, Ridgeway Oil Co. drilled an oil exploratory well in Arizona T12N R29E (13 miles west of the point where the boundary between New Mexico T2N and T3N intersects the state line) that ended up being completed as a CO_2 discovery well (Rauzi, 1999). The drilling of additional wells indicated that the trap for the CO_2 us formed by the northwest-southeast trending St. John's anticline that originates in Arizona and intersects the New

Mexico-Arizona state line at the T1-2S boundary (Figure WC 3). The anticline is doubly plunging, has a length of 40 miles and a width of approximately 20 miles. Closure is 900 ft. The New Mexico part of the field is on the eastern down-plunge part of the structure.

The primary reservoirs in Arizona are sandstones in the Big A Butte Member of the Supai Formation (Lower Permian). This section is stratigraphically correlative with parts of the lower Yeso Formation in New Mexico and the same part of the section forms the primary reservoirs in New Mexico (see Plate VI in Appendix B). At present wells in the field are shut-in because there is no pipeline connection to oilfields in the Permian Basin, but there has apparently been some production of helium in the Arizona part of the field.

In New Mexico the gas is composed almost entirely of CO_2. In the Ridgeway Arizona No. 1 State 1-4 well (Table WC 1; Plate VI in Appendix B) the gas is 99.42 percent CO_2, 0.13 percent CH_4, 0.15 percent gas liquids, and 0.20 percent helium. In the Ridgeway Arizona No. 1 State 1-4 well (Table WC 1) the gas is 99.42 percent CO_2, 0.13 percent CH_4, 0.14 percent hydrocarbon gas liquids (C_{2+}), and contains 0.20 percent helium. Helium content increases westward into Arizona where it attains a maximum value of 8 percent (Rauzi, 2003) with a corresponding decrease in CO_2 content. CO_2 content of gases in the Arizona part of the trend ranges from 78 to 90 percent. The gases in Arizona carry 6 to 10 percent nitrogen, an element not described in the single analysis of gas from the New Mexico part of the trend (Ridgeway Arizona No. 1 State 1-4 well).

The origin of the CO_2 in west-central New Mexico appears to be dominantly magmatic. Isotopic analysis of the associated Noble gases in the St. Johns accumulation are close to the isotopes found in air-derived gases, as opposed to mantle-derived gases (Gilfillan et al., 2008). However, Gilfillan and others (2008) also used the concentration of ^{20}Ne in the St. Johns gases to conclude that the CO_2 was injected through natural processes into the reservoirs after migration through the large fault that forms the southwestern flank of the St. Johns anticline (see Figure WC 3). The observed isotopic composition of the Noble gases is consistent with Gilfillan's model that has the Noble gases reintroduced into the system by groundwater after emplacement of the CO_2.

As mentioned above and by Rauzi (1999) and as mapped by the New Mexico Bureau of Geology and Mineral Resources (2003), Tertiary-age volcanic rocks are widespread in west-central New Mexico and adjacent parts of Arizona. The magmas that formed these volcanic rocks almost certainly carried large volumes of CO_2 that were exsolved as a separate phase as the magmas rose through the crust. When the magmas passed through the reservoir strata, a portion of the CO_2 would have entered the reservoirs and then migrated updip until it was either trapped or found a migration pathway to the surface. Because CO_2 is significantly more soluble than methane in ground water, a large part of the CO_2 may be entrained in aquifers as a dissolved phase and is therefore disseminated throughout the aquifer systems as soda water rather than trapped as a separate gas phase.

Alternatively the intruding magmas may have heated adjacent carbonate rocks in the sedimentary section with CO_2 formed by high-temperature decomposition on the carbonate rocks. Although this process may explain the presence of CO_2-rich gases in the Pennsylvanian section and in San Andres reservoirs, it does not readily explain the presence of CO_2-rich gases in the primary reservoirs (lower Yeso Formation and equivalents) of western Catron County and adjacent parts of Arizona. In this area, the Abo Formation rests unconformably on Precambrian basement. Both the Abo and lower Yeso are composed dominantly of sandstones and shales with few carbonate rocks present. Therefore the CO_2 in the main reservoirs, if thermally generated would originated in carbonate-bearing strata (the upper Yeso or the San Andres Limestone) and subsequently migrated downward through water-saturated rocks where it would be trapped as a separate gas phase. The more straightforward explanation is that the CO_2 originated by exsolution from rising magmas.

There is a paucity of hydrocarbon source rocks in the area (Broadhead, 1994). It is therefore not plausible that the CO_2 originated by the thermal maturation of organic matter in the sedimentary section. This is reinforced by the negligible hydrocarbon component in the natural gases of west-central New Mexico.

Rauzi (1999) concluded that some of the CO_2 in Arizona originated from the dissolution of carbonate rocks by groundwater. Supporting evidence includes the widespread presence of travertine deposits in Arizona, lost-circulation zones encountered while drilling San Andres limestones, and the associated fractured and cavernous limestone strata within the San Andres. The San Andres has similar lithologic features in west-central New Mexico. It is possible that at least some of the CO_2 in well gases originated in this manner, for example the CO_2 in the San Andres water wells in eastern Cibola County (Figure WC 1; Table WC 1).

It is unknown whether CO_2 in the subsurface of west-central New Mexico has accumulated as a separate gas phase in traps or whether it is mostly distributed throughout the reservoir (aquifer) systems as carbonated soda water. This water, when produced or otherwise recovered from a well, would suffer a pressure decrease and an accompanying exsolution of CO_2 gas that would be recorded as a show. Nevertheless, the CO_2 potential of west-central New Mexico must be considered high when gas analysis data from wells (Table WC 1) are used in conjunction with regional geologic considerations, primarily the accumulation of CO_2 gas in the St. Johns anticline, the presence of large volumes of Tertiary-age volcanic rocks and the presence of known reservoir-quality rocks (Yeso and Abo Formations). A further positive element is the lack of identified, thermally mature petroleum source rocks in the region; thermally mature petroleum source rocks would have produced hydrocarbon gases which would dilute the CO_2 content in the reservoirs. A negative consideration is that the extensive Tertiary-age volcanic and tectonic activity in the region may have breached seals and traps, leading to leakage of gaseous CO_2 into the atmosphere.

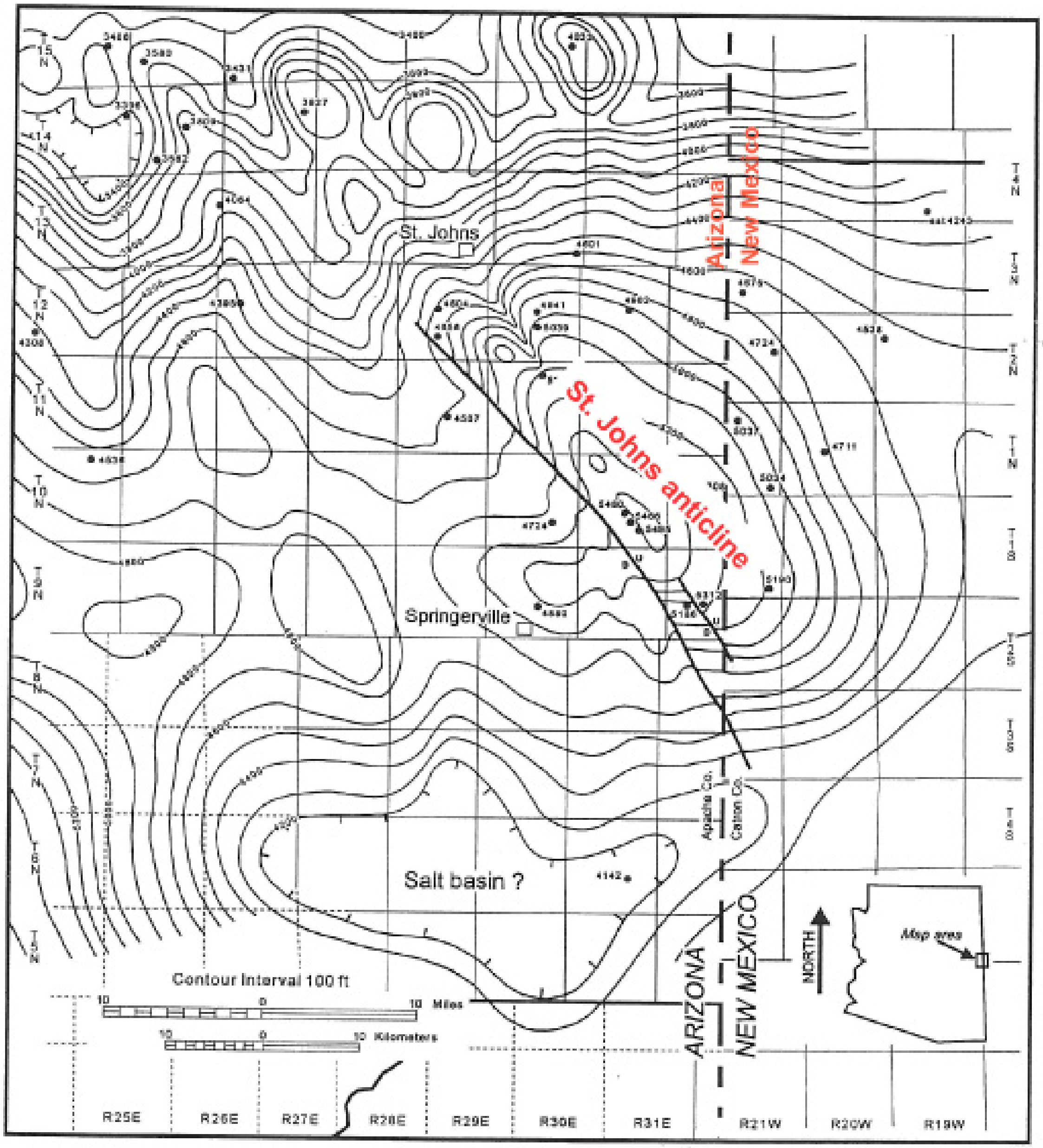

Figure WC 3. Structure contours on base of Fort Apache Limestone Member of Supai Formation (Permian, equivalent to part of middle part of Yeso Formation), Apache County Arizona and westernmost Catron County, New Mexico. From Rauzi (1999).

CO_2 in Southwestern New Mexico

Relatively few petroleum exploration wells have been drilled in Hidalgo, Luna, Grant and western Dona Ana Counties of southwestern New Mexico (Thompson, 1982). These counties are characterized by rugged mountain ranges and intervening bolsons. The geology at the surface is dominated by Tertiary-age intrusive and extrusive volcanic rocks in the mountain ranges and Quaternary-age valley fill sediments in the basins (New Mexico Bureau of Geology and Mineral Resources, 2003). Several calderas are present (see Wilks, 2005). Within the region, Tertiary-age extensional basins have been superimposed on Laramide-age, dominantly compressional pre-volcanic basins.

Within the Tertiary-age basins, thick sections of Phanerozoic sedimentary rocks ranging age from Cambrian to Tertiary are present with aggregate thickness of more than 30,000 ft in the deepest basinal areas (Kottlowski, 1963; Clemons and Mack, 1988; Zeller, 1965). Limestones and dolostones dominate the Paleozoic section. During the Pennsylvanian and Early Permian, the region was subdivided into a deep-marine basinal area to the south (Pedregosa Basin) and a shelf to the north. North of the shelf were the emergent Burro and Florida uplifts (Figure IN 1). Several wells drilled in the Tertiary-age basins penetrated complexes of Tertiary-age igneous intrusive rocks (Thompson, 1977, 1982). Intrusive igneous rocks appear to be pervasive in the basins.

Several exploratory wells drilled both on the uplifts and in the basins have reported shows of oil and gas (Thompson, 1982). Unfortunately no compositional analyses of the gases are available and descriptions of the gases are somewhat vague. Mudlogs indicate that at least some of the gases carry a significant hydrocarbon component. It is not known whether or not any of the gases contain CO_2.

The overall geology of southwestern New Mexico indicates at least some potential for CO_2 accumulations in the intermontane Tertiary-age basins. Thick sections of sedimentary strata contain numerous reservoir and seal intervals (Thompson, 1982; Thompson and Jacka, 1981). The pervasive intrusive igneous complexes of Tertiary-age suggest that large volumes of CO_2 gas have been transported into reservoir strata. It is unknown whether accumulations of free CO_2 gas are present or whether the CO_2 is disseminated throughout the reservoir/aquifer systems in solution as natural soda water.

In addition, the extensive Tertiary-age extensional tectonism that formed the basins may have breached traps and seals, allowing any accumulated CO_2 gas to escape to the atmosphere. Although there is positive potential for CO_2 accumulations, factors such as trap and seal integrity as well as gas composition need to be analyzed and assessed for a more definitive evaluation of CO_2 potential.

Summary

1. CO_2 occurs as a common component of natural gases throughout New Mexico. In most gases, CO_2 is a minor constituent and comprises less than 1 percent of the gas. More rarely, CO_2 is the dominant component of the gases and may constitute more than 99 percent of the gas. Some accumulations of this nearly pure CO_2 have been produced commercially for their CO_2 content.
2. Gases in the Permian Basin of southeastern New Mexico contain low levels of CO_2. The gases in this basin are composed mostly of hydrocarbons. Average CO_2 concentrations range from a low of 0.11 percent in reservoirs of the Abo (Lower Permian) redbeds to a high of 4.11 percent in Silurian carbonates. In general, stratigraphic units comprised predominantly of carbonate rocks have gases that contain higher concentrations of CO_2 than units comprised predominantly of siliciclastic sedimentary rocks.
3. Most gases in Cretaceous reservoirs of the San Juan Basin of northwestern New Mexico contain less than 1 percent CO_2. Gases in coal reservoirs of the Fruitland Formation (Upper Cretaceous) and sandstone reservoirs of the Pictured Cliffs Sandstone, Mesaverde Group and Dakota Group (Upper Cretaceous) contain more than 1 percent CO_2 along trends in the deep northern part of the New Mexico side of the San Juan Basin. Gases in Triassic and Permian reservoirs contain less than 1 percent CO_2. Gases in Pennsylvanian reservoirs contain more than 10 percent CO_2 along trends on the Four Corners platform and in the deeper parts of the San Juan Basin. Mississippian gases contain more than 50 percent CO_2 throughout most of the basin and have more than 90 percent CO_2 over large areas. Devonian reservoirs bear gases with less than 1 percent CO_2 on the Four

Corners platform. Fractured Precambrian basement rocks may locally contain CO_2-rich gases.

4. Widespread accumulations of gases that are nearly pure CO_2 are present throughout large portions of the Bravo Dome and Sierra Grande uplift of northeastern New Mexico. CO_2 has been produced commercially from the presently active Bravo Dome field and the now-abandoned Des Moines field. The Bravo Dome field has produced more than 1 trillion ft^3 CO_2 gas that has been used mostly for enhanced oil recovery in the Permian Basin. The primary reservoir at Bravo Dome is the Tubb sandstone member of the Yeso Formation (Lower Permian). Secondary reservoirs are Triassic sandstones. The reservoirs at the much smaller Des Moines field are lenticular conglomerates near the base of the Abo Formation (Lower Permian). Apart from the Bravo Dome and Des Moines fields, CO_2 has been encountered over large areas of the Sierra Grande uplift in Abo and Yeso (Lower Permian) sandstones, the Glorieta Sandstone and the San Andres Formation (Upper Permian), and in Triassic sandstones. Gases in basins adjacent to the Sierra Grande uplift and Bravo Dome are hydrocarbon rich and CO_2 poor. The CO_2, at least in the Bravo Dome field, is mantle derived and migrated into crustal reservoirs via Tertiary-age volcanism.
5. CO_2-rich gases are also present in north-central New Mexico. Gases in Pennsylvanian and Lower Permian strata that fill in the Las Vegas Basin consist primarily of hydrocarbons but may be mostly CO_2 in the vicinity of large Tertiary-age igneous intrusions. Two types of gases are present in the Raton Basin. One type is combustible and is composed predominantly of hydrocarbons; the second type is noncombustible and is composed predominantly of CO_2. Most of the gases in the Raton Basin are of the first type. Gases in Triassic strata and in the Glorieta Sandstone (Permian) are of the second type.
6. CO_2-rich gases have been encountered in three areas of central New Mexico: the Estancia Basin, the Chupadera Mesa area, and the Albuquerque Basin. In the Estancia Basin, CO_2 has been produced from two small and now-abandoned accumulations in Lower Pennsylvanian sandstones. Potential for additional CO_2 resources in the Estancia Basin is limited. Recent exploratory drilling has revealed

the presence of CO_2-rich gases in Lower Permian sandstones on Chupadera Mesa. And in the Albuquerque Basin which has a structural relief of more than 30,000 ft, CO_2 is present in sandstone aquifers of the Tertiary-age valley fill. Gases in pre-Tertiary reservoirs appear to be predominantly hydrocarbons. It is possible that the CO_2 is present in water solution and not as a free gas phase.

7. CO_2-rich gases have been encountered by exploratory wells drilled in west-central New Mexico. The St. Johns CO_2 field is formed by an anticlinal trap that is located mostly in Arizona and extends eastward into westernmost Catron County. Reservoirs in the St. Johns field are Lower Permian sandstones. The CO_2 appears to have been mantle derived. The sparse exploratory wells drilled elsewhere in west-central New Mexico have encountered CO_2-rich gases in Pennsylvanian and Permian reservoirs. Widespread Tertiary-age volcanics, abundant reservoirs, and a dearth of hydrocarbon source rocks indicate significant CO_2 potential in west-central New Mexico. It is unknown if accumulations of free gas are present or if the CO_2 is distributed primarily in water solution throughout the reservoir/aquifer systems. It is also unknown if Tertiary age tectonism and volcanism, pervasive in the region, breached traps and seals.
8. Few petroleum exploration wells have been drilled in southwestern New Mexico. Shows of oil and gas have been reported from several wells, but analyses of gas composition are not available. The magmas that formed the pervasive Tertiary-age volcanic rocks in the region are possible CO_2 sources. The Tertiary-age extensional intermontane basins contain thick sections of Cambrian through Tertiary strata, which harbor favorable reservoirs. Therefore conditions for CO_2 accumulations are favorable. As in west-central New Mexico, it is unknown if accumulations of free gas are present or if the CO_2 is distributed primarily in water solution throughout the reservoir/aquifer systems. It is also unknown if Tertiary age tectonism and volcanism, pervasive in the region, breached traps and seals.

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