Helium in New Mexico: Geologic Distribution and Exploration Possibilities

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Abstract

Helium gas has been produced in New Mexico since 1943. Production has been from eight oil and gas fields located on the Four Corners Platform of northwestern New Mexico. Almost 950 MMCF helium have been produced from reservoirs of Permian, Pennsylvanian, Mississippian, and Devonian age on the Four Corners Platform in San Juan County

In northwest New Mexico, elevated levels of helium in natural gases occur not only in Paleozoic reservoirs on the Four Corners Platform but also in Paleozoic reservoirs in the deeper parts of the San Juan Basin located east of the Four Corners Platform. The regional set of orthogonal faults that offset Precambrian basement throughout the deeper parts of the San Juan Basin may have acted as migration pathways that transmitted helium from its basement source into overlying Paleozoic reservoirs.

Helium has not been extracted from produced gases in the New Mexico part of the Permian Basin where the concentration of helium in most reservoir gases is significantly less than 0.1 percent. However, gases with helium contents ranging from 0.3 to almost 1.0 percent occur in Pennsylvanian and Permian reservoirs along the northwest flank of the basin. The helium originated by radiogenic decay of uranium and thorium in Precambrian granitic rocks and migrated vertically into Pennsylvanian and Permian reservoirs through regional, high-angle, strike-slip faults. Known accumulations of helium-rich gases are located near these faults. In this area, lower and middle Paleozoic strata are only a few hundred feet thick, resulting in short vertical migration distances between the Precambrian source and helium-bearing reservoirs.

Other basins and areas in New Mexico are characterized by helium-rich gases and are of significant exploratory interest. These areas include the Chupadera Mesa region of eastern Socorro and western Lincoln Counties in the central part of the state, the Tucumcari Basin in the east-central part of the state, and a wide region across Catron and southern Cibola Counties in the west-central part of the state. Elevated levels of helium are found in Pennsylvanian and Permian gases in these areas.

Introduction

Helium is a common constituent of natural gases. It is believed to occur trace amounts in all natural gases (Tongish, 1980). More than one-half of all natural gases contain less than 0.1 mole percent helium (Table 1). Only 17.6 percent of all natural gases in the U.S. contain more than 0.3 mole percent helium. In general, gases with helium contents of more than 0.3 percent are considered to be of commercial interest as helium sources.

Table 1. Distribution of helium-bearing natural gas reservoirs in United State by helium content of gases. Data from Tongish (1980).

Helium content of reservoir gas, mole percent	Percent of U.S. reservoirs in helium-content range
< 0.1%	55.6%
0.1 – 0.3%	26.8%
> 0.3%	17.6%

A very few reservoirs have gases with more than 7 percent helium. In New Mexico, known (that is, discovered) reservoirs with more than seven percent helium are confined to the Four Corners platform in the extreme northwest part of the state. The content of hydrocarbon gases in most of these reservoirs is less than 20 percent; most of the non-helium fraction of the reservoir gas is nitrogen. Although gas has been produced from these New Mexico reservoirs for the helium they contain, most of the helium produced in the United States is obtained from reservoirs with less than 1 percent helium in their gases. Six natural gas reservoirs contain an estimated 97 percent of all identified helium reserves in the United States (Pacheco, 2002; Table 2). The reservoirs listed in Table 2 have also been produced for their hydrocarbons, which constitute the largest component of the reservoir gas.

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

Table 2. The six natural gas reservoirs that contain 97 percent of identified helium reserves in the United States. Data from Pacheco (2002) and Parham and Campbell (1993).

Reservoir	**State**	**Helium content of gas Mole percent**
Hugoton	Kansas, Oklahoma, Texas	0.2-1.18
Panoma	Kansas	0.4-0.6
Keyes	Oklahoma	Not available
Panhandle West	Texas	Not available
Riley Ridge area	Wyoming	Not available
Cliffside	TX	He-storage reservoir

Purpose

The purpose of this report is to provide basic geologic information pertinent to helium exploration and prospecting in New Mexico. This report is meant to provide the user with a useful source of geologic data and information for those involved with helium exploration and is also meant to provide an introduction to the geologic principles of helium occurrence.

This report contains three major parts. **The first part of this report** is this pdf document that presents key geologic data, maps, and analyses of helium distribution in New Mexico and summarizes helium geology. **The second part of this report** is a database of natural gas analyses (The New Mexico Helium Database; ***NMgases.xls***) and includes parameters such as well location, sample depth, reservoir stratigraphy, and a variety of data on gas composition including helium, carbon dioxide, nitrogen, and hydrocarbon content of analyzed gases. **The third part of this report** is a series of Geographic Information System (GIS) maps of key parameters useful in helium assessments. The GIS maps are presented in *ArcReader*, *ArcMap*, and pdf formats. Portions of the maps are also presented statically as part of this pdf document, but the GIS portrayal allows the user to overlay the maps on top of each other. *ArcReader* is a free program made available by ESRI Corp. that allows the user to view maps after the *ArcReader* software is downloaded from this CD-ROM but does not allow modification of the maps with new data that the user may have; administrator privileges are required to install *ArcReader* on your computer. For this reason all maps are also presented as an

ArcMap project. If the user has *ArcMap* software then the maps may be modified to accommodate additional data or additional map types may be created from either the well database or from databases the user may supply. The *ArcMap* files on this computer were created with *ArcMap* version 8.2. The GIS maps utilize the data presented in the helium database as well as structure data presented in this report. In order to use *ArcReader* you must have one of the following operating systems installed on your computer: 1) Windows 2000; 2) Windows XP; or 3) Windows NT 4.0 with Service Pack 6a or later. The GIS maps are also presented in a static pdf format for those who do not with to utilize either *ArcReader* or *ArcMap* to view information in map format.

Acknowledgments

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A number of people and companies graciously provided data on gas compositions. These include Mr. Ben Donegan, Primero Operating Company, Manzano Oil Corporation, Mr. Jack Frizzell, Mr. Mike Dawson of Burlington Resources, Ms. Riann Holder of Agave Energy Company, Mr. Gene Wilson and Coulthurst Management, Apache Corporation, and Mr. Roy Johnson of the New Mexico Oil Conservation Division. Mr. Bob Gallagher, President of the New Mexico Oil and Gas Association (NMOGA), sent out a call to NMOGA members asking that helium analyses of natural gases be donated to the project; we are indebted to him for his sincere support.

Helium uses, demand and economics

Helium has a number of uses (Pacheco, 2002). Major uses in the United States include cryogenics, pressurizing and purging, welding, and controlled atmospheres. Leak detection, synthetic breathing mixtures, chromatography, lifting, and heat transfer are other uses. The major cryogenic use is in magnetic resonance imaging (MRI) instruments. There is no substitute for helium in cryogenic applications where temperatures less than -429^{o} F are required (Pacheco, 2004).

Sales of Grade A refined helium have been increasing in recent years (Pacheco, 2002). Total helium sales in the United States increased from 112 million m^3 during 1998 to 127 million m^3 during 2002, an increase of 13 percent. As sales have increased, domestic production has fallen by 22 percent from 112 million m^3 during 1998 to 87 million m^3 during 2002 (Peterson, 2001; Pacheco, 2004). The shortfall in production in recent years has been filled by withdrawing helium from storage. The trends of increasing demand and decreasing production indicate a need to identify and develop new sources of helium.

Helium prices have increased as production has fallen below demand. The private industry price for Grade A helium was estimated to be \$60 to \$65 per thousand ft^3 in 2003 (Pacheco, 2004), up from \$42 to \$50 per thousand ft^3 in 2000 (Peterson, 2001). Some producers added a surcharge to these prices.

History of Helium Production in New Mexico

Helium has been extracted from produced gases in New Mexico since 1943 (Casey, 1983). All production has been from Paleozoic reservoirs located on the Four Corners Platform in San Juan County (Figures 1, 2; Table 3). The gases in most reservoirs contain a low percentage of hydrocarbons and have, in most cases, been produced solely for their helium content. Helium content of the gases ranges from 3.2 percent to 7.5 percent (Table 3). Production began during World War II as a result of increased need for lifting gases for lighter-than-air ships (blimps).

The first production of helium in New Mexico was from the Rattlesnake field (Figure 2). The helium produced from Rattlesnake was transported in a pipeline to a

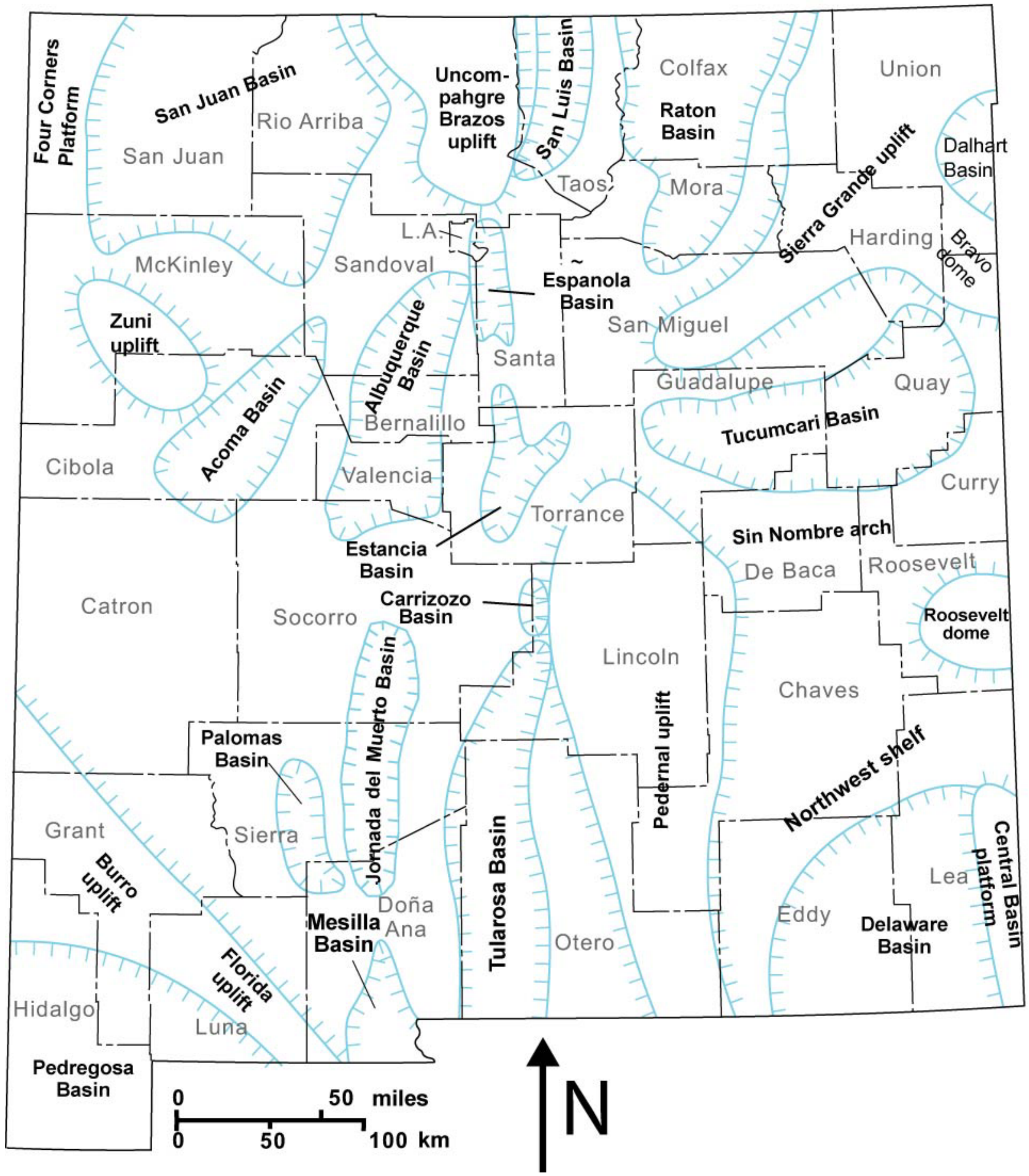

Figure 1. Locations of major basins and uplifts in New Mexico.

separation plant near Shiprock that was operated by the U.S. Bureau of Mines. During the early 1970's the Navajo Refined Helium gas processing plant was built south of Shiprock (Casey, 1983). This plant replaced the U.S. Bureau of Mines plant and utilized some of the equipment from the older plant. Demand increased with time. As production from existing wells declined, more helium-bearing gas fields were discovered, developed, and produced (Table 3). Production of helium in San Juan County ceased around 1990.

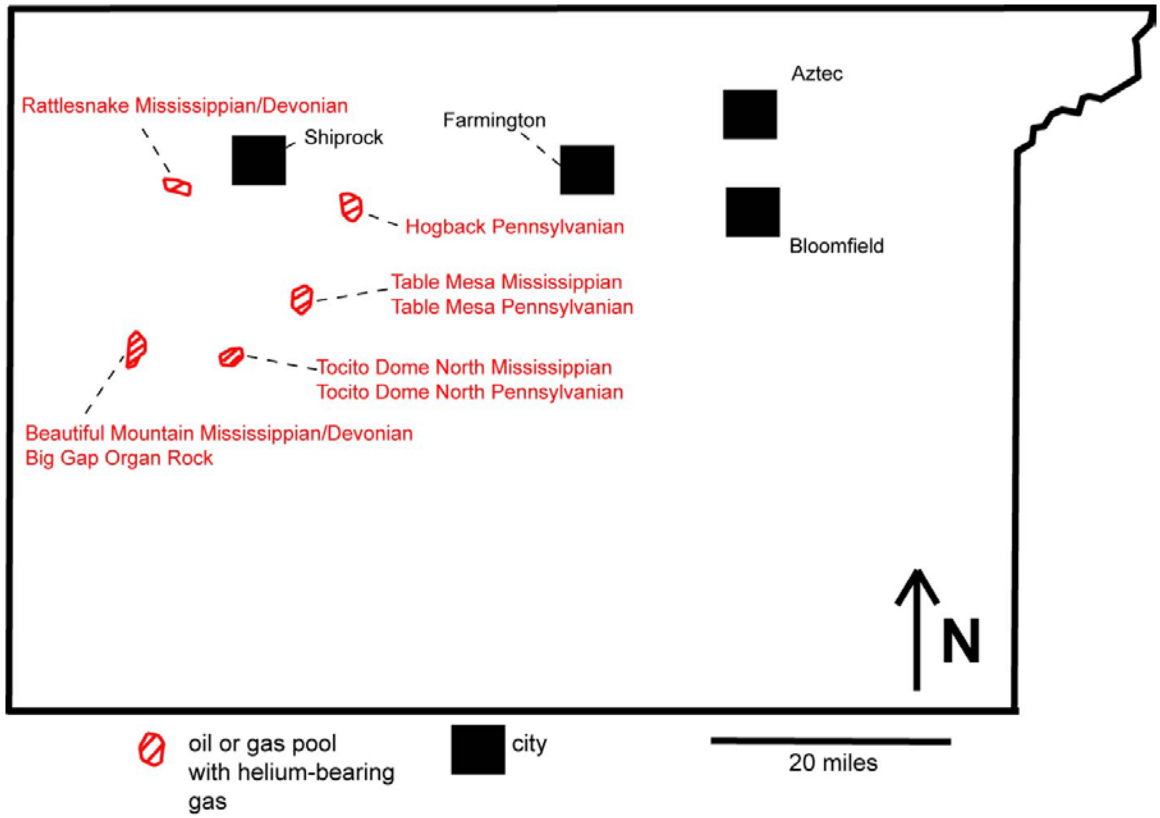

Figure 2. Outline of San Juan County, New Mexico showing locations of major cities and oil and gas pools that have been produced for their helium content.

In 2001, production began again from the Beautiful Mountain Mississippian and Big Gap Organ Rock reservoirs. The latter reservoir saw additional development. The gas is produced from wells operated by Mountain States Petroleum. The produced gas is processed at the Red Valley Plant, which is owned by Newpoint Gas Services and is located just south of Shiprock.

Statistics regarding the total amount of helium produced and sold or otherwise utilized are not available. However, the total amount of gas produced from reservoirs with helium-rich gas is approximately 16.3 billion ft^3 (BCF). An estimate of the total helium produced from San Juan County is 949 million ft^3 (MMCF). This value is calculated from the average composition of helium in the gas in each reservoir and the total gas production from each reservoir. The amount of helium shipped to market or other end use is probably less than this since it is likely that some helium was lost in separation and processing.

Table 3. Oil and gas pools that have produced commercial helium in New Mexico, percent helium in gas, 2003 annual and cumulative gas production, and estimated cumulative volume of produced helium. MCF, thousand ft^3. See Figure 2 for locations of pools.

Field	Reservoir age	Reservoir units	Location (township, range)	Percent helium in gas	2003 gas production (MCF)	Cumulative gas production (MCF)	Helium produced, estimated (MCF)
Beautiful Mountain	Mississippian, Devonian	Leadville Limestone, Ouray Formation	T27N R19W	7.14	169,568	2,455,230	***175,303***
Big Gap	Permian	Organ Rock member of Cutler Formation	T27N R19W	5.5	212,663	3,260,416	***179,323***
Hogback	Pennsylvanian	Paradox Formation	T29N R16W	7.17	0	666,714	***47,803***
Tocito Dome North	Mississippian	Leadville Limestone	T27N R18W	7.19	0	1,104,668	***79,426***
Tocito Dome North	Pennsylvanian	Paradox Formation	T27N R18W	3.26	0	532,856	***17,371***
Table Mesa	Mississippian	Leadville Limestone	T27N R17W	5.7	0	1,193,006	***68,001***
Table Mesa	Pennsylvanian	Paradox Formation	T27N R17W	5.37	0	7,100,076	***381,274***
Rattlesnake	Mississippian, Devonian	Leadville Limestone, Ouray Formation	T29N R19W	7.5	0	2,000	***150***
TOTALS					**382,231**	**16,314,966**	**948,652**

Helium Reservoirs in New Mexico

Helium has been extracted from gas produced from eight oil and gas pools in New Mexico (Figure 2; Table 3). The geology of these reservoirs is summarized briefly below. For additional information, the reader is directed to Casey (1983), Picard et al. (1960), Picard (1962), and the individual references cited in the brief discussion of each reservoir.

Beautiful Mountain Mississippian pool (Brown, 1978)

The Beautiful Mountain Mississippian pool has produced helium-bearing gas and small volumes of oil and water from the Leadville Limestone (Mississippian). The pool was discovered in 1975. Depth to production is approximately 6000 ft. The gas is 7.14 percent helium, 87.83 percent nitrogen, 3.41 percent hydrocarbons, and 1.62 percent carbon dioxide. The reservoir rock is a densely fractured, finely crystalline limestone. The trap is formed by fractured limestones that were folded on a structural nose. Limestones of the Ouray Formation (Devonian) apparently contribute to production in some wells. Although the reservoir was shut in during the 1990's, production started again in 2001. During 2003, approximately 170 million ft^3 (MMCF) gas were produced from two active wells in this reservoir. Mountain States Petroleum Corporation is the current operator. The Big Gap Organ Rock and Beautiful Mountain Mississippian pools are the only reservoirs in New Mexico produced for their helium content at the time this report was written.

Big Gap Organ Rock pool

The Big Gap Organ Rock pool has produced helium-bearing gas and small volumes of oil and water from the Organ Rock member of the Cutler Formation (Permian). The reservoir was discovered in 1980. Depth to production is approximately 3900 ft. The gas contains 5.5 percent helium (Walker, 1983). The Cutler Formation consists primarily of continental red beds. Reservoir facies in the Organ Rock member are poorly indurated sandstones that are interbedded with red shales. Production from this reservoir ceased during the 1990's but started again in 2001. During 2003, approximately 213 MMCF gas were produced from four wells in the Big Gap Organ Rock reservoir. Mountain States Petroleum Corporation is the current operator. The Big Gap Organ Rock and Beautiful Mountain Mississippian pools are the only reservoirs in New Mexico produced for their helium content at the time this report was written.

Hogback Pennsylvanian pool (Maynard, 1978)

The Hogback Pennsylvanian pool has produced oil, helium-bearing gas, and water from limestones of the Paradox Formation (Pennsylvanian). The pool was discovered in 1952. Depth to production is approximately 6200 ft. The trap is formed by a faulted domal structure. Gas in the reservoir is 7.17 percent helium, 54.6 percent nitrogen, 35.4 percent hydrocarbons, and 2 percent carbon dioxide. The Hogback Pennsylvanian pool is not currently productive and has been abandoned.

Tocito Dome North Mississippian pool (Riggs, 1978)

The Tocito Dome North Mississippian pool has produced helium-bearing gas and small volumes of oil and water from the Leadville Limestone (Mississippian). The pool was discovered in 1963. Depth to production is approximately 6800 ft. The trap is formed by a faulted anticlinal structure. Gas in the reservoir is 7.19 percent helium, 89.65 percent nitrogen, 2.05 percent hydrocarbons, and 0.10 percent carbon dioxide. The Tocito Dome North Mississippian pool is not currently productive and has been abandoned.

Tocito Dome North Pennsylvanian pool (Spencer, 1978)

The Tocito Dome North Pennsylvanian pool has produced helium-bearing gas along with some oil and water from limestones of the Paradox Formation (Pennsylvanian). The pool was discovered in 1967. Depth to production is approximately 6200 ft. The trap is formed by an updip porosity pinchout draped over a faulted structural nose. The gas is 3.26 percent helium, 34.2 percent nitrogen, 60 percent hydrocarbons, and 2.1 percent carbon dioxide. The Tocito Dome North Pennsylvanian pool is not currently productive.

Table Mesa Mississippian pool (Hoppe, 1983)

The Table Mesa Mississippian pool has produced helium-bearing gas, oil, and water from the Leadville Limestone (Mississippian). The pool was discovered in 1951. Depth to production is approximately 7500 ft. The trap is formed by an anticline acting in conjunction with stratigraphic variations in the reservoir stratum. The gas is 5.7 percent helium, 83.8 percent nitrogen, 8.3 percent hydrocarbons, and 1.0 percent carbon dioxide. The Table Mesa Mississippian pool is not currently productive and has been abandoned.

Table Mesa Pennsylvanian pool (Hoppe, 1983)

The Table Mesa Pennsylvanian pool has produced helium-bearing gas, oil and water from vuggy algal limestones of the Paradox Formation (Pennsylvanian). The pool was discovered in 1953. Depth to production is approximately 7000 ft. The trap is formed by an anticline acting in conjunction with stratigraphic variations in the reservoir stratum. Gas in the reservoir is 5.37 percent helium, 77.83 percent nitrogen, 16.61 percent hydrocarbons, and 0.19 percent carbon dioxide. The Table Mesa Pennsylvanian pool is not currently productive and has been abandoned.

Rattlesnake Mississippian pool (Hinson, 1947; Baars, 1983)

The Rattlesnake Mississippian pool has produced helium-bearing gas from the Leadville Limestone (Mississippian) and the Ouray Formation (Devonian). The pool was discovered in 1943. Depth to production is approximately 7030 ft. The reservoir consists of 85 ft of porous limestone and dolostone. The trap is formed by an anticline. The gas contains 7 to 8 percent helium. The Rattlesnake Mississippian pool is not currently productive and has been abandoned.

The Rattlesnake field has also been productive from the Hermosa Group (Pennsylvanian), the Dakota Sandstone (Cretaceous), and the Gallup Sandstone (Cretaceous). The gases in these shallower zones contain only trace amounts to 0.3 percent helium. The Pennsylvanian and Cretaceous reservoirs were produced for oil and hydrocarbon gases, not for helium.

Geology of Helium in Crustal Reservoirs – An Overview

Helium has two isotopes, ^{3}He and ^{4}He. ^{3}He is derived mostly from the mantle and is relatively rare in reservoir gases (Mamyrin and Tolstikhin, 1984; Hunt, 1996; Oxburgh et al., 1986). Some ^{3}He is derived from neutron capture reactions by hydrogen in lithium-bearing sediments (Hiyagon and Kennedy, 1992; Mamyrin and Tolstikhin, 1984). ^{4}He, on the other hand, is derived mainly from radiogenic decay of uranium and thorium in crustal rocks (Hunt, 1996; Jenden et al., 1988; Oxburgh et al., 1986; Ballentine and Lollar, 2002). Granitic basement rocks are major sources of radiogenic helium. ^{4}He may also be derived from radiogenic decay of uranium and thorium in ore bodies (Selley, 1998).

Most helium in reservoir gases is ^{4}He derived from radiogenic decay of uranium and thorium in crustal rocks. Enhanced concentrations of ^{4}He in crustal fluids have been ascribed to three processes (Pierce et al., 1964; Torgersen et al., 1998; Ballentine and Lollar, 2002): 1) mass-related diffusive transport out of the basement (granitic) rocks the helium is produced in; 2) thermal release of ^{4}He from the crustal rocks it is produced in; and 3) production in sedimentary ore deposits with high concentrations of uranium and thorium. Transport of radiogenic helium out of basement rocks appears to be related to the presence of fracture and fault systems that may act as migration pathways for the movement of the gas out of the otherwise impermeable granites in which it is generated.

Enhanced levels of helium in groundwater, as well as in gases, are associated with proximity to faults and fractures (Ciotoli et al., 2004; Dyck, 1980; Gupta and Deshpande, 2003; Hunt, 1996; Maione, 2004; Kennedy et al., 2002; Lollar et al., 1994; Selley, 1988). Thermal activity, or heating of basement rocks, also may increase expulsion of helium (Selley, 1998). Once the helium is expelled from the granitic rocks it may move through fractures into the overlying sedimentary column. Enhanced concentrations of radiogenic helium in reservoirs are also associated with proximity to uranium ore bodies (Devoto et al., 1980; Hunt, 1996; Pogorski and Quirt, 1980; Selley, 1998).

^{3}He is derived mostly from the mantle (Hunt, 1996; Mamyrin and Tolstikhin, 1984; Oxburgh et al., 1986). One mechanism for the transport of mantle ^{3}He into crustal rocks is the devolatilization of rising magmas (Giggenbach et al., 1991; Oxburgh et al., 1986; Poreda et al., 1986). Another mechanism is vertical migration through deep-seated fractures in extensional domains (Jian-Guo, 1998; Lollar et al., 1994; Sheng et al., 1995; Yongchang et al., 1997); apparently this mechanism is effective in concentrating helium only in tectonic regimes of Tertiary or younger age.

^{3}He is also derived from beta emission decay of ^{3}H to ^{3}He. Hiyagon and Kennedy (1992) concluded that gases with elevated concentrations of ^{3}He relative to ^{4}He may be attained in sedimentary carbonates, anhydrites, and clays with lithium concentrations in excess of 1000 ppm. Magnesium-rich clays deposited in evaporitic settings are enriched in lithium and may contain as much as 6200 ppm lithium (Tardy et al., 1972). Therefore, clay-rich sediments deposited in evaporitic settings may be capable of producing radiogenic helium accumulations with high concentrations of ^{3}He relative to ^{4}He.

Helium Exploration Models

Five exploration models are presented in this report. These models are based on general geological principles of helium occurrence developed by other workers (see preceding section on Geology of Helium in Crustal Reservoirs). The five models relate helium concentrations in gases to a number of geologic variables, including: composition of Precambrian basement, presence of faults and other fractures that connect Precambrian basement with the overlying sedimentary column, the presence of deep-seated extensional fractures that provide a migration pathway from the mantle to the crust, regional thermal events that may have heated the Precambrian and aided in release of helium from Precambrian granitic rocks, the presence of volcanic rocks whose formative magmas may transport helium from the mantle, and the presence of uranium- and thorium-bearing sedimentary ore deposits. These models utilize information available in this report and in readily accessible geologic references pertaining to New Mexico and the application of these models does not rely on helium isotope analyses. A short section on seals for helium traps is also included because the rock types that make effective seals for helium appear to be more limited than rock types that make effective seals for hydrocarbon gases.

Most modern published papers related to helium exploration utilize analyses of the isotopic composition of helium in order to draw conclusions as to the origin and migration history of helium in crustal reservoirs. The isotopic compositions of related reservoir gases, especially neon and argon, are also typically used. Isotopic compositions of gases are difficult, time-consuming and expensive to obtain and were not used in this project. It is not practical or economically feasible to obtain isotopic data on gases from all stratigraphic intervals on a statewide basis. Therefore, the exploration models used in this report utilize analyses of the molecular composition of natural gases obtained from produced gases, gases recovered during testing of exploratory wells and, in some cases, samples of gases that are emitted naturally by springs or gas seeps at the land surface (see database ***NMgases.xls*** on this CD). These analyses are present over a wide geographic distribution and also provide a sampling of reservoir gases from several stratigraphic units in most parts of the state. However, the general exploration models are based on work that has relied heavily on isotopic analyses to develop general principles of helium occurrence.

Model 1: Radiogenic helium derived from uranium- and thorium-bearing basement rocks

This is helium (^4He) derived from radiogenic decay of uranium- and thorium-bearing basement rocks, especially granitic lithologies. Although helium is generated by radioactive decay in these lithologies, they are generally impermeable to helium and other gases so that helium generated in these rocks tends to remain in place unless liberated by processes that enhance permeability of the rock. The formation of fractures and associated cataclastic textures can provide conduits through which helium can migrate out of the granitic basement and into overlying sedimentary reservoirs. The helium will collect along the fracture faces and in cataclastically deformed basement rocks adjacent to the fracture faces and will migrate upward within the fracture system due to buoyant forces. If, on its upward journey through faults and other fractures, the helium encounters a barrier to vertical migration that seals the fracture, such as salt, anhydrite or a ductile non-fractured shale, it will then move laterally from the fault or fracture into adjacent permeable reservoir strata. Once the helium has moved into the sedimentary column, it will migrate through permeable strata in a manner similar to oil and natural gas. Migration will be driven updip because of the density difference between helium and the water that saturates the pore space in most porous sedimentary rocks.

Favorable settings for the accumulation of radiogenic helium generated from basement rocks include Paleozoic sandstones overlain by shales or evaporites. One place where this model is believed to have provided enhanced helium concentrations is in the Pecos Slope Abo gas reservoirs of Chaves County, southeastern New Mexico (Kennedy et al., 2002). There, radiogenic helium thought to be derived from basement granites has migrated vertically through faults into low-permeability sandstones of the Abo Formation (Permian: Wolfcampian to Leonardian). Anhydrite in the lowermost part of the overlying Yeso Formation (Permian; Leonardian) has sealed the faults and helped create the trap for the helium, as well as the hydrocarbon gases found in the reservoirs.

In a variation on this model, helium emitted from basement rocks may collect in basal sandstones that directly overlie Precambrian basement over large geographic areas. If seals overlie the basal sandstones, helium that enters the sandstones will migrate regionally updip through the basal reservoirs or be swept along by regional groundwater flow until the helium either collects in a trap or is dissipated throughout the reservoir. Migration and accumulation of helium in this latter manner is thought to have occurred in the Hugoton-Panhandle gas field of southwestern Kansas and the Oklahoma and Texas panhandles (Ballentine and Lollar, 2002).

Model 2: Radiogenic helium derived from uranium- and thorium-bearing sedimentary ore deposits

Radiogenic decay of uranium- and helium-bearing minerals in sedimentary ore deposits may also lead to the production of helium (^{4}He), which may accumulate as a gas phase in a trap. In New Mexico, this exploration concept is limited in its possible applications because most known uranium- and thorium-bearing sedimentary deposits are near the surface where reservoirs are saturated with fresh water and gas traps are either nonexistent or have been breached at the outcrop. Most helium generated from these ore bodies would likely have migrated updip to the outcrop where it would have dissipated into the atmosphere. Nevertheless, there are occurrences of thick sections of radioactive uranium-bearing rocks in the deep subsurface that could be possible sources of helium.

Model 3: Mantle-derived helium transported into the crust via volcanism

There are significant volumes of Tertiary age volcanic rocks in central, western, north-central and southwestern New Mexico. The magmas that formed these volcanic rocks may have transported helium (as ^3He) into the crust where degassing results from a decrease in pressure on the magmatic fluids. Areas with substantial volumes of volcanic rocks therefore have potential for accumulations of helium gas. However, these areas generally have significant Tertiary and Cenozoic age faults that may have acted as conduits for volcanic gases to escape to the surface. Exploration challenges in these areas include finding traps and seals that have not been breached by tectonic and volcanic activity. Large volumes of CO_2 degassed from rising magmas could occur in the reservoirs along with helium because CO_2 is one of the most abundant volcanic gases (Giggenbach, 1996; Bullard, 1984).

Model 4: Mantle-derived helium transported into the crust via deep extensional fractures

This process has apparently been effective in concentrating helium (as ^3He) in crustal reservoirs in places where megafractures and faults developed during Tertiary or Cenozoic extension, but not during pre-Tertiary extension. In New Mexico, the areas where this model may be most viable are basins of the Rio Grande rift where extensive extensional faulting occurred during the Tertiary. As in the preceding model, integrity of the traps and seals in this model presents an exploration challenge. Degassing of CO_2 from magmas during Tertiary volcanism may have introduced CO_2 into reservoirs.

Model 5: Crustal-derived He trapped in crustal reservoirs.

This helium (^3He) is derived from beta emission decay of ^3H to ^3He. Local concentrations of ^3He may be produced in this manner in strata where clays that were deposited in evaporitic settings and may therefore be lithium rich. Obvious settings for this model include Permian-age strata in the southeastern and east-central parts of New Mexico. Many of these strata were deposited in evaporitic settings and contain interbedded shales, evaporites, sandstones, and dolostones. The evaporites and shales will seal the generated helium within sandstone and dolostone reservoirs. Whether or not the geologic conditions of this model can lead to commercial accumulations of ^{3}He is uncertain.

Seals for helium traps

A seal that has the capability to retain helium gas molecules is essential to entrapment. Helium gas molecules have a diameter of 0.2 nanometers (nm; 10^{-9} meters; Hunt, 1996). Molecular diameters for other common gases are 0.33 nm for CO_2, 0.34 nm for N_2, and 0.38 nm for methane (Hunt. 1996). Because of the smaller size of helium molecules, some seals that contain CO_2, nitrogen and methane may leak helium. The smaller diameter of helium molecules may increase loss from a trap by diffusion through a seal. Seals with smaller pore diameters will have lower rates of diffusive losses. Therefore, it may be expected that salt, anhydrite and possibly kerogen-rich shales may be more effective seals for helium than rock types with larger pores such as micritic limestones and kerogen-poor shales. Salt and anhydrite do not contain interconnected pore waters through which gases can diffuse (Downey, 1984) and therefore may be the most effective seals for helium. Of course, helium that diffuses upward through one seal may accumulate underneath the next higher seal in the vertical sequence.

Geologic Structure Map

A map of major faults and fold axes in New Mexico was compiled for this project (Figure 3). The location of major, deep-seated faults is an important consideration in helium exploration because faults can be migration pathways for helium. Major fold axes may also be important because major folds may be cored by faults at depth; fractures may be concentrated in areas of maximum fold curvature. Faults and fold axes mapped in the subsurface as well as those mapped on the surface are shown on Figure 3.

The faults and fold axes portrayed on the structure map have been compiled from a number of sources in the published literature. Structures that have been mapped on the surface were compiled from the Geologic Map of New Mexico (New Mexico Bureau of Geology and Mineral Resources, 2003), as well as Kelley (1971, 1972), and Chapman, Wood, and Griswold, Inc. (1977). Structures that have been mapped in the subsurface were compiled from Kelley (1971), Taylor and Huffman (1998), Stevenson and Baars

(1977), Haigler and Cunningham (1972), Stipp and Haigler (1957), Broadhead (1990, 1997, 2002), Broadhead and others (2002), and Broadhead and Jones (2002, 2004).

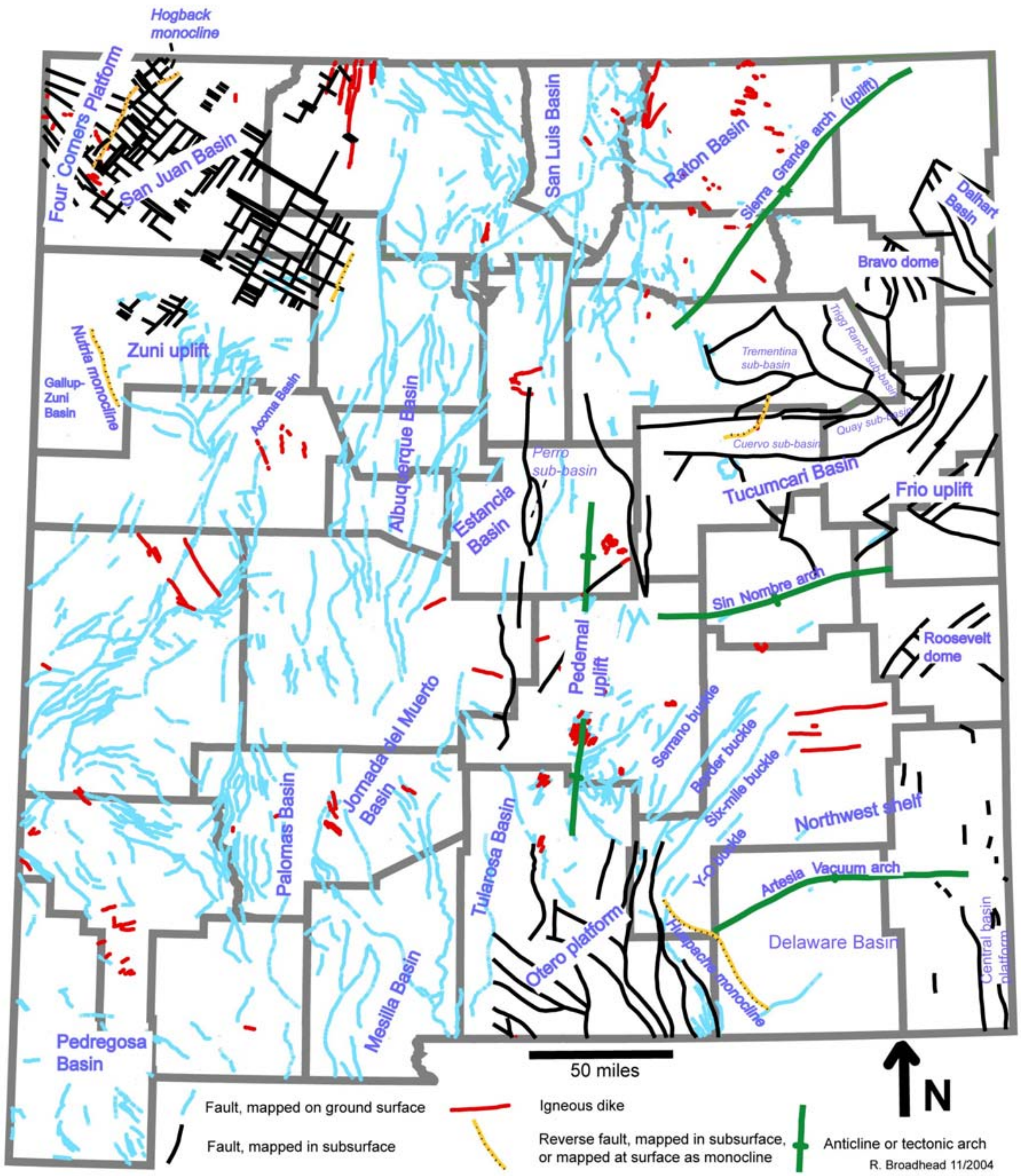

Figure 3. Tectonic map of New Mexico, showing major faults mapped on surface, in subsurface, major igneous dikes mapped at surface, and major tectonic arches and anticlines. See text for data sources.

Aeromagnetic Anomaly Map of New Mexico

An aeromagnetic anomaly map of New Mexico is included in this report (Figure 4). This map was obtained from digital data of the U.S. Geological Survey (Kucks et al., 2001). The map is included in this report and in the GIS projects so that the reader may use it to interpret faults and fault trends in the subsurface. The interpreted locations of faults and fault trends may be useful in helium exploration because faults can act as migration pathways for helium.

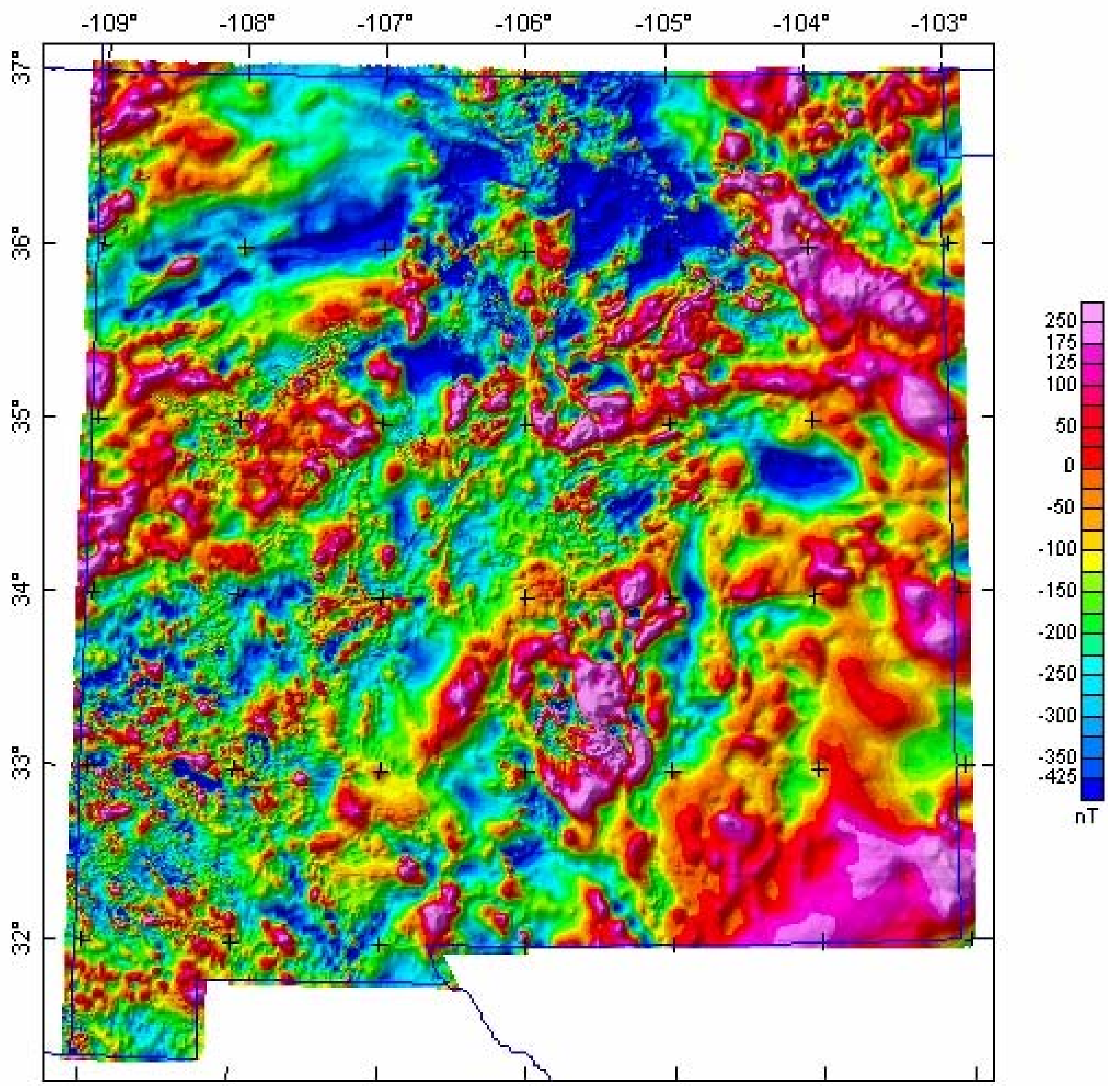

Figure 4. Aeromagnetic anomaly map of New Mexico. This map is from the U.S. Geological Survey (Kucks et al., 2001).

The New Mexico Helium Database

A major part of this report is the database of gas analyses (see database ***NMgases.xls*** on this CD). This database contains analyses of the composition of 937 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.

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 within the well with stratigraphic information regarding individual wells on file at the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. Other data were added or verified as time permitted, especially well location, depth of production within the wellbore, operator, well name, and surface elevation. Other data fields that 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, the standard legal descriptions of well locations. 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, 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 for this project because of the relatively low density of data points (sample locations) across New Mexico.

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 = Fassett, 1978a, 1978b, 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 that 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 cells with a white background have values of latitude calculated at the New Mexico Bureau of Geology and Mineral Resources. Samples in cells with a yellow background have latitude obtained from the U.S. Bureau of Mines/Bureau of Land Management database. Samples in cells with a blue background have latitude obtained from the U.S. Geological Survey database.

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

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

Contour maps of Helium Distribution

This open-file report contains a number of maps that show helium distribution in reservoirs of a common geologic system or age. Helium distribution is presented as contours of helium content of gases, in mole percent. The data upon which the contours are based are given in the database of gas analyses (***NMgases.xls***) on this CD. In areas of relatively dense data distribution, such as the San Juan and Permian Basins, it was possible to contour the helium content of gases using conventional hand-contouring techniques. In these cases, the maps show the distribution of the helium content of gases in reservoirs of similar age across a basin and are thought to do so in a geologically realistic manner that approximates true helium distribution.

Contouring of helium distribution is more problematic in sparsely drilled areas for which few gas analyses are available. It is not possible to objectively determine the distribution of helium over large geographic areas where only one or two gas analyses are available. In these areas, closed contours were drawn around data points in order to emphasize the presence of enhanced concentrations of helium in natural gases and to call attention to areas with enhanced helium concentrations. The reader may wish to modify contours to reflect the presence of geologic elements that may affect helium generation, migration and entrapment. One obvious contouring technique is to draw contours elongate parallel to basement faults that may have acted as migration pathways. The contour intervals differ from map to map (reservoir age to reservoir age). The contour intervals for each map were chosen with the data variability of that map in mind.

Helium Distribution in New Mexico

The distribution of helium in New Mexico is discussed by stratigraphic as well as geographic (basinal) occurrence (Table 4). Each geologic system for which substantial amounts of data area available is discussed separately, starting with the youngest strata. The discussion of each geologic system is divided into parts on the ***San Juan Basin***, the ***Permian Basin***, and ***other areas*** (where sufficient data are available). Within each of these areas, relations of the data to geologic features are summarized. Finally, helium distribution within the San Juan and Permian Basins and other key areas is summarized and implications for exploration are discussed. For each geologic system with sufficient data, there are one or more maps that show contours of helium content of gases in reservoirs.

Quaternary System

No sample analyses are available for gases from Quaternary sediments in New Mexico.

Tertiary System

Only three analyses were available for gases obtained from Tertiary reservoirs. All three analyses were from the San Juan Basin. Two analyses are from northeastern San Juan County and one analysis is from south-central Rio Arriba County. All three samples were from flammable gases with significant hydrocarbon contents and helium contents ranging from a trace to 0.01 percent. Based on these sparse data, it appears that the helium potential of Tertiary reservoirs in the San Juan Basin is low. No gas analysis data are available for Tertiary reservoirs elsewhere in New Mexico.

Cretaceous System

San Juan Basin: Small percentages of helium are ubiquitous in gases within Cretaceous reservoirs of the San Juan Basin (Figure 5). The average helium content of Cretaceous gases in the San Juan Basin is 0.04 percent. In general, reservoirs lower in the section (Gallup and Dakota sandstones) have the highest amounts of helium (Table 5). The sample with the highest helium concentration was obtained from the Otero Chacra pool and had a helium content of 0.27 percent. Helium in Fruitland Formation coal gases ranges in concentrations from a trace to 0.04 percent; it is thought to have originated in the crust, the mantle, and in the atmosphere (Sorek, 2003). The atmospheric portion of the helium was incorporated into the groundwater system during recharge at the outcrop.

Permian Basin: Only erosional remnants of Cretaceous strata are present in the New Mexico part of the Permian Basin. These remnants are present only at the surface or at very shallow depths. No gas samples have been collected from Cretaceous strata in the New Mexico part of the Permian Basin.

Other areas: Gas samples have been analyzed from three wells and one outcrop gas seep from Colfax, Mora and Union Counties (Table 6). None of the samples contained significantly elevated concentrations of helium.

Jurassic System

Gases have been recovered and analyzed from Jurassic reservoirs in one well in Mora County and from two outcrop seeps in Union County. None contained significant reported concentrations of helium (Table 7). No gas analyses are available for Jurassic reservoirs in the San Juan Basin. No Jurassic strata are present in the New Mexico part of the Permian Basin.

Triassic System

Significant concentrations of helium are present in gases recovered from Triassic sandstones in the San Juan Basin and on the Bravo Dome in Harding County (Table 8). Gases from sandstones in the Chinle Formation on the Four Corners Platform contain helium in excess of 9 percent. One sample of gas recovered from Chinle sandstones on the Bravo Dome contained 1.8 percent helium.

Table 4. Helium content of natural gases in New Mexico subdivided by geologic system and basin or geographic area.

Geologic system	Helium content of gases		
	San Juan Basin	Permian Basin	other areas
Quaternary	no data	no data	no data
Tertiary	Tr-0.01%	no data	no data
Cretaceous	Tr-0.04%	only erosional remnants of Cretaceous preserved	0-0.01%
Jurassic	no data	Jurassic strata not present	0-0.02%
Triassic	8.92-9.1%	no data	0.02-1.8%
Permian	0.52-5.5%	Tr-0.974%	Tr-2.56%
Pennsylvanian	0-8.2%	Tr-0.348%	0.03-0.351%
Mississippian	0.1-7.5%	0.03% (1 sample)	no data
Devonian	2.45-7.99%	no data	no data
Silurian	Silurian strata no present	Tr-0.29%	no data
Ordovician	Ordovician strata not present	0.07-0.233%	no data
Cambrian	no data	no data	no data
Precambrian	0.11 (1 sample)	no data	no data

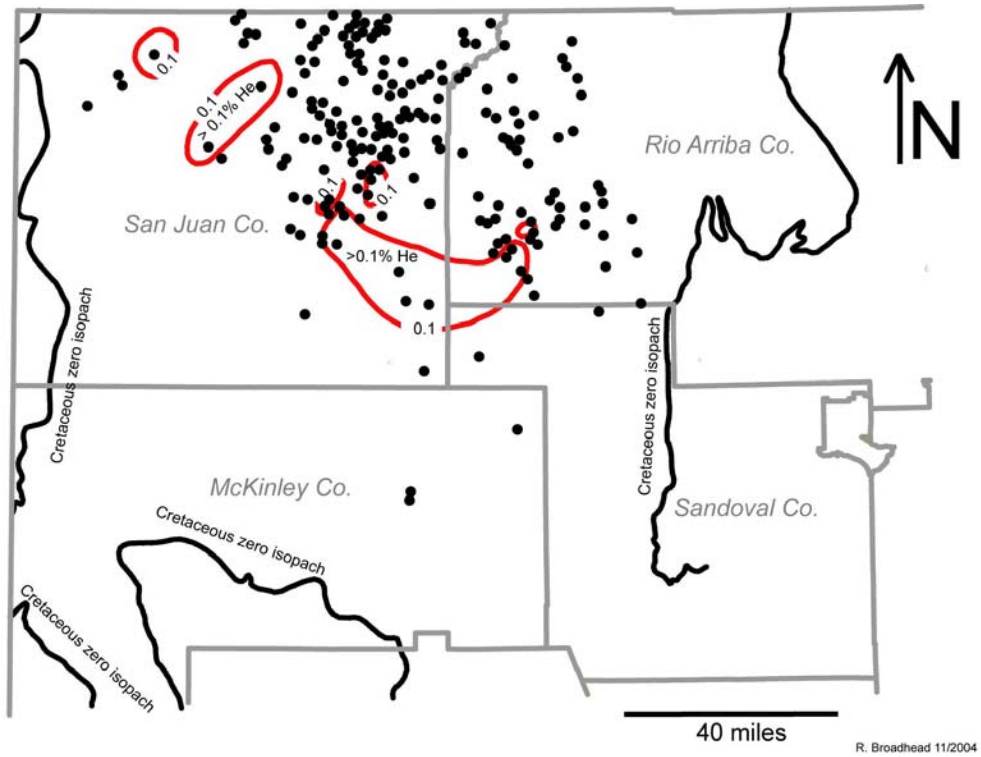

Figure 5. Contours of percent helium in natural gases recovered from Cretaceous reservoirs in the San Juan Basin.

Table 5. Concentration of helium in natural gases recovered from Cretaceous strata of the San Juan Basin of northwestern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage. Reservoirs are presented in stratigraphic order.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Fruitland	0.01	Tr	0.04 (Flora Vista and Huerfano Dakota pools)	21
Pictured Cliffs	0.01	Tr	0.04 (Ballard Pictured Cliffs pool)	65
Cliff House	0.02	0.01	0.03	3
Chacra	0.04	0.01	0.27 (Otero Chacra pool)	12
Point Lookout	0.02	Tr	0.04	13
Mesaverde	0.04	Tr	0.09 (La Plata gas pool)	53
Gallup	0.07	Tr	0.15 (Ojo gas pool)	18
Tocito	0.08	Tr	0.16	4
Graneros	0.05	Tr	0.1 (Otero gas field)	3
Dakota	0.06	Tr	0.2 (Basin Dakota pool)	47

Table 6. Concentration of helium in natural gases recovered from Cretaceous strata of the other areas of New Mexico, subdivided by stratigraphic unit and by county. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	County	Average He Content	Minimum He Content	Maximum He content	Number of samples
Dakota	Colfax	0.01	Tr	0.01	2
Dakota (Wagon Mound gas pool)	Mora	He analysis not reported			1
Dakota (gas seeps at outcrop)	Union	0	0	0	2

Table 7. Concentration of helium in natural gases recovered from Jurassic strata in New Mexico, subdivided by stratigraphic unit and by county. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	County	Average He Content	Minimum He Content	Maximum He content	Number of samples
Morrison	Mora (Wagon Mound gas field)	No helium analysis reported			1
Jurassic undifferentiated	Union (gas seeps at outcrop)	0.01	0	0.02	2

Table 8. Concentration of helium in natural gases recovered from Triassic strata in New Mexico, subdivided by stratigraphic unit and by county. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic unit	County	Average He content	Minimum He content	Maximum He content (oil or gas pool)	Number of samples
Santa Rosa	Colfax	He analysis not reported			
Chinle	Harding (Bravo Dome CO_2 field)	1.8			1
Santa Rosa	Harding (Bravo Dome CO_2 field)	He analysis not reported			
Santa Rosa	Mora (Wagon Mound gas field)	0.02			1
Chinle	San Juan (near Beclabito)	9.0	8.92	9.1	2
Santa Rosa	Union (Bravo Dome CO_2 field)	He analysis not reported			1

Permian System

San Juan Basin: Permian strata have yielded few gas samples from the San Juan Basin. Helium is produced commercially from sandstones and conglomerates of the Organ Rock member of the Cutler Formation (Lower Permian) at the Big Gap pool on the Four Corners Platform (Figure 6). The gas produced from the Big Gap pool contains 5.5 percent helium (Walker, 1983). Gas recovered from clastic reservoirs in the Cutler Formation (Lower Permian) in the Pan American No. 1 Navajo Tribal AD well, located approximately 20 miles north of the Big Gap pool, had a helium content of 0.52 percent and a methane content of 82.8 percent (Figure 6).

Permian Basin: Permian reservoirs are prolifically productive of oil and gas in the Permian Basin, having produced more than 3.5 billion bbls of oil from the New Mexico part of the basin (Broadhead et al., 2004). Most reservoir gases in Permian strata have low concentrations of helium (Figure 7; Table 9). The average concentration of helium in most Permian gases is significantly less than 0.1 percent.

Significant percentages of helium occur in gases produced from low-permeability, fluvial-deltaic reservoirs of the Abo red beds in north-central Chaves County. Helium concentrations in Abo reservoirs in the Pecos Slope and Pecos Slope West pools range from 0.09 percent to 0.974 percent and average 0.48 percent. The Pecos Slope pools produce dry gas. Trapping appears to be stratigraphic or a combination of stratigraphic variations and capillary pressure barriers (Broadhead, 1984, 2001a). The hydrocarbon gases trapped in the Pecos Slope reservoirs appear to have been generated elsewhere, perhaps in underlying dark-gray shales and limestones of the Hueco Formation (Permian: Wolfcampian) or in dark-gray to black shales that are stratigraphically lower than the Abo and are present to the south, down structural dip (Broadhead. 1984). The gases may have migrated upward from their sub-Abo source through the near-vertical strike-slip faults that cut across the area from southwest to northeast (Broadhead (1984, 2001a). Anhydrites in the lowermost Yeso Formation have provided a vertical seal across the faults and have helped trapped gas within the low-permeability Abo sandstones. Kennedy and others (2002) utilized isotopic analyses of helium, argon and neon in the Pecos Slope gases to conclude that helium in the Abo reservoirs originated from radiogenic decay of Precambrian granitic rocks and migrated vertically through the strike-slip faults into the Abo. Trapping is provided by the same geologic elements that trap the hydrocarbon gases. Helium concentration generally seems to decrease with increasing distance from the faults. In the area around the Pecos Slope pools, Upper Pennsylvanian and Lower Permian strata rest unconformably on Precambrian basement in most places; lower and middle Paleozoic strata are either absent in most places or are perhaps present only as local erosional remnants. Therefore, vertical migration distances from basement to the Abo reservoirs are less than encountered to the southeast where several thousand feet of Ordovician through Middle Pennsylvanian strata are present. Favorable areas for helium exploration are located along the southwest-northeast trend of the faults. The presence of anhydrite or salt in the Yeso Formation is favorable to the accumulation of helium in the Abo. In places without evaporites, the helium may have leaked vertically along the fault to the surface or have moved upward along the fault and into shallower reservoirs. Similar structural zones near or west of the Pennsylvanian pinchout (Figure 9) may also be favorable for helium accumulation in the Abo.

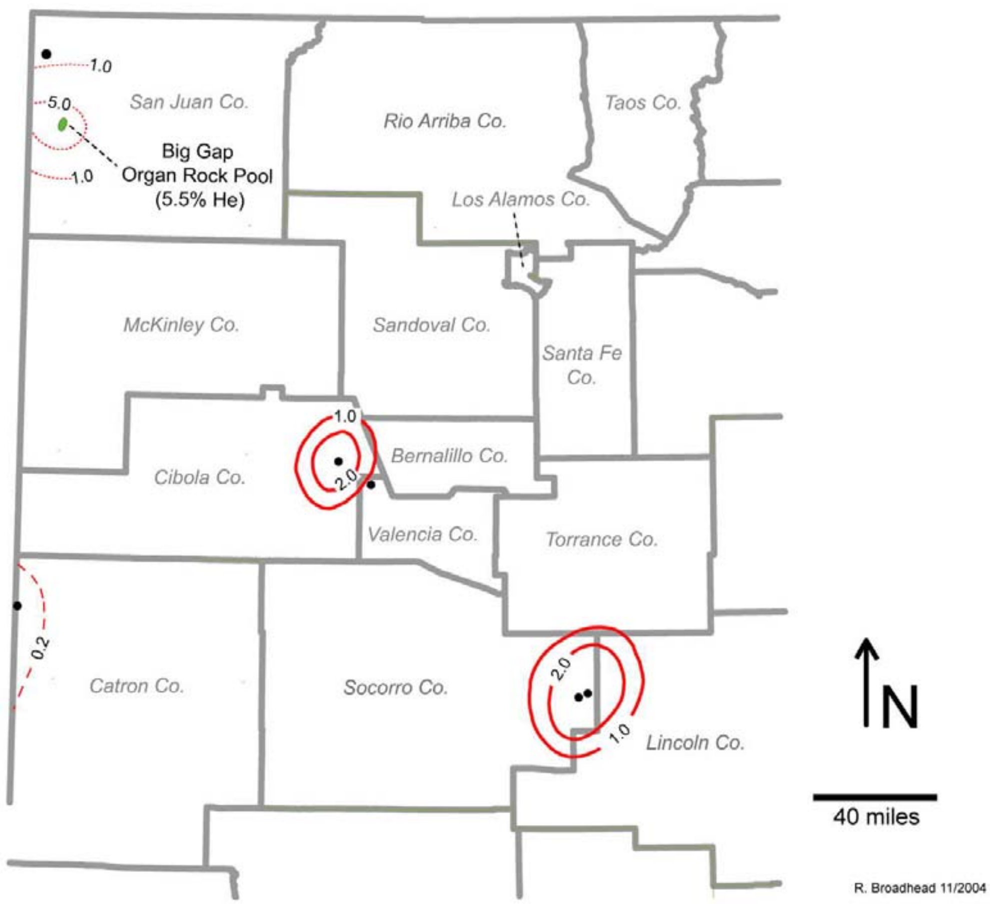

Figure 6. Contours of percent helium in natural gases recovered from Permian reservoirs in the San Juan Basin and in central New Mexico.

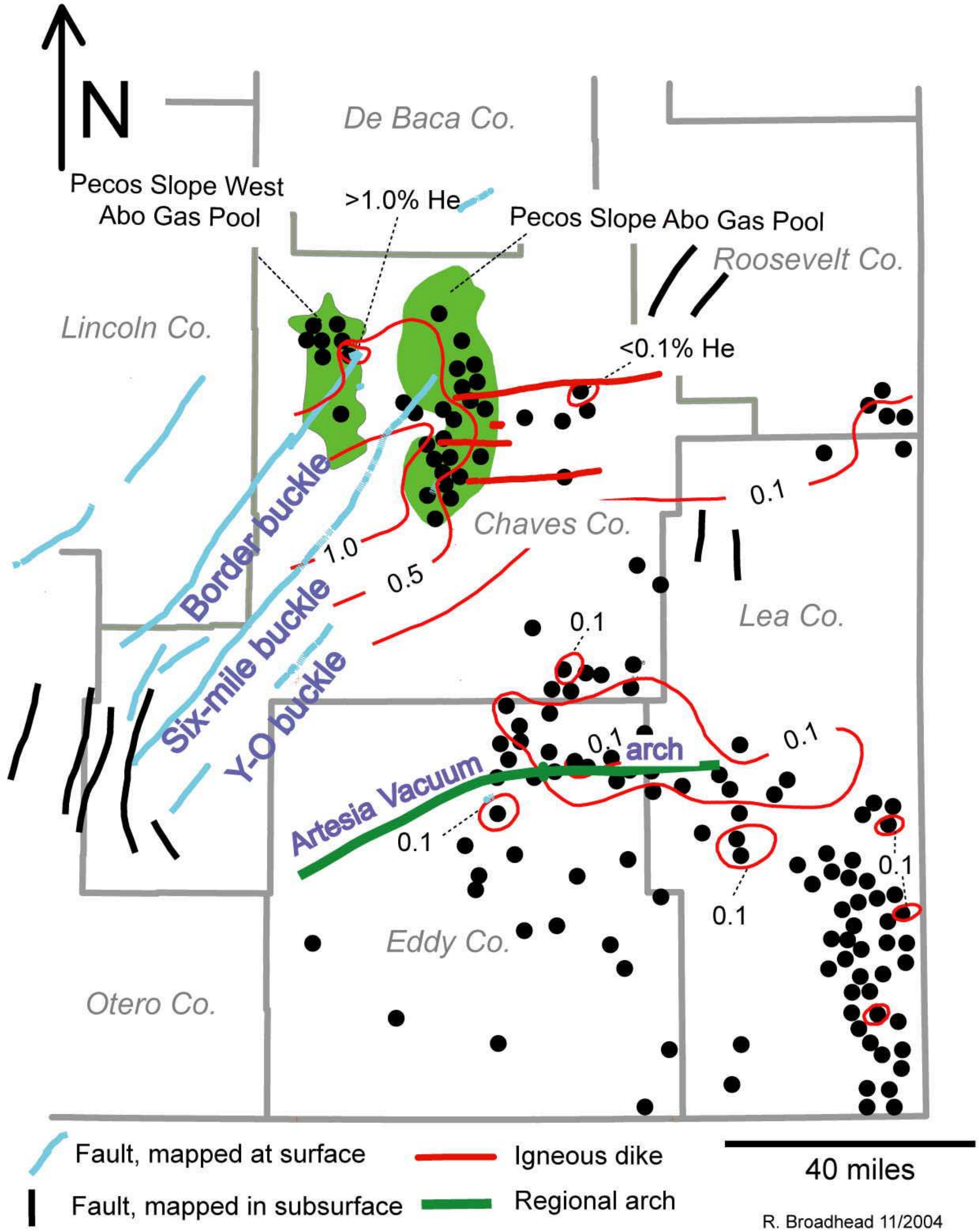

Figure 7. Contours of percent helium in natural gases recovered from Permian reservoirs in the Permian Basin in southeastern New Mexico.

Elsewhere in southeastern New Mexico, helium concentrations in Permian gases have slightly elevated levels over the Artesia Vacuum arch in Eddy and Lea Counties. This wide, gentle anticlinorium acts to trap oil and gas in Middle and Upper Permian strata. It overlies the deeper Abo shelf-margin carbonate (“reef”) complex which is probably defined on its basinward margin by high-angle faults of late Paleozoic age that extend from Precambrian basement upward into Permian strata. Perhaps these faults, which acted to localize the deposition of carbonate reservoirs along the shelf margin, also acted as conduits along which helium generated in Precambrian granitic rocks migrated upward into Permian reservoirs where it was trapped.

Table 9. Concentration of helium in natural gases recovered from Permian strata in the Permian Basin of southeastern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Salado	0.02	Tr	0.05	3
Artesia	0.05	Tr	0.14 (Maljamar)	23
Yates	0.06	Tr	0.26 (Quail Ridge)	13
Seven Rivers	0.06	0.02	0.095 (Jalmat)	4
Queen	0.08	Tr	0.18 (Reeves North)	24
Grayburg	0.10	0.02	0.22 (Grayburg-Jackson)	10
San Andres	0.08	Tr	0.18 (Red Lake)	14
Glorieta	0.03			1
Delaware	0.13	0.07	0.16 (Lea Northeast)	3
Paddock	0.02			1
Blinebry	0.04	0.03	0.11 (Blinebry)	9
Tubb	0.04	0.04	0.047 (Monument)	2
Drinkard	0.045			1
Bone Spring	0.06	0.02	0.08 (Airstrip)	5
Abo carbonates	0.03	0.01	0.04 (Monument)	2
Abo red beds	0.48	0.09	0.974 (Pecos Slope)	52
Wolfcamp	0.06	0	0.28 (Leslie Spring)	16

Other areas: Helium-rich gases have been recovered from Permian strata in central and western New Mexico (Figure 6; Table 10). On Chupadera Mesa in eastern Socorro County, gas recovered from Abo (Permian: Wolfcampian) sandstones had a helium content in excess of 2.5 percent. In Cibola County near Laguna, gas with helium in excess of 2 percent has been recovered from water wells in the San Andres Formation.

Helium appears to be present in only low concentrations (< 0.01%) in Lower Permian sandstone reservoirs of the Tubb member of the Yeso Formation in and around the Bravo Dome carbon dioxide gas field of Union and Harding Counties in northeastern New Mexico. The Tubb sandstones are the main reservoirs for carbon dioxide gas; more than 99% of CO_2 from the Bravo Dome field has been produced from the Tubb. These reservoirs directly overlie Precambrian basement that consists in large part of granitic rocks. The vertical seal to the carbon dioxide accumulation is the Cimarron anhydrite member of the Yeso Formation that immediately overlies the Tubb. Yet enhanced concentrations of helium occur in Triassic sandstones higher in the section.

Table 10. Concentration of helium in natural gases recovered from Permian strata in other areas of New Mexico, subdivided by stratigraphic unit and by county. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic unit	County	Average He content	Minimum He content	Maximum He content (oil or gas pool)	Number of samples
Yeso	Catron	0.203			1
San Andres (water well samples)	Cibola	2.1	2	2.3	3
Glorieta	Colfax	0.46			1
Tubb (Bravo Dome CO_2 field)	Harding	0.01	Tr	0.01	8
Glorieta (Wagon Mound gas field)	Mora	0.15			1
San Andres	Quay	0.21			1
Abo	Socorro	1.56	0.088	2.56	3
Glorieta	Union	0.004			1
Tubb	Union	0.02			1
Abo	Union	Helium analysis not reported			2
San Andres (water from spring)	Valencia	0.6			1

Pennsylvanian System

San Juan Basin: Significant concentrations of helium are present within Pennsylvanian gases in the San Juan Basin (Figure 8; Table 11). Most gas analyses are from wells on the

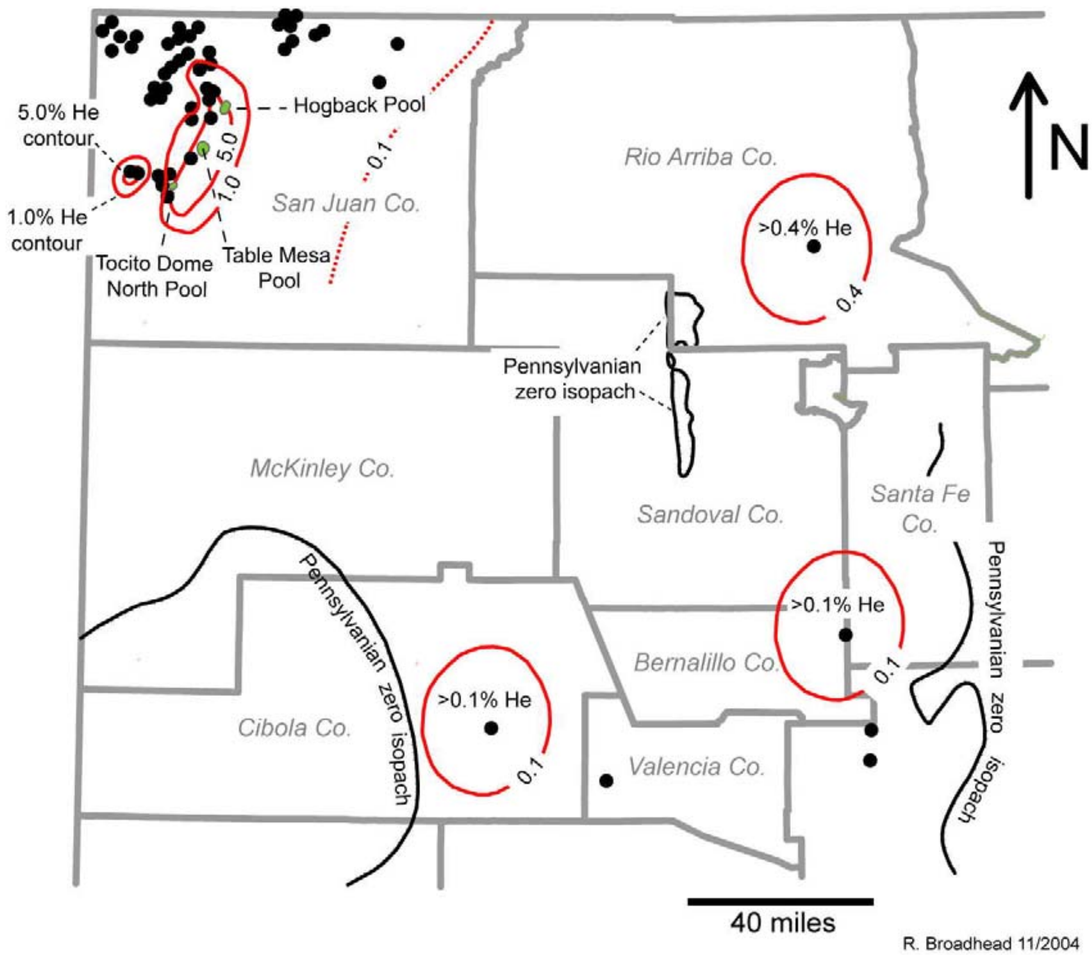

Figure 8. Contours of percent helium in natural gases recovered from Pennsylvanian reservoirs in the San Juan Basin and in central New Mexico. Pennsylvanian zero isopach lines modified from Kottlowski (1959, 1960, 1963) and Broadhead (1997).

Four Corners Platform where significant commercial production of helium has occurred. Maximum known helium concentration in Pennsylvanian reservoirs on the Four Corners Platform is 8.2 percent in the Paradox Formation at the Hogback field. All commercial oil and gas production from Pennsylvanian reservoirs in the San Juan Basin has been obtained from the Four Corners Platform. No commercial production has been obtained to date from deeper parts of the basin that are to the east of the Four Corners Platform.

Although no commercial oil or gas production has been obtained from the deeper parts of the San Juan Basin east of the Four Corners Platform, analyses of gases recovered from sparse, deep exploratory tests indicate that elevated levels of helium are present. The Burlington No. 2 Marcotte well, located in T31N R10W, sampled gas with a helium content of 0.42 percent and a methane content of 94.9 percent while drilling through Pennsylvanian strata at a depth of 13,390 ft. The Burlington No. 2 Vasaly well, located in T30N R11W, recovered gas with a 0.16 percent helium content in Pennsylvanian strata at a depth of 12,685 ft, gas with 0.058 percent helium and 83.9 percent methane at a depth of 12,136 ft, and gas with 0.03 percent helium and 97.48 percent methane at a depth of 11,876 ft.

Table 11. Concentration of helium in natural gases recovered from Pennsylvanian strata in the San Juan Basin of northwestern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Hermosa	3.67	0	8.0 (Hogback)	27
Ismay	0.21	0.039	0.351 (Barker Dome)	3
Paradox	2.61	0.07	8.2 (Hogback)	52
Table Mesa	5.29	1.9	6.05 (Table Mesa)	16

Permian Basin: Pennsylvanian reservoirs are prolifically productive of oil and natural gas in the Permian Basin. Pennsylvanian reservoirs have produced more than 424 million bbls oil in the New Mexico part of the Permian Basin (Broadhead et al., 2004). The concentration of helium in Pennsylvanian gases is low (Figure 9), averaging 0.03 percent in Morrow and Atoka (Lower Pennsylvanian) and Strawn (Middle Pennsylvanian) reservoirs and 0.10 percent in Canyon and Cisco (Upper Pennsylvanian) reservoirs (Table 12). The highest concentration of helium is found in Upper Pennsylvanian carbonates in the Haystack Cisco gas pool where helium is 0.343 to 0. 348 percent of the gas. This pool is located in Chaves County near the northwestern limit of established oil and gas production in the Permian Basin. At the Haystack pool, Lower and Middle Pennsylvanian strata are not present (see Meyer, 1966) and the combined Ordovician, Silurian and Mississippian sections have an aggregate thickness of less than 250 ft. Similar to the Pecos Slope Abo reservoirs, the helium may be radiogenically derived from Precambrian granites and migrated into Pennsylvanian reservoirs through basement-involved faults or fractures. Perhaps not coincidentally, the Haystack Cisco gas pool lies along trend of the fault block formed by the Six-mile and Y-O faults (Figure 9). Those faults appear to be the principal migration pathways for helium trapped in the Pecos Slope Abo reservoirs.

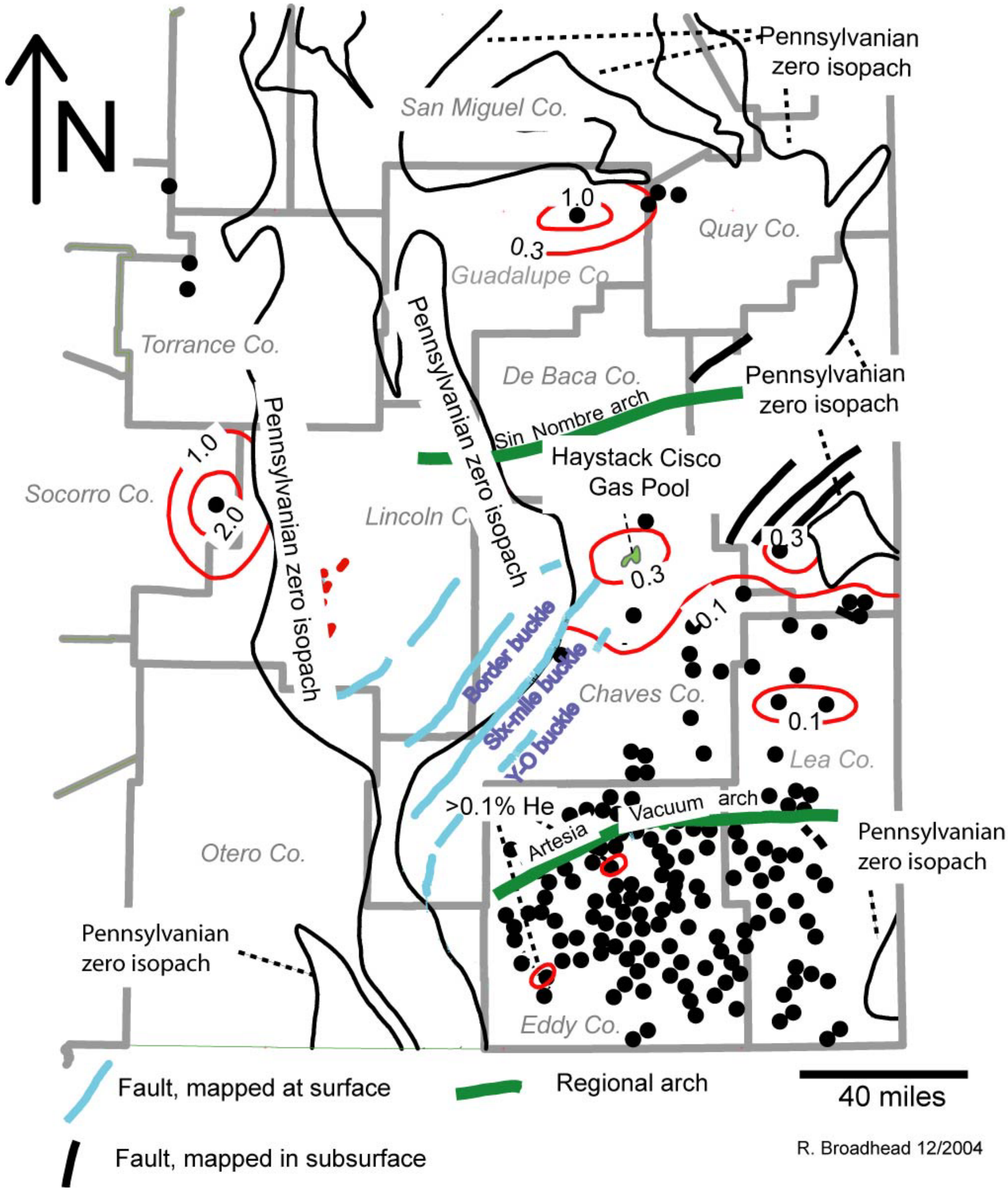

Figure 9. Contours of percent helium in natural gases recovered from Pennsylvanian reservoirs in southeastern New Mexico. Pennsylvanian zero isopach lines modified from Meyer (1966), Kottlowski (1963), Broadhead (2002), Broadhead and King (1988) and Broadhead and others (2002).

Table 12. Concentration of helium in natural gases recovered from Pennsylvanian strata in the Permian Basin of southeastern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Upper Pennsylvanian (Cisco & Canyon)	0.10	0.01	0.348 (Haystack)	17
Strawn	0.03	Tr	0.09 (Dagger Draw)	21
Atoka	0.03	Tr	0.09 (Jenkins)	45
Morrow	0.03	0.01	0.05 (Sand Ranch)	111

Other areas: Elevated levels of helium (1.3 percent) have been found in Strawn (Middle Pennsylvanian) sandstones in the deeper parts of the Tucumcari Basin in Guadalupe and Quay Counties (Figure 9; Table 13). In Cibola County, gas with modest concentration of helium (0.13 percent) has been recovered from Sandia (Lower Pennsylvanian) sandstones in a well drilled by Sun Oil Company where it is associated with carbon dioxide (Figure 8). In Bernalillo County near Albuquerque, gas recovered from a water well in the Madera Group contained 0.13 percent helium as well as 78.7 percent carbon dioxide and 18.9 percent hydrogen (Figure 8; Table 13).

Table 13. Concentration of helium in natural gases recovered from Pennsylvanian strata in other areas of New Mexico, subdivided by stratigraphic unit and by county. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic unit	County (Basin)	Average He content	Minimum He content	Maximum He content	Number of samples
Madera (water well)	Bernalillo	0.13			1
Sandia	Cibola	0.13			1
Strawn	Guadalupe (Tucumcari Basin)	1.303			1
Strawn	Quay (Tucumcari Basin)	0.24	0.18	0.351	3
Sandia (Estancia CO_2 fields)	Torrance	0.05	0.03	0.08	4
Madera (spring at outcrop)	Valencia	0.01			1

Mississippian System

San Juan Basin: Mississippian reservoirs in the San Juan Basin have yielded gases with significant concentrations of helium (Figure 10; Table 14). The highest known helium concentrations are in reservoirs on the Four Corners Platform. Helium has been produced commercially from Mississippian reservoirs on the Four Corners Platform. Concentrations are variable in this setting and range from a high of 7.5 percent in an unproductive exploration well drilled near Beclabito to a low of 0.1 percent in an exploration well drilled approximately 5 miles to the east. Although sparse data indicate known helium concentrations are lower in the deeper parts of the basin to the east of the Four Corners Platform, they are still significant and range from 0.2 to 0.43 percent.

Permian Basin: Only one gas compositional analysis was available for gas produced from Mississippian reservoirs in the Permian Basin. Gas produced from the Austin Mississippian gas pool in north-central Lea County contains a small concentration of helium, 0.03 percent (Figure 11).

Other areas: Although Mississippian strata are widespread throughout south-central and southwestern New Mexico, no analyses of natural gases from these reservoirs are available. No oil or gas has been produced Mississippian reservoirs in these areas.

Table 14. Concentration of helium in natural gases recovered from Mississippian strata in the Permian Basin of southeastern New Mexico and the San Juan Basin of northwestern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Mississippian (undifferentiated strata in Permian Basin)	0.03			1 (Austin gas pool)
Mississippian (undifferentiated strata in San Juan Basin)	4.16	0.1	7.5 (wildcat near Beclabito)	35

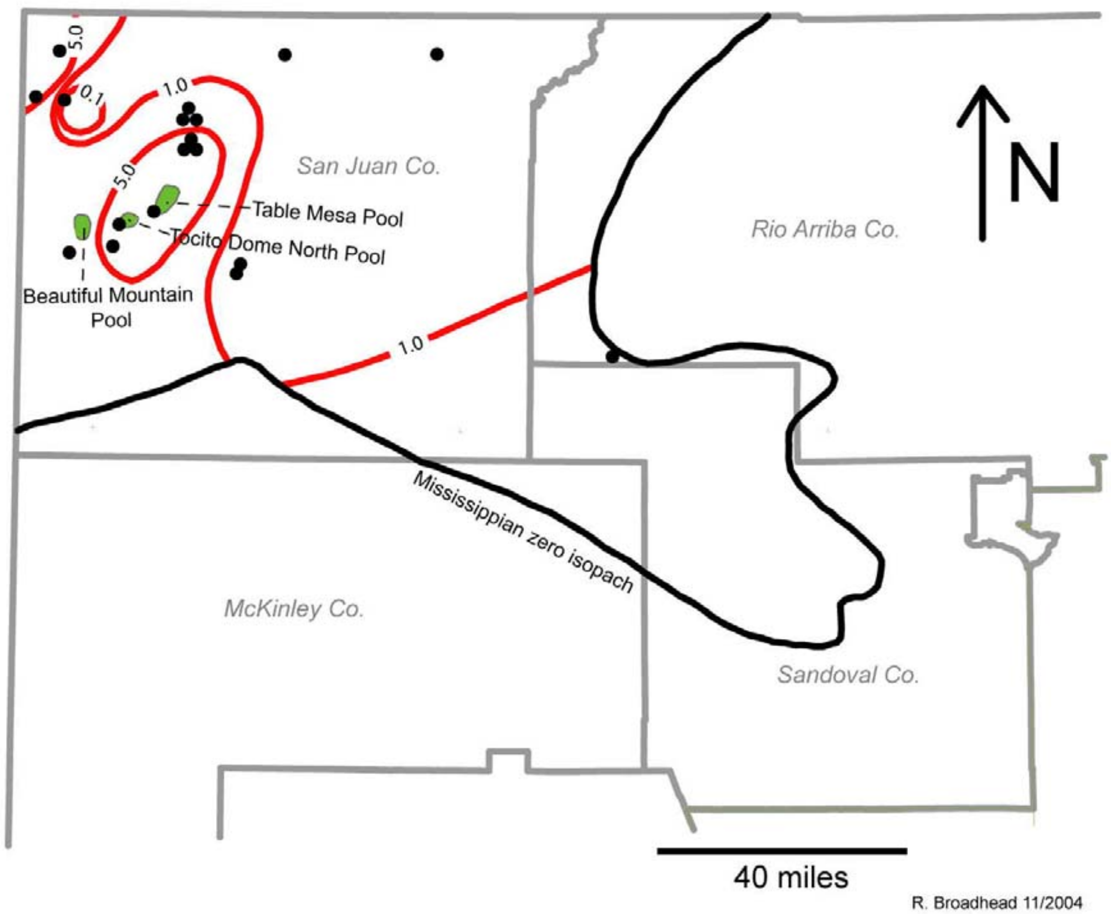

Figure 10. Contours of percent helium in natural gases recovered from Mississippian reservoirs in the San Juan Basin. Mississippian zero isopach line from Armstrong and Mamet (1977), and Armstrong and Holcomb (1989).

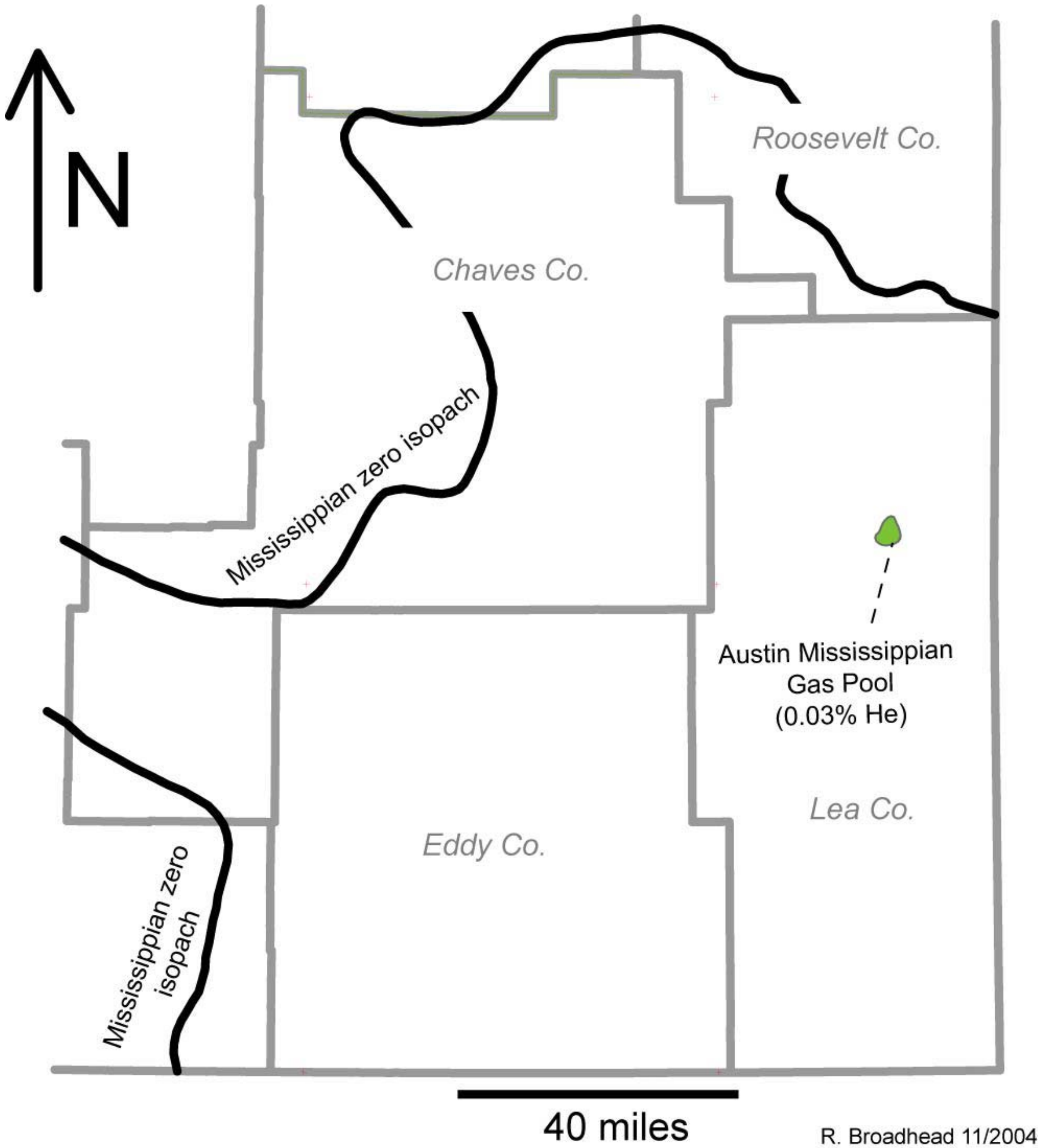

Figure 11. Percent helium in natural gases recovered from Mississippian reservoirs in southeastern New Mexico. The only available data are for gas produced from the Austin gas pool, where helium content is 0.03 mole percent of the gas. Mississippian zero isopach lines modified from Meyers (1966) and Armstrong and Mamet (1987).

Devonian System

San Juan Basin: Although Devonian strata are widespread in the San Juan Basin, gases have been recovered and analyzed from wells drilled on the Four Corners Platform. In this area, Devonian gases contain between 2.45 and 7.99 percent helium and have an average value of 5.58 percent helium (Figure 12; Table 15). Because elevated concentrations of helium are found in Mississippian reservoirs that directly overlie

Devonian strata in deeper parts of the basin east of the Four Corners Platform, it is reasonable to hypothesize that Devonian reservoirs may also contain elevated concentrations of helium.

Table 15. Concentration of helium in natural gases recovered from Devonian strata in the San Juan Basin of northwestern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Devonian (total section)	5.58	2.45	7.99 (Rattlesnake)	11
Ouray	6.73	2.45	7.99 (Rattlesnake)	6
McCracken	4.78	4.05	5.5 (exploratory well)	2
Aneth	3.81	2.87	4.4 (Table Mesa South)	3

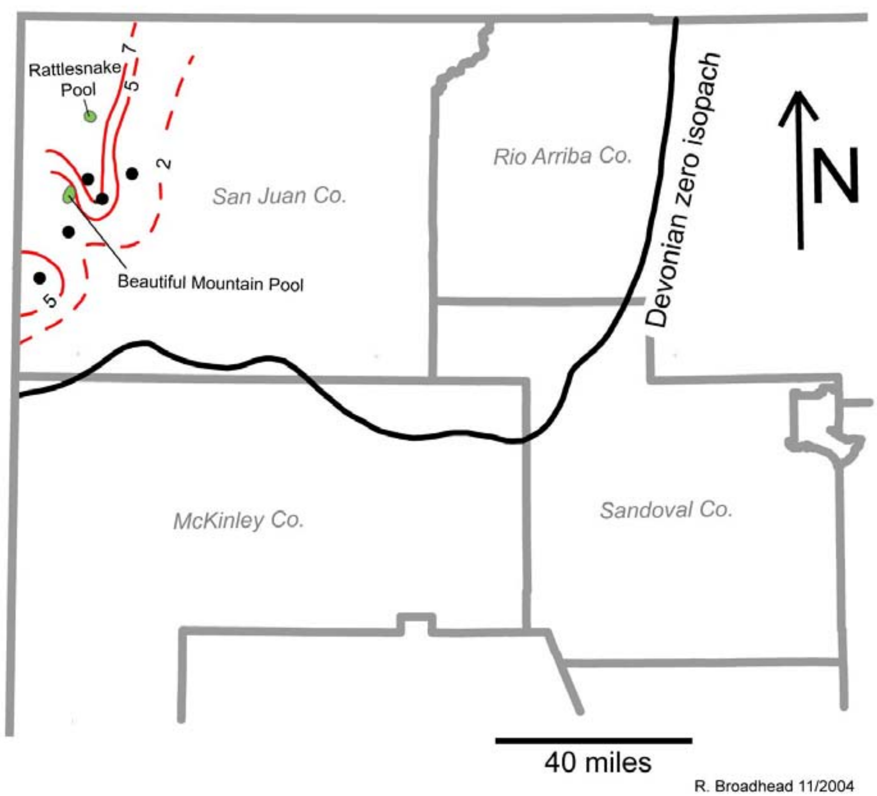

Figure 12. Contours of percent helium in natural gases recovered from Devonian reservoirs in the San Juan Basin. Devonian zero isopach lines modified from Stevenson and Baars (1977).

Permian Basin: In the New Mexico part of the Permian Basin, Devonian strata are present only in southeastern Lea County (Barrick et al., 1993; Barrick, 1995; Ruppel and Holtz, 1994). Productive strata and reservoirs in southeastern New Mexico traditionally correlated as "Devonian" are mostly Silurian in age and belong to the Wristen group (Broadhead et al., 2004). Other Silurian reservoirs are within the Fusselman Formation, which lies underneath the Wristen Group. The only true Devonian reservoirs are cherts and cherty carbonates of the Thirtyone Formation in southeastern Lea County. The Thirtyone reservoirs have produced almost 10 million bbls oil in southeastern New Mexico (Broadhead et al., 2004). No analyses are available for gases produced from the Thirtyone Formation. The low concentrations of helium in gases recovered from pre-Thirtyone and post-Thirtyone strata in southeastern Lea County indicate that Thirtyone gases may also have little helium.

Silurian System

San Juan Basin: No strata of Silurian age are known to be present in the San Juan Basin.

Permian Basin: As discussed above, Silurian strata of the Wristen Group and Fusselman Formation are widespread in the New Mexico part of the Permian Basin. Wristen and Fusselman dolostone and limestone reservoirs have produced substantial volumes of oil and gas and have yielded more than 430 million bbls oil (Broadhead et al., 2004). Production has been obtained from oil and gas pools on the Central Basin Platform, the eastern part of the Northwest Shelf, and in the eastern part of the Delaware Basin. Helium contents of Silurian gases are low, averaging 0.11 percent in the Wristen and 0.08 percent in the Fusselman (Figure 13; Table 16). Maximum known helium concentration is 0.29 percent in the Bagley Wristen pool on the Northwest Shelf in northwestern Lea County. Although data are sparse, the concentration of helium in Silurian gases appears to exhibit a general northwest increase toward the regional Silurian zero isopach line.

Other areas: Although the Fusselman Formation is widespread throughout south-central and southwestern New Mexico, no analyses of natural gases from these reservoirs are available. No oil or gas has been produced from Fusselman reservoirs in these areas.

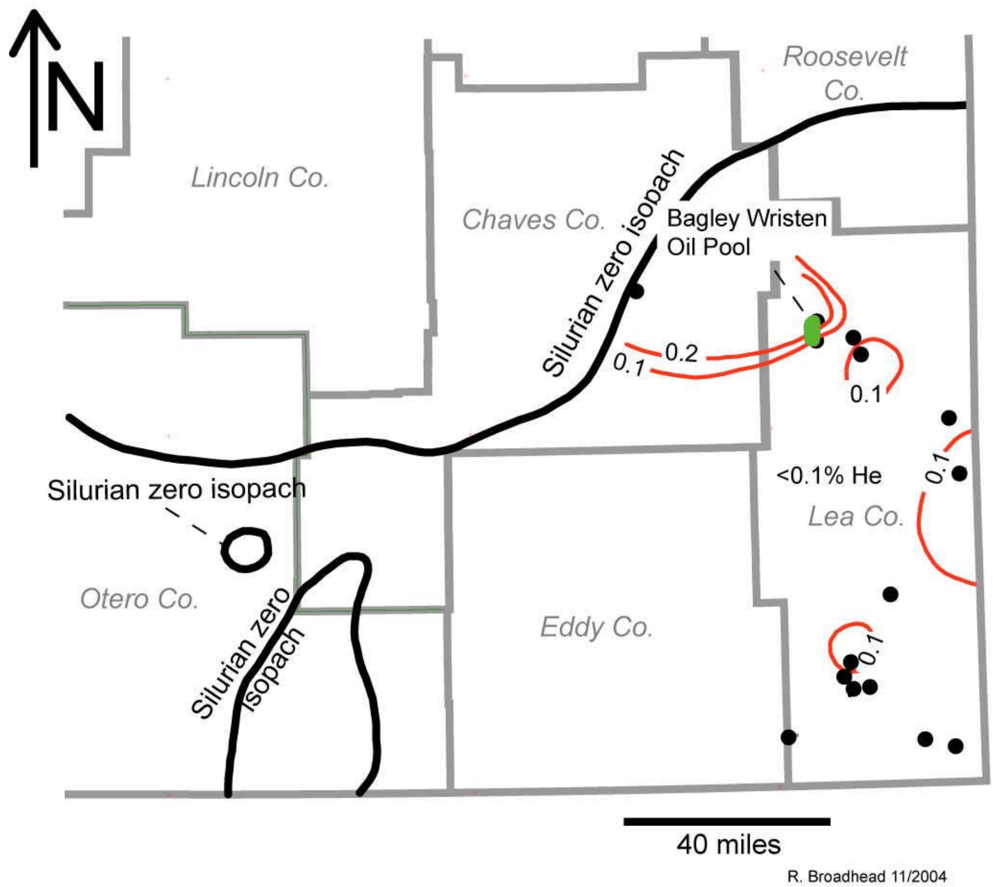

Figure 13. Contours of percent helium in natural gases recovered from Silurian reservoirs in southeastern New Mexico. Silurian zero isopach line modified from Grant and Foster (1989), Kottlowski (1963), and Broadhead (2002).

Table 16. Concentration of helium in natural gases recovered from Silurian strata in the Permian Basin of southeastern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Wristen	0.11	0.05	0.29 (Bagley)	14
Fusselman	0.08	Tr	0.215 (Diablo)	3

Ordovician System

Permian Basin: Only five analyses of gases recovered from Ordovician reservoirs are available (Table 17). In general, helium concentrations are low, averaging 0.12 percent. The highest known helium concentration is 0.233 percent from a carbonate reservoir in the Ellenburger Formation at the Palma Mesa field in central Chaves County.

San Juan Basin: No strata of Ordovician age are known to be present in the San Juan Basin.

Other areas: Although Ordovician strata are widespread throughout south-central and southwestern New Mexico, no analyses of natural gases from these reservoirs are available. No oil or gas has been produced from Fusselman reservoirs in these areas.

Table 17. Concentration of helium in natural gases recovered from Ordovician strata in the Permian Basin of southeastern New Mexico, subdivided by stratigraphic unit. Concentrations are in mole percent of gas. Tr equals trace percentage.

Stratigraphic Unit	Average He content	Minimum He content	Maximum He content (gas or oil pool)	Number of samples
Ordovician (total section)	0.12	0.09	0.233 (Palma Mesa)	5
Ellenburger	0.126	0.07	0.233	3
Montoya	0.13			1
Simpson	0.09			1

Cambrian System

No gas analyses are available for gases that may be present in Cambrian strata. There has been no oil or gas produced from Cambrian strata in New Mexico.

Precambrian Systems

Only one gas analysis is available for gases recovered from Precambrian rocks. Gas recovered from a Precambrian diorite at a depth of 13,890 ft in the Burlington No. 2 Marcotte well, located in T31N R10W contained 0.11 percent helium, 82.18 percent carbon dioxide, and 15.61 percent hydrocarbons.

Helium Potential and Possibilities

San Juan Basin

Helium has been produced, separated from well gas, and marketed or otherwise used at eight gas and oil pools in the San Juan Basin (Table 3). Reservoirs with significant concentrations of helium are Devonian, Mississippian, Pennsylvanian, Permian, and Triassic in age (Table 4; Figures 6, 8, 10, 12). Gas has been produced for its helium content from reservoirs of Devonian, Mississippian, Pennsylvanian, and Permian age.

Strata of interest for helium exploration are Devonian through Triassic in age. Highest known concentrations of helium have been encountered in wells drilled on the Four Corners Platform (Figures 2, 3). All commercial production to date has been from this tectonic uplift. Productive accumulations are located along or near major faults that penetrate Precambrian basement and overlying Paleozoic strata. In general, commercial accumulations appear to be located near the intersections of major faults.

Known oil and gas accumulations on the Four Corners Platform have been found on relatively small structures, many of which are mappable at the surface. Casey (1983) concluded that helium on the Four Corners Platform was generated by radiogenic decay in basement rocks and possibly also by degassing of rising magmas that formed the numerous Tertiary dikes in the region. The large fractures that penetrate basement would have acted as conduits for migration of helium from the Precambrian source into Paleozoic reservoirs.

The Four Corners Platform has been sparsely drilled outside of productive oil and gas fields. Yet, elevated levels of helium appear to be widespread across this feature, especially in Devonian and Mississippian reservoirs (Figures 8, 10, 12). Potential for additional resources is high in this area. Favorable targets include Cambrian sandstones, Devonian sandstones and carbonates, Mississippian carbonates, Pennsylvanian carbonates, and Permian sandstones and conglomerates. Stevenson and Baars (1977) indicated that reservoir development in Cambrian and Devonian strata is related to position on paleostructure with thickened sections of Cambrian sandstones preserved in grabens and the best Devonian sandstone reservoirs developed on the flanks of paleostructures. Inasmuch as productive Pennsylvanian reservoirs in the Four Corners region are mostly algal mounds (Chidsey et al., 1996), it is also likely that the distribution of Pennsylvanian reservoirs will also be largely controlled by paleostructures with the best algal mounds developed on the tops or flanks of the structures. Because reservoir distribution is influenced by structural trends, major fault trends on the Four Corners Platform may not only have acted as migration pathways for helium generated in basement rocks but may have also controlled reservoir distribution in Paleozoic strata.

Few wells have been drilled to pre-Cretaceous strata in the deeper parts of the San Juan Basin that lie to the east of the Four Corners Platform. No production has been established in the pre-Jurassic section in this part of the basin. Known, discovered, productive reservoirs in the Jurassic have been limited to the southern flank of the basin. Cretaceous reservoirs are prolifically productive of gas and some oil across much of the basin. Because of the sparse drilling and lack of production in the pre-Jurassic section, few gas analyses are available from reservoirs in these older strata. The available analyses indicate elevated levels of helium are present in Mississippian and Pennsylvanian reservoirs in this region with helium concentrations in excess of 0.4 percent. The network of orthogonal faults that offset Precambrian basement throughout the deeper parts of the San Juan Basin (Figure 3; Taylor and Huffman, 1998) may have acted as migration pathways that carried helium from its basement source into overlying Paleozoic strata, with the highest concentrations in the lowermost Paleozoic reservoirs. Basal Devonian sandstones may act as reservoirs for helium generated in Precambrian granitic rocks that directly underlie the Devonian. Presumably, controls on helium distribution in the Paleozoic section are similar to the controls on the Four Corners Platform.

Gases in Cretaceous and Tertiary reservoirs are characterized by low helium concentrations in the San Juan Basin (Figure 5; Table 5). In general, helium concentrations are significantly lower than 0.1 percent. Helium concentrations in excess of 0.1 percent are located mostly along a northwest-southeast trend in the south-central part of the basin. The low helium concentrations across the basin indicate that Cretaceous and Tertiary strata are not of major interest in helium exploration

Permian Basin

There has been no commercial production of helium in the New Mexico part of the Permian Basin. In general helium concentrations in Permian Basin gases are less than 0.1 percent, rendering most reservoirs of little interest for helium. However, helium increases to the north and northwest in Silurian, Pennsylvanian, and Permian reservoirs

(Figures 7, 9, 13). Reservoirs in these stratigraphic units are of most interest along the northern and northwestern fringes of the basin where helium concentrations are higher.

The highest known concentrations of helium in Silurian strata are in the Bagley oil pool (Figure 13), which is productive from strata of the Wristen Group. At Bagley, helium is 0.29 percent of the reservoir gas. In the area around Bagley, the Silurian stratigraphic section and the underlying Ordovician stratigraphic section thin to the north and northwest. The thinner sections result in a shorter vertical migration distance between helium-generative Precambrian basement and Wristen reservoirs and there are fewer sub-Wristen zones that helium could migrate into along its journey from basement sources. The Bagley structure is formed by a high-angle fault along its east side. Perhaps this fault acted as a migration path for helium. If this is the case, then similar structures that form traps in Wristen reservoirs on the Northwest Shelf of the Permian Basin may also contain gases with enhanced helium concentrations.

Gases in Pennsylvanian reservoirs exhibit similar trends of helium concentration as gases in Silurian reservoirs (Figures 9, 13). In general, helium concentrations are low and of little interest to explorationists in the Delaware Basin and the southern part of the Northwest Shelf. To the north, however, concentrations exceed 0.3 percent and may be of interest. Areas of enhanced helium concentrations appear to coincide with basement-involved, high-angle faults that may have acted as migration pathways for helium generated in basement rocks. In addition, the lower and middle Paleozoic sections are thin or absent, resulting in decreased vertical migration distances for the helium as well as fewer reservoirs into which the helium would dissipate as it moved upward through vertical faults. Areas of most exploratory interest lie along major faults or fault trends and are near or north of the zero isopach lines of Silurian and Mississippian strata (see Figures 11, 13).

Permian reservoirs contain gases with the highest known helium concentrations in the Permian Basin. The highest concentration of helium in Permian gases is 0.974 percent in the Pecos Slope Abo gas pool of Chaves County. High concentrations of helium appear to be related to proximity to the major high-angle strike-slip faults that cut across the region from southwest to northeast. These faults have been mapped and described by Kelley (1972) who referred to them as buckles. As discussed previously, these faults are thought to be migration pathways along which helium generated in the Precambrian moved into the Abo reservoirs (Kennedy et al., 2002). In the area of the Pecos Slope and Pecos Slope West pools, bedded anhydrites in the lowermost Yeso Formation, which directly overlies the Abo Formation, have sealed the faults and blocked further upward movement of both helium and hydrocarbon gases. As a result, the helium is trapped within low-permeability sandstones of the Abo Formation. A major area of exploratory interest lies along a southwest-northeast trending band broadly defined by the Y-O, Six-Mile, Border, and Serrano buckles and the southwestern and northeastern extensions of those buckles in the subsurface (Figure 3).

Permian strata in the Permian Basin hold some interest for exploring for ^3He that is produced from ^3H by beta emission decay. Many of these strata were deposited in evaporitic settings and contain interbedded shales, evaporites, sandstones, and dolostones. The shales, deposited in evaporitic settings and therefore possibly rich in lithium, favor local generation of ^3He. The evaporites and shales will seal the generated helium within sandstone and dolostone reservoirs.

Other areas

Wells with analyses of helium contents in natural gases are sparsely distributed in areas outside of the San Juan and Permian Basins. In spite of the sparse data distribution, the contour maps of helium content (Figures 5-9) indicate there are several areas with elevated levels of helium in natural gases. These areas are the Chupadera Mesa region of central New Mexico, the Tucumcari Basin of east-central New Mexico, and a part of west-central New Mexico extending over Catron and southern Cibola Counties. Although other frontier areas may be geologically favorable to helium accumulation, these three are emphasized because analyses of gases have demonstrated enhanced helium concentrations. Specific aspects of geology related to helium in each of these three areas are discussed below.

Chupadera Mesa region: Exploratory wells recently drilled on Chupadera Mesa in eastern Socorro and western Lincoln Counties have recovered gases from Atokan (Lower Pennsylvanian) and Abo (Lower Permian) sandstones that have helium contents of more than 2 percent (Figures 6, 9). Other gas constituents in the recovered samples include nitrogen and carbon dioxide, which vary in percentages from reservoir to reservoir and well to well (see database ***NMgases.xls***). Pennsylvanian and Permian shales are seals for the sandstone reservoirs. The Yeso Formation (Lower Permian), which directly overlies the Abo, contains bedded salts that further seal the gas system against vertical migration (Broadhead and Jones, 2004). In the part of Chupadera Mesa where helium is known to exist, Lower Pennsylvanian strata rest unconformably on Precambrian basement. The Pennsylvanian section is approximately 300 ft thick and consists of fine- to medium-grained sandstones and black to dark-gray shales overlain unconformably by fine-grained red sandstones and red shales of the Abo Formation. Middle and Upper Pennsylvanian strata have been removed by erosion. Five miles to the east of the wells with helium shows Pennsylvanian strata are absent. Where the Pennsylvanian is absent, Abo sandstones and shales rest unconformably on Precambrian basement.

Sources of helium undoubtedly include granitic rocks in the Precambrian basement. Several high-angle faults penetrate basement as well as Pennsylvanian and Lower Permian strata in this region and may act as migration conduits for helium (Figure 3; Broadhead and Jones, 2004). Significant heating as a result of Tertiary igneous activity may have facilitated release of helium from the basement granites. Tertiary igneous activity may also have introduced helium into reservoirs as gases devolved from rising magmas.

Uranium mineralization in the Pennsylvanian and Abo sections, as well as in the Precambrian, may have also contributed to helium generation. The Primero Operating No. 1 Dulce Draw State well, located in T4S R9E, penetrated sedimentary rocks with abnormally high radioactivity in the lower part of the Abo Formation, in the Pennsylvanian, and in the Precambrian, with gamma ray readings up to 2000 API units. The spectral gamma ray log indicates that the high levels of radioactivity are caused mostly by uranium. Although mineralogical and elemental analyses have not been performed on well cuttings, the high levels or uranium-based radioactivity suggest that the Precambrian, Pennsylvanian and Lower Abo have been mineralized. The mineralized rock may provide an additional source of helium, in addition to the Precambrian basement.

In summary, the Chupadera Mesa area holds considerable interest for helium exploration. Multiple sources of radiogenic helium may have resulted in the enhanced levels of helium measured in well gases. Major high-angle faults are migration pathways for helium generated in the Precambrian basement. Extensive Tertiary igneous activity in the region has provided a regional heating event (Broadhead and Jones, 2004; Broadhead, 2004), facilitating release of helium from basement rocks and also possibly introduced mantle helium into reservoirs. Pennsylvanian and Lower Permian shales as well as Lower Permian salts have acted to seal gases in the system. Pennsylvanian and Lower Permian sandstones are reservoirs. Exploratory interest extends north and south of present known high-helium well gases along areas parallel to the north-south high-angle faults that cut through this region.

Tucumcari Basin: Elevated levels of helium have been found in gases recovered from Pennsylvanian sandstones in the Tucumcari Basin of east-central New Mexico. The Tucumcari Basin contains four deep sub-basins (elevator basins): the Cuervo, Quay, Trementina, and Trigg Ranch sub-basins (Figure 14). Helium contents in excess of 1.3 percent are known from the Cuervo elevator sub-basin. Helium concentrations of 0.18 to 0.19 percent are known in the adjacent Quay elevator sub-basin. Other fluids in the reservoirs are methane, natural gas liquids, and nitrogen as well as water. The four elevator sub-basins in the Tucumcari Basin are bounded by high angle faults that separate them from adjacent uplifts and shelf areas (Broadhead and King, 1988; Broadhead, 2001b; Broadhead et al., 2002). The faults were active primarily during the Pennsylvanian and Early Permian and extend from Precambrian basement upward into Lower Permian strata. Some faults were reactivated during Laramide and Tertiary tectonism and exhibit offset of strata upward to the ground surface. Pennsylvanian strata, which are dominantly black shales and interbedded fine- to coarse-grained conglomeratic sandstones, rest unconformably on Precambrian basement or are separated from Precambrian basement by erosional remnants of Mississippian limestones and sandstones; the Mississippian has maximum thickness of 300 ft but is mostly 0 to 200 ft thick. Precambrian basement consists primarily of granites and gabbros. In some places, a sequence of Precambrian metasediments and volcanic rocks up to several thousand feet thick are present on top of the granites and gabbros.

The geologic models of helium occurrence discussed earlier in this report explain the elevated helium levels in the sub-basins. Helium generated radiogenically in basement rocks migrated vertically upward through the large faults that bound the sub-basins. The helium gas then entered the Pennsylvanian sandstones. Thick shale sections in the Pennsylvanian and Lower Permian have acted to vertically seal the faults in most places. As a result, significant volumes of helium are trapped in the Pennsylvanian sandstones along with hydrocarbons generated within the Pennsylvanian shales. The elevator sub-basins therefore hold interest for helium exploration. This applies to the two sub-basins that have no gas analyses, the Trementina and the Trigg Ranch sub-basins as well as the Cuervo and Quay sub-basins.

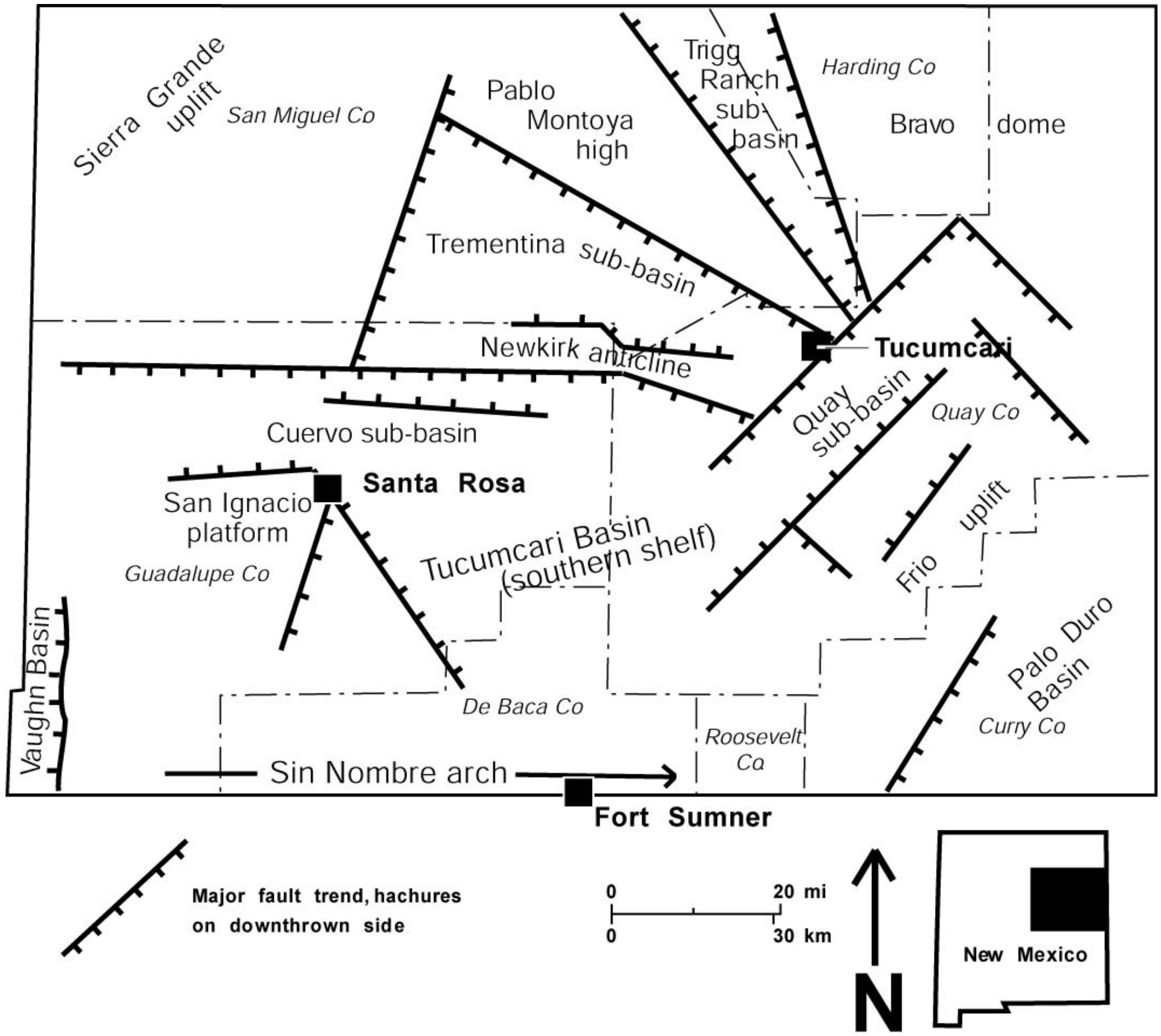

Figure 14. The Tucumcari Basin and its component tectonic elements, including the Cuervo, Quay, Trementina, and Trigg Ranch elevator sub-basins.

The Bravo Dome lies to the north of the Tucumcari Basin. On the Bravo Dome, Lower Permian sandstones rest unconformably on Precambrian basement. The Precambrian is composed mostly of granite on the Bravo Dome although substantial volumes of mafic laccoliths, sills, and dikes are also present. The basal Permian sandstones are reservoirs for one of the world's largest known accumulations of carbon dioxide gas in a structural-stratigraphic trap (Broadhead 1990, 1993). Original gas in place exceeded 10 trillion ft^3 (TCF). The carbon dioxide originated in the mantle and was emplaced during the Tertiary through degassing of basaltic magmas as they rose to the surface (Staudacher, 1997; Broadhead, 1998). The Cimarron anhydrite (Permian: Leonardian) rests on top of the sandstone reservoir and provides a regional seal. Numerous high-angle faults cut through basement and Lower Permian strata. Helium concentrations in the Permian reservoirs on the Bravo Dome are low and attain maximum levels of 0.02 percent. One gas sample obtained from a sandstone in the Chinle Formation (Triassic) had a helium content of 1.8 percent.

The faults within the Bravo Dome, the superposition of the reservoir on a largely granitic basement, and the presence of a widespread anhydrite seal suggest that the Bravo Dome should contain a significant helium accumulation. Yet helium concentrations are low. Perhaps the large volume of CO_2 emplaced during volcanism diluted helium to very low concentrations. Alternatively the Cimarron anhydrite and plastic red shales in the Triassic may have sealed the CO_2 in the basal Permian sandstones but have allowed the smaller helium molecules to leak upward through high-angle faults that cut across the Bravo Dome.

Catron and southern Cibola Counties, west-central New Mexico: Elevated levels of helium have been detected in gases in west-central New Mexico. In the San Andres Formation (Middle Permian), elevated levels of helium have been found in water wells near Laguna (Figure 6). In Lower Permian strata equivalent to the Yeso Formation, elevated levels of helium were found in a carbon dioxide exploration well drilled in western Catron County near the New Mexico-Arizona border (Figure 6). In Pennsylvanian strata, elevated levels of helium have been found in a petroleum exploration well drilled in eastern Cibola County near Acoma (Figure 8). Significantly, no gas analyses in this region have encountered helium concentrations less than 0.1 percent. The few analyses available indicate that elevated levels of helium are pervasive in gases of this region.

Significant concentrations of helium in well gases have been encountered in the Holbrook Basin of Arizona, which lies west of Catron County (Rauzi and Fellows, 2003; Rauzi, 2003). In the Holbrook Basin, the helium content of gases ranges from 0.3 to 8 percent. Helium-rich gases are known to be trapped in Lower Permian reservoirs on anticlines within the basin. Widespread salt beds in strata equivalent to the Yeso Formation (Lower Permian) are favorable to retention of helium. The Holbrook Basin extends into westernmost Catron County. Several carbon dioxide exploratory wells have been drilled in recent years in the Catron County part of the basin and have encountered carbon dioxide gas. A single available analysis of gas recovered from one of the New Mexico wells indicates a helium content of 0.2 percent, which is within the general range of helium contents present within the Arizona part of the basin.

Quaternary and Tertiary basalts and other volcanic rocks are widespread in the region. The natural gases tend to contain high levels of carbon dioxide that is probably derived from the degassing of magmas during ascent through the crust.

The isotopic composition of helium in Catron and Cibola County gases is unknown. Therefore it is not possible to directly determine whether the helium was derived from the mantle or from radiogenic decay of granitic basement rocks. The fractured and faulted nature of the region, the presence of abundant volcanic rocks, and the presence of granitic rocks in Precambrian basement suggest that both helium origins are possible. Structures in the region are largely extensional (Crews, 1994; Houser, 1994). This structural regime is similar to those where helium has migrated from the mantle to the crust via extensional faults (Jian-Guo and others, 1998; Lollar et al., 1994; Sheng et al., 1995; Yongchang et al., 1997). Increased heat flow resulting from Tertiary and Quaternary volcanism in the region would have contributed to the liberation of helium from granitic basement rocks where it was generated by radiogenic decay of uranium and thorium.

New Mexico State Trust Lands

New Mexico has 13 million acres of State Trust Lands that are distributed throughout the state. The Trust Lands are administered by the New Mexico State Land Office and a large percentage is available for oil and natural gas leasing. The distribution of the State Trust Lands is shown as a separate layer on the *ArcMap and ArcReader* GIS projects that accompany this report.

Summary

Helium is a common constituent of natural gases. In natural gases, it is present in concentrations ranging from a trace to approximately 10 percent. In general, gases with helium contents of more than 0.3 percent may hold economic interest for their helium content. Natural gases have been produced for their helium content in New Mexico since 1943. All commercial helium production to date has been from eight oil and gas pools on the Four Corners Platform in San Juan County. Productive reservoirs range in age from Devonian to Permian. An estimated 948 MMCF helium gas has been produced from the eight oil and gas pools. Helium concentration in these reservoirs ranges from 3.2 to 7.5 percent.

Helium found in reservoir gases has two main origins. The mode of origin determines the isotopic composition of the helium. ^{4}He is produced mainly by radiogenic decay of uranium and thorium that is present in granitic basement rocks or in strata-bound ore bodies. ^{3}He originates mainly in the mantle and migrates into crustal reservoirs either through deep-seated faults or by devolatilization of rising magmas. Perhaps more rarely, ^{3}He may be derived from ^{3}H by neutron capture in crustal reservoirs with lithium-rich sediments, chiefly in clay-rich evaporitic sediments. Helium that is generated in granitic basement rocks or originates in the mantle migrates into the crust through faults and other fractures that connect reservoirs to the helium source. Alternatively, helium generated in basement rocks that underlie regional basal Paleozoic sandstones may migrate directly into the sandstones and then move updip through the sandstone until it is either trapped or dissipated. In either case, helium is trapped in porous reservoirs in a manner similar to other natural gases.

Helium has been produced commercially from Permian, Pennsylvanian, Mississippian, and Devonian reservoirs on the Four Corners Platform on the western flank of the San Juan Basin. Productive accumulations are located over high-angle faults that offset Precambrian basement. Presumably these faults acted as migration pathways for helium generated in Precambrian basement. The faults also act to form structural traps and may have even influenced depositional location of reservoirs, especially the location of Pennsylvanian phylloid algal mounds. Although no helium production has been established in the deep part of the San Juan Basin east of the Four Corners Platform, sparsely distributed gas analyses indicate gases with elevated concentrations of helium are present in this region. The regional set of orthogonal faults that offset Precambrian basement throughout the deeper parts of the San Juan Basin may have acted as migration pathways that carried helium from its basement source into overlying Paleozoic reservoirs. Cretaceous strata, although prolifically productive of hydrocarbon gases within the San Juan Basin, contain only low concentrations of helium and are of little exploratory interest.

Helium has not been extracted from produced gases in the New Mexico part of the Permian Basin. Concentrations of helium in reservoir gases are significantly less than 0.1 percent throughout most of the basin. However, gases with helium contents ranging from 0.3 to almost 1.0 percent have been produced from Pennsylvanian and Permian reservoirs along the northwest flank of the basin. The helium originated by radiogenic decay in granitic Precambrian rocks and migrated vertically into the Pennsylvanian and Permian reservoirs through regional high-angle faults. These faults trend northeast-southwest and have a strike-slip component to their displacement. Known concentrations of helium-rich gas are located near or along these faults. In the area characterized by helium-rich gases in Pennsylvanian and Permian reservoirs, lower and middle Paleozoic strata are only a few hundred feet thick, resulting in decreased vertical migration distances between the Precambrian and the helium-bearing reservoirs. Furthermore, the faults are vertically sealed within Lower Permian reservoirs by evaporites.

Other basins and areas in New Mexico are characterized by helium-rich gases and are of significant exploratory interest. These areas include the Chupadera Mesa region of eastern Socorro and western Lincoln Counties in the central part of the state, the Tucumcari Basin in the east-central part of the state, and a wide region across Catron and southern Cibola Counties in the west-central part of the state. Elevated levels of helium are found in Pennsylvanian and Permian gases in these areas.

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