Helium in New Mexico—geologic distribution, resource demand, 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 (million cubic feet) helium has 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 orthogonal sets of high-angle faults that offset Precambrian basement throughout the deeper parts of the San Juan Basin 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%. However, gases with helium contents ranging from 0.3 to almost 1.0% occur in Pennsylvanian and Permian reservoirs along the northwest flank of the basin. The helium appears to have 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. Lower Permian evaporites provide vertical fault seals. 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. The fault trends define exploration fairways.

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 be present in trace amounts in all natural gases (Tongish 1980). More than one-half of all natural gases contain less than 0.1 mole% helium (Tongish 1980). Only 17.6% of all natural gases in the United States contain more than 0.3 mole% helium. A very few reservoirs have gases with more than 7% helium. In general, gases with helium contents of more than 0.3% are considered to be of commercial interest as helium sources. Most of the helium produced in the United States is obtained from reservoirs with less than 1.5% helium in their gases. Six natural gas reservoirs contain an estimated 97% of all identified helium reserves in the United States (Table 1; Pacheco 2002). Several of the reservoirs listed in Table 1 also have been produced for their hydrocarbons, which constitute the largest component of the reservoir gas and drive the economics of production. Total gas production, and therefore helium production, from these reservoirs is in decline.

In New Mexico, known (that is, discovered) reservoirs with more than 7% helium are confined to the Four Corners platform in the extreme northwest part of the state (Figs. 1, 2; Table 2). The content of hydrocarbon gases in most of these reservoirs is less than 20%; most of the non-helium fraction of the reservoir gas is nitrogen. Production from these reservoirs is driven by helium economics and not by hydrocarbon economics.

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 (blimps), 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° F are required (Pacheco 2005).

Sales of Grade A refined helium have increased in recent years (Pacheco 2002, 2005). Total helium sales in the United States increased from 112 million m^3 during 1998 to 121 million m^3 during 2004, an increase of 8%. As sales have increased, domestic production has fallen by 24% from 112 million m^3 during 1998 to 85 million m^3 during 2004 (Peterson 2001; Pacheco 2005). The shortfall in production in recent years has been filled by withdrawing helium from storage. The United States does not import helium but instead exports it as a major worldwide supplier; in 2004 the United States provided 85% of the world's helium production (see Pacheco 2005). 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 from \$60 to \$65 per thousand ft^3 in 2003 (Pacheco 2005), 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 (Figs. 1, 2; Table 2). 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% to 7.5% (Table 2). 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

TABLE 1—The six natural gas reservoirs that contain 97% of identified helium reserves in the United States. Data from Pacheco (2002), Parham and Campbell (1993), and U.S. Bureau of Mines data.

Reservoir	State	Helium content of gas mole percent
Hugoton	Kansas, Oklahoma, Texas	0.2–1.18
Panoma	Kansas	0.4–0.6
Keyes	Oklahoma	1.0–2.7
Panhandle West	Texas	0.15–2.1
Riley Ridge area	Wyoming	0.5–1.3
Cliffside	Texas	Currently He-storage reservoir

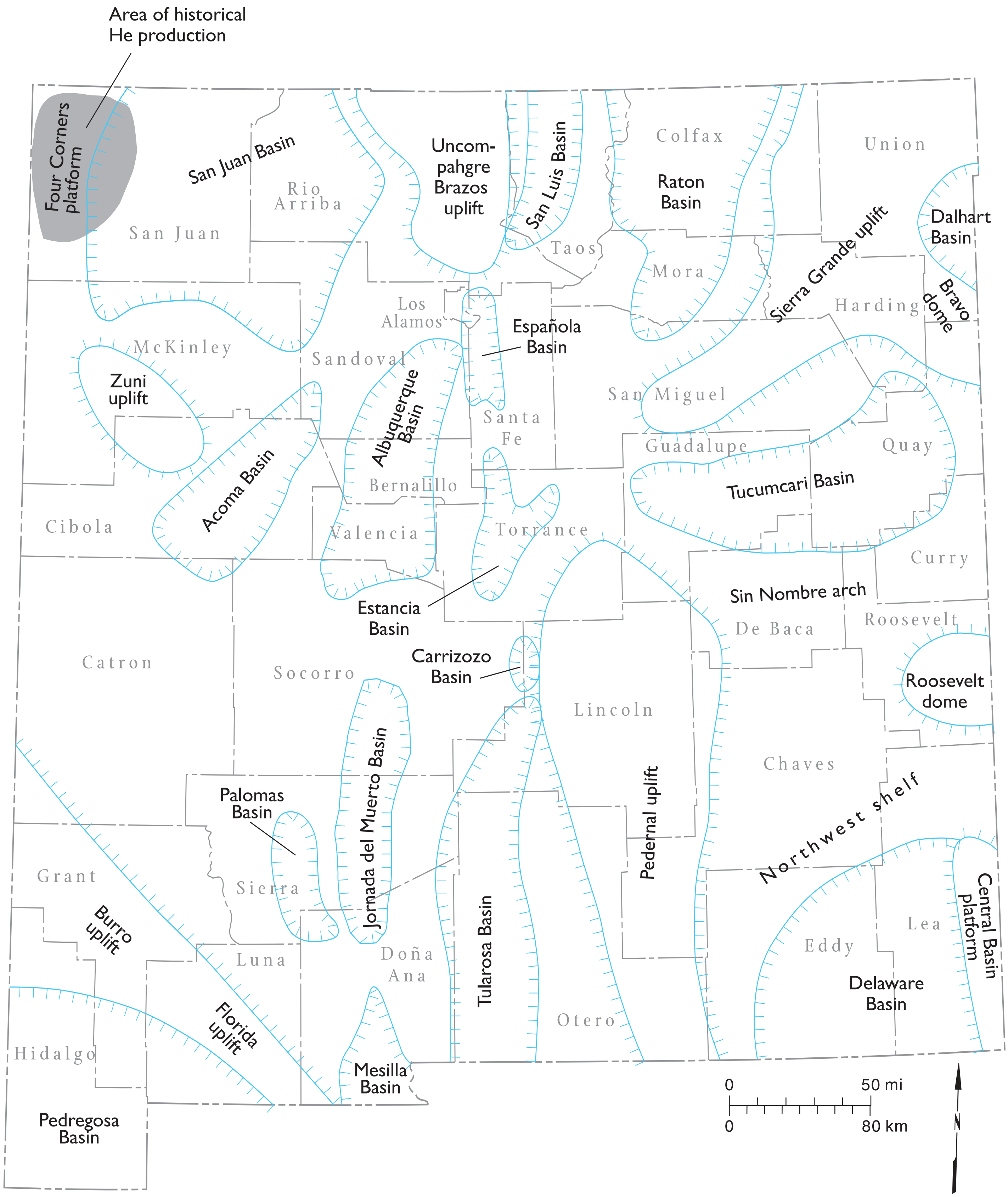

FIGURE 1—Principal basins and uplifts in New Mexico and area of historical helium production (shaded).

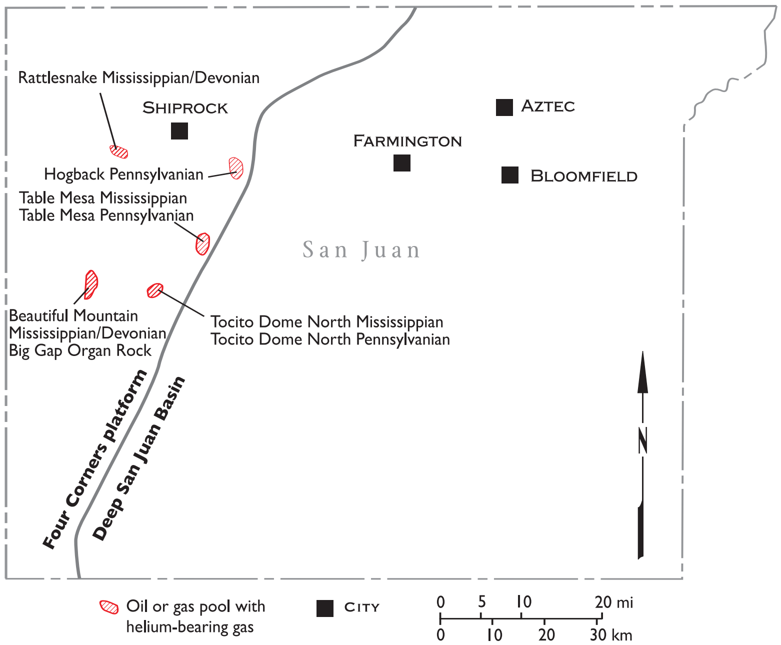

FIGURE 2—Outline of San Juan County, eastern edge of the Four Corners platform, and oil and gas reservoirs that have been produced for their helium gas.

(Fig. 2). The helium produced from Rattlesnake was transported in a pipeline to a separation plant near Shiprock, which was operated by the U.S. Bureau of Mines. As the demand for helium increased with time and as production from existing, discovered reservoirs declined, exploration increased, and several additional helium-bearing gas reservoirs were discovered, developed, and produced (Table 2). Production of helium in San Juan County ceased around 1990.

In 2001 production resumed from the Beautiful Mountain Mississippian and Big Gap Organ Rock (Permian) reservoirs. New wells were drilled in the latter reservoir. The gas is produced from wells operated by Mountain States Petroleum Corp. The produced gas is processed at the Red Valley plant, which is owned by Newpoint Gas Services and is located just south of Shiprock.

Geology of helium in crustal reservoirs—an overview

Origin and migration of helium

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 may be 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 ^{4}He. ^{4}He may also be derived from radiogenic decay of uranium and thorium in orebodies (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 in which the helium is produced; 2) thermal release of ^{4}He from the crustal rocks in which it is produced; 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 serve 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 ground

TABLE 2—Oil and gas reservoirs 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 reservoirs. Geologic and helium-content data from Baars (1983), Brown (1978), Hinson (1947), Hoppe (1983), and Maynard (1978), Riggs (1978), and Spencer (1978).

Field (discovery year)	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 (1975)	Mississippian, Devonian	Leadville Limestone, Ouray Formation	T27N R19W	7.14	169,568	2,455,230	175,303
Big Gap (1979)	Permian	Organ Rock member of Cutler Formation	T27N R19W	5.5	212,663	3,260,416	179,323
Hogback (1952)	Pennsylvanian	Paradox Formation	T29N R16W	7.17	0	666,714	47,803
Tocito Dome North (1963)	Mississippian	Leadville Limestone	T27N R18W	7.19	0	1,104,668	79,426
Tocito Dome North (1967)	Pennsylvanian	Paradox Formation	T27N R18W	3.26	0	532,856	17,371
Table Mesa (1951)	Mississippian	Leadville Limestone	T27N R17W	5.7	0	1,193,006	68,001
Table Mesa (1951)	Pennsylvanian	Paradox Formation	T27N R17W	5.37	0	7,100,076	381,274
Rattlesnake (1943)	Mississippian, Devonian	Leadville Limestone, Ouray Formation	T29N R19W	7.5	0	2,000	150
TOTALS					**382,231**	**16,314,966**	**948,652**

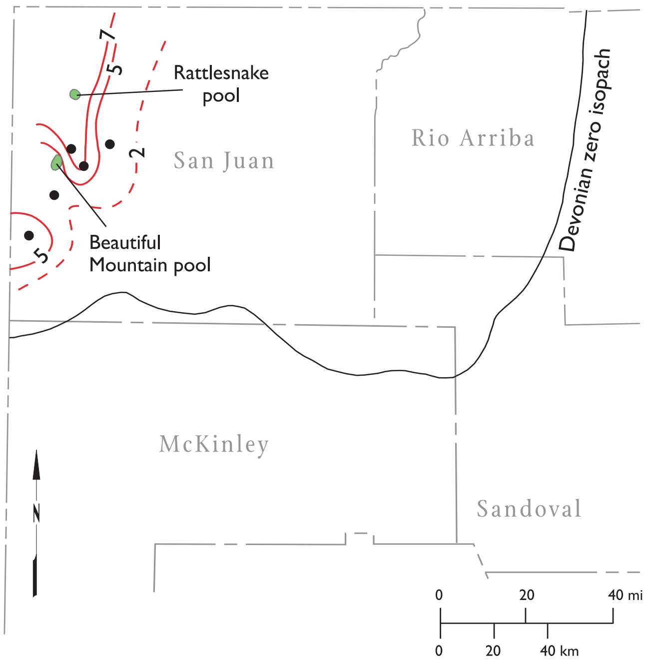

FIGURE 3—Contours of mole percent helium in gases recovered from Devonian reservoirs in northwestern New Mexico. Black dots are wells outside of reservoir (oil or gas pool) boundaries with helium gas analyses.

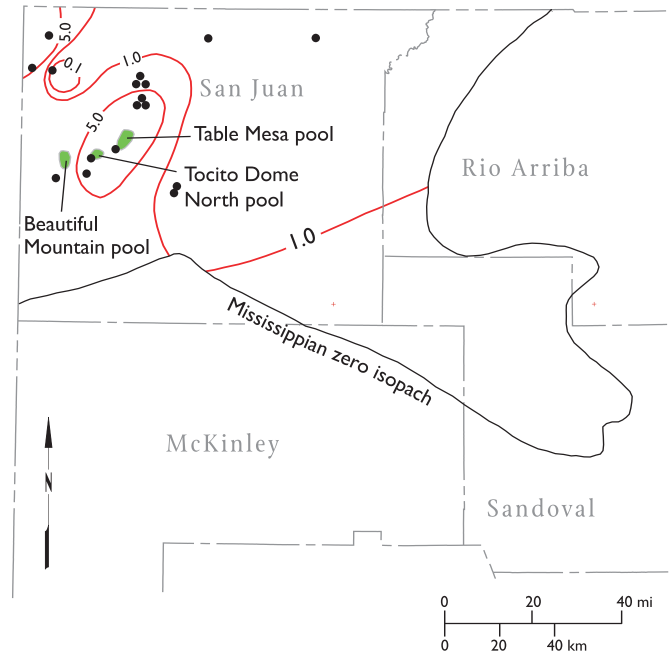

FIGURE 4—Contours of mole percent helium in gases recovered from Mississippian reservoirs in northwestern New Mexico. Black dots are wells outside of reservoir (oil or gas pool) boundaries with helium gas analyses.

water, 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. 1994a; Selley 1998). Regional thermal activity, or heating of basement rocks, is also thought to 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 orebodies (DeVoto et al. 1980; Hunt 1996; Pogorski and Quirt 1980; Selley 1998). Alternatively, helium generated in basement rocks that underlie and are in physical contact with basal Paleozoic sandstones may migrate directly into the sandstones and then updip within the basal sandstones until it is either trapped or dissipated (see Ballentine and Lollar 2002).

^{3}He is mostly primordial and 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 et al. 1998; Lollar et al. 1994b; Sheng et al. 1995; Yongchang et al. 1997); apparently this mechanism has been effective in concentrating helium only in post-Cretaceous tectonic regimes.

^{3}He is also derived from neutron capture reactions involving ^{3}H. Hiyagon and Kennedy (1992) concluded that gases with elevated concentrations of ^{3}He relative to ^{4}He might be attained in sedimentary carbonates, anhydrites, and clays with lithium concentrations in excess of 1,000 ppm. Magnesium-rich clays deposited in evaporitic settings are enriched in lithium and may contain as much as 6,200 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.

TABLE 3—Helium content of natural gases in New Mexico subdivided by geologic system and basin or geographic area. Tr = trace.

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–0.2%	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–3.5%
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 not 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

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 CH_4 (Hunt 1996). Because of the smaller size of helium molecules, some seals that contain CO_2, N_2, and CH_4 may leak helium. The smaller diameter of helium molecules may also 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

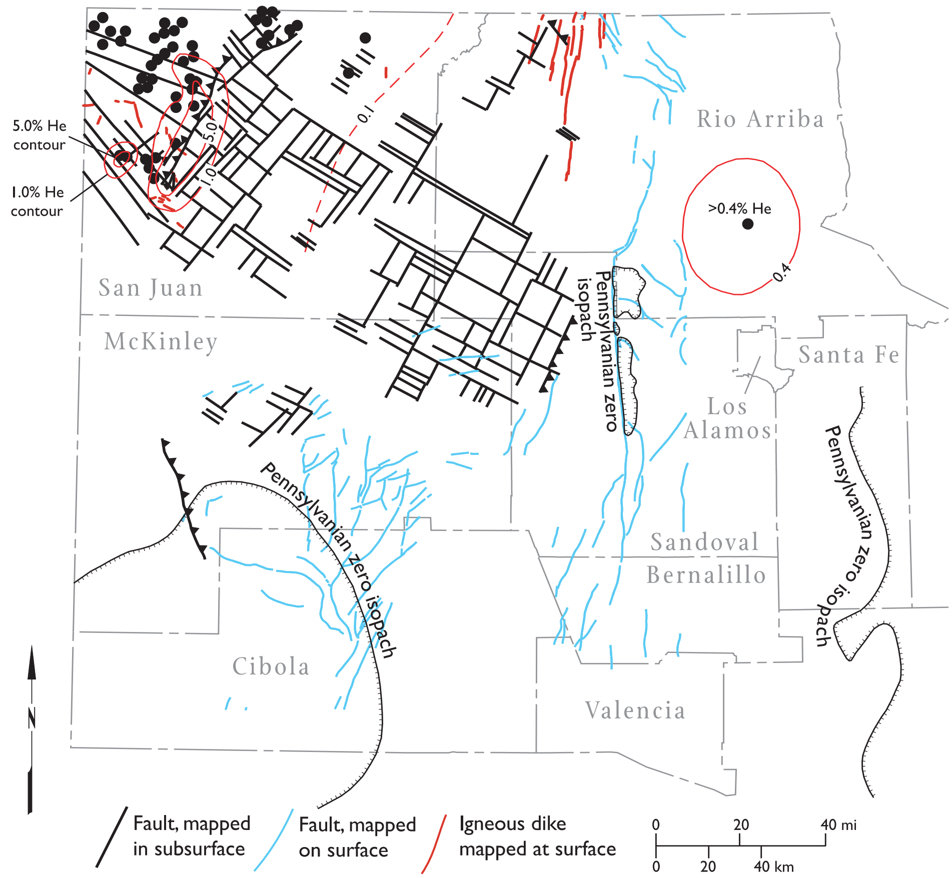

FIGURE 5—Contours of mole percent helium in gases recovered from Pennsylvanian reservoirs in northwestern New Mexico and major faults that offset Precambrian basement. Faults from Taylor and Huffman (1998), Stevenson and Baars (1977), Chapman, Wood, and Griswold, Inc. (1977), and New Mexico Bureau of Geology and Mineral Resources (2003). Black dots are wells outside of reservoir (oil or gas pool) boundaries with helium gas analyses.

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.

A summary of helium distribution in New Mexico

San Juan Basin

The San Juan Basin of northwestern New Mexico contains natural gases with the highest known concentrations of helium in New Mexico (Tables 2, 3). In the San Juan Basin, gases with concentrations of helium in excess of 5% are known from Devonian, Mississippian, Pennsylvanian, Permian, and Triassic reservoirs (Tables 2, 3; Figs. 3–5). Commercial production has been obtained from strata of Devonian through Permian age. Known concentrations of helium in excess of 1% are confined to the Four Corners platform. Gases with more than 0.4% helium are known from Pennsylvanian reservoirs in the sparsely drilled deep basin east of the Four Corners platform. Concentrations of helium in excess of 0.2% are known from Mississippian reservoirs in the deep basin east of the Four Corners platform (Fig. 4). The orthogonal sets of high-angle faults that offset Precambrian basement throughout the deeper parts of the San Juan Basin (see Taylor and Huffman 1998), as well as on the Four Corners platform (Stevenson and Baars 1977), acted as migration pathways that transported the helium from its basement source into overlying Paleozoic reservoirs (Broadhead and Gillard 2004). These faults moved episodically during the Paleozoic; this episodic movement during deposition of Paleozoic sediments acted to localize deposition of reservoirs in Devonian, Mississippian, and Pennsylvanian strata, most notably in Pennsylvanian phylloid algal mounds (see Stevenson and Baars 1977; Broadhead and Gillard 2004). The presence of regional fault sets and known, enhanced helium concentrations in gases in the deeper parts of the basin suggest significant potential for helium resources. Cretaceous strata, although prolifically productive of hydrocarbon gases within the San Juan Basin, mostly contain gases with helium concentrations less than 0.05% and are of little exploratory interest.

Permian Basin

Elevated concentrations of helium in gases recovered from reservoirs of Ordovician, Silurian, Pennsylvanian, and Permian age are known from the New Mexico part of the Permian Basin (Table 3; Figs. 6, 7). The highest known concentrations of helium are from reservoirs in the northern part of Chaves County. In this area, high helium concentrations are associated with regional, northeast-southwest trending strike-slip faults (termed “buckles” by Kelley 1971) that appear to have served as vertical migration pathways for helium that was generated within granitic rocks of the Precambrian basement. Widespread bedded anhydrites in the lower part of the Yeso Formation (Lower Permian) have acted as vertical fault seals. The stratigraphically highest known concentrations of helium are in fine-grained, fluvial-deltaic, red bed sandstones of the Abo Formation (Lower Permian) in the Pecos Slope and Pecos Slope West reservoirs of Chaves County (Fig. 7). In these reservoirs, helium content of gases ranges from 0.09% to 0.974% of the gas and averages 0.48%. Helium content

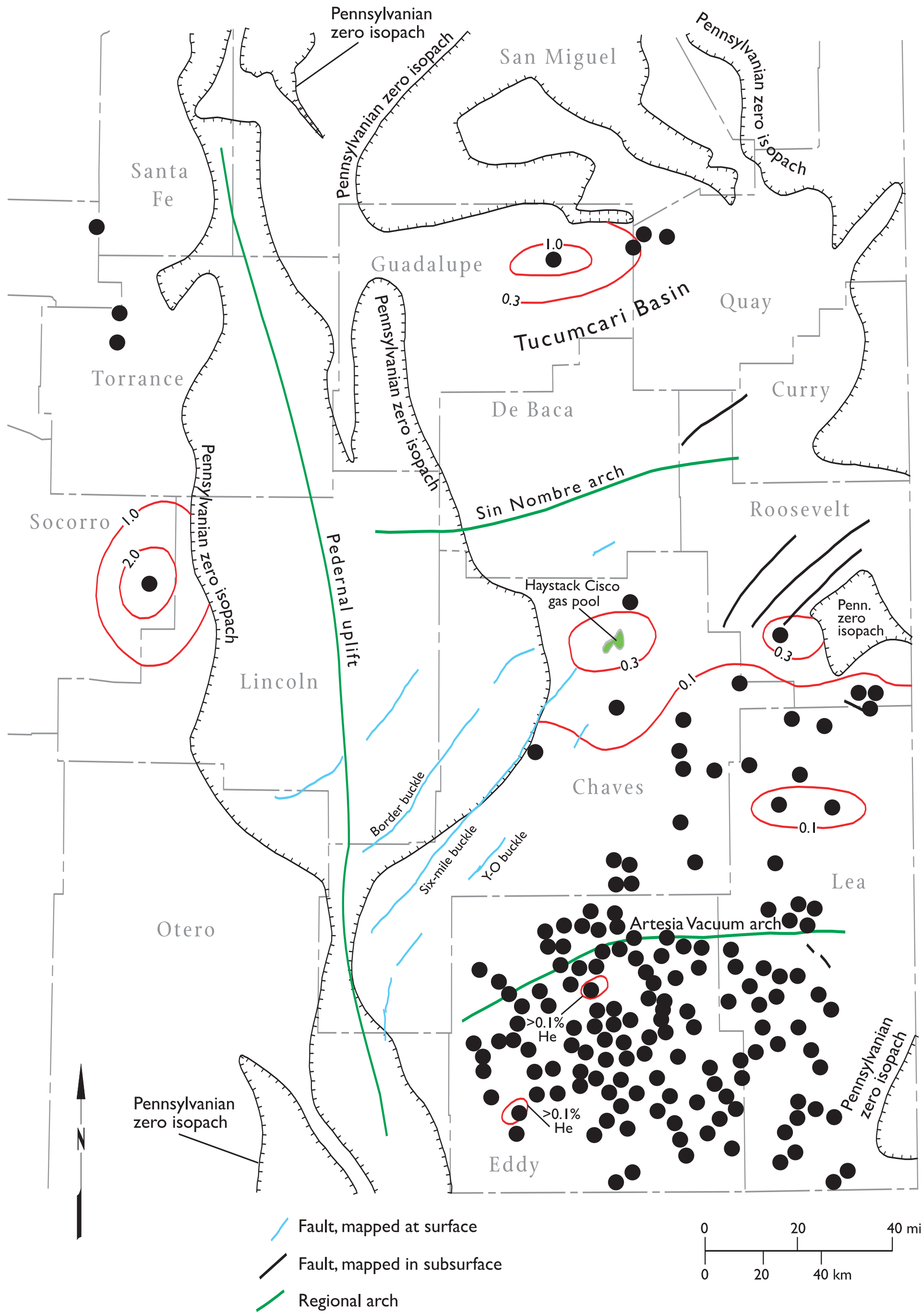

FIGURE 6—Contours of mole percent helium in gases recovered from Pennsylvanian reservoirs in southeastern, northeastern, and central New Mexico. Black dots are wells outside of reservoir (oil or gas pool) boundaries with helium gas analyses.

increases with proximity to the faults. Lower and middle Paleozoic strata have a maximum thickness of only a few hundred feet in the area characterized by elevated helium concentrations; the relative thinness of lower and middle Paleozoic strata in this area results in short vertical migration distances from the basement source to the reservoirs and fewer porous zones into which the helium may be dissipated as it migrates upward from the Precambrian.

Frontier basins

Several frontier areas outside of the San Juan and Permian Basins, although very sparsely drilled, contain substantially elevated levels of helium in gases recovered by exploratory wells (Table 3). Notable among these areas is the Chupadera Mesa area of eastern Socorro County (Broadhead and Jones 2004) where helium concentrations of greater than 3% are present in gases recovered from Abo (Lower Permian) sandstones (Fig. 8). Elevated levels of helium have also been found in gases associated with ground water in San Andres (middle Permian) carbonates in eastern Cibola County and in gases recovered from Lower Permian sandstones in western Catron County where reservoirs in adjacent parts of Arizona are characterized by helium-rich gases (Fig. 8; Rauzi 2003; Rauzi and Fellows 2003). In the Tucumcari Basin of Guadalupe and Quay Counties in east-central New Mexico, helium concentrations as high as 1.3% have been measured in hydrocarbon-rich gases recovered from Pennsylvanian sandstones in exploratory wells (Fig. 6). All of these occurrences are associated with the presence of major deep-seated high-angle faults. Many of the faults in all three areas

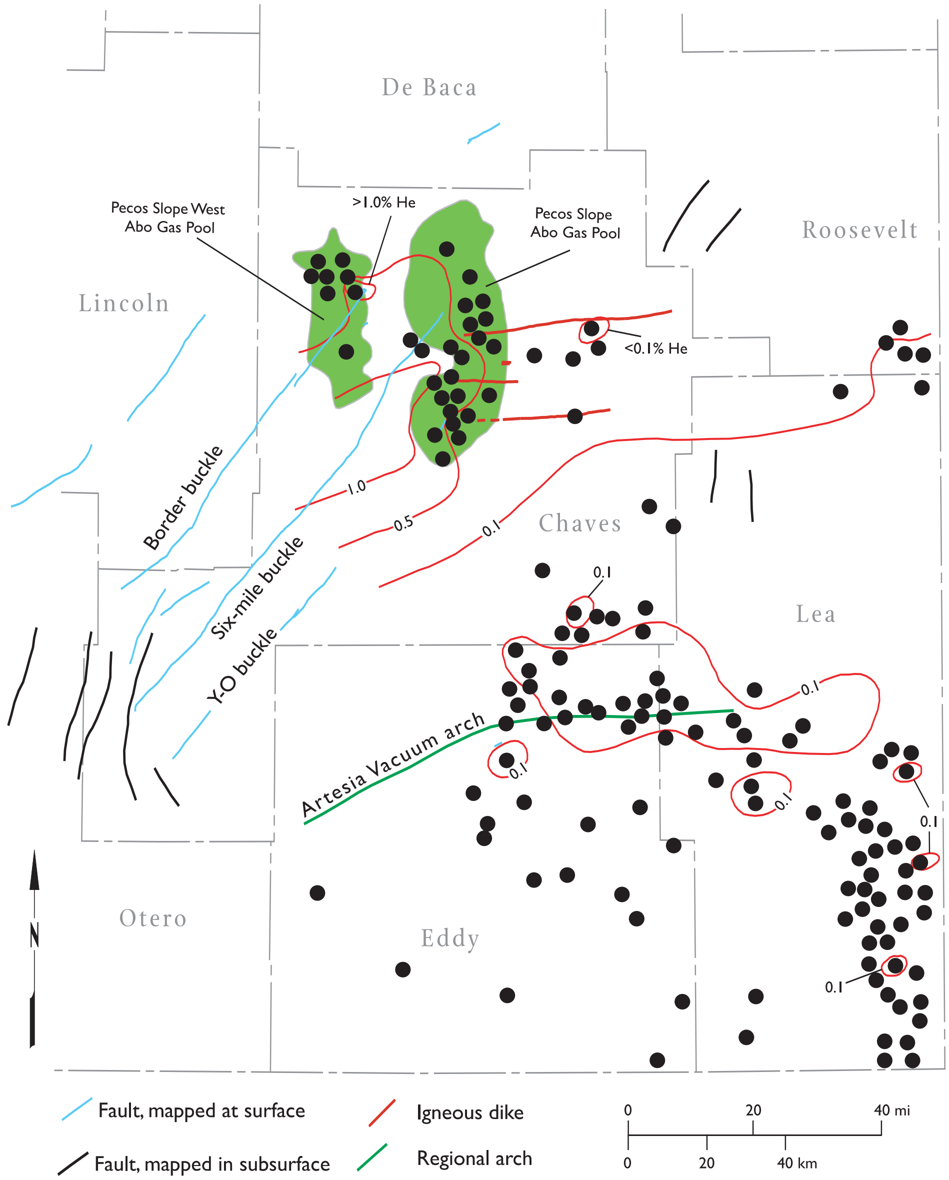

FIGURE 7—Contours of mole percent helium in gases recovered from Permian reservoirs in southeastern New Mexico. Black dots are wells outside of reservoir (oil or gas pool) boundaries with helium gas analyses.

were active during the Pennsylvanian and Early Permian and die out upward in Lower Permian strata. Regional distribution of Yeso (Lower Permian) salts probably influences retention of helium in pre-Yeso reservoirs by providing effective vertical fault seals.

Conclusions

1. 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 concentrations in these reservoirs range from 3.2 to 7.5%.
2. In the San Juan Basin, productive helium accumulations are located over or near orthogonal systems of high-angle faults that offset Precambrian basement. These faults probably acted as migration pathways for helium generated in Precambrian basement and also have influenced deposition and location of Paleozoic reservoirs.
3. Although no helium production has been established in the deep part of the San Juan Basin east of the Four Corners platform, significant potential within Mississippian and Pennsylvanian reservoirs is suggested by elevated concentrations of helium in reservoir gases and by orthogonal sets of high-angle faults that offset Precambrian basement and may act as migration pathways.
4. Helium has not been extracted from produced gases in the New Mexico part of the Permian Basin. However, gases with helium contents ranging from 0.3 to almost 1.0% have been produced from Pennsylvanian and Permian reservoirs along the northwest flank of the basin. The helium probably originated by radiogenic decay in granitic Precambrian rocks and migrated vertically into the Pennsylvanian and Permian reservoirs through regional high-angle, strike-slip faults. These faults trend northeast-southwest and define exploratory fairways.
5. Other basins and areas in New Mexico

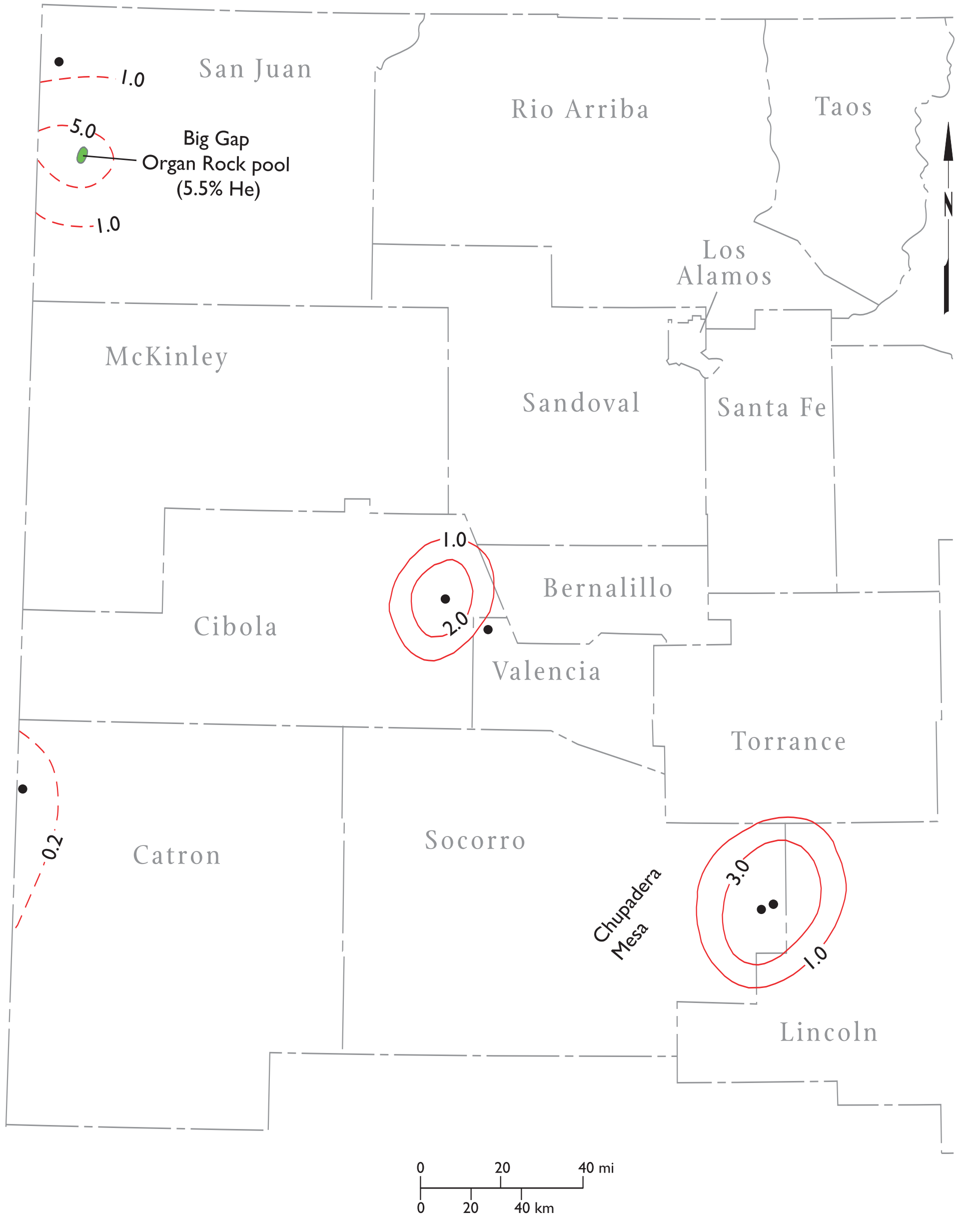

FIGURE 8—Contours of mole percent helium in gases recovered from Permian reservoirs in northwestern, central, and west-central New Mexico. Black dots are wells outside of reservoir (oil or gas pool) boundaries with helium gas analyses.

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.

Acknowledgments

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References

Baars, D. L., 1983, Rattlesnake Mississippian; *in* Fassett, J. E. (ed.), Oil and gas fields of the Four Corners area, v. III: Four Corners Geological Society, pp. 1006–1007.

Ballentine, C. J., and Lollar, B. S., 2002, Regional ground water focusing of nitrogen and noble gases into the Hugoton-panhandle giant gas field, USA: Geochimica et Cosmochimica Acta, v. 66, pp. 2483–2497.

Broadhead, R. F., and Gillard, L., 2004, Helium in New Mexico: geologic distribution and exploration possibilities: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 483, CD-ROM.

Broadhead, R. F., and Jones, G., 2004, Oil, natural gas, and helium potential of the Chupadera Mesa area, Lincoln and Socorro Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 478, CD-ROM.

Brown, H. H., 1978, Beautiful Mountain Mississippian; *in* Fassett, J. E. (ed.), Oil and gas fields of the Four Corners area, v. I: Four Corners Geological Society, pp. 207–208.

Casey, T. A. L., 1983, Helium potential of the Four Corners area; *in* Fassett, J. E. (ed.), Oil and gas fields of the Four Corners area, v. III: Four Corners Geological Society, pp. 749–754.

Chapman, Wood, and Griswold, Inc., 1977, Geologic map of Grants Uranium region: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 31, scale 2 miles = 1 inch.

Ciotoli, G., Lombardi, S., Morandi, S., and Zarlenga, F., 2004, A multidisciplinary, statistical approach to study the relationships between helium leakage and neotectonic activity in a gas province—the Vasto Basin, Abruzzo—Molise (central Italy): American Association of Petroleum Geologists, Bulletin, v. 88, pp. 355–372.

DeVoto, R. H., Mead, R. H., Martin, J. P., and Bergquist, L. E., 1980, Use of helium in uranium exploration, Grants district; *in* Rautman, C. A. (comp.), Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, pp. 368–379.

Downey, M., 1984, Evaluating seals for hydrocarbon accumulations: American Association of Petroleum Geologists, Bulletin, v. 68, pp. 1752–1763.

Dyck, W., 1980, Uranium, radon, helium and other trace elements and gases in well waters of the St. Lawrence lowlands (Ottawa region) Canada: Journal of Geochemical Exploration, v. 13, pp. 27–39.

Giggenbach, W. F., Sano, Y., and Schmincke, H. U., 1991, CO_2-rich gases from Lake Nyos and Monoun, Cameroon; Laacher See, Germany; Dieng, Indonesia, and Mt. Gambier, Australia—variations on a common theme: Journal of Volcanology and Geothermal Research, v. 45, no. 3–4, pp. 311–323.

Gupta, S. K., and Deshpande, R. D., 2003, Origin of ground water helium and temperature anomalies in the Cambay region of Gujarat, India: Chemical Geology, v. 198, no. 1–2, pp. 33–46.

Hinson, H. H., 1947, Reservoir characteristics of Rattlesnake oil and gas field, San Juan County, New Mexico: American Association of Petroleum Geologists, Bulletin, v. 31, pp. 731–771.

Hiyagon, H., and Kennedy, B. M., 1992, Noble gases in CH^4-rich gas fields, Alberta, Canada: Geochimica et Cosmochimica Acta, v. 56, pp. 1569–1589.

Hoppe, W. F., 1983, Table Mesa Mississippian, Table Mesa Pennsylvanian "C"; *in* Fassett, J. E. (ed.), Oil and gas fields of the Four Corners area, v. III: Four Corners Geological Society, pp. 1046–1049.

Hunt, J. M., 1996, Petroleum geochemistry and geology, second edition: W.H. Freeman and Company, New York, 743 pp.

Jenden, P. D., Newell, K. D., Kaplan, I. R., and Watney, W. L., 1988, Composition and stable-isotope geochemistry of natural gases from Kansas, midcontinent, U.S.A: Chemical Geology, v. 71, pp. 117–147.

Jian-Guo, D., Yongchang, X., and Ming-Lang, S., 1998, Helium isotopes and heat flow in the oil and gas bearing basins in China's continent: Acta Geophysica Sinica, v. 41, pp. 494–501.

Kelley, V. C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 24, 75 pp.

Kennedy, B. M., Torgersen, T., and van Soest, M. C., 2002, Multiple atmospheric noble gas components in hydrocarbon reservoirs—a study of the Northwest Shelf, Delaware Basin, SE New Mexico: Geochimica et Cosmochimica Acta, v. 66, pp. 2807–2822.

Lollar, B. S., O'Nions, R. K., and Ballentine, C. J., 1994b, Helium and neon isotope systematics in carbon dioxide-rich and hydrocarbon-rich gas reservoirs: Geochimica et Cosmochimica Acta, v. 58, pp. 5279–5290.

Lollar, B. S., Weise, S. M., Frape, S. K., and Barker, J. F., 1994a, Isotopic constraints on the migration of hydrocarbon and helium gases of southwestern Ontario: Bulletin of Canadian Petroleum Geology, v. 42, pp. 283–295.

Maione, S. J., 2004, Helium exploration—a 21st century challenge: Houston Geological Society, Internet article.

Mamyrin, B. A., and Tolstikhin, L. N., 1984, Helium isotopes in nature: Elsevier, Amsterdam, 273 pp.

Maynard, J., 1978, Hogback Pennsylvanian; *in* Fassett, J. E. (ed.), Oil and gas fields of the Four Corners area, v. I: Four Corners Geological Society, p. 334.

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic map of New Mexico: New Mexico Bureau of Geology and Mineral Resources, 2 sheets, scale 1:500,000.

Oxburgh, E. R., O'Nions, R. K., and Hill, R. I., 1986, Helium isotopes in sedimentary basins: Nature, v. 324, pp. 632–635.

Pacheco, N., 2002, Helium: U.S. Geological Survey, Minerals Yearbook, Chapter 36.

Pacheco, N., 2005, Helium: U.S. Geological Survey, Mineral Commodity Summaries.

Parham, K. D., and Campbell, J. A., 1993, Wolfcampian shallow-shelf carbonate—Hugoton embayment, Kansas and Oklahoma; *in* Bebout, D. G., White, W. A., and Hentz, T. F. (eds.), Atlas of major mid-continent gas reservoirs: Bureau of Economic Geology, University of Texas (Austin), pp. 9–12.

Peterson, J. B., 2001, Helium: U.S. Geological Survey, Mineral Commodity Summaries.

Pierce, A. P., Gott, G. B., and Mytton, J. W., 1964, Uranium and helium in the Panhandle gas field, Texas, and adjacent areas: U.S. Geological Survey, Professional Paper 454-G, 57 pp.

Pogorski, L. A., and Quirt, G. S., 1980, Helium surveying for deeply buried uranium deposits (abs): American Association of Petroleum Geologists, Bulletin, v. 64, pp. 766–767.

Poreda, R. J., Jenden, P. D., Kaplan, I. R., and Craig, H., 1986, Mantle helium in Sacramento Basin natural gas wells (USA): Geochimica et Cosmochimica Acta, v. 50, pp. 2847–2853.

Rauzi, S. L., 2003, Review of helium production and potential in Arizona: Arizona Geological Survey, Open-file Report 03-05, 29 pp.

Rauzi, S. L., and Fellows, L. D., 2003, Arizona has helium: Arizona Geology, v. 33, no. 4, pp. 1–4.

Riggs, E. A., 1978, Tocito Dome Mississippian, North; *in* Fassett, J. E. (ed.), Oil and gas fields of the Four Corners area, v. II: Four Corners Geological Society, pp. 519–521.

Selley, R. C., 1998, Elements of petroleum geology, second edition: Academic Press, San Diego, 470 pp.

Sheng, X., Xianbin, W., Nakai, S., Wakita, H., and Yongchang, X., 1995, Helium isotope compositions in sedimentary basins in China: Applied Geochemistry, v. 10, pp. 643–656.

Spencer, C. W., 1978, Tocito Dome Pennsylvanian, North; *in* Fassett, J. E. (ed.), Oil and gas fields of the Four Corners area, v. II: Four Corners Geological Society, pp. 528–531.

Stevenson, G. M., and Baars, D. L., 1977, Pre-carboniferous paleotectonics of the San Juan Basin; *in* Fassett, J. E., and James, H. L. (eds.), San Juan Basin III: New Mexico Geological Society, Guidebook 28, pp. 99–110.

Tardy, Y., Krempp, G., and Trauth, N., 1972, Le lithium dans les mineraux argileux des sediments et des sols: Geochimica et Cosmochimica Acta, v. 36, pp. 397–412.

Taylor, D. J., and Huffman, A. C., Jr., 1998, Map showing inferred and mapped basement faults, San Juan Basin and vicinity, New Mexico and Colorado: U.S. Geological Survey, Geologic Investigations Series Map I-2641, scale 1:500,000.

Tongish, C. A., 1980, Helium—its relationship to geologic systems and its occurrence with the natural gases, nitrogen, carbon dioxide, and argon: U.S. Bureau of Mines, Report of Investigations 8444, 176 pp.

Torgersen, T., Kennedy, B. M., Hiyagon, H., Chiou, K. Y., Reynolds, J. H., and Clarke, W. B., 1998, Argon accumulation and the crustal degassing flux of ^{40}Ar in the Great Artesian Basin, Australia: Earth and Planetary Science Letters, v. 84, pp. 345–355.

Yongchang, X., Ping, S., Ming-Liang, S., and Sheng, X., 1997, Geochemistry on mantle-derived volatiles in natural gases from eastern China oil/gas provinces (1): a novel helium resource—commercial accumulation of mantle-derived helium in the sedimentary crust: Science in China, Series D, v. 40, pp. 120–129.