Review of
Helium Production and Potential
in Arizona

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October 2003

Arizona Geological Survey
Open-File Report OFR 03-05

30 pages including title page

Introduction

Some of the richest helium-bearing gas in the world was produced from fields completed specifically for helium in northeastern Arizona in the 1960s and 1970s. All production came from fields in Apache County (Figure 1). Three fields were located in the Holbrook Basin south of the Defiance uplift about 35 miles northeast of Holbrook. One field was located in the Four Corners area north of the Defiance uplift near the small community of Teec Nos Pos. Helium-rich gas was discovered in the Dineh-bi-Keyah oil field on the northeastern flank of the Defiance uplift in the late 1960s but was not produced until 2003. Helium concentrations range from trace amounts up to 10% in the Holbrook Basin and Four Corners area. Both areas have good potential for additional discovery and production of helium.

Helium content in gas is generally considered to be of commercial interest when the concentration is above 0.3% (Casey, 1983, p. 749). Most of the helium produced in the United States is extracted from natural gas from fields in Wyoming, Utah, Colorado, New Mexico, Kansas, Oklahoma, and Texas (Pacheco, 2003, p. 80). The extracted helium is processed into a crude helium product, which varies from 50% to 80% helium, and is ultimately purified to a Grade-A helium product, which is 99.995% or better. Most helium is shipped as a liquid to distribution centers in trucks from where it is sold as bulk liquid helium or gasified and compressed into tanks and small cylinders for delivery to end users.

The recent price for private industry's Grade-A gaseous helium has ranged from $45 to $52 per thousand cubic feet (Pacheco, 2003, p. 80). The Amarillo Field Office of the U.S. Bureau of Land Management (formerly Amarillo Field Office of the U.S. Bureau of Mines) has posted a helium price of $54.00 per thousand cubic feet for the period October 2003 through September 2004. Private industry sold 3 billion cubic feet of Grade-A helium in the United States in 2002. Total world production was 3.7 billion cubic feet.

Helium is vital in obtaining the extremely cold temperatures essential in cryogenic and superconductor technologies, which provide more efficient methods of generating, transmitting, and storing electricity. In addition, there is a growing need for helium in space exploration, national defense, high intensity lasers in industry, and in medicine (Casey, 1983, p. 749). In 2002, 24% of domestic helium consumption was used for cryogenic applications, 20% for pressurizing and purging, 18% for welding cover gas, 16% for controlled atmospheres, 6% for leak detection, 3% for breathing mixtures and 13% for other uses. Cryogenics, specifically magnetic resonance imaging applications, dominated liquid helium use (Pacheco, 2001, p. 36.2). Demand for helium is anticipated to grow at a rate of about 5% per year through at least 2004. Pacheco (2001 and 2003) summarizes domestic and world production and reserves, lists salient statistics, and discusses future demand, trends, and issues.

The current high price and anticipated future demand for helium have resulted in a renewed search for helium in Arizona. Oil and gas operators are developing helium prospects near the old helium fields in the Holbrook Basin in central Apache County and are starting to produce the helium-rich gas at the Dineh-bi-Keyah field in northern Apache County as well as the Beautiful Mountain Field just across the state line in New Mexico.

Geology

Northeastern Arizona is part of the Colorado Plateau Physiographic province. The Colorado Plateau is characterized by flat-lying, relatively undisturbed, largely marine sedimentary rocks of Paleozoic and Mesozoic age that are covered by Tertiary to recent volcanic flows near Flagstaff and Springerville. Permian strata truncate Cambrian, Devonian, Mississippian, Pennsylvanian, and Proterozoic rocks along the margins of the Defiance uplift. Maximum submergence of the Defiance uplift may have occurred during the Mississippian but the Mississippian rocks were subsequently eroded back, probably by renewed, slow emergence of the uplift in Pennsylvanian through Permian time. As much as 2000 ft of Permian strata were eventually deposited on the Proterozoic basement rocks of the Defiance uplift. All past production of helium and current production of oil, natural gas and carbon dioxide (CO_2) are from rock formations of Paleozoic age in the Plateau province.

The major tectonic features in northeastern Arizona include the Defiance and Kaibab uplifts in the northern part of the area (Figure 1). The Black Mesa Basin is situated between the Kaibab and Defiance uplifts. The Holbrook Basin lies between the Defiance uplift on the north and the Mogollon Slope on the south. A prominent escarpment known as the Mogollon Rim defines much of the southern edge of the Plateau province.

Numerous diatremes (volcanic pipes that consist mainly of breccia) and dikes including Agathla Peak in northeastern Arizona and Ship Rock in northwestern New Mexico are present throughout the Four Corners region (Fitzsimmons, 1973). To the south, the Hopi Buttes volcanic field, which includes many necks and diatremes with related flows, covers an area of approximately 1500 square miles in the northern part of the Holbrook Basin (Figure 1). There appears to be a correlation between the diatremes and other deep-seated intrusive rocks and the presence and production of helium.

Helium production in the Holbrook Basin

The Pinta Dome, Navajo Springs, and East Navajo Springs fields are relatively small anticlinal structures located in the Holbrook Basin in Townships 19 and 20 North, Ranges 26, 27, and 28 East (Figures 2 - 4). Wells in the Pinta Dome and Navajo Springs fields produced helium from the Permian Coconino Sandstone. Several wells in the East Navajo Springs field produced helium from the Shinarump Conglomerate at the base of the Triassic Chinle Formation. Figure 5 shows the generalized stratigraphy in the Pinta

Dome-Navajo Springs area. A composite well log of the Pinta Dome, Navajo Springs, and East Navajo Springs fields is shown in Figure 6.

Masters (1960) and Dean (1960) published the history of the exploration and development of the helium resources in the Navajo-Chambers area. The Navajo-Chambers region represented the only area in the history of the helium industry that had experienced sustained exploration and development for helium gas alone (Dean, 1960, p. 33).

Kipling Petroleum Company discovered helium on Pinta Dome in 1950 when it drilled the #1 Macie in search of oil. No oil was found but a large flow of gas was encountered in the Coconino Sandstone. The gas did not burn so it was allowed to flow unrestricted from the well bore for about eight weeks (Dean, 1960, p. 33; Dean and Lauth, 1961, p. 195). Contemporaneous reports indicated that the gas escaping from the open well "roared like a jet engine" at an estimated initial rate of 24 million cubic feet per day (Heindl, 1952, p. 1331; Beaumont, 1959, p. 160). The operator shut the well in after testing by the U.S. Bureau of Mines (USBM) showed that the gas was rich in helium (Masters, 1960, p. 30).

In 1951, Kipling Petroleum Company drilled the #2 Macie, which was abandoned because of stuck pipe. In 1955, the Apache Oil and Helium Corporation took over development of the field, reworked the #2 Macie, which blew out, and drilled the #3 Macie, which it abandoned before penetrating the Coconino sand. In 1956, Kerr-McGee Oil Industries made an agreement with Apache Oil and Helium to complete the development of the field. Kerr-McGee completed the #2 and #3 Macie wells and drilled three more gas wells and two dry holes. In 1959, Eastern Petroleum Corporation drilled three gas wells and extended the area of helium production to the southeast.

Kerr-McGee constructed a helium-extraction plant at Navajo and started processing helium from the Pinta Dome field in 1961, the Navajo Springs field in 1964, and the East Navajo Springs field in 1969. Some of the wells completed in the Navajo Springs and East Navajo Springs fields were not produced because of unitization. Kerr-McGee's helium plant was the first privately financed helium plant in the world producing Grade-A helium (Smith and Pylant, 1962, p. 136). Average surface shut-in pressure at the Pinta Dome field was 99.3 pounds per square inch in 1961. The average pressure was down to 60.3 pounds per square inch in 1968. Production in the Pinta Dome area had declined to such an extent that the plant was closed in early 1976 and the fields were abandoned. Nearly 9 billion cubic feet of gas containing more than 700 million cubic feet of Grade-A helium were produced from the Pinta Dome and adjacent Navajo Springs and East Navajo Springs fields (Figures 7 - 11). Gas produced from the Coconino Sandstone averaged 90% nitrogen, 8-10% helium, and 1% carbon dioxide (Figure 12).

Shows of helium in wells in the Holbrook Basin

The first recorded report of helium-bearing gas in Arizona was from the Great Basin Oil Company #1 Taylor-Fuller, a non-productive oil test drilled to a depth of 4675 ft a few miles southwest of Holbrook in 1927 (Beaumont, 1959, p. 160). A test of the Cambrian Tapeats Sandstone at a depth of 3500 ft was reported to have flowed 100,000 cubic feet of gas containing 1.12% helium a day (Turner, 1968, Table II).

Helium is associated with carbon dioxide (CO_2) being produced by Ridgeway Arizona Oil Corporation between St. Johns and Springerville in southern Apache County. All production is from the Supai Formation of Permian age. Ridgeway drilled the discovery well, the #1 Plateau Cattle, near St. Johns in 1994 and a follow-up well, the #3-1 State, 4 miles south of the #1 Plateau Cattle well in 1995. The only determination that Ridgeway was able to make at the well site was that the gas from the discovery well would not burn. Ridgeway sent samples of the nonflammable gas from the discovery well, and subsequently from the follow up well, to the USBM [The USBM was eliminated and its minerals information and analysis functions were transferred to the U.S. Geological Survey in January 1996] in Amarillo, Texas, for analysis. The USBM analysis indicated 90% CO_2, 6% nitrogen, and 0.5 to 0.8% helium in the #1 Plateau Cattle well and 89% CO_2, 10% nitrogen, 0.7% helium, and 0.1% each of methane and argon in the #3-1 State well.

Ridgeway drilled six additional wells south of the #3-1 State well in 1997. In July 2002, Ridgeway started producing CO_2 from one of the wells, the #10-22 State, for a liquid plant located near the Tucson Electric Power Company's electric generating station. No helium is currently being produced for commercial use but Ridgeway plans to eventually extract helium from the CO_2 gas stream.

Shows of oil and gas have been reported in numerous wells drilled in the Holbrook Basin (Bahr, 1962, p. 121; Turner, 1968, Table II, Peirce and Wilt, 1970, Table D; and Conley and Giardina, 1979, Tables D, E, and F). Gas analyses show that helium is present in many of the wells (Figure 12). High concentrations of helium were reported in at least three oil tests and in several of the stratigraphic wells drilled to delineate potash deposits in the Holbrook Basin in the 1960s and 1970s. These are included in the following list.

- The James G. Brown & Associates #2 Chambers-Sanders in Sec. 27, T. 21 N., R. 28 E. Encountered a show of nonflammable gas in the Permian Coconino Sandstone at a depth of 542 ft. Analysis showed the gas contained 93.6% nitrogen, 1.2% argon, 2.3% helium, and 2.8% CO_2.

- The Kern County Land #1 State in Sec. 2, T. 18 N., R. 24 E. Gas blew out of the hole for 26 hours from the Permian Supai Formation at 965 ft. Analysis showed the gas contained 0.22% methane, 4.09% helium, and 95.10% nitrogen.

- The Great Basin Oil Company #1 Taylor-Fuller in Sec. 16, T. 17 N., R. 20 E. A gas flow was reported from the Cambrian Tapeats Sandstone at a depth of 3500 ft. The gas was reported to contain 18.98% nitrogen, 79.5% CO_2, and 1.12% helium.

- The New Mexico and Arizona Land Company #3 Fee in Sec. 28, T. 17 N., R. 22 E. Gas blew out of the hole while coring at a depth of 1040 ft in the Supai Formation. The gas was reported to contain helium.

- The Arkla Exploration #22 NMA in Sec. 23, T. 17 N., R. 23 E. Air blew out of the hole while coring below a depth of 1367 ft in the Supai Formation. A strong blow was reported in a drill stem test of the interval 1342-1523 ft. No analysis of the gas is available.

- The Arkla Exploration #37 NMA in Sec. 25, T. 16 N., R. 22 E. Gas blew out of the hole from the Supai Formation at 821 ft in the straight hole and at 816 ft and 818 ft in the side track hole. A drill stem test of the interval 779-819 ft measured an initial and final flowing pressure of 175 pounds. Initial shut-in pressure was 240 pounds and final shut-in pressure was 175 pounds. No analysis of the gas is available.

- The Arkla Exploration #68 NMA in Sec. 19, T. 16 N., R. 23 E. Gas blew out of the hole from the Supai Formation at 896 ft and 970 ft. All drill fluid was lost both times.

- The Arkla Exploration #10 NMA in Sec. 27, T. 16 N., R. 23 E. Gas and fluid blew out of the hole from the Supai Formation at 940 ft, 959 ft, and 1007 ft. The gas tested 2.4% helium at the Kerr McGee lab at Navajo, Arizona.

- The Arkla Exploration #7 State in Sec. 10, T. 15 N., R. 23 E. Gas blew out of the hole out while drilling – no depth interval was given.

- The L.M. Lockhart #1 Aztec Land & Cattle Company in Sec. 33, T. 14 N., R. 20 E. Gas blew out of the hole for 18 minutes during a drill stem test of the Fort Apache limestone from 1678-1742 ft. Analysis of the gas indicated 23.8% methane, 3.2% ethane, 70.7% nitrogen, and 0.267% helium.

No gas analyses are available for some of the wells. However, the nonflammable gas reported in these wells may have contained helium, especially in light of the high helium concentrations reported in the wells with a gas analysis. The location of the wells in the Holbrook Basin with reported shows of helium or nonflammable gas is shown in Figure 13.

Helium production in the Four Corners area

The Texaco #1 Navajo-Z produced helium from the Mississippian Leadville Limestone in the late 1960s. The #1 Navajo-Z is located in sec. 36, T. 41 N., R. 30 E. in the Tohache Wash area near Teec Nos Pos in northern Apache County (Figures 14 and 15). A composite gamma ray-neutron and graphic lithologic log of the #1 Navajo-Z well is shown in Figure 16. The Leadville is equivalent to the Redwall Limestone in Grand Canyon. Texaco originally completed the well as an oil producer in the Devonian Aneth Formation. Texaco plugged the Devonian interval in 1961 after less than a year of poor production and recompleted the well as a helium producer in the overlying Mississippian Leadville Limestone (Figure 17). Gas in the Mississippian contained approximately 6% helium mixed mostly with nitrogen, methane, and CO_2 (Figure 12). Texaco abandoned the Tohache Wash field in 1969 after producing more than 385 million cubic feet of helium-rich gas from the Mississippian.

Casey (1983, p. 752) pointed out that the Texaco #1 Navajo-Z was abandoned because of technical and economic conditions, which implied that additional reserves remained in the ground. Spencer (1978, p. 93) concluded that once future helium markets and prices improved, the Tohache Wash accumulation would be redrilled and its full potential would be defined.

Kerr-McGee discovered oil in an igneous sill of Tertiary age at the Dineh-bi-Keyah field in 1967 (Figures 1 and 15). Gas associated with the oil in the igneous sill, which intruded strata of Pennsylvanian age, averaged 4.2% helium. Gas in the underlying Devonian McCracken Sandstone ranged from 4.8% to 5.6%. Kerr-McGee completed two gas wells, the #2 Navajo-B and the #2 Navajo-C, in the deeper Devonian strata but shut-in both wells in 1967 for lack of a market and pipeline. A composite gamma ray-sonic and graphic lithologic log of the #2 Navajo-C well is shown in Figure 18.

In 1994, Kerr-McGee sold the Dineh-bi-Keyah field to Mountain States Petroleum. In 2003, Mountain States Petroleum started producing the helium-rich gas from the Devonian strata. Gas is shipped through a pipeline to the Newpoint Gas Services helium gas plant south of Ship Rock in New Mexico (Figure 15). The Dineh-bi-Keyah field is located on the northern flank of the Defiance uplift (Figure 1).

Shows of helium in wells in the Four Corners area

Peirce and Wilt (1970, Table D) tabulated wells with shows of oil, gas, and helium in the Four Corners area of Arizona. Casey (1983, p. 752 and Figure 2) described wells that encountered helium in the Four Corners area of New Mexico and Arizona. Turner (1968, Table II) listed several wells in the East Boundary Butte field with high concentrations of helium. The highest concentrations were in the Mississippian Leadville limestone but helium in the Pennsylvanian strata ranged from 0.34% to 1.10%. Helium-rich gas is commonly found in strata of Devonian and Mississippian age but is also found in strata of Pennsylvanian, Permian, and Triassic age. Wells that encountered helium-rich gas in the Four Corners area of Arizona are listed below. Selected analyses are listed in Figure 12. Location of wells is shown in Figures 14 and 15.

- The Shell #2 Navajo in Sec. 3, T. 41 N., R. 28 E. Shut-in gas well at the East Boundary Butte field. Gas from different intervals in the Pennsylvanian was reported to range from 0.34% to 1.10% helium. Well has been shut-in since October 1998.

- The Humble #1 Navajo in Sec. 4, T. 41 N., R. 28 E. Shut-in gas well at the East Boundary Butte field. Gas in the Pennsylvanian was reported to contain

1.0% helium. Gas in the Mississippian tested at 4.4% helium. Well has been shut-in since December 1998.

- The Shell #1 Navajo in Sec. 6, T. 41 N., R. 29 E. Gas in the Pennsylvanian was reported to contain 0.35% helium.

- The Atlantic Refining #7-1 Navajo in Sec. 7, T. 40 N., R. 29 E. Gas in the Mississippian tested at 5.1% helium.

- The Kenai Oil & Gas #34-7 Navajo in Sec. 7, T. 40 N., R. 29 E. Gas in the Mississippian tested at 4.92% helium.

- The Pan American Petroleum # 1 Moko-Navajo in Sec. 15, T. 40 N., R. 29 E. Gas in the Pennsylvanian tested at 0.73% helium. Gas in the Mississippian tested at 8.07% helium.

- The Universal Resources #1-15 Navajo in Sec. 15, T. 40 N., R. 29 E. Gas in the Pennsylvanian ranged from 0.51% to 0.53% helium. Gas in the Mississippian ranged from 0.24% to 0.28% helium.

- The Socony Mobil Oil #1 Navajo-155 in Sec. 28, T. 39 N., R. 25 E. Gas in the Pennsylvanian contained 15 units of helium by chromatograph.

- The Gulf #1 Navajo-CS in Sec. 34, T 37 N., R. 30 E. Gas in the Pennsylvanian contained 7.4% helium.

- The Humble Oil & Refining #1 Navajo-87 in Sec. 23, T. 36 N., R. 29 E. Gas in the Devonian tested at 5.6% helium.

- The Humble Oil & Refining #1 Navajo-88 in Sec. 25, T. 36 N., R. 29 E. Gas in the Devonian ranged from 4% to 4.4% helium.

- The Humble Oil & Refining #2 Navajo-88 in Sec. 25, T. 36 N., R. 29 E. Gas in the igneous sill of Tertiary age ranged from 3.5% to 5.2% helium.

- The Union Texas Petroleum #1-6 Navajo in Sec. 6, T. 36 N., R. 30 E. Gas in the Pennsylvanian tested at 4.7% helium.

- The Anadarko #1 Navajo-135 in Sec. 3, T. 35 N., R. 30 E. Gas in the Devonian tested at 6.23% helium.

- The Humble Oil & Refining #1 Navajo-140 in Sec. 8, T. 35 N., R. 30 E. Gas in the Devonian averaged 5.2% helium.

- The Humble Oil & Refining #151-1 Navajo in Sec. 35, T. 35 N., R. 30 E. Gas in the Devonian ranged from 3.1 to 4.8% helium.

Several wells encountered nonflammable gas in drill-stem and other tests but no samples were collected for analysis. It is probable that nonflammable gas in the Four Corners area contains helium, especially when encountered in strata of Devonian or Mississippian age.

Origin of helium

Spencer (1983, p. 15) described two sources of terrestrial helium: (1) primordial helium derived from sources deep within the earth and (2) radioactive decay of uranium and thorium that are concentrated in the earth's crust. The helium 3 isotope signifies primordial helium whereas the helium 4 isotope signifies helium from radioactive decay. Low ratios of helium 3 to helium 4 indicate that helium in most natural gas fields was primarily derived from radioactive decay.

Two possible sources for the helium in Arizona are the Precambrian crystalline rocks beneath the helium reservoir rocks (primordial helium) or sediments containing significant amounts of radioactive material overlying the helium reservoir rocks (radioactive decay). The current lack of information about the isotopic ratios prevents a definitive conclusion as to the source of helium encountered as shows or produced in Arizona. But in either case, stratigraphic thinning, fracturing, faulting, or volcanic activity would be a necessary component in bringing the potential helium-source rocks into contact with the reservoir rocks.

Prospective areas for helium exploration and production

All known helium occurrences in Arizona are within the Colorado Plateau and adjacent to the Defiance uplift (Spencer, 1983, p. 6). Spencer (1983, p. 15) concluded that if the crystalline rocks of the Defiance uplift were the source of the helium in the Pinta Dome and related helium fields then many other areas around the Defiance uplift would be promising targets for helium exploration. The largest accumulations have been south of the Defiance uplift in the Holbrook Basin.

The proximity of many helium occurrences to diatremes should not be ignored. Diatremes often contain eclogite, peridotite, kimberlite, and other igneous rock types associated with the earth's mantle (Nealy and Sheridan, 1989, p. 621), thus indicating a possible common origin for both the diatremes and the helium. There is a striking correlation between helium production in the Four Corners area and the location of Ship Rock (Figure 15).

The production of helium from Permian and Triassic strata in the Pinta Dome area, high concentrations of helium in several wells drilled to delineate potash deposits, and helium in CO_2 being produced between St. Johns and Springerville demonstrate that subsurface conditions are favorable for the generation and entrapment of helium throughout the Holbrook Basin. Structural and stratigraphic traps near diatremes and other deep-seated intrusive rocks throughout the basin and especially along the margins of the Defiance uplift may have exceptional potential for the entrapment of helium.

The obvious areas for discovery of helium-rich gas would be in or near fields known to contain helium-rich gas. Some operators have recently identified several helium prospects near the old helium fields northeast of Holbrook. The old fields themselves may have potential for re-entry and production of additional helium reserves.

Past production from Mississippian strata at the Tohache Wash field and shows in Devonian, Mississippian, and Pennsylvanian strata demonstrate favorable conditions for the generation and entrapment of helium in the Four Corners area. The Devonian McCracken sandstone is being produced at the Dineh-bi-Keyah field for its helium content. High concentrations of helium in Mississippian strata at the East Boundary Butte field makes that shut-in field a promising candidate for re-entry and production of helium. Casey (1983, p. 753) noted that the high helium values in the Four Corners area might be related to deep-seated faulting, the trend of deep-seated intrusive complexes, or the characteristics of the large Defiance basement uplift. He concluded that the helium potential of the Four Corners region was enormous.

Selected reports and articles on helium in Arizona

Masters (1960), chief geologist with Kerr-McGee Oil Industries, described the geology, helium reserves, and history of discovery and development of the Pinta Dome field. Dean (1960), vice-president of Eastern Petroleum Company, described the helium potential of the Navajo-Chambers area in light of the significant helium accumulations in the Four Corners area of Arizona, New Mexico, Colorado, and Utah. Dunlap (1969) described the subsurface geology of the Pinta Dome-Navajo Springs helium fields and tabulated the basic well data used in the structure maps and cross sections that accompanied his report. Allen (1978a, 1978b) complied basic statistics about the geology, discovery well, drilling and completion practices, and reservoir data for the Pinta Dome and Navajo Springs fields. Spencer (1978) compiled similar statistics for the Tohache Wash helium field near Teec Nos Pos in the Four Corners area. Spencer (1983) summarized helium resources and production in Arizona. He described the geology of the helium fields and discussed the origin of helium. Casey (1983) described helium resources and production in the Four Corners area. He discussed the geology of helium and related that to the most important reservoir beds for helium.

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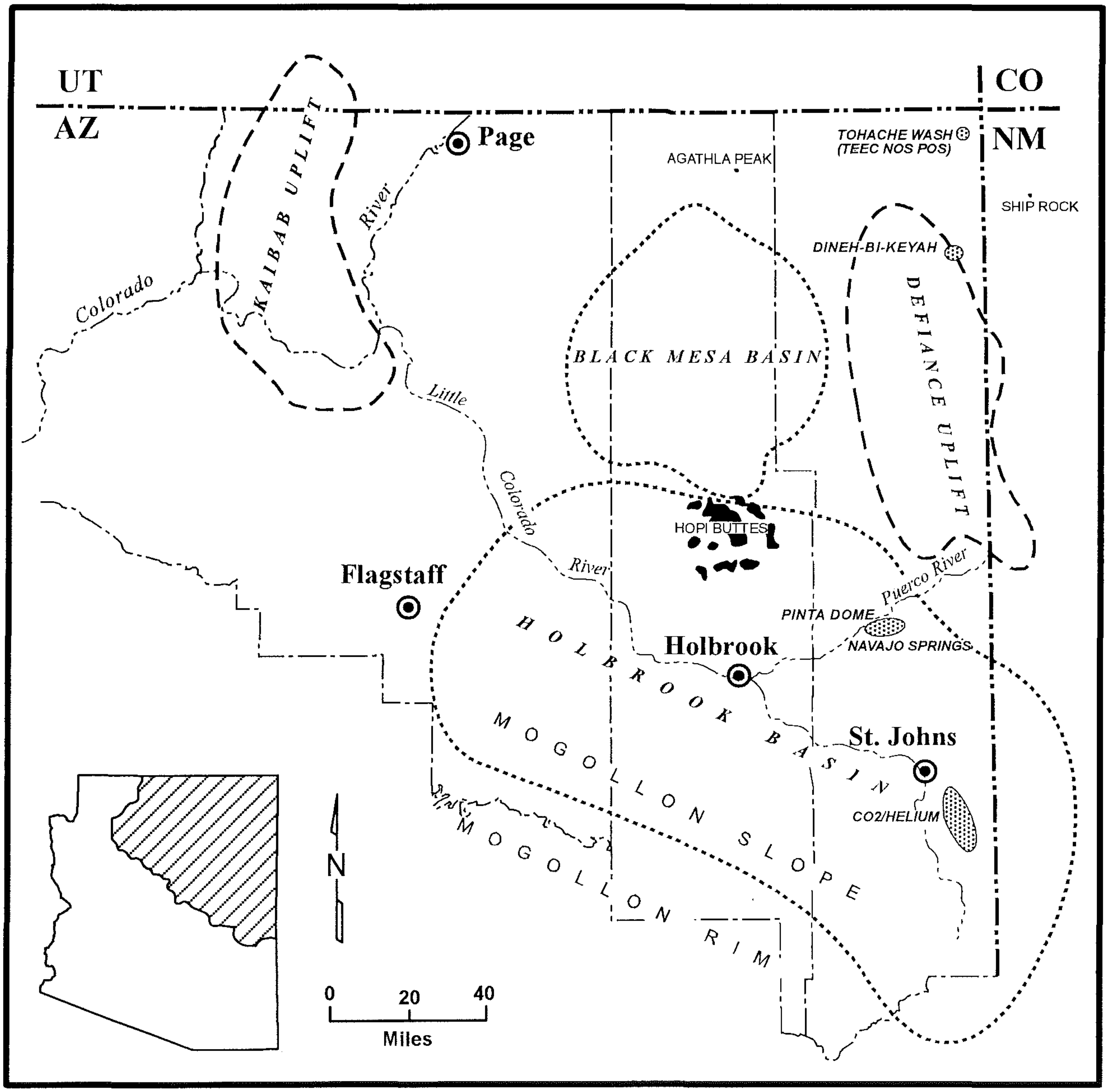

Figure 1. Index map of northeastern Arizona showing location of major geologic features and fields where helium has been produced or where significant concentrations of helium have been encountered in wells (After Dunlap, 1969). See Figures 2 through 4 for details of the Pinta Dome - Navajo Springs area. See Figure 13 for details of the Holbrook Basin. See Figures 14 and 15 for details of the Four Corners area.

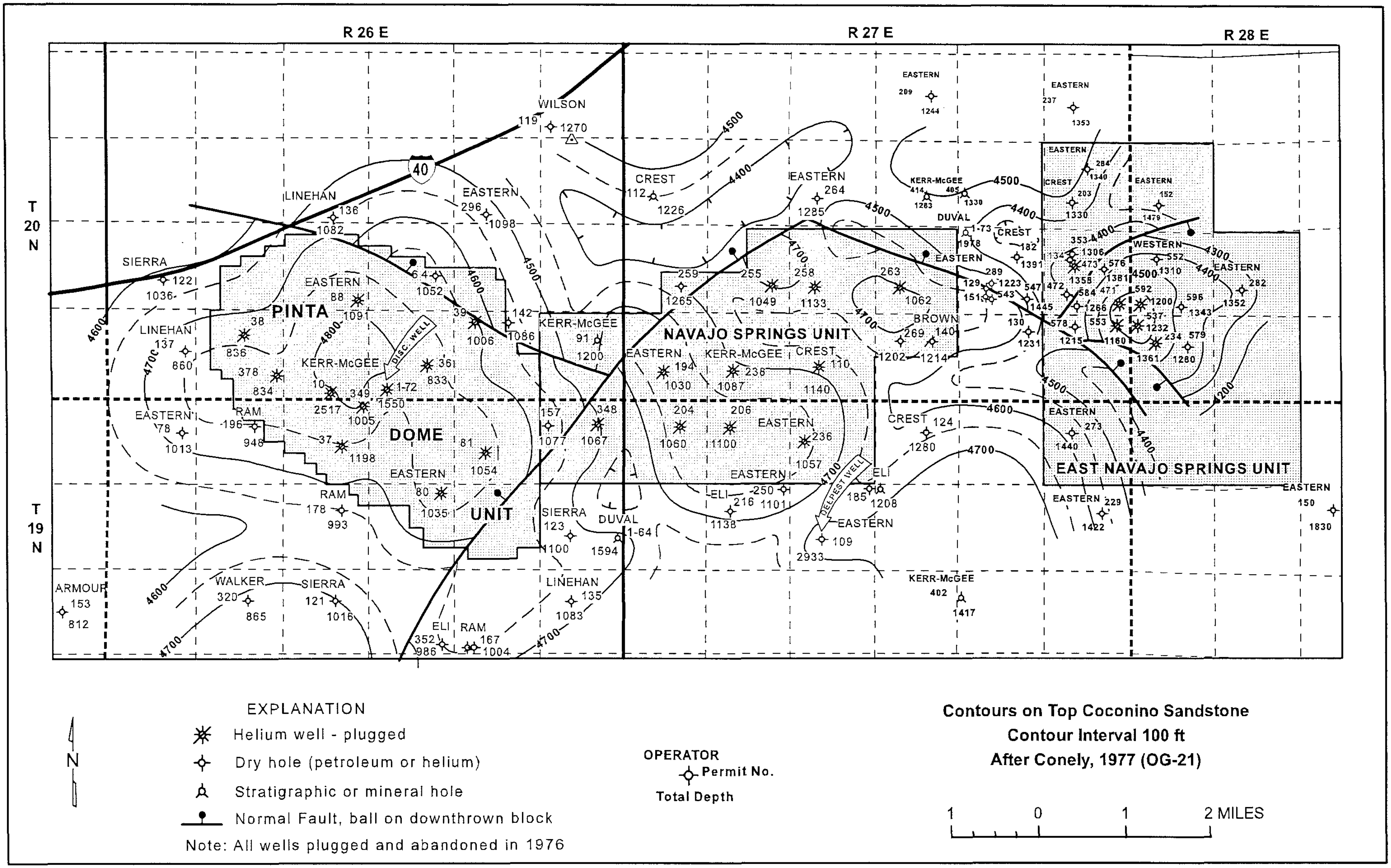

Figure 2. Structural contour map of the Pinta Dome, Navajo Springs, and East Navajo Springs abandoned helium fields in the Holbrook Basin, Apache County, Arizona (Modified from Conely, 1974). See Figures 3 and 4 for more detail. See Figure 1 for regional map.

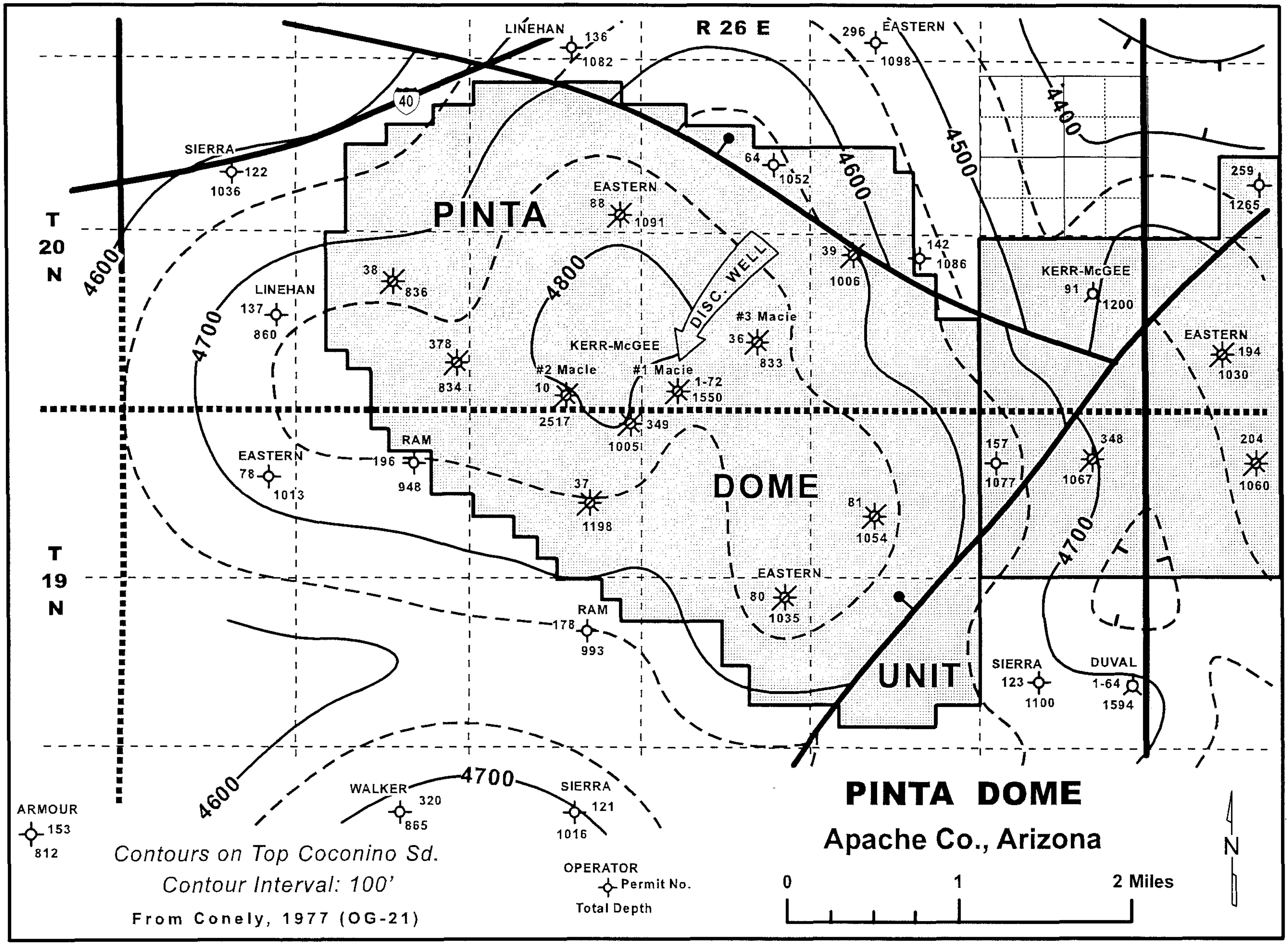

Figure 3. Pinta Dome Unit. See Figure 2 for explanation of symbols. See Figure 7 for wells with record of annual and cumulative production.

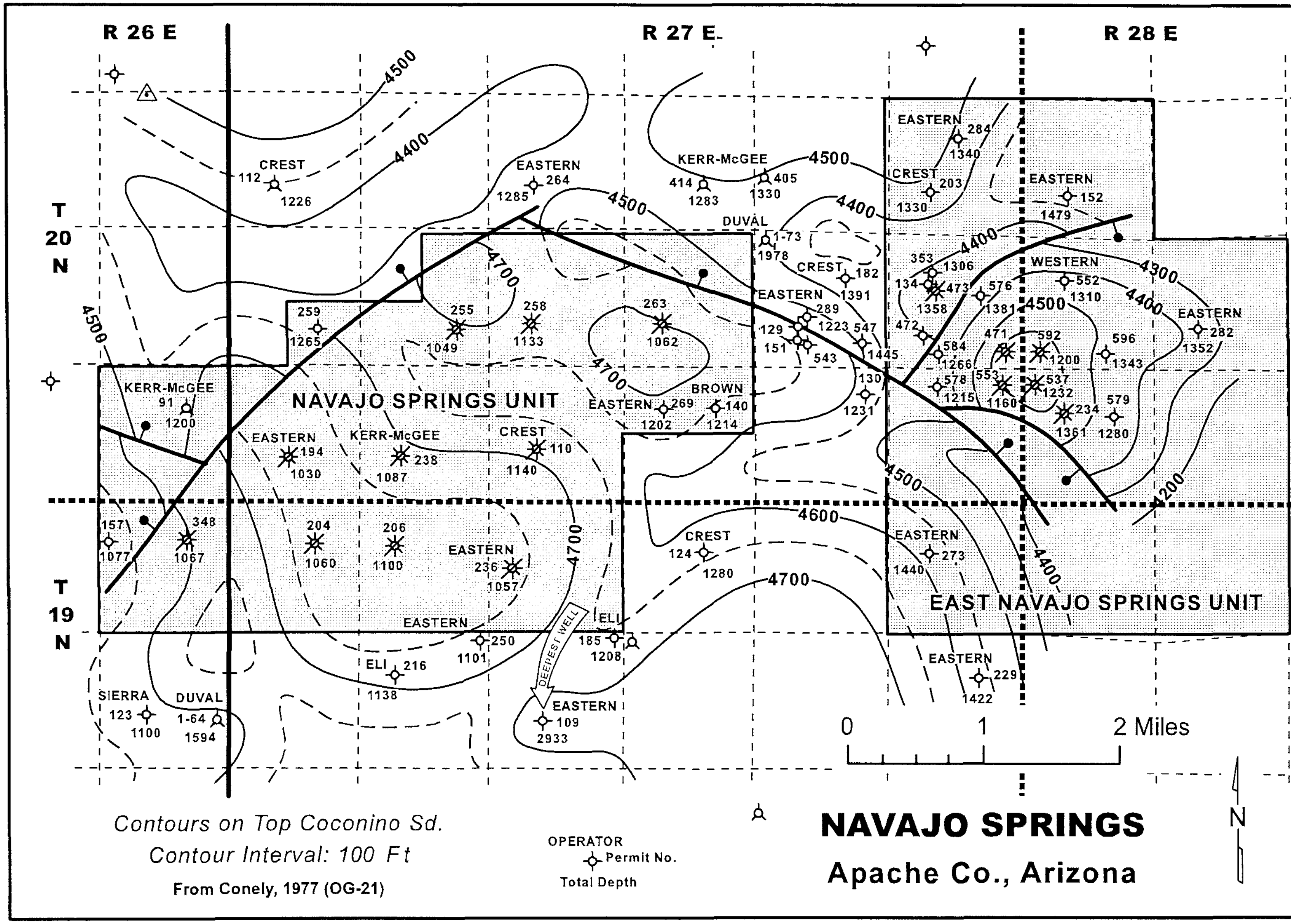

Figure 4. Navajo Springs and East Navajo Springs Units. See Figure 2 for explanation of symbols. See Figure 8 for wells with record of annual and cumulative production.

SYSTEM OR SERIES		FORMATION	THICKNESS (FT)	LITHOLOGIC CHARACTERISTICS
Quaternary				Alluvium, sand and gravel
		UNCONFORMITY		
Tertiary		Bidahochi Formation	0-180	Grayish-brown calcareous sandstone interbedded with silty mudstone and volcanic ash; bentonitic
		UNCONFORMITY		
Triassic	Upper	Chinle Formation	650-850	Reddish-brown to grayish-blue mudstone and claystone with some silty sandstone; some limestone and gypsum in upper portion; siltstone and conglomeratic sandstone in lower portion
		UNCONFORMITY		
	Lower to Middle (?)	Moenkopi Formation	125-150	Brown to gray calcareous siltstone and mudstone; slightly gypsiferous; very silty
		UNCONFORMITY		
Permian	Lower	Coconino Sandstone	250-325	Light gray to buff, fine- to medium-grained sandstone loosely to firmly cemented with silica
		Supai Formation	1,700?	Reddish-brown sandstone, siltstone, and mudstone; some dolomitic limestone; thick interbedded evaporitic sequence in upper portion
Pennsylvanian (?)				
		UNCONFORMITY		
Precambrian				Crystalline basement rocks

Figure 5. Generalized stratigraphy of sedimentary rocks exposed at the surface and encountered in the subsurface in the Pinta Dome-Navajo Springs area, Apache County, Arizona (From Dunlap, 1969).

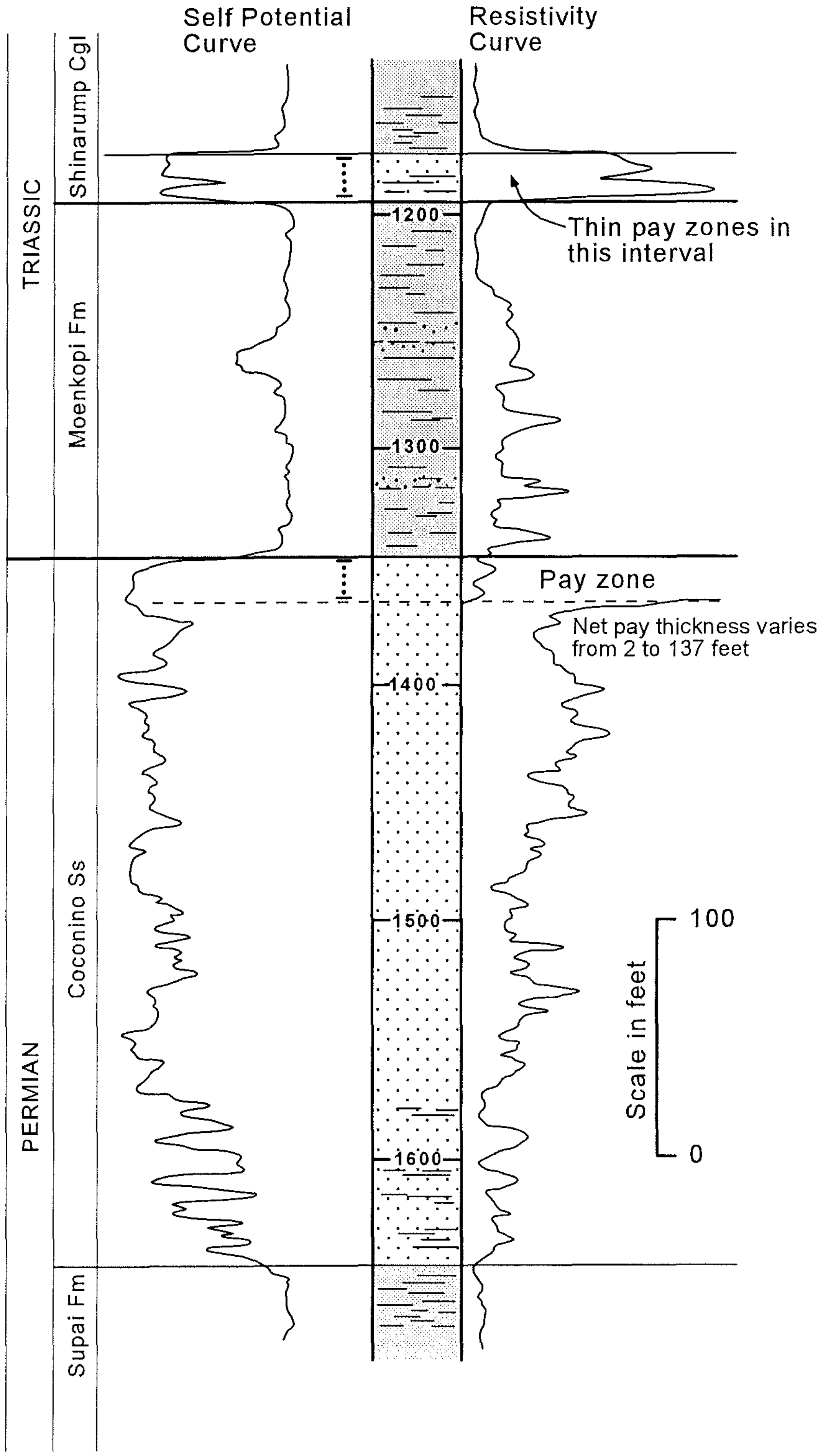

Figure 6. Composite log of Pinta Dome-Navajo Springs-East Navajo Springs pools, showing stratigraphic position of the two gas-productive reservoirs. The Coconino Sandstone produced in all three pools, the Shinarump Conglomerate was productive only in the East Navajo Springs pool. (After Allen, 1978).

Date	Pd 10	Pd 36	Pd 37	Pd 38	Pd 39	Pd 80	Pd 81	Pd 88	Pd 349	Pd 378	Pd 1-72	Field total
1960												0
1961	3763	8587	164	1840	6833						9171	30358
1962	63282	121401	2405	16829	54491	6620	22905	55074			28144	371151
1963	85319	138743	1928	18793	64361	7254	24106	58225			38689	437418
1964	92987	185046	1133	7329	76068	7546	35795	72601			52559	531064
1965	73524	214937	513	2719	99029	9968	40028	89074			61354	591146
1966	44374	146752	41	712	100829	7268	40221	84235	28064		66961	519457
1967	65702	207069		22	90872	4731	55683	94796	94420	266	89180	702741
1968		85697					174122	136091			269948	665858
1969	19334	54348					153303	92914	29179		186300	535378
1970	34246	136654					131502	72489	38446		172348	585685
1971	23500	80979					79593	39142	10082		265419	498715
1972	16640	37601					146902	10320	6480		268543	486486
1973	5893	8260			21163		114739		11718		184948	346721
1974	1272	4862					64219		19662		84912	174927
1975	758	9569					16546		24695		899	52467
1976	98	644					589		3381		5	4717
1977												
Well totals	530692	1441149	6184	48244	513646	43387	1100253	804961	266127	266	1779380	
Field total												6534289

Figure 7. Annual and cumulative production (Mcf) by well permit number at the Pinta Dome (Pd) field. Gas averaged about 8 percent helium. See Figure 3 for location of wells in the field.

DATE	Ns 194	Ns 206	Ns 236	Ns 238	Ns 263	Ns field total	Ens 234	Ens 471	Ens 537	Ens 553	Ens 592	Ens field total	Tw 113
1960													
1961													
1962													
1963													
1964				22606		22606							
1965	62957			50131		113088							
1966	191107			56144		247251							
1967	165738			31304		197042							
1968	92975			45108		138083							174275
1969	86576			22228	6169	114973	5445	7600				13045	211499
1970	155207	7281	2570	14457	701	180216	7873		2492			10365	
1971	205293	6299	14254	17393	3148	246387	5540	862	2569			8971	
1972	219372	21251	31765	9533	8759	290680	3199	15333	3238	11321	365	33456	
1973	223352	12763	38359	2692	6782	283948		18278		12016	626	30920	
1974	207760			2609		210369							
1975	158813			2174		160987							
1976	14918			433		15351							
1977													
Well totals	1784068	47594	86948	276812	25559		22057	42073	8299	23337	991		
Field totals						2220981						96757	385774

Figure 8. Annual and cumulative production (Mcf) by well permit number at the Navajo Springs (Ns), East Navajo Springs (Ens), and Tohache Wash (Tw) fields. See Figures 4 and 10 for well locations.

Date	Pd	Pd total	Ns	Ns total	Ens	Ens total	Tw	Tw total	Arizona	Arizona total
1960										
1961	30358	30358							30358	30358
1962	371151	401509							371151	401509
1963	437418	838927							437418	838927
1964	531064	1369991	22606	22606					553670	1392597
1965	591146	1961137	113088	135694					704234	2096831
1966	519457	2480594	247251	382945					766708	2863539
1967	702741	3183335	197042	579987					899783	3763322
1968	665858	3849193	138083	718070			174275	174275	978216	4741538
1969	535378	4384571	114973	833043	13045	13045	211499	385774	874895	5616433
1970	585685	4970256	180216	1013259	10365	23410			776266	6392699
1971	498715	5468971	246387	1259646	8971	32381			754073	7146772
1972	486486	5955457	290680	1550326	33456	65837			810622	7957394
1973	346721	6302178	283948	1834274	30920	96757			661589	8618983
1974	174927	6477105	210369	2044643					385296	9004279
1975	52467	6529572	160987	2205630					213454	9217733
1976	4717	6534289	15351	2220981					20068	9237801
1977										

Figure 9. Annual and cumulative production (Mcf) at the Pinta Dome (Pd), Navajo Springs (Ns), East Navajo Springs (Ens), and Tohache Wash (Tw) fields. See Figures 10 and 11 for graph of data.

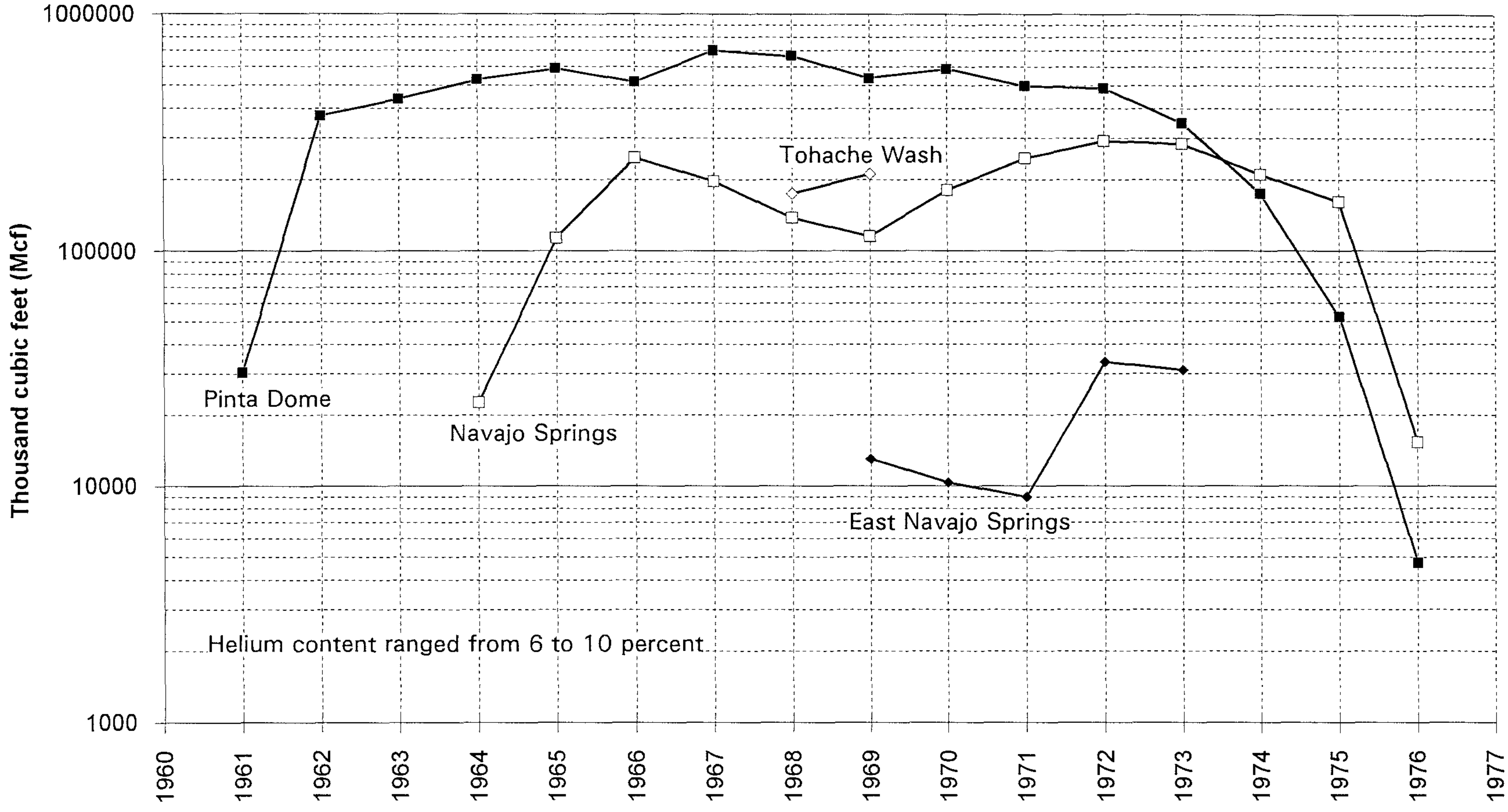

Figure 10. Annual helium production at the Pinta Dome, Navajo Springs, East Navajo Springs, and Tohache Wash fields.

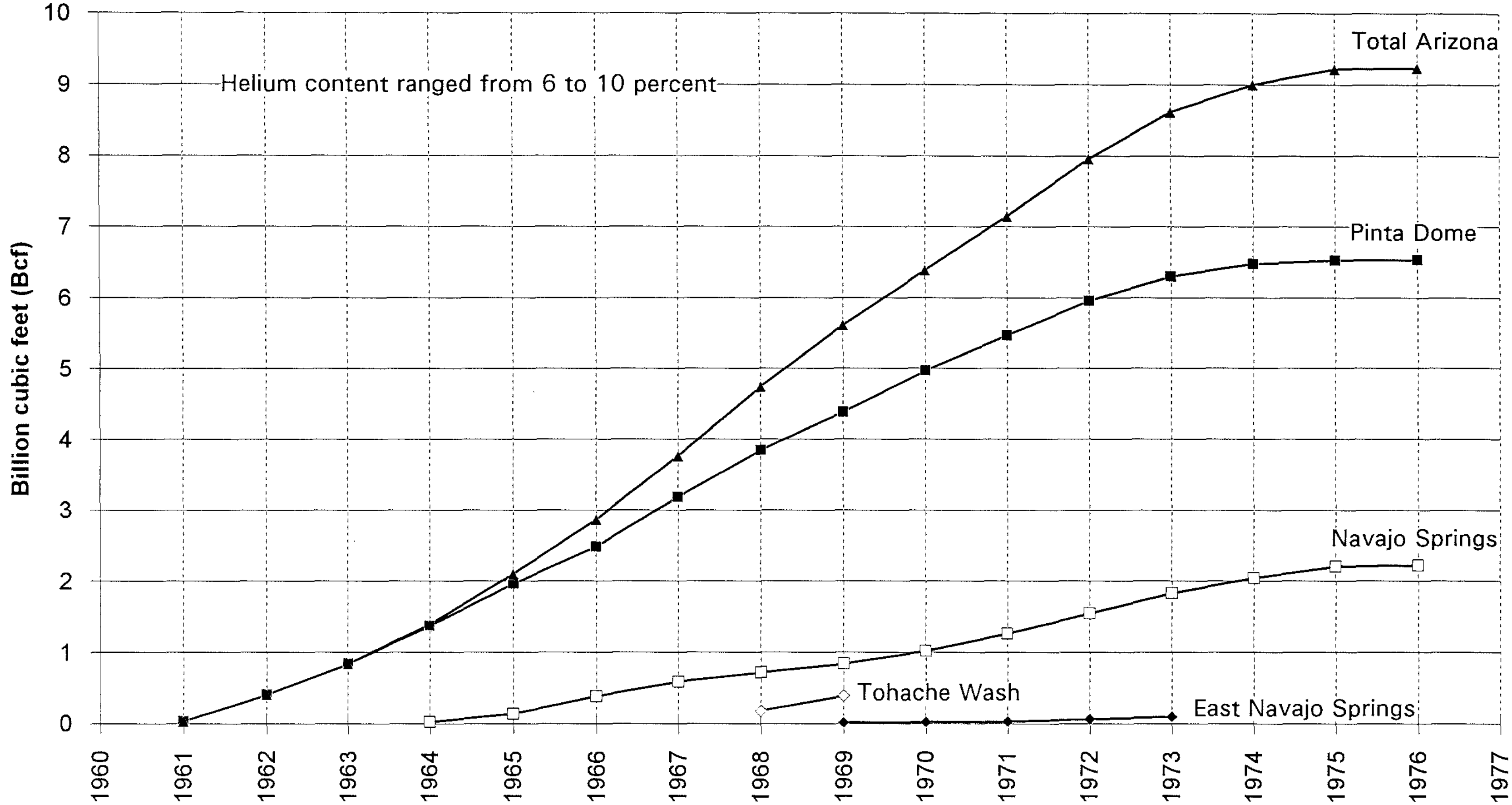

Figure 11. Cumulative helium production at the Pinta Dome, Navajo Springs, East Navajo Springs, and Tohache Wash fields.

Permit	Well	Location	Depth (ft)	Formation	Methane	Ethane	Propane	I-butane	N-butane	I-pentane	N-pentane	Hexanes +	H2S	Nitrogen	HELIUM	CO2	Argon	Hydrogen	Oxygen	Sp Grav	Btu
66	Belcher	09n-31e-20	892	Limestone	0.001	0.1								18.5	0.17	78.7	0.3	t	2.2		2
884	Ridgeway 3-1	11n-29e-03	1536-1676	Supai	0.07	0.05	t	t	t	t	t	t	t	9.75	0.695	89.3	0.12	0.0019	0.049	1.463	2
"	"	"	"	Supai	0.07	t	t	t	t	t	t	t	t	9.91	0.692	89.8	0.12	0.0019	0.049	1.472	2
880	Ridgeway Pc-1	12n-29e-15	1410	Supai	0.1	0.1								9.5	0.81	88.3	0.2	1	0.1	1.448	5
"	"	"	1680	Supai	0.1	0.1								6	0.52	93.1	0.1	0.049	0.005	1.487	2
9-3	Lockhart	14n-20e-33	na	na	23.8	3.2	1.1	0.3	0.3	0.1		0.1	0.1	70.7	0.267	0.1	0.1		t		357
"	"	"	na	na	24.6	3.2	1.5	0.2	0.3		0.1			69.6	0.28	t	0.1	0.1		0.884	372
359	Arkla	16n-23e-27	940-1007	Supai											2.4						
9-23	Great Basin	17n-20e-16	3500	Tapeats										18.98	1.12	79.5					
89	Tucson	18n-20e-30	1556-1630	Supai	3.8	0.3	0.1		0.04					93.4	1.2	0.07	0.1	0.4			48
1-35	Kcl 1	18n-24e-02	963-965	Supai	0.22	t	t							95.1	4.09	t			0.58		
178	Ram 1-9	19n-26e-09	732	Chinle	t		0.2		0.04		0.04	0.1		83.2	2.39		0.7	4.2	9.1		24
"	"	"	"	Chinle	t	t	0.2							85.7	1.55	0.1	0.7	1.2	10.5		9
167	Ram 1-14	19n-26e-14	773	Chinle	t									93.9	5.56	0.1	0.4		t		
143	Teil	19n-26e-22	na	Shinarump										93.7	5.3						
204	Crest	19n-27e-06	1044	Coconino										90.6	8.03	0.8	0.5				
1-72	Kipling	20n-26e-34	780-810		0.85	0.11	0.04		0.06					90.76	6.98	0.26	0.62	0.03	0.29		
"	"	"	1032-1055	Coconino	0.96	0.13	0.06		0.08					89.08	8.09	0.91	0.66	0.03			
"	"	"	1032	Coconino	t									89.8	8.4	1.1	0.6	t	t		
471	Crest	20n-27e-25	1225	Coconino	t									90	8.61	0.7	0.8				
134	Apache	20n-27e-25	1351	Coconino	t									88.9	9.68	0.7	0.7				2
255	Eastern 31	20n-27e-29	na	na										90	8.32	0.89	0.79			0.9065	
258	Eastern 32	20n-27e-28	na	na										89.99	8.34	0.88	0.79			0.9063	
263	Eastern 35	20n-27e-27	na	na										90.08	8.34	0.9	0.6			0.9059	
194	Eastern 13	20n-27e-31	977	Coconino	0.1		0.1	t		t				89.6	8.16	0.9	0.8	t	0.5		4
110	Crest 2	20n-27e-33	1063	Coconino	0.2		0.1							89.9	8.16	0.9	0.7	t	0.1		4.6
234	Apache 21	20n-28e-31	1172	Shinarump	0.1	0.1								80.5	8.71	9.8	0.8				3
234	Eastern 21	20n-28e-31	na	Shinarump										89.5	9.3	0.4	0.8		0.05		
537	Eastern 21a	20n-28e-31	na	Coconino										89.7	8.79	0.7	0.8		0.1		
74	Brown 2	21n-28e-27	542	Coconino	t									93.6	2.3	2.8	1.2				
395	Anadarko	35n-30e-03	na	Devonian	0.14	0.01	0.01	t	t					92.18	6.23	1.43		t		0.923	
393	Humble	35n-30e-08	4532	McCracken	2.2	0.2	0.1		0.2					83.4	5.18	7.8	0.8	t		0.964	35
"	"	"	4663	Aneth	3.4	0.5	0.2		0.2					78.7	5.23	11.1	0.8	t		0.98	55
454	Humble	35n-30e-35	3695	McCracken	0.3		t							90.9	4.81	3.1	0.9			0.947	3
"	"	"	3788	Dolomite	0.2		t							92.6	4.59	1.3	0.9		0.3	0.939	2
"	"	"	3836	Aneth	0.2		t							94.2	3.11	1.6	0.9			0.958	2
401	Humble	36n-29e-23	5223	McCracken	3.1	0.4	0.2		0.1					78.8	5.58	10.6	0.8	t	0.3	0.973	47
421	Humble 1	36n-29e-25	3407	Igneous	23.9	3.8	2.2	0.4	0.7	0.3		0.1		63.8	4.04	0.1	0.6	0.1		0.872	423
"	"	"	3407	Igneous	24	3.7	2.2	0.3	0.6	0.1	0.2	0.1		63.5	4.39	0.1	0.6	0.2		0.865	415
431	Humble 2	36n-29e-25	4580	McCracken	2	0.3	0.1		0.1					78.3	3.49	9.9	0.8		5.1	0.999	32
"	"	"	4580	McCracken	2.6	0.4	0.1		0.2					78.4	4.6	13	0.8			1.003	43
"	"	"	"	McCracken	2.7	0.4	0.1		0.2					78.1	5.16	12.6	0.8		0.1	0.992	44
"	"	"	4626	McCracken	2.7	0.4	0.1		0.3					77.3	5.17	13.8	0.8			1.001	47
146	Atlantic	40n-29e-07	5604	Lwr Miss	11.5	1.5	1.3	0.3	0.4	0.1	0.1	t		76.3	5.1	2.9	0.4		t		209
717	Kenai	40n-29e-07	5562-67	Leadville	11.1	1.4	1.41	0.22	0.5	0.15	0.17	0.27		76.45	4.92	3.41				0.926	223
598	Universal	40n-29e-15	5282	Paradox	80.9	5.2	2.6	0.6	0.9	0.1	0.3	0.3		6.7	0.53	1.7	t		t	0.687	1067
"	"	"	"	Paradox	78.9	5.1	2.7	0.6	0.9		0.5	0.3		8.2	0.51	1.8	0.1		0.5	0.702	1052
"	"	"	5695	Leadville	1.8		1.3							92.5	0.24	2.1	2			0.99	52
"	"	"	"	Leadville	0.4		2.1							93.8	0.28	0.3	3			0.993	59
176	Pan am	40n-29e-15	4881-5042	Paradox	81.81	5.28	2.32	0.34	0.64	0.23	0.23	0.36		7.42	0.73	0.64				0.6691	1029
"	"	"	5665-5739	Leadville	18.36	1.32	0.56	0.23	0.24	0.14	0.15	0.19		70.72	8.07	0.02				0.8649	255
28	Humble	41n-28e-04	5570-5582	Leadville										35.2	4.4	11.2				0.825	
113	Texaco	41n-30e-36	6270-6320	Leadville	32									36	6.03	22					

Figure 12. Gas analyses showing helium content in selected Arizona wells (na = not available, t = trace).

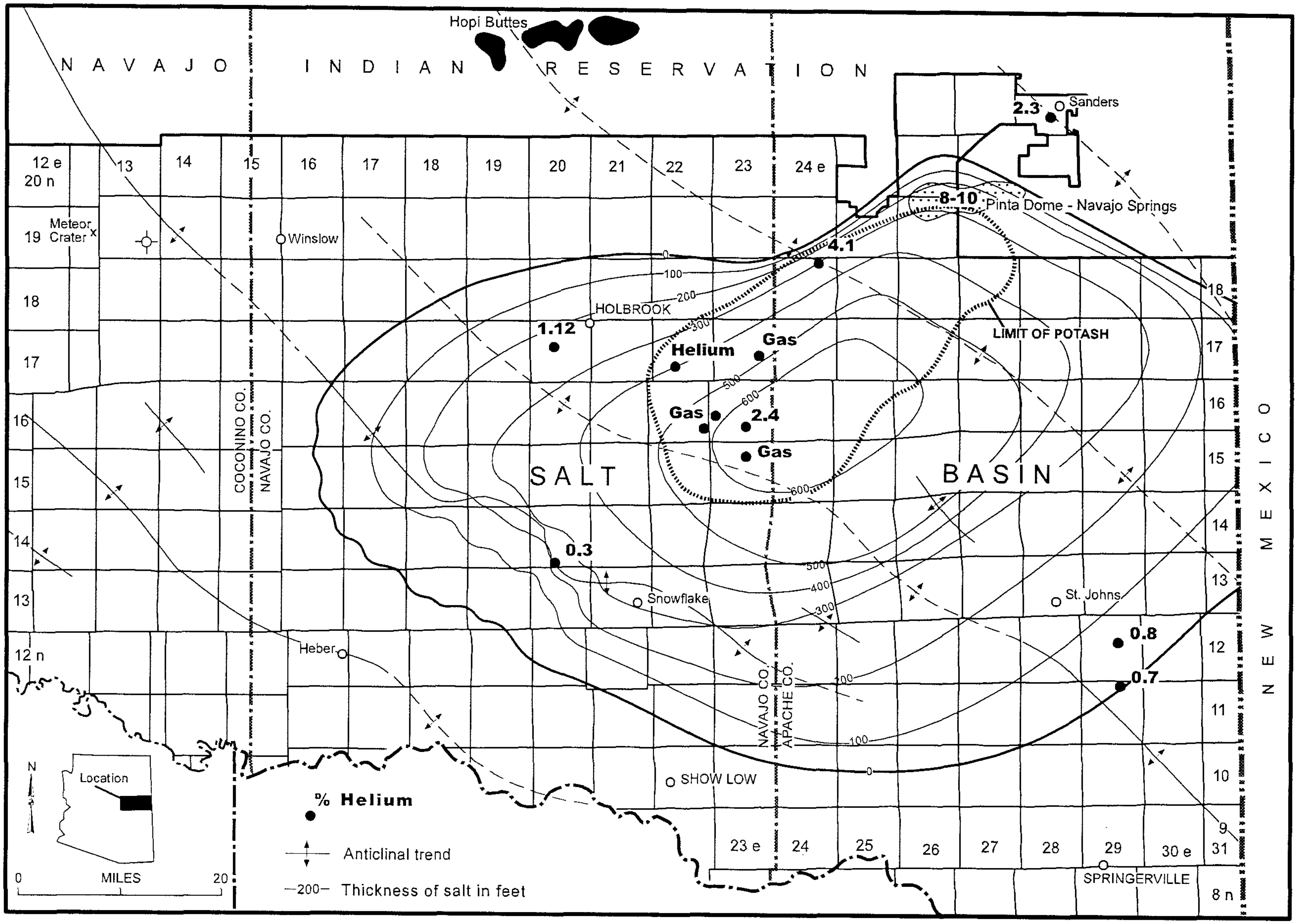

Figure 13. Map showing limit of Holbrook salt basin, aggregate thickness of Permian salt, regional structural trends, and helium content of selected wells in the Holbrook Basin (From Rauzi. 2000, Figure 1). See Figure 1 for regional map.

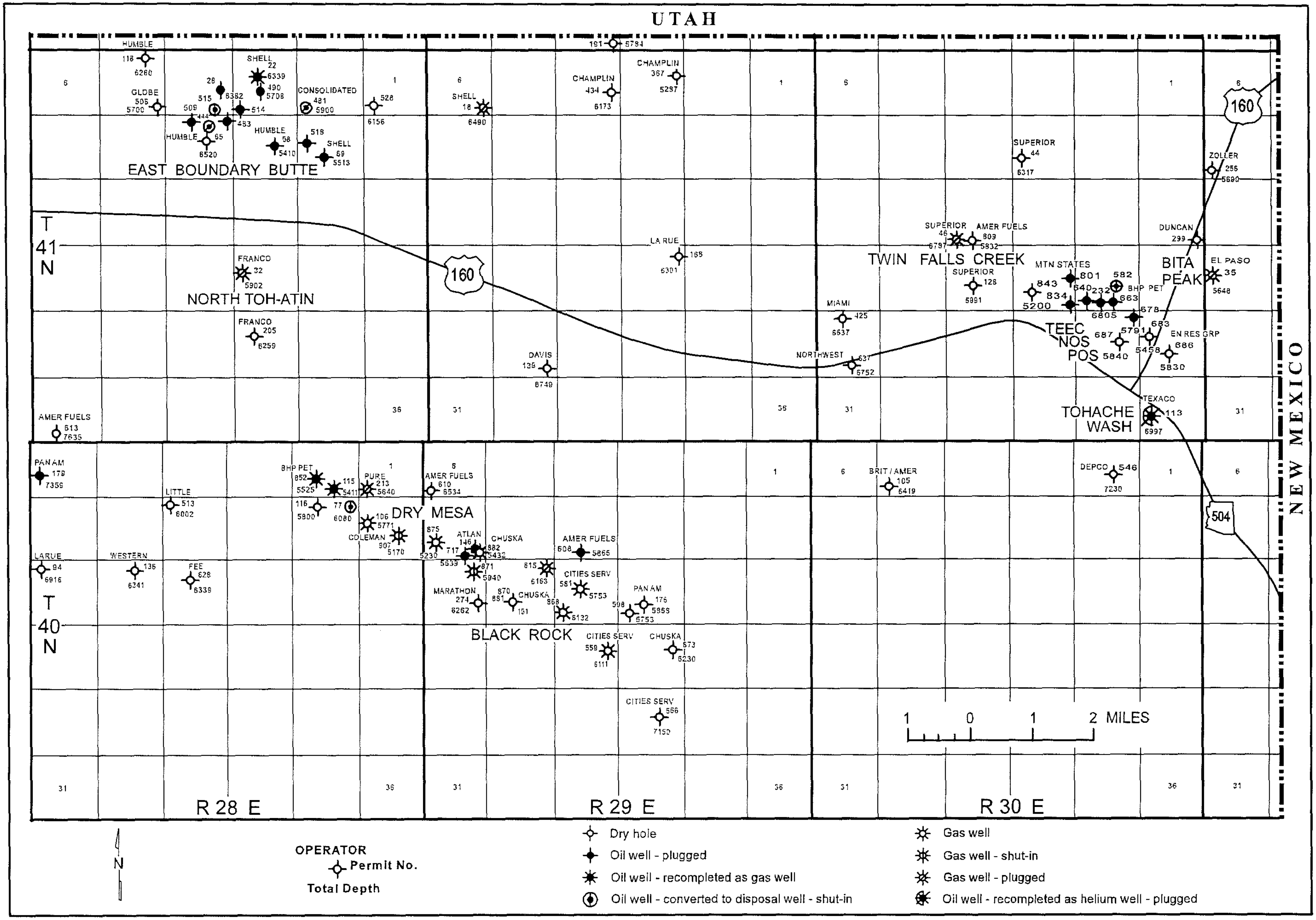

Figure 14. Oil, natural gas, and helium development map, Four Corners area, Arizona (From Rauzi, 2003, Sheet 2, Map A). See Figure 1 for regional map.

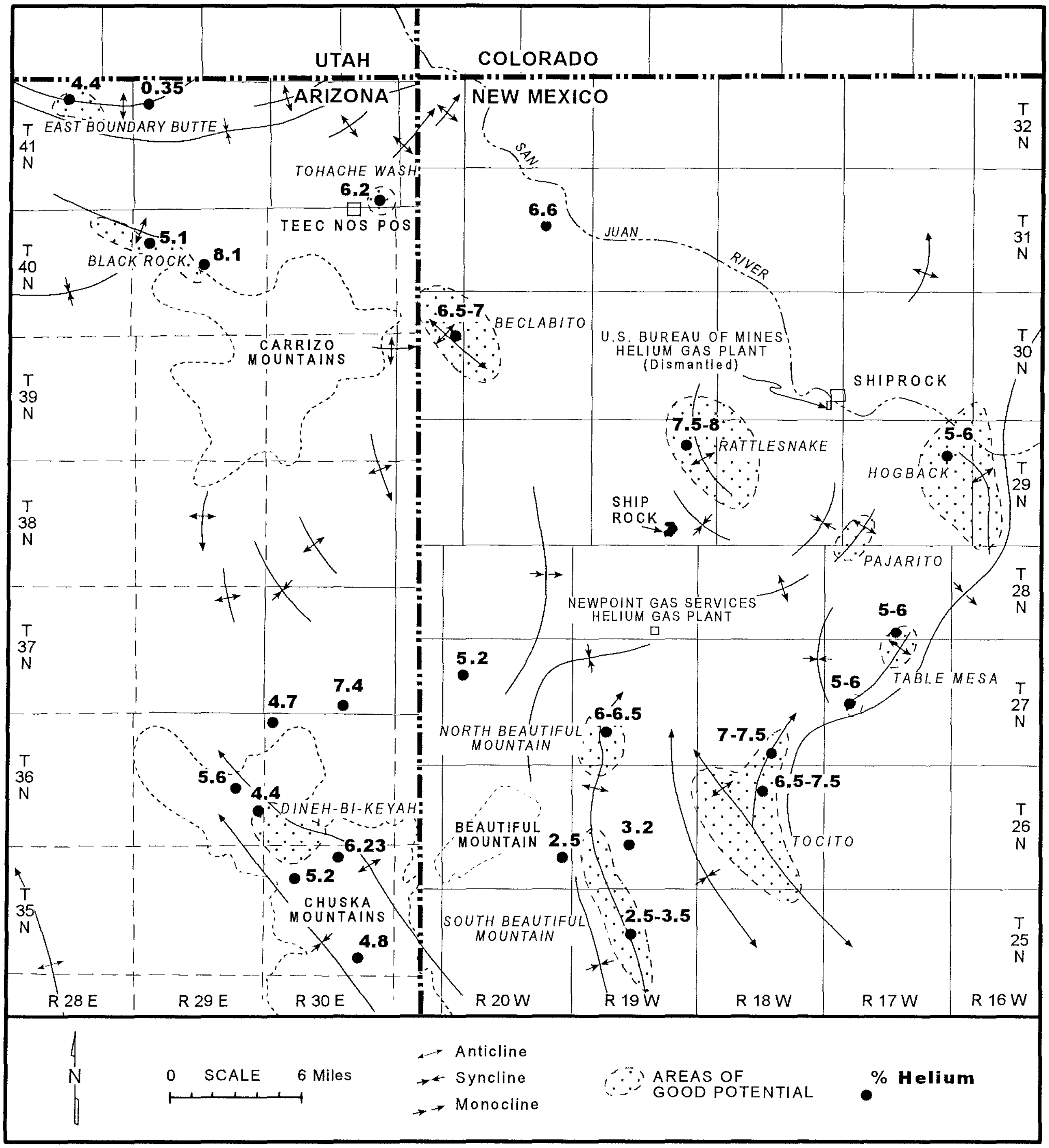

Figure 15. Map showing areas with helium potential and helium content of wells in the Four Corners area of Arizona and New Mexico (Modified after Casey, 1983, Figure 2). See Figure 1 for regional map.

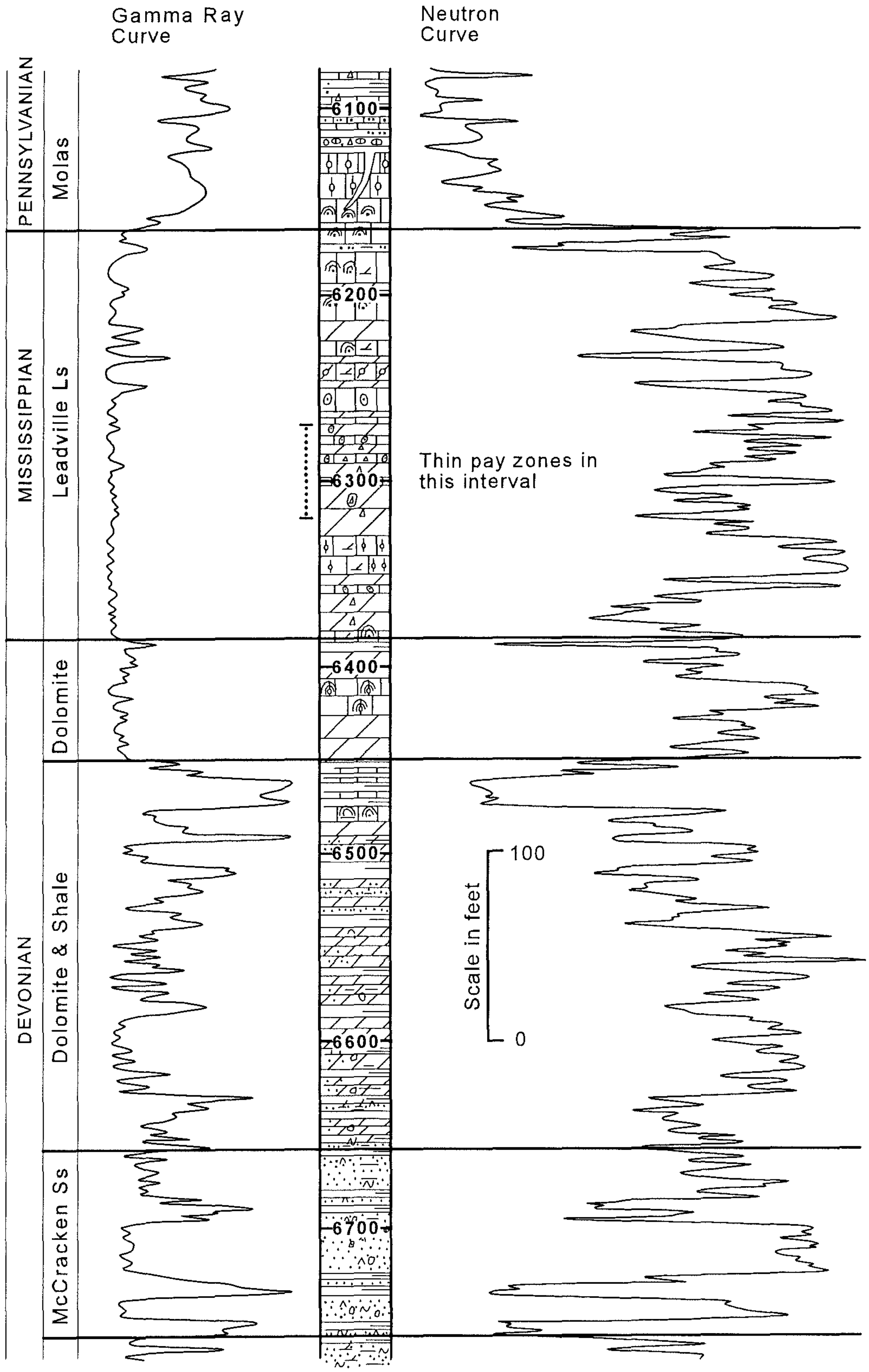

Figure 16. Log of the Texaco Inc. #1 Navajo-Z well showing the stratigraphic position of the helium-bearing reservoir in the Tohache Wash Field. Gas in the Mississippian was 6.03% helium. Cumulative production was 385,774 Mcf. Lithology from Amstrat. See Figure 14 for location of well.

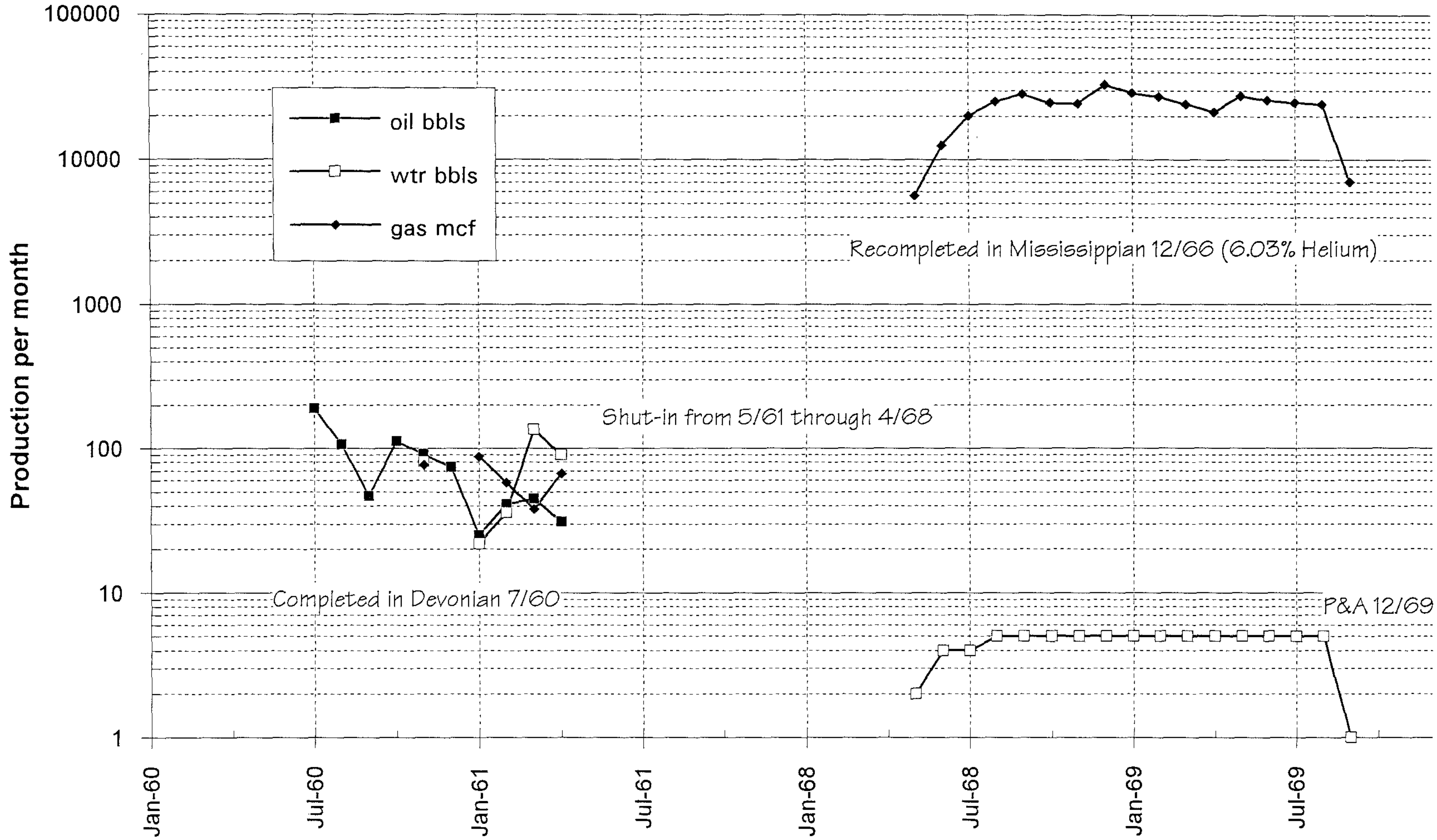

Figure 17. Monthly production at the Texaco 1 Navajo-Z well (Permit 113) in the Tohache Wash field. See Figure 14 for location of well.

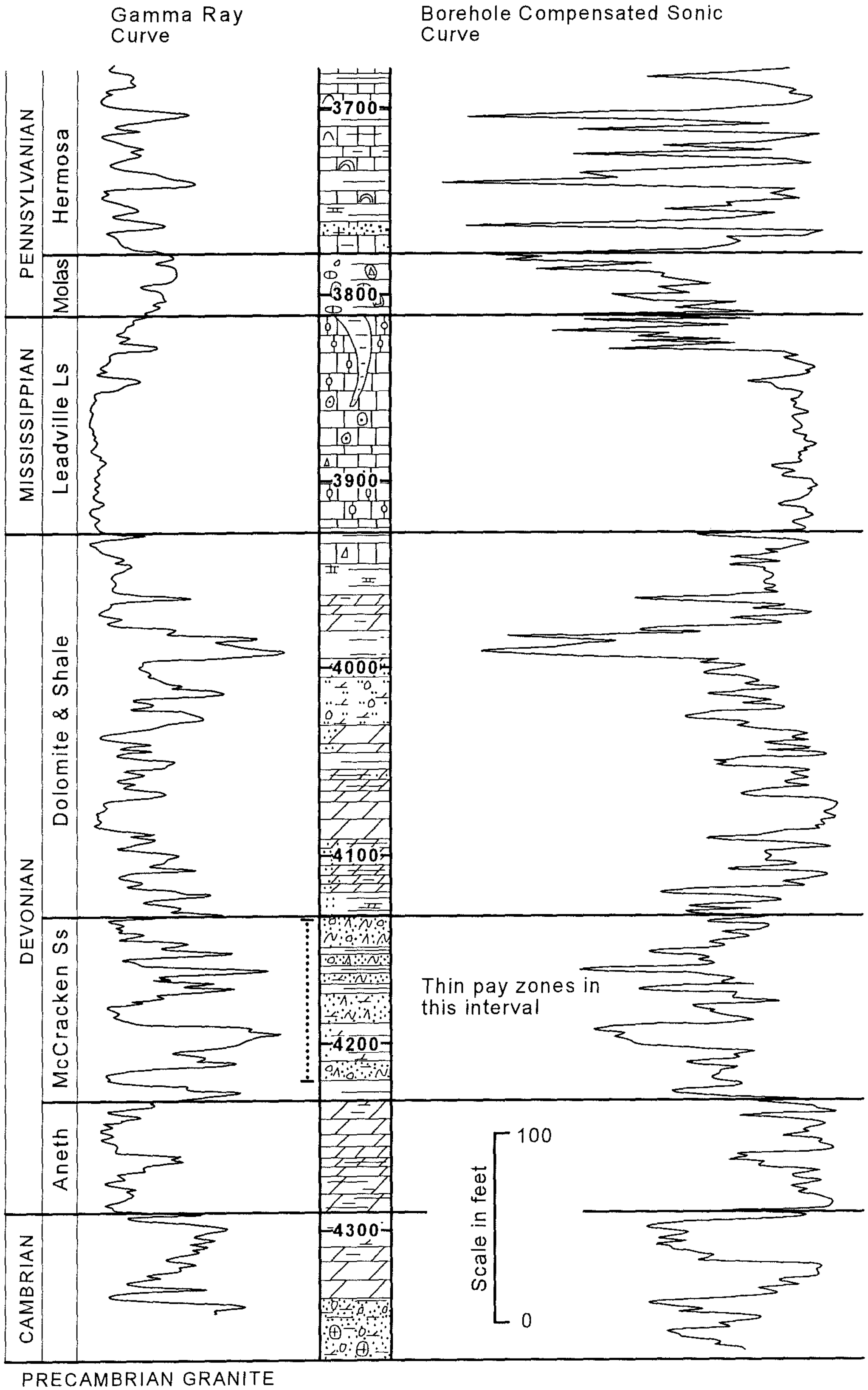

Figure 18. Log of the Kerr-McGee #2 Navajo-C well showing the stratigraphic position of the helium-bearing reservoir in the Dineh-bi-Keyah Field. Gas in the Devonian ranges from 3.11% to 6.23% helium and averages 4.83% helium. Lithology from Amstrat.