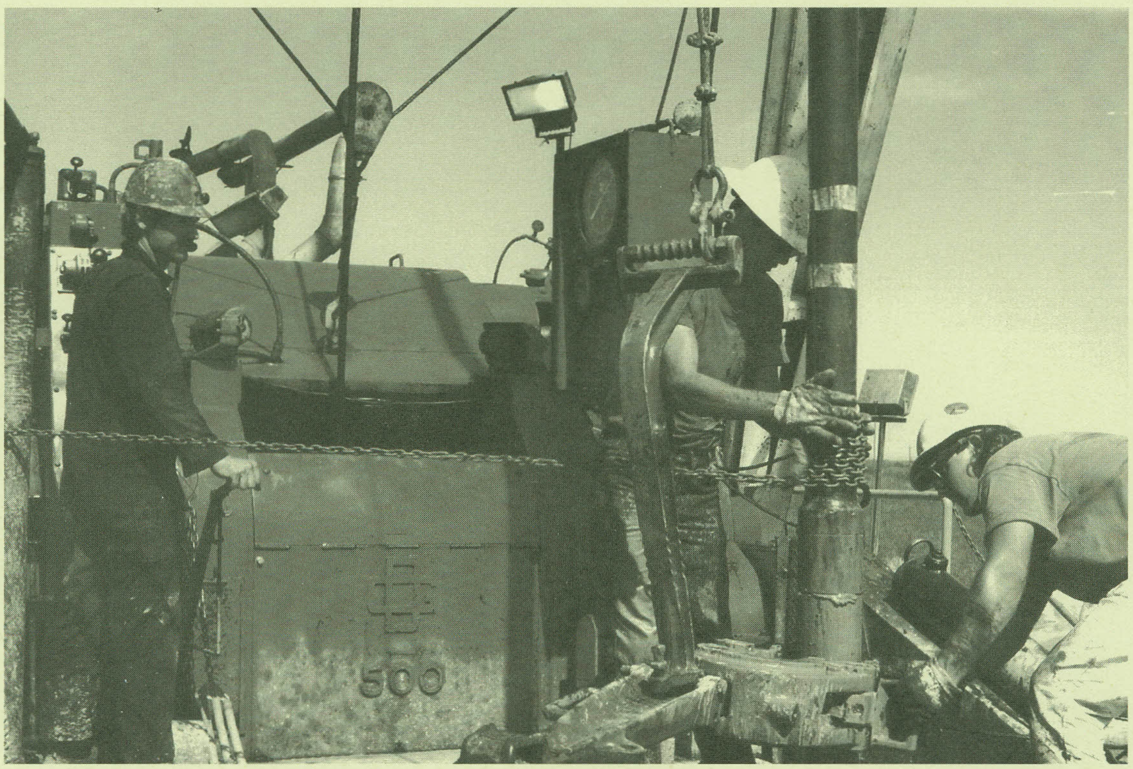
Arizona has Oil & Gas *Potential!*



by

Steven L. Rauzi

Arizona Geological Survey

Circular 29

Oil and Gas Conservation Commission

The Oil and Gas Conservation Commission (OGCC) has statutory responsibility to regulate the drilling for and production of oil, gas, helium, carbon dioxide, and geothermal resources. It consists of five members appointed by the Governor and one ex-officio member, the State Land Commissioner. The OGCC is attached to the Arizona Geological Survey, which provides administrative and staff support. Current OGCC members include J. Dale Nations, Flagstaff, Chairman; Donald C. Clay, Yuma; Robert L. Jones, Sun City West; Zed Veale, Flagstaff; Michael E. Anable, ex-officio member and State Land Commissioner, and one vacancy.

ACTIVITIES

- Conduct regular Commission meetings and special hearings
- Review applications for permits to drill, and approve if properly completed
- Inspect wells for compliance, both during drilling and after completion
- Monitor oil, gas, geothermal, and helium drilling activities
- Compile oil, gas, geothermal, and helium production statistics
- Provide information to the exploration and development communities and the public

Book design and layout by John A. Birmingham

On the cover: *Drilling crew connecting another 30 ft joint of drill pipe to the drill string. Arzon #1 State hole in Sec. 27, T. 13S., R. 30 E., Cochise County, Arizona.* Photo by Steven L. Rauzi.

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Arizona has Oil & Gas Potential!

by

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Foreword

Domestic oil production declined gradually from 3.5 billion barrels in 1970 to 2.2 billion barrels in 1999. The average annual number of drilling rigs in the United States declined from nearly 4,000 in 1981 to fewer than 1,000 in 1986 and reached an historic low of about 625 in 1999. The lowest weekly number of active drilling rigs in the United States since 1940 was 488 in April 1999.

While domestic production declined, the amount of crude oil imported increased steadily since 1985. The United States now imports more foreign oil than ever before. The world crude-oil price is controlled by the Organization of Petroleum Exporting Countries (OPEC). For example, on October 5, 1973 Egypt and Syria, equipped by the Soviet Union, attacked Israel on Yom Kippur. When the United States and other Western countries came to the aid of Israel, the OPEC retaliated by unilaterally raising crude oil prices and cutting production. This was the first oil-supply disruption to cause major price increases and a world energy crisis. Saudi Arabia increased oil production substantially in 1986 causing oil prices to fall almost immediately to less than half of what they were the year before. The domestic petroleum industry, devastated by this sharp drop in oil price, has never fully recovered.

The reality is that the United States is dependent on foreign oil, the price and availability of which are determined by OPEC. To date, the President and members of Congress have been unable or unwilling to look beyond their current terms of office, address the needs of the Nation, and develop a national energy policy.

The crude-oil price increased significantly in 1999 and was sustained throughout 2000. Companies and individuals are looking once again for exploration target areas that have hydrocarbon potential but have not been adequately tested. Abundant evidence suggests that Arizona meets these criteria. Steven L. Rauzi, the author of this report, compiled and summarized this evidence on an area-by-area basis.

In January 1994 the *Oil and Gas Journal* published a brief article Rauzi wrote to describe an oil show in a geothermal test well near Alpine, Arizona. On the basis of that article Ridgeway Petroleum Company drilled an oil test well near St. Johns and discovered carbon dioxide. We believe that other hydrocarbons and associated gases may be present in commercial quantities beneath Arizona. We hope that this publication will provide the incentive for additional exploration.

Larry D. Fellows
Director and State Geologist
Arizona Geological Survey
January 2001

Introduction

Eight areas within Arizona have potential for commercial production of hydrocarbons or industrial gases (Figure 1). In addition, at least 14 Tertiary basins, which have not been adequately tested, contain evidence of hydrocarbon source and reservoir rocks. These conclusions are based on the following evidence: (1) current production of oil and natural gas in the northeastern part of the state, (2) past production of helium in the Holbrook Basin, (3) recent discovery of carbon dioxide in the Holbrook Basin, (4) surface seeps of tar and high gravity oil, (5) outcrops of petroliferous rocks, and (6) shows of oil and gas in wells. The status of drilling and indications of hydrocarbon potential in each area are described in this report.

History of oil and gas production in Arizona

Current production of oil and gas in Arizona (Figure 2) has its roots in the early 1900s when the first wells were drilled specifically in search of oil. The earliest recorded attempt to find oil in Arizona was in 1905 when a well was drilled to a depth of 2,000 ft in the Chino Valley, about 20 miles north of Prescott in Yavapai County. Traces of oil were reported in the well, which was eventually abandoned. Several periods of intense oil speculation and drilling followed this effort. Berg (2000) described several "oil booms" in northern Arizona between 1900-1930. Wilson (1996) described oil exploration in southeastern Arizona in the 1920s and 1930s. Even though oil was the objective and driving force of these early "oil booms," helium, a valuable industrial gas, eventually became the first important commercial discovery in Arizona.

Kipling Petroleum Company discovered helium in the Holbrook Basin in 1950 when it drilled a well in search of oil at Pinta Dome, about 20 miles east of Holbrook. The gas in this well did not burn, so it was allowed to flow unrestricted from the well bore for about 8 weeks (Dean and Lauth, 1961, p. 195). Contemporaneous reports indicated that the helium gas escaping from the open well "roared like a jet engine" at an estimated initial rate of 24 million cubic feet per day. The operator eventually recognized the value of the non-burning gas and shut the well-in to prevent further waste. Commercial production of helium started in 1961, when Kerr-McGee constructed a helium-extraction plant at Navajo, and continued until 1976, when the plant was closed. Nearly 9 billion cubic feet of gas containing more than 700 million cubic feet of 99.9-percent-pure helium were produced from the Pinta Dome and adjacent Navajo Springs and East Navajo Springs fields. Gas, produced from the Coconino Sandstone (Permian), averaged 90 percent nitrogen, 8-10 percent helium, and 1 percent carbon dioxide.

Shell Oil Company discovered the East Boundary Butte field in 1954 when it drilled the #1 Navajo well on the Navajo Indian Reservation in northernmost Apache County. Even though Shell did not establish production

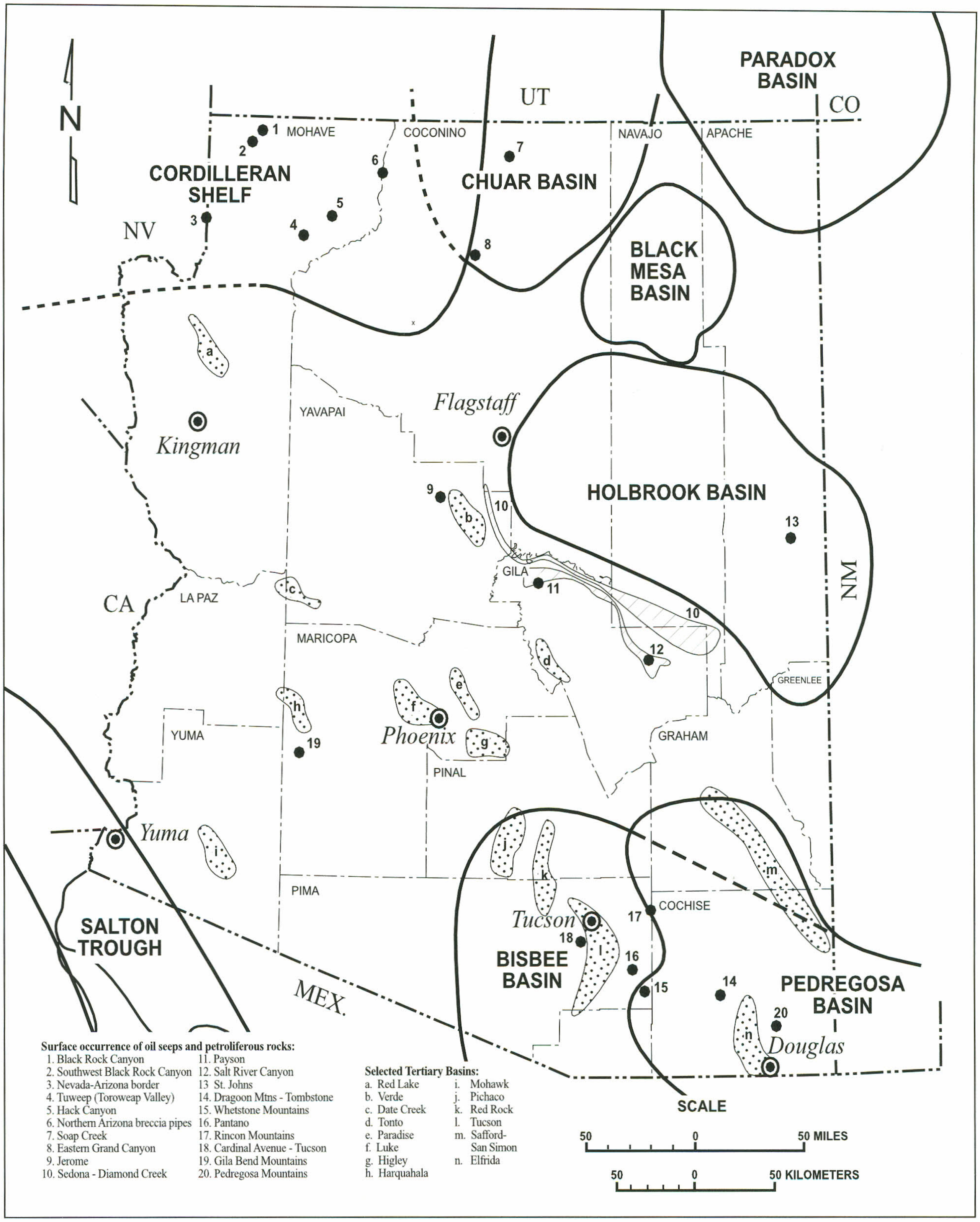

Figure 1. *Areas with oil and gas potential and surface occurrence of oil seeps and petroliferous rocks in Arizona. Numbers refer to locations with surface occurrence of oil seeps and petroliferous rocks described in Table 1. Letters refer to selected Tertiary basins described in text.*

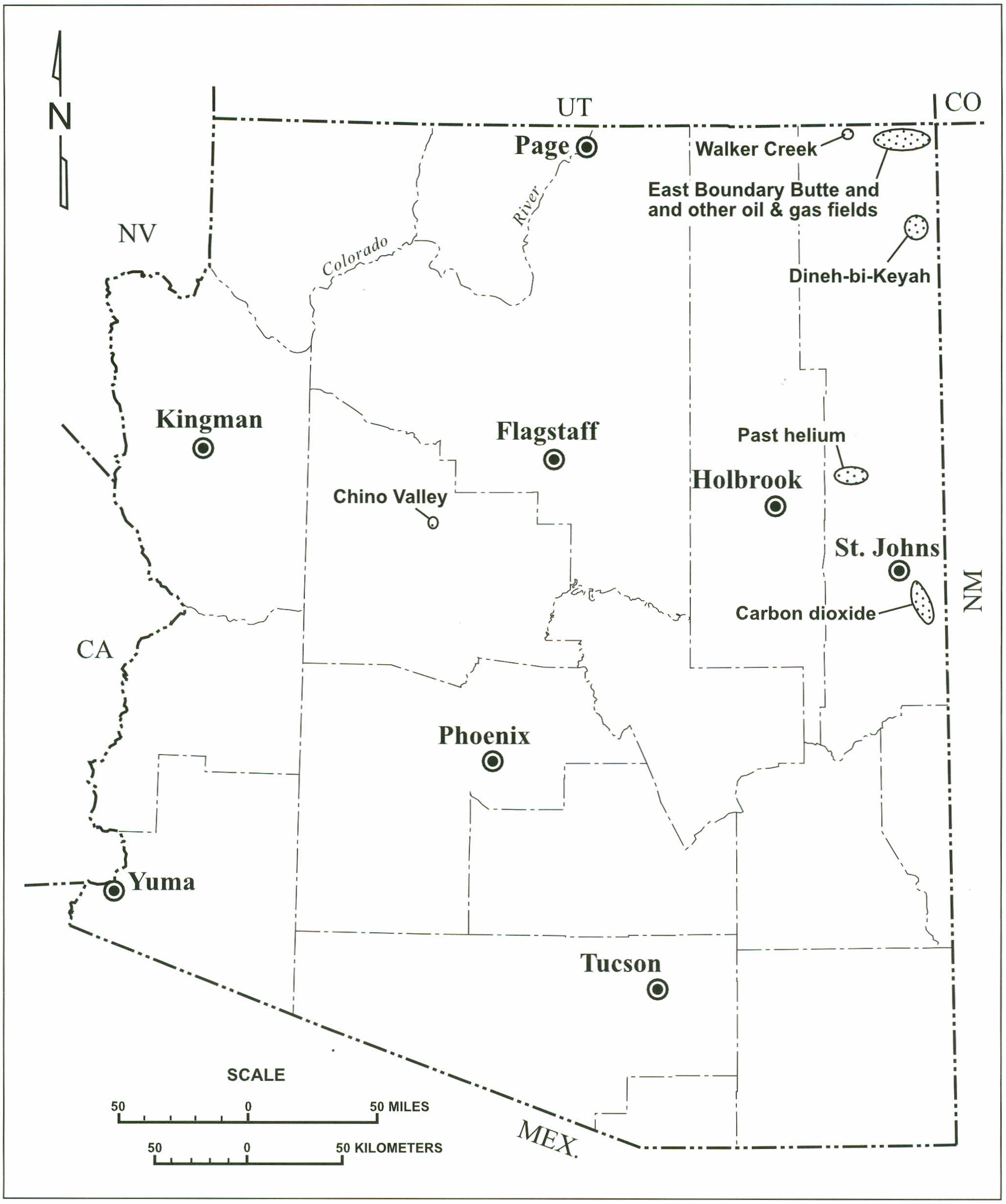

Figure 2. *Location of current and past oil, gas, and helium production in Arizona and of the earliest reported oil test in Chino Valley. See Figure 7 for details of oil and gas fields in northeastern Arizona.*

from the #1 Navajo, it did from a follow-up well, the #2 Navajo. Industry trade journals of the time followed the progress of Shell's #2 Navajo with great interest. The headline in the August 30, 1954 issue of *Oil and Gas Journal* was "Arizona Next? Shell may be ready to add third oil state this year." The headline in the November 1, 1954 issue was "Arizona Is Added, Shell well flowed 11 bbl., 2,200 M.c.f. daily on test." The #2 Navajo marked the first discovery of commercial hydrocarbons in the State of Arizona and was the first producing well in the East Boundary Butte field. Initial production from the #2 Navajo, which was completed as a gas well, was 3.1 million cubic feet of gas and 3.6 barrels of condensate per day from the Paradox Formation (Pennsylvanian age) at depths between 4,500 and 4,700 ft. A total of 13 wells have been drilled in the East Boundary Butte field, which has produced more than 885,000 barrels of oil and 9.8 million cubic feet of gas. All but four of the wells have been plugged. The four remaining wells have been shut-in since late 1998.

Eight small oil and gas pools were discovered near the East Boundary Butte field between 1955 and 1965. All are now abandoned. The most significant oil pool was Walker Creek. Its single well produced 98,000 barrels of oil from the McCracken Formation (Devonian age) before it was abandoned in 1970. The most significant gas pool was Bita Peak. Its single well produced 2.3 billion cubic feet of gas from the Paradox Formation before abandonment in 1969.

Dry Mesa and Teec Nos Pos fields were discovered in 1959 and 1963, respectively. Dry Mesa field produced oil from the Leadville (Redwall) Limestone of Mississippian age from 1959 to 1998. A pipeline was laid from the Dry Mesa field to the adjacent Black Rock field in 1990. By 1998 all of the wells that produced oil from the Redwall Limestone in the Dry Mesa field were plugged back and re-completed to produce natural gas from the overlying Paradox Formation. Dry Mesa field has produced more than 830,000 barrels of oil from Mississippian-age reservoirs and almost 1.5 billion cubic feet of natural gas from those of Pennsylvanian age. Teec Nos Pos field produced more than 486,000 barrels of oil and 1.4 billion cubic feet of gas from the Paradox Formation before it was abandoned in 1990.

Cities Service Oil Company discovered the Black Rock field in 1971. Even though two more wells were drilled in 1972 and 1973, no gas was produced until a pipeline was constructed to the field in 1989. Chuska Energy Company (now Harken Southwest Energy) connected the three shut-in wells to the pipeline in 1989, obtained 160-acre spacing for the Black Rock and adjacent Dry Mesa fields, and drilled several more wells at the Black Rock field. Black Rock field has produced more than 7.5 billion cubic feet of natural gas from the Paradox Formation since 1989.

Kerr-McGee Corporation discovered the Dineh-bi-Keyah field, the most productive oil field in Arizona, in 1967. Initial production from the discovery well, the #1 Navajo, was 634 barrels of oil and 85,000 cubic feet of gas per day from an igneous reservoir rock between 2,860 and 2,885 feet. Production from the #1 Navajo improved to more than 1,800 barrels of oil and 135,000 cubic feet of gas per day after the well was hydraulically fractured with lease oil and sand. Hydraulic fracturing is used to maintain permeability and high production rates. The #1 Navajo, which is still producing, has produced more than 1.1 million barrels of oil and 137 million cubic feet of gas. The best well in the field, the #4 Navajo, initially produced more than 3,000 barrels of oil per day and has produced more than 3.6 million barrels of oil. Dineh-bi-Keyah field has produced more than 18.1 million barrels of oil and 4.7 billion cubic feet of gas. It continues to produce about 5,000 barrels per month.

The Dineh-bi-Keyah field is unique because the producing reservoir is igneous rock of Tertiary (Oligocene) age that was intruded into carbonate and organic-rich, black shale of Pennsylvanian age. The igneous reservoir rock has intercrystalline and fracture porosity and permeability and has reservoir properties similar to those of the host carbonate rocks. This may be the only reservoir of this type in the country. It is unquestionably the best reservoir rock in Arizona. More than 88 percent of the 20.5 million barrels of oil produced in Arizona has come from the Dineh-bi-Keyah field.

In summary, 25 oil and nine gas wells are currently producing 200 barrels of oil and 1 million cubic feet of gas per day from the Black Rock, Dry Mesa, and Dineh-bi-Keyah fields in the northeastern corner of Arizona. Cumulative production from active, shut-in, and abandoned fields is more than 20.5 million barrels of oil, 28.5 billion cubic feet of natural gas, and nearly 740 million cubic feet of 99.9-percent-pure helium.

Carbon dioxide was discovered about seven miles southeast of St. Johns in 1994. Subsequent drilling suggests that much of the area between St. Johns and Springerville has potential for production of carbon dioxide and helium. The gas in the discovery well, analyzed by the U.S. Bureau of Mines, contained about 90 percent carbon dioxide and 0.5 to 0.81 percent helium.

Land status

Arizona is the sixth largest state based on area and encompasses 113,955 square miles. According to AzStats (1996, p. 73) 15.3 percent (17,435 mi^2) is managed by the U.S. Forest Service; 16.7 percent (19,031 mi^2) by the U.S. Bureau of Land Management; 27.3 percent (31,110 mi^2) is Indian Reservations; 12.9 percent (14,700 mi^2) is State Trust; 17.6 percent (20,056 mi^2) is privately owned; and 10.2 percent (11,623 mi^2) is other public lands such as monuments, parks, recreation areas, and military reservations.

The U.S. Bureau of Land Management in Phoenix administers oil and gas leasing on all public lands including forest and other public lands. The Arizona State Land Department in Phoenix administers oil and gas leasing on all State Trust land. The Bureau of Indian Affairs in Phoenix, in cooperation with the individual Indian Nations, administers oil and gas leasing on Indian lands.

Leasing of State Trust land is noncompetitive (over-the-counter), has a five-year primary term with an annual rental of $1.00 per acre, and may be extended through a five-year secondary term with an annual rental of $2.00 per acre. Leasing of public land is competitive (requires acreage of interest to be nominated or receive a pre-sale offer by an interested party and then offered for lease at a public auction) and has a 10-year primary term with an annual rental of $1.50 per acre for the first five years and $2.00 per acre for any year thereafter. Lease terms on Indian or fee (private) land are negotiated directly with the Indian Tribes or fee owners.

Large blocks of State Trust, public, and fee lands are available in several of the areas that have hydrocarbon potential in the state. Indian lands encompass all of northeastern Arizona including all lands in the Paradox and Black Mesa basins and at least half of the land in the Chuar Basin. All current production in Arizona is from Navajo Indian land. Past production of helium was from State Trust and fee land.

Oil field services and supplies

The closest locations for most oil-field drilling, service, and supply companies are Farmington or Artesia, New Mexico (Figure 3). A few companies have used drilling equipment from as far away as California, Texas and Oklahoma, depending on the availability of drilling rigs in New Mexico. El Centro, California is the closest source for field services in southwestern Arizona. Several drilling mud companies in Arizona provide services to companies that drill water wells.

Oil and gas regulation and permitting

The Oil and Gas Conservation Commission (OGCC) regulates oil, gas, helium, carbon dioxide, and geothermal drilling and production in Arizona. The OGCC is attached administratively to the Arizona Geological Survey (AZGS), which provides administrative and staff support for the OGCC. The AZGS reviews drilling applications for compliance with rules, issues permits to drill, and performs wellsite inspections on behalf of the OGCC.

The oil, gas, and geothermal resources rules are part of the Arizona Administrative Code (A.A.C.) in Title 12 (Natural Resources), Chapter 7 (Oil and Gas Conservation Commission). The OGCC has authority to grant requests for variance or exception to many of the general statewide rules after notice and hearing. All requests for a hearing about any matter under the jurisdiction of the OGCC are submitted to the AZGS. The oil, gas, and geothermal rules may be viewed on the Arizona Secretary of State's web page (www.sosaz.com). Paper copies of the rules may be purchased from the Secretary of State's office.

Prior to drilling one must submit an application form, organization report, surety or cash bond, drilling prognosis, and a small application fee. These requirements are described in A.A.C. R12-7-104 (Application for Permit

The southern part of the Colorado Plateau makes up the northeastern 40 percent of Arizona. It 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. A prominent escarpment known as the Mogollon Rim defines much of the southern edge of the Plateau province. Butler (1988) identified and described seven oil and gas plays with good potential in northern Arizona based on potential source and reservoir rocks, geothermal maturity, trap development, and migration and timing. All current production of oil and natural gas, past production of helium, and the recent discovery of carbon dioxide are from rock formations in the Plateau province.

The Basin and Range makes up the southwestern 40 percent of the state. It is characterized by folded and faulted igneous, metamorphic, and marine sedimentary rocks of Precambrian to Mesozoic age that are exposed in north- to northwest-trending, linear mountain blocks (ranges). The mountains are separated by wide, deep valleys (basins) that are filled largely with alluvial sand and gravel of Tertiary to Recent age. Sediment in the basins was derived from weathering of the adjacent range blocks. Several of the deep basins contain thick deposits of lacustrine mudstone, carbonate, anhydrite, and salt of Tertiary age. At least two of the Tertiary basins contain at least 10,000 ft of salt, which is solution-mined for industrial purposes and used to store liquefied petroleum gas (LPG) near Phoenix. No wells have yet penetrated the entire thickness of salt in these basins. The Tertiary basins in southwestern Arizona contain marine deposits. Butler (1989) identified and described at least four potential hydrocarbon plays in Paleozoic and Tertiary strata in southern Arizona.

The Colorado Plateau and Basin and Range provinces are separated by a central mountainous region or "transition zone" that extends southeastward across the state from the Grand Wash Cliffs near Lake Mead to the New Mexico border near the White Mountains. This subprovince, known as the Transition Zone, averages 50 miles in width (Peirce, 1985) and includes at least two Tertiary basins, which have not been conclusively drilled for oil and gas.

Seeps, petroliferous rocks, and oil and gas shows in wells

Surface seeps, petroliferous rocks, and shows of oil and gas in wells confirm the existence of organic-rich rocks in the subsurface that are capable of generating oil and gas. The surface seeps and shows suggest that oil and gas have migrated through the rocks. If oil and gas have migrated through subsurface rocks, some may have been trapped as well. The challenge is to find the traps.

Surface seeps, outcropping petroliferous rocks, and shows of oil and gas in wells are common in some parts of Arizona. Locations of the known surface seeps and petroliferous rocks are shown in Figure 1 and tabulated and described in Table 1. Surface seeps, present at several places in northwestern and at least one locality in central Arizona, are commonly characterized by tar in fractures or along bedding planes of the host rock. The host rock fluoresces under long-wave ultraviolet light and yields a good coffee-colored cut and strong, milky-white to milky-yellow cut fluorescence in 111-trichloroethane. Petroliferous rocks crop out in the eastern Grand Canyon, along the Mogollon Rim, in many places in southeastern Arizona, and at least one locality in southwestern Arizona. The petroliferous rocks are characterized by a strong odor of petroleum on freshly broken surfaces. When crushed, these rocks generally yield a faint milky-white cut fluorescence in 111-trichloroethane, which indicates the presence of petroleum.

Holm (1938), Bahr (1962, p. 121), Peirce and Wilt (1970, Table D), Peirce and Scurlock (1972), Thompson and others (1978, Table 2), Conley and Giardina (1979, Tables D, E, and F), Giardina (1979, Table 2), Butler (1989, Table 3), and Petzet (1997, p. 85) compiled and described oil and gas shows that were reported in Arizona wells. Rauzi discussed the implications of bleeding oil in a geothermal core south of Springerville (1994, p. 11) and described shows of oil and gas in several wells that were drilled for potash in the Holbrook Basin (2000, p. 18-19).

Table 1. Surface occurrences of oil seeps and petroliferous rocks in Arizona. Numbers correspond to locations shown on Figure 1.

(1) Black Rock Canyon

Location:	About 15 miles south of Hurricane, Utah, in Secs. 3, 10, and 15, T. 40 N., R. 13 W. (township unsurveyed) and Secs. 11, 14, 23, 26, and 35, T. 41 N., R 13 W. in northwestern Mohave County.
Description:	Oil-impregnated Kaibab Limestone (Permian), immediately beneath the overlying Moenkopi Formation (Triassic) red beds. The asphalt is in seams, veins, and along the formation contact, particularly where the contact is irregular. Irregularities are filled with sediment from the Moenkopi. The asphalt appears to have migrated from below and impregnated the sediment filling an old karst surface on the Kaibab.
References:	Bassler and Reeside, 1922, p. 105; Swapp, 1961, p. 38; Ball Associates, 1964.

(2) Southwest Black Rock Canyon

Location:	In northwestern Mohave County in Secs. 17-18, T. 40 N., R. 13 W. (unsurveyed).
Description:	A crushed zone in the Moenkopi Formation (Triassic), 100 ft wide, with bituminous material in veins and other openings.
References:	Bassler and Reeside, 1922, p. 105; Ball Associates, 1964.

(3) Nevada-Arizona border near south end of Virgin Mountains

Location:	Just west of the Arizona border at the north end of Whitney Ridge in T. 15 S., R. 71 E.; White (Azure) Ridge in T. 19 S., R. 71 E. (unsurveyed); and Tramp Ridge in T. 18 & 19 S., R. 70 E. (unsurveyed) in Clark County, Nevada.
Description:	Petroliferous carbonate in Cambrian, Ordovician, Devonian, Pennsylvanian, and Permian rocks. Oil residue in bedded porous dolomite of the Toroweap Formation (Permian). Petroliferous Triassic carbonate that commonly contains black tarry hydrocarbons and some small bioherms that are saturated with bitumen.
References:	McCarthy, 1939; Bissell, 1969, p. 146, 159-160.

(4) Tuweep (Toroweap) Valley

Location:	In northern Mohave County in Sec. 10, T. 34 N., R. 7 W.
Description:	Petroliferous dolomite in the Woods Ranch Member of the Toroweap Formation (Permian).
References:	Rawson and Turner, 1974, p. 170; Rawson, 1974.

(5) Hack Canyon

Location:	In northern Mohave County in Sec. 22, T. 35 N., R. 5 W.
Description:	Petroliferous dolomite in the Woods Ranch Member of the Toroweap Formation (Permian).
References:	Hendricks, 1973; Rawson and Turner, 1974, p. 170; Rawson, 1974.

Table 1 (continued). Surface occurrences of oil seeps and petroliferous rocks in Arizona. Numbers correspond to locations shown on Figure 1.

<u>(6) Northern Arizona Breccia Pipes</u>

Location:	In northeastern Mohave and northwestern Coconino Counties in breccia pipes clustered near Snake Gulch and Kanab Creek in T. 38 N., R. 2-4 W.
Description:	Irregularly shaped pieces of solid, black, glassy bitumen associated with clasts of the Hermit Shale and Esplanade Sandstone (Permian). Some similarities exist between bitumens in the Chuar Group and the breccia pipes.
Reference:	Wenrich and Palacas, 1992, p. 40 and 49.

<u>(7) Soap Creek</u>

Location:	In northern Coconino County in Sec. 34, T. 39 N., R. 6 E.
Description:	Petroliferous dolomite in the Woods Ranch Member of the Toroweap Formation (Permian).
References:	Rawson and Turner, 1974, p. 170 and plate 3c; Rawson, 1974.

<u>(8) Eastern Grand Canyon</u>

Location:	In north-central Coconino County on the northeastern flank of Nankoweap Butte in the protracted NE/4 Sec. 8, T. 33 N., R. 5 E. and in Lava Canyon in the protracted W/2 Sec. 23, T. 32 N., R. 5 E.
Description:	Laminated algal dolomite with petroleum odor and thinly laminated, carbonaceous black shale with organic odor in the Walcott Member of the Kwagunt Formation (Precambrian) on Nankoweap Butte. Petroliferous dolomite in the Jupiter Member of the Galeros Formation (Precambrian) in Lava Canyon. The total organic carbon content of the black shale of the Walcott Member ranged up to 8.29 percent.
References:	Personal observation; Wiley and others, 1998, p. 75 and 78.

<u>(9) Jerome</u>

Location:	On the road between Clarksdale and Jerome in Sec. 23, T. 16 N., R. 2 E.
Description:	Petroliferous dolomite and limestone of the Martin Formation (Devonian).
Reference:	J. Dale Nations, 2000.

<u>(10) Sedona-Diamond Creek</u>

Location:	From Sedona in T. 17 N., R. 6 E., Coconino County, southeast along the Mogollon Rim to Diamond Creek in T. 6 N., R. 23 E., Apache County.
Description:	A 110-mile outcrop of the Fort Apache Member of the Supai Formation (Permian) smells strongly of petroleum and shows an oil sheen on fresh fractures for most of its length.
References:	Huddle and Dobrovolny, 1945; Turner, 1958a; Pye, 1961, p. 49; Ball Associates, 1964.

Table 1 (continued). Surface occurrences of oil seeps and petroliferous rocks in Arizona. Numbers correspond to locations shown on Figure 1.

(11) Payson	
Location:	About seven miles northwest of Payson on State Highway 87 in Sec. 17, T. 11 N., R. 10 E. (unsurveyed), one-half mile west of the East Verde River Bridge in Gila County.
Description:	An oil seep, reportedly 40-50° API gravity oil, from an outcrop along the bank of a creek. The Martin Limestone (Devonian) is petroliferous (has strong petroleum odor) on fresh breaks at many localities between Payson and Salt River Canyon. Rocks at the seep contain asphalt in fractures.
References:	Turner, 1958b, p. 71; Cooley and Johnson, 1962, p. 35; Ball Associates, 1964; Somers, 1994; Petzet, 1997, p. 85.
(12) Salt River Canyon	
Location:	Roadcut of Arizona Highway 77 north of Salt River in W/2 Sec. 20, T. 5 N., R. 18 E. (unsurveyed) and measured section at the Prochnow mines in Sec. 25, T. 5 N., R 18 E.
Description:	Dark brown dolomitic limestone of the Martin Formation (Devonian) that emits a strong petroliferous odor and yields a faint cut fluorescence in 111-trichloroethane. Dark gray shaly mudstone has a total organic carbon content of 2.81 percent.
References:	Personal observation; Huddle and Dobrovolny, 1945; Huddle and Dobrovolny, 1952; Desborough and others, 1984, p. 51 and 54.
(13) St. Johns	
Location:	In outcrops along the Little Colorado River in T. 13 N., R. 28 E., Apache County.
Description:	An oil seep and oil-stained Coconino Sandstone (Permian). Freshly broken sandstone has the odor of petroleum.
References:	Turner, 1958a; Ball Associates, 1964.
(14) Dragoon Mountains-Tombstone Area	
Location:	In the Dragoon Mountains and near Tombstone in Cochise County.
Description:	Martin Limestone (Devonian) is reported to be petroliferous on the outcrop in the Dragoon Mountains near Tombstone. Also near Tombstone the Earp and Colina limestones and the Epitaph Dolomite (all Permian) are reported to be petroliferous in outcrops.
Reference:	Buck, 1961, p. 24 and 26.

Table 1 (continued). Surface occurrences of oil seeps and petroliferous rocks in Arizona. Numbers correspond to locations shown on Figure 1.

(15) Whetstone Mountains

Location:	In Apache Canyon in T. 18 S., R. 18 E. in Pima County
Description:	The base of the Cretaceous section is composed of black shale, some of which give a distinct test for petroleum (faint cut fluorescence in 111-trichloroethane).
References:	Personal observation; Butler and Tenney, 1931, p. 43.

(16) Pantano

Location:	About one mile south of Interstate 10 in SE/4 Sec. 3, T. 17 S., R. 17 E. in Pima County
Description:	Petroliferous limestone in Pantano Formation (Miocene-Oligocene age).
References:	Grimm, 1978, p. 64; Heylmun, 2000.

(17) Rincon Mountains

Location:	Several localities in T. 13 S., R. 18 E. on the east flank of the Rincon Mountains in Pima County.
Description:	Petroliferous limestone of Mineta Formation (Miocene-Oligocene age). The rock is also uraniferous.
References:	Chew, 1952, p. 17, 19, 51; Chew, 1962, p. 38; Clay, 1970, p. 48; Scarborough, 1981, p. 83; Heylmun, 2000.

(18) Cardinal Avenue, Tucson Basin

Location:	In southwest Tucson just south of the intersection of Cardinal Avenue and Valencia Road in Secs. 16 and 17, T. 15 S., R. 13 E. in Pima County.
Description:	Petroliferous limestone of Miocene-Oligocene age. The rock is also uraniferous.
References:	Personal observation; Grimm, 1978, p. 5 and 67; Heylmun, 2000.

(19) Gila Bend Mountains

Location:	In Sec. 30, T. 2 S., R. 9 W. (unsurveyed) in Gila Bend Mountains in western Maricopa County.
Description:	Petroliferous thin-bedded limestone of early Miocene to late Oligocene age.
Reference:	Heylmun, 2000.

Table 1 (continued). Surface occurrences of oil seeps and petroliferous rocks in Arizona. Numbers correspond to locations shown on Figure 1.

(20) Pedregosa Mountains

Location:	Walnut Spring on north slope of hills on south side of Leslie Canyon in T. 21 S., R. 28 E. in Cochise County. Spring located in outcrop of Cretaceous sandstone striking N. 60° W., dipping 55° SW.
Description:	Said by William Hunsaker (Hunsaker Ranch) to have seeped oily material about four years ago [circa 1934] when spring was fresh.
Reference:	Holm, 1938, Appendix p. vi.

Well files and sample cuttings maintained by the Arizona Geological Survey, detailed sample-analysis logs of the American Stratigraphic Company (Amstrat), and databases of Petroleum Information / Dwights document the reported shows of oil and gas and drill-stem-test results in wells. Most shows are described as oil stains on grains and along fractures, as fluorescence and cut fluorescence in drilling mud and on rock fragments, or as blows or bubbles of gas in drilling mud. Stronger shows are described as residual or dead oil in pores of the rock, films or rainbows on drilling mud, or as oil bleeding from fractures in conventional cores. The strongest shows are reported as gas blow-outs while drilling or as free oil and oil-cut mud recovered from tests performed during or shortly after drilling.

Areas with Hydrocarbon Potential

Areas with hydrocarbon potential include thick accumulations of untested rocks that contain organic-rich layers capable of generating oil and gas (source rocks), and porous and permeable layers capable of holding commercial accumulations of oil and gas (reservoir rocks). Oil and gas are trapped in porous layers where impermeable layers, such as shale or salt, seal the porous layers over folds or against faults (structural traps) or when porous layers change laterally into impermeable layers or extend into regional unconformities (stratigraphic traps).

Areas with hydrocarbon potential are present in several sparsely drilled parts of Arizona (Figure 1). Drilling density in the State of Arizona and the Holbrook Basin is about one well per 100 square miles. For the Black Mesa, Pedregosa, and Bisbee basins it is closer to one well per 250 square miles.

Eight areas within Arizona are considered to have the best potential for additional oil, natural gas, helium, or carbon dioxide discovery. Each area contains potential source and reservoir rocks, seeps or petroliferous rocks, or wells with shows of oil or gas. Some contain all three. One has current oil and gas production. One has past production of helium and a recent discovery of carbon dioxide. It is important to note that oil and gas potential exists among the eight identified areas to the same extent that the strata of one region extend into another.

The eight areas with the best oil and gas potential (Figure 1) are, from north to south, (1) the Cordilleran shelf in northwestern Arizona, (2) Chuar Basin in north-central Arizona, (3) Paradox Basin and (4) Black Mesa Basin in northeastern Arizona, (5) Holbrook Basin in east-central Arizona, (6) Pedregosa and (7) Bisbee Basins in southeastern Arizona, and (8) the Yuma Basin (Salton Trough) in southwestern Arizona. At least 14 Tertiary basins have hydrocarbon potential in the Basin and Range Province.

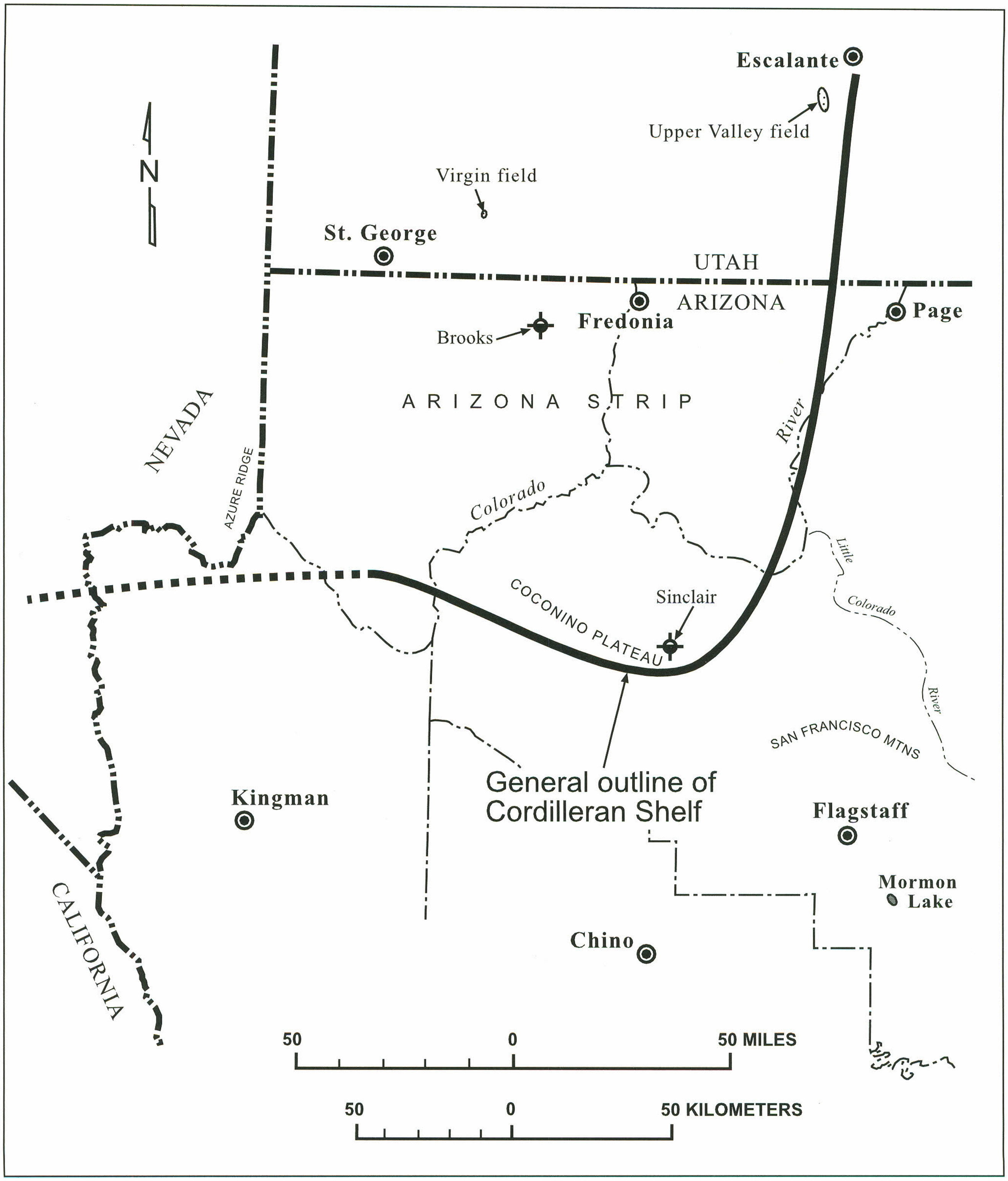

Figure 5. *General outline of the Cordilleran Shelf showing location of features discussed in the text.*

Cordilleran Shelf

The Cordilleran shelf in northwestern Arizona includes the Arizona Strip, which is between Grand Canyon and Utah, and the Coconino Plateau south of Grand Canyon (Figure 5). This area contains Paleozoic and Triassic rocks that grade from basin or deep marine origin on the west to shelf or shallow marine origin on the east. The truncated Cambrian and Ordovician units in the westernmost part of the Arizona Strip and the common facies changes from carbonate to clastic beds across the Arizona Strip and Coconino Plateau are favorable for stratigraphic and structural accumulations of oil and gas. Paleozoic strata beneath the Coconino Plateau are considered prospective as far south as Chino Valley and as far southeast as the Mormon Lake area. Local, abrupt structural and stratigraphic traps may be present in this region and in undrilled Paleozoic strata beneath the volcanic rocks of the San Francisco Mountains.

Strata equivalent to the Upper Paleozoic rocks (Kaibab Formation of Permian age) in the Arizona Strip have produced more than 20 million barrels of oil in south-central Utah from the Upper Valley field. Strata equivalent to the Triassic rocks in the Arizona Strip have produced oil from the Virgin field in southwestern Utah.

Evidence of hydrocarbons and potential hydrocarbon source rocks within the Arizona Strip include surface seeps of tar in fractures and along bedding planes in Triassic rocks, solid, black bitumen in clasts of Permian rocks in the numerous breccia pipes throughout the area, and petroliferous rocks in most of the Paleozoic units [Table 1 (1-7)]. The bitumen associated with clasts of Permian rocks in the breccia pipes are of particular interest because Wenrich and Palacas (1992, p. 49) reported similarities between the Chuar Group (Precambrian) and the breccia-pipe bitumens. McCarthy (1939) reported petroliferous limestone and dolomite in Cambrian, Ordovician, Devonian, Mississippian, Pennsylvanian, and Permian rocks exposed on Whitney and Azure Ridges just west of the Arizona border in Nevada. Bissell (1969, p. 159-160) reported black tarry hydrocarbons and hydrocarbon-saturated bioherms in Triassic carbonate units just west of the Arizona border.

Shows of oil and gas in wells are evidence of the migration or movement of oil and gas through northwestern Arizona, most likely from the deep marine basin facies on the west to the shallow marine shelf facies on the east. Giardina (1979, Table 2) tabulated and described shows of oil and gas in at least 13 wells drilled on the Arizona Strip. Drill-stem tests in the Brooks #1-26 Federal southwest of Fredonia in Sec. 26, T. 40 N., R. 6 W., drilled in 1983 after Giardina published his tabulation, recovered 20 ft of oil and 70 ft of oil-cut mud from Triassic rocks and 1 cm^3 of free oil from Permian rocks. Fluorescence and cut fluorescence were reported in sample cuttings of Permian, Devonian, and Cambrian strata in the only well drilled for oil on the Coconino Plateau (Sinclair #1 Santa Fe, Sec. 35, T. 28 N., R. 1 W.). Gas was noted in a deep water well about 20 miles southeast of the oil test drilled on the Coconino Plateau.

Paleozoic and Triassic formations underlying the Arizona Strip are essentially flat, dipping only 0.5-1° north-northeast between Grand Canyon and the Utah border. The Precambrian basement rises 3,000-4,000 ft across this same distance. As a result, there is an increased possibility for stratigraphic and structural trapping of any up-dip migration of oil or gas in the southern, less-explored part of the Arizona Strip. These hydrocarbons would be trapped before reaching the outcrop in Grand Canyon.

Strata on the Cordilleran shelf on the Arizona Strip are largely under-pressured because of a low water table and removal of Mesozoic and Cenozoic overburden. Those having experience with the Red Cave Formation of the Texas Panhandle and the Pecos Slope field, north of Roswell, know that it is easy to miss oil and gas shows and to damage under-pressured reservoirs when using conventional rotary-drilling techniques. Crossover on the neutron-density curves was the only indication that the under-pressured, redbed Abo Formation of Permian age was productive in the Pecos Slope field, which now has more than 500 producing wells. Under-pressured formations on the Arizona Strip and Coconino Plateau should be drilled with under-balanced or low-pressure drilling techniques so that oil and gas shows are not masked and the under-pressured strata are not damaged by drilling mud. Rotary drilling with mud weight greater than the under-pressured formation simply grouts the under-pressured strata with mud as they are drilled. Neutron-density curves should be run in all wells drilled in northwestern Arizona to identify under-pressured gas shows and reservoirs. Drill-stem tests in this region should include long-duration shut-in periods to obtain accurate initial reservoir pressures.

Oil and gas in the shallow (less than 1,000 ft, i.e. above the water table) under-pressured and oil-impregnated Triassic units may have accumulated preferentially in the sags or low, synclinal parts of undulations, as it has at the San Juan field in southeastern Utah, rather than in the high or anticlinal parts. In this geologic setting, the shallow Triassic rocks should be drilled in the synclines and low on the structural flanks of anticlines. Stratigraphic traps are not dependent on structural position.

The combination of surface seeps, petroliferous rocks, and shows of oil and gas in numerous wells in northwestern Arizona, plus oil production from equivalent units in southwestern and south-central Utah, indicate that the potential for trapped hydrocarbons in the Arizona Strip and Coconino Plateau is fair to good. Land available for leasing in this region is mostly federal, although scattered tracts of State Trust and private land are also present. Future wells should be drilled with unconventional, under-balanced techniques. Drilling depths are shallow to moderate, ranging from less than 4,000 to 6,000 ft. Drilling density within the Cordilleran shelf area is about one well per 135 square miles.

Chuar Basin

Chuar Group strata (Precambrian age) were deposited in a basin in northern Arizona and southern Utah that may have extended into north-central Utah (Rauzi, 1990). The southern margin of the basin appears to have been influenced by the Mesa Butte fault in northern Arizona (Figure 6). Its eastern margin was influenced by a north-trending fault on the western flank of Monument uplift. Timmons and others (1999) associated the Chuar Basin to the breakup of Rodina and initiation of the Cordilleran rift margin. What is not clear is the form and extent of the basin or half-graben that may preserve Chuar Group source rocks in the subsurface.

Chuar Group strata exposed in eastern Grand Canyon include at least 2,685 ft of organic-rich gray-to-black mudstone and siltstone intercalated with thin sequences of sandstone and stromatolitic and cryptalgal carbonate rocks. Depositional environments identified in the Chuar Group include a sediment-starved, possibly non-marine basin rich in organic material, a coastal or alluvial plain, and mixed coastal or fresh-water swamp and alluvial plain (Reynolds and Elston, 1986) to an equatorial tide- and wave-influenced shallow marine environment (Dehler and others, 1999).

The Chuar Group contains good to excellent petroleum source rocks in northern Arizona (Reynolds and others, 1988; Summons and others, 1988; Palacas and Reynolds, 1989; Cook, 1991; Wiley and others, 1998). Organic-rich Chuar mudstones and petroliferous carbonates contain up to 8.87 percent total organic carbon and average 3 percent. Most of the Walcott Member is within the principal oil-generating window. Original organic matter is comprised of Type I-II kerogen in the mature region of the Van Krevelen diagram for kerogen types. Rock-Eval T_{max} values from 430-440 °C indicate that source rocks in the upper part of the Chuar Group at the outcrop are within the principal oil-generating window. Hydrogen Index values up to 190 mgHC/gC (milligrams of hydrocarbon per gram of carbon) and genetic potentials up to 6 kg/ton demonstrate that the hydrocarbon source rocks of the Chuar Group still have potential for generating commercial accumulations of gaseous and liquid hydrocarbons. Uphoff (1997, p. 7) calculated that the total generated hydrocarbon volume of a 150-square-mile portion of the Chuar fairway is between 2,700 and 7,300 million barrels of oil. Assuming a 25 percent entrapment rate, potential trapped oil in place is 700 to 1,800 million barrels for this small portion of the Chuar fairway.

Wiley and others (1998, p. 28-29) identified significant reservoir rocks in the Chuar Group of Precambrian age, underlying Nankoweap Formation (Precambrian), and overlying Sixtymile (Precambrian) and Tapeats (Cambrian) Formations (Table 2). Reservoir rocks within the Chuar Group include karsted dolomite in the Walcott Member and the Carbon Butte Sandstone Member. Porosity needed for potential hydrocarbon production was also identified in dolomite units in the Tanner, Jupiter, Carbon Canyon, and Walcott Members of the Chuar Group.

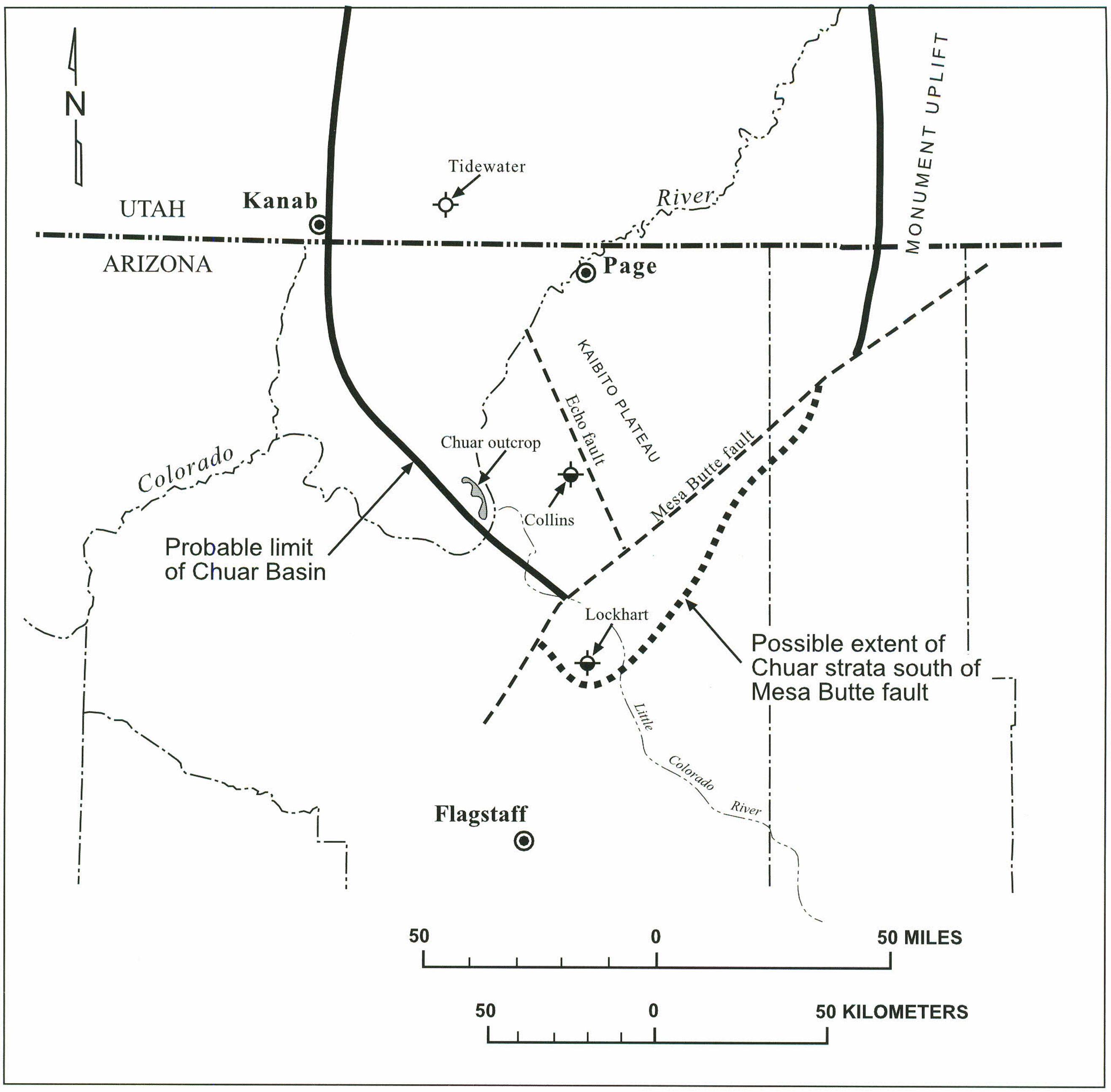

Figure 6. *Probable limit of the Chuar Basin in northern Arizona and southern Utah showing the wells and features discussed in the text.*

Age				Rock Unit	Lithology
Є				Bright Angel Shale	
Є				Tapeats Sandstone	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP			Sixtymile Formation	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP	CHUAR GROUP	KWAGUNT FM	Walcott Member	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP	CHUAR GROUP	KWAGUNT FM	Awatubi Member	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP	CHUAR GROUP	KWAGUNT FM	Carbon Butte Mbr	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP	CHUAR GROUP	GALEROS FM	Duppa Member	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP	CHUAR GROUP	GALEROS FM	Carbon Canyon Mbr	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP	CHUAR GROUP	GALEROS FM	Jupiter Member	
LATE PROTEROZOIC	GRAND CANYON SUPERGROUP	CHUAR GROUP	GALEROS FM	Tanner Member	
MIDDLE PROTEROZOIC	GRAND CANYON SUPERGROUP			Nankoweap Formation	
MIDDLE PROTEROZOIC	GRAND CANYON SUPERGROUP	UNKAR		Cardenas Basalt	
MIDDLE PROTEROZOIC	GRAND CANYON SUPERGROUP	UNKAR		Dox Sandstone	
MIDDLE PROTEROZOIC	GRAND CANYON SUPERGROUP	UNKAR		Shinumo Quartzite	
MIDDLE PROTEROZOIC	GRAND CANYON SUPERGROUP	UNKAR		Hakatai Shale	
MIDDLE PROTEROZOIC	GRAND CANYON SUPERGROUP	UNKAR		Bass Limestone	

Table 2. *Stratigraphy of Grand Canyon Supergroup through Bright Angel Shale.*

The Chuar Group extends northward from outcrops in Grand Canyon into south-central Utah, where the Tidewater Kaibab Gulch Unit #1 well penetrated 1,128 ft of it. Rollover anticlines, sand pinchouts, and stratigraphic traps could be present in northern Arizona between the Tidewater well and the Grand Canyon. In structurally low areas within Grand Canyon, the continental Sixtymile Formation overlies the Chuar Group. The Tapeats Sandstone of Cambrian age probably overlies the Chuar throughout much of the Chuar's subcrop. Oil was reported in the Tapeats Sandstone east and southeast of Grand Canyon in the Collins Cobb Navajo #1-X and the Lockhart #1 Babbitt wells in Coconino County. This oil may have migrated from underlying Chuar Group source rocks. Structural closure on the top of Precambrian rocks is mapped east of the Cobb well beneath Kaibito Plateau in northern Arizona (Rauzi, 1990, Plate 1).

No exploratory wells have adequately tested the Tapeats Sandstone or penetrated Precambrian rocks to test for oil and gas accumulations on the broad ridge beneath Kaibito Plateau, on the broad ridge north of Mesa Butte fault, or on the western flank of Monument uplift. Structural closure on the top of Precambrian rocks just east of Echo fault remains untested even though Hager (1948, Table 2) reported oil shows in the overlying Tapeats Sandstone in the Collins Cobb Navajo #1-X well just west of Echo fault in Sec. 35, T. 34 N., R. 8 E. The Collins Cobb well was a cable tool test that recovered black mud from the Tapeats zone that Swapp (1957) reported was sufficiently petroliferous to burn. The Collins Cobb well did not penetrate Precambrian rocks.

The presence of good to excellent hydrocarbon source rocks indicates that the oil and gas potential in the Chuar Basin is good to very good. The shape and extent of the Precambrian graben that may preserve Chuar Group source rocks in the subsurface has not been identified clearly. Is the Chuar preserved to the north and northeast as suggested by Rauzi (1990), to the north and northwest as implied by Wenrich and Palacas (1992), or even in an unidentified graben south and southeast of eastern Grand Canyon?

Land available for leasing in this region is mostly federal forest and public land northwest and north of the outcrops in Grand Canyon, Navajo Indian land to the east, and scattered tracts of State Trust and private land to the southeast. Drilling depths are moderate to deep, ranging from 6,000 to 15,000 ft or more. The density of drilling to delineate the extent of the Chuar Basin in Arizona is an astonishing one well per 1,300 square miles.

Paradox Basin

The northeastern corner of Arizona includes the southernmost margin or shelf of the Paradox Basin (Pennsylvanian age), most of which is in southeastern Utah (Figure 7). The shelf facies in northeastern Arizona grades laterally into the hydrocarbon-prolific basin and evaporite facies in southeastern Utah. The giant Aneth oil field, just north of the Arizona-Utah line, has produced more than 415 million barrels of oil. This area contains Paleozoic rocks largely of shallow marine shelf origin, including rich source rocks (black mudstone and dolomite) that encase discontinuous, porous carbonate mounds, oolite bars, reefs, and algal bioherms. Other potential reservoirs include lenticular and irregular clastic deposits of Paleozoic age and fractured igneous rocks of Tertiary age that intruded organic-rich Paleozoic units. Conley and Giardina (1979) identified and described several areas with favorable potential for Pennsylvanian, Mississippian, and Devonian hydrocarbon accumulations.

Paleozoic strata in northeastern Arizona are considered to have hydrocarbon potential southward along the western flank of the Defiance uplift to approximately the southern boundary of the Navajo Reservation. The unusual oil accumulation in the Dineh-bi-Keyah field is the main evidence for this prospective trend, which may also contain more typical reservoirs such as lenticular and irregular clastic deposits of Devonian age and porous carbonate mounds and bioherms of Mississippian and Pennsylvanian age. In any event, the Dineh-bi-Keyah field, which is the most prolific oil field in Arizona, demonstrates the positive relationship between igneous intrusion, thermal maturation, and trap creation along the western flank of the Defiance uplift. The presence of helium in Devonian and Mississippian strata at the north end of the Defiance uplift and in Permian strata at the south end suggest that the entire west flank of the Defiance uplift has potential for helium as well as hydrocarbons.

All current production in Arizona is from the Paradox Basin. Current and past production in the Paradox Basin documents the presence of hydrocarbon source and reservoir rocks and provides strong evidence for the potential discovery and production of oil, gas, and helium in northeastern Arizona. Oil and natural gas have been produced from strata of Devonian, Mississippian, Pennsylvanian, and Tertiary ages. Most oil, however, has been produced from igneous rocks that were intruded into Pennsylvanian strata during Tertiary time. More than 385 million cubic feet of helium (average 6 percent) have been produced from Mississippian rocks north of the Defiance uplift in the Four Corners area. Helium (average 5 percent) is present in Devonian strata on the Defiance uplift in the Dineh-bi-Keyah field.

The approximate oil and gas reserves per well in the producing fields of northeastern Arizona range from about 100,000 barrels at Walker Creek field (Devonian) to about 500,000 barrels of oil per well at Dineh-bi-Keyah field. Reserves at Black Rock field are about one billion cubic feet of gas per well. This range provides a reasonable minimum estimate of potential reserves of oil or gas per well from the next discovery in northeastern Arizona.

The potential for discovery of oil, gas, or helium in northeastern Arizona is considered to be good to very good. There is also excellent potential to enhance and extend existing production by the application of horizontal drilling technology or enhanced recovery methods such as water or carbon dioxide flooding. Carbon dioxide in the St. Johns-Springerville area may be used for enhanced oil recovery in northeastern Arizona and northwestern New Mexico. Several states and some Indian Tribes have adopted incentive programs to stimulate these types of projects to increase and extend existing production and revenue. All land in this region is part of the Navajo Reservation. Drilling depths are moderate, ranging from 4,000 to 6,000 ft.

Black Mesa Basin

The Black Mesa Basin includes the present-day highlands of Black Mesa (outline of Cretaceous outcrop) and the greater region between the Kaibab upwarp to the west, Defiance uplift to the east, and the boundary of the Navajo Reservation to the south (Figure 8). This area contains shallow marine shelf facies of Paleozoic age that grade into deeper marine basin facies toward the north and northeast, nonmarine fluvial and eolian strata of Triassic and Jurassic age, and marine to nonmarine strata of Cretaceous age. The Oraibi trough contains a thick accumulation

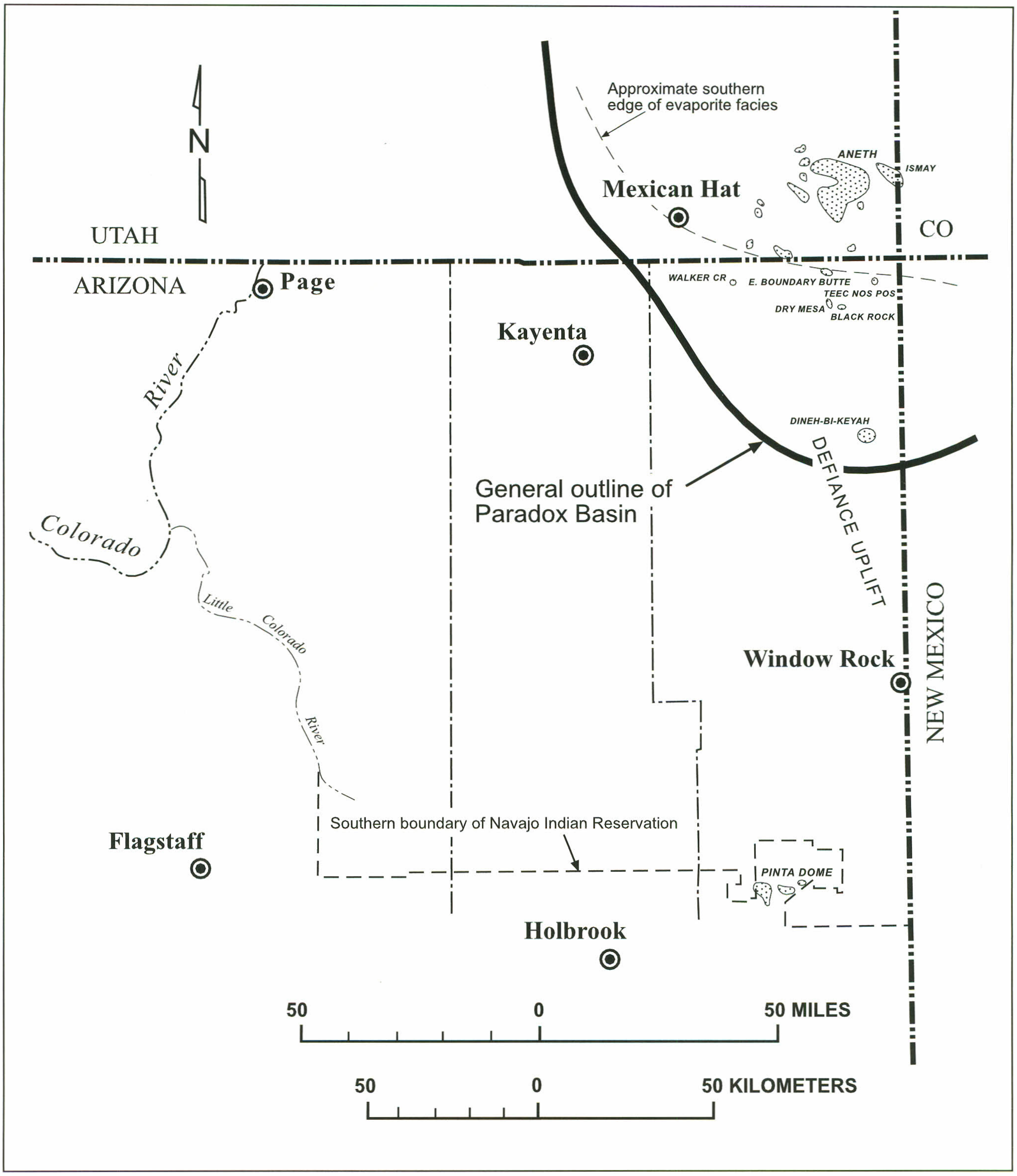

Figure 7. *General outline of the Paradox Basin in southeastern Utah and northeastern Arizona showing the location of the oil, gas, and helium fields and other features discussed in the text.*

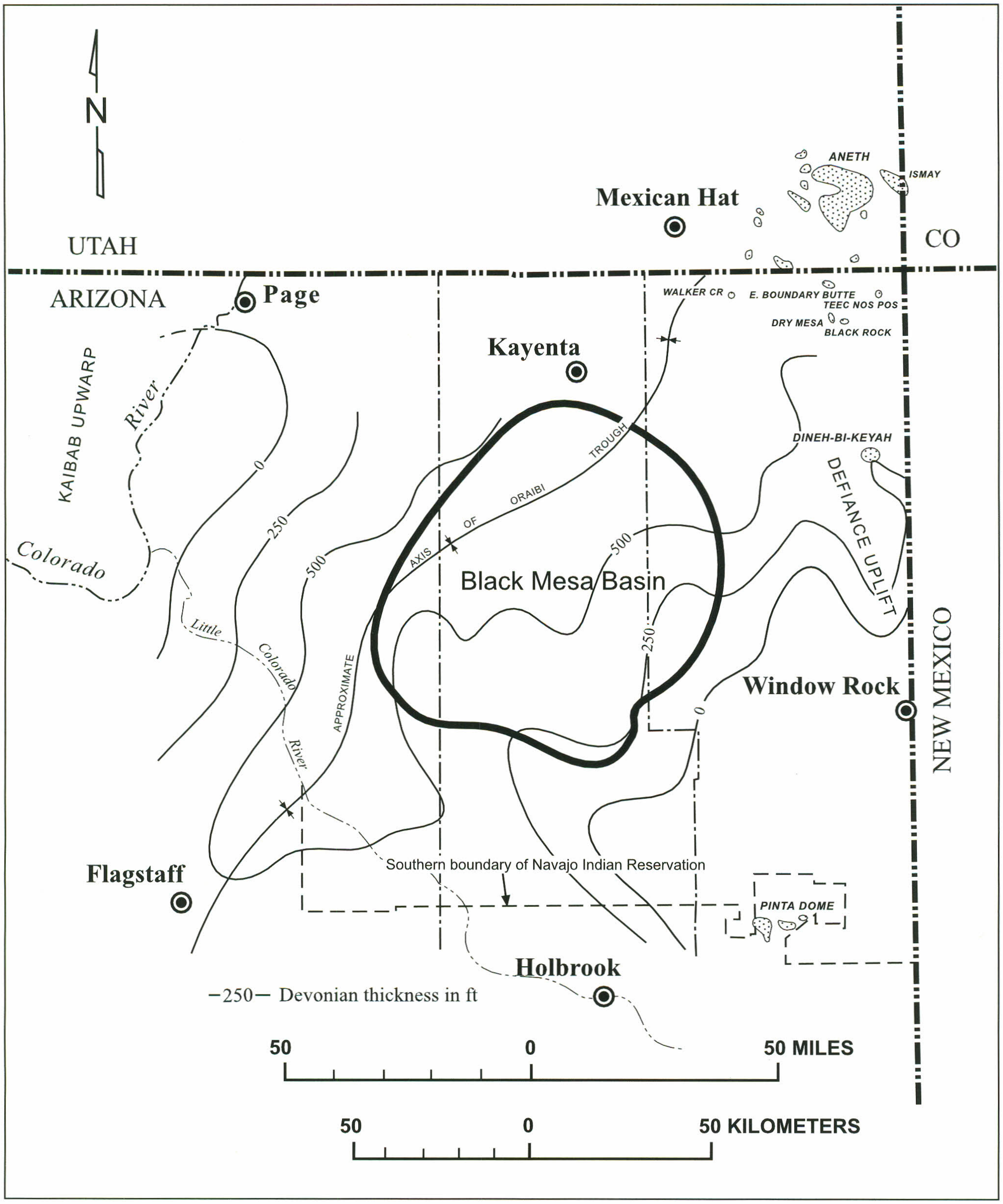

Figure 8. *General outline of the Black Mesa Basin (outline of Cretaceous outcrop) showing the location of features discussed in the text. Devonian thickness contours from Conley and Giardina, 1979, Figure 5.*

of Devonian and Mississippian strata, including dark carbonate and shale. The trough extends northeastward from the Little Colorado River on the southwest across the Black Mesa Basin to the Four Corners area. Stratigraphic traps in the Oraibi trough are possible in connection with lenticular and irregular porous sandstone deposits associated with buried ridges and bioherms.

Peirce and Wilt (1970, p. 99) and Kashfi (1983) described the wedge out of Devonian and Mississippian strata to the east and the thinning of Devonian strata to the west. The zones outlined by these conditions are conducive to the existence of a combination of lengthy structural and stratigraphic trends that remain untested over thousands of square miles in eastern Coconino and central Navajo and Apache Counties.

Cretaceous strata in the Black Mesa Basin contain an estimated 21 billion tons of coal reserves with only one billion tons considered recoverable by mining. The remaining 20 billion tons, at depths between 300 and 1,700 ft, are inappropriate for surface or other mining but may hold excellent potential for coalbed methane gas. Nations and others (2000) recently mapped the distribution and thickness of coal in the Black Mesa Basin. These maps provide useful information regarding areas especially favorable for exploration and development of coalbed methane.

Potential for oil and gas in Paleozoic strata of the Black Mesa Basin is considered fair to good. Potential for coalbed methane in Cretaceous strata is considered very good to excellent. Devonian, Mississippian, and Pennsylvanian strata contain and produce or have produced oil and gas north of the Black Mesa Basin in the Four Corners area. Shows of oil have been reported in cuttings and cores of Devonian strata in wells drilled south of the Black Mesa Basin. A seep of high-gravity oil is present in the Martin Formation (Devonian) northwest of Payson. Outcrops of petroliferous dolomite in Salt River Canyon exhibit a strong odor of petroleum and yield a faint milky-white cut fluorescence in 111-trichloroethane [Table 1 (11-12)]. Turner (1961; 1968) concluded that the Black Mesa Basin has all the criteria for a major gas province.

All land in the Black Mesa Basin in northeastern Arizona is part of the Navajo or Hopi Reservations and all lease applications must be submitted to the respective tribe. Much of the land in the central part of the region is within the Navajo-Hopi joint-use area. Reeves and others (1996, p. 191) summarized the land situation and leasing in the Black Mesa Basin. Drilling depths for coalbed methane are shallow, ranging from 500 to 2,000 ft. Drilling depths for oil and gas range from 4,000 to 6,000 ft.

Holbrook Basin

The Holbrook Basin in east-central Arizona is a structural and stratigraphic basin between the Mogollon Rim to the south and the Defiance uplift to the northeast. The basin is connected on the northwest to the Oraibi trough (early Paleozoic age) that extends northeastward through the Black Mesa Basin area (Figure 9). The southern part of the Holbrook Basin consists of north-northeast dipping Paleozoic strata that form the Mogollon slope. This area contains more than 4,000 ft of Paleozoic rocks. In addition, some Triassic rocks, which have produced helium, are present in the central and northern parts of the basin. The Paleozoic strata include 500 ft of shelf and shallow marine deposits of Cambrian, Devonian, and Mississippian age that wedge out to the east (Rauzi, 1996a), 500 ft of largely marginal marine deposits of Pennsylvanian age that pinch out to the east, and sabkha and salt deposits of Permian age that form the Holbrook salt basin (Rauzi, 2000). The sabkha deposits consist principally of fine-grained red beds that are locally interbedded with limestone, dolomite, anhydrite, and salt (Figure 10). This sequence, which attains a maximum thickness of more than 3,000 ft in the subsurface near Holbrook, grades laterally into continental eolian deposits along the Sedona arch to the west and shallow marine deposits of the Central Arizona shelf to the south (Blakey and Knepp, 1989, Figure 5). Deep marine deposits in the Pedregosa Basin lie south of the Central Arizona shelf.

The sabkha and salt-pan deposits in the Holbrook Basin are similar in age and character to deposits in the Permian Basin of West Texas, which has had prolific hydrocarbon production. The Holbrook Basin, like the Paradox and Permian basins, contains extensive evaporite deposits, which are commonly associated with major hydrocarbon reserves and production in many parts of the world. Kirkland and Evans (1981, p. 181) showed that

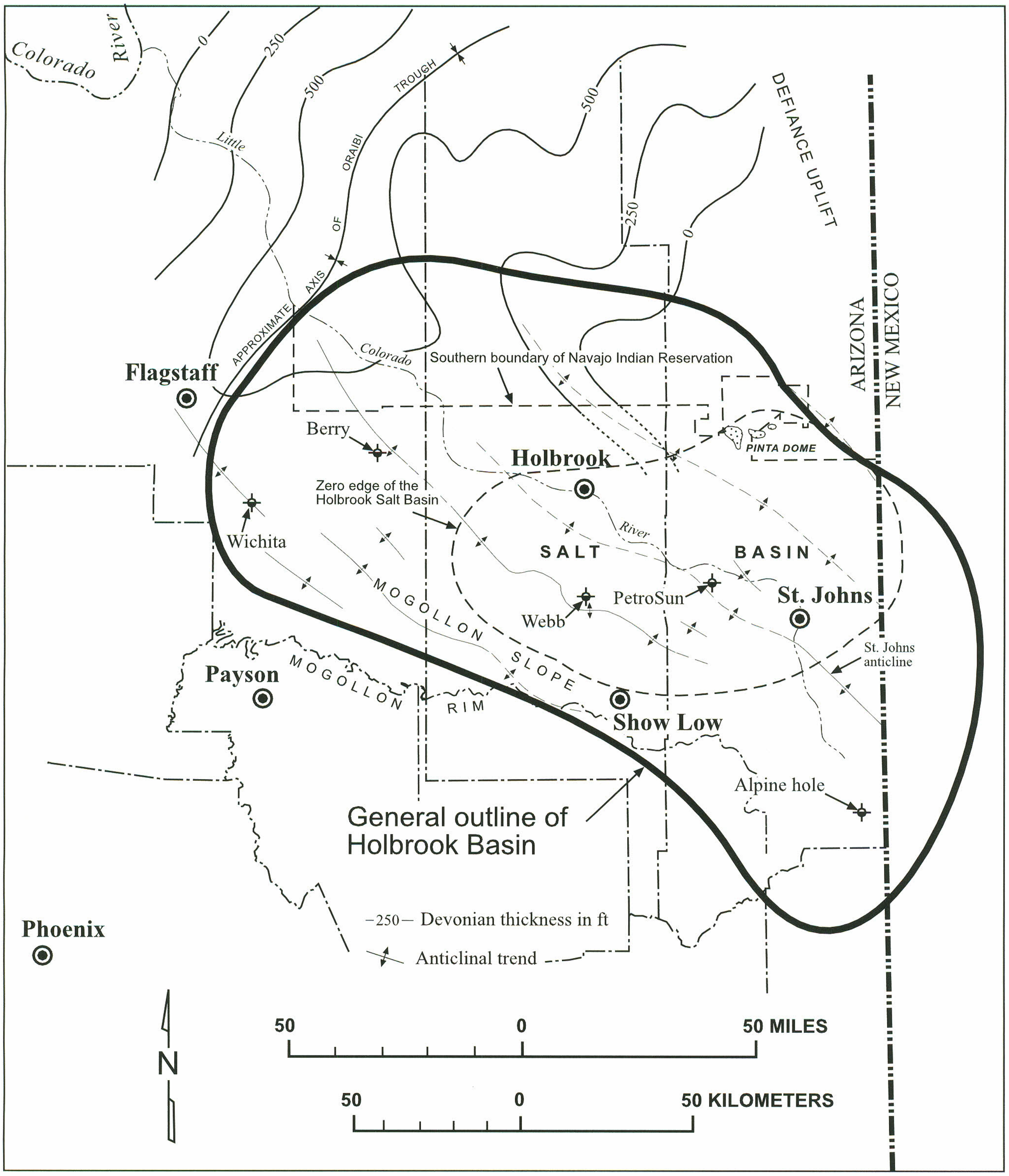

Figure 9. *Holbrook Basin showing the location of features discussed in the text. Devonian thickness contours from Conley and Giardina, 1979, Figure 5. Perimeter of Holbrook Salt Basin from Rauzi, 2000, Plate 1.*

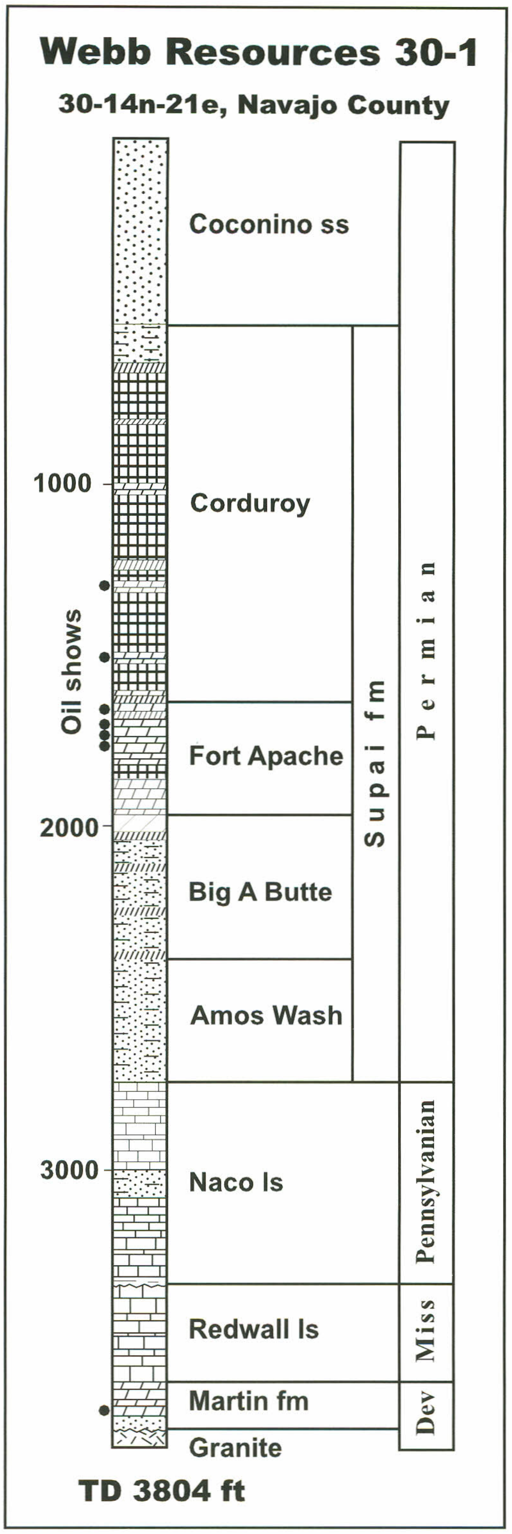

Figure 10. *Subsurface stratigraphy in the Holbrook Basin showing the sabkha deposits in the Supai Formation. See Figure 9 for location of the Webb well.*

this association is due to the high organic productivity of evaporite environments. Permian strata are also considered to have hydrocarbon potential south of the Holbrook Basin beneath the volcanic rocks of the White Mountains. In that area, sabkha and salt-pan deposits may fill additional salt basins and form stratigraphic and structural traps along the northern margin of the Central Arizona shelf (Rauzi, 1996b).

At least four regionally extensive carbonate beds of Permian age are present in the Holbrook Basin. The lowest of these, the Fort Apache Member, crops out in the steep escarpment all along the southern edge of the Holbrook Basin. Freshly broken pieces of the Fort Apache have a strong petroliferous odor [Table 1 (10)]. The entire Fort Apache Member was cored in the Tonto Drilling #1 Alpine Federal hole south of Springerville in Sec. 23, T. 6 N., R. 30 E (Figure 9). There, it is a fossiliferous, vuggy-to-cavernous dolomite. Dead oil is present in the vugs and along fractures (Figure 11). The application of acid resulted in brown bubbles and a strong smell of crude oil. The author observed free oil bleeding from vertical fractures in carbonate beds just above the Fort Apache Member in the Alpine well (Figure 11; Rauzi, 1994a; 1994b). The presence of bioherms in the Fort Apache Member in the eastern part of the Holbrook Basin is suggested by the fossils, vugs, and pin-point porosity in the Alpine well and good permeability and porosity (up to 30 percent) that were recorded in several wells southeast of St. Johns between 1994 and 1997 (Rauzi, 1999, p. 5).

In 1997, PetroSun Exploration and Production encountered a pocket of methane gas in Permian rocks that had sufficient pressure to blow the drill string out of the hole in its #15-1 NMAL between Concho and Holbrook (Sec. 15, T. 14 N., R. 25 E.). Gas shows were also reported in granite wash in that well. Strong gas shows were reported in Pennsylvanian and Mississippian strata in the Resource Operating #1 Federal north of Show Low (Sec. 29, T. 11 N., R. 22 E.) and the Sumatra Energy Company #1-17 Santa Fe near Concho (Sec. 17, T. 12 N., R. 26 E.).

The Martin Formation (Devonian) has a strong petroleum odor on fresh breaks and commonly yields a faint milky-white cut fluorescence in 111-trichloroethane throughout its outcrop south of the Holbrook Basin between Payson and Salt River Canyon [Table 1 (11-12)]. A seep of high-gravity oil was reported northwest of Payson (Petzet, 1997, p. 85). Amstrat reported oil stains on a conventional core of Devonian carbonate in the Wichita Industries #1-11 Federal well in the western part of the basin near Mormon Lake (Sec. 11, T. 17 N., R. 9 E.). Amstrat noted that when carbonate rock in the Wichita well was dissolved in acid an oily scum covered the insoluble residue. Fair to heavy oil stain, good fluorescence, and trace cut were reported in Devonian strata west of Winslow in the Gus Berry #26-1

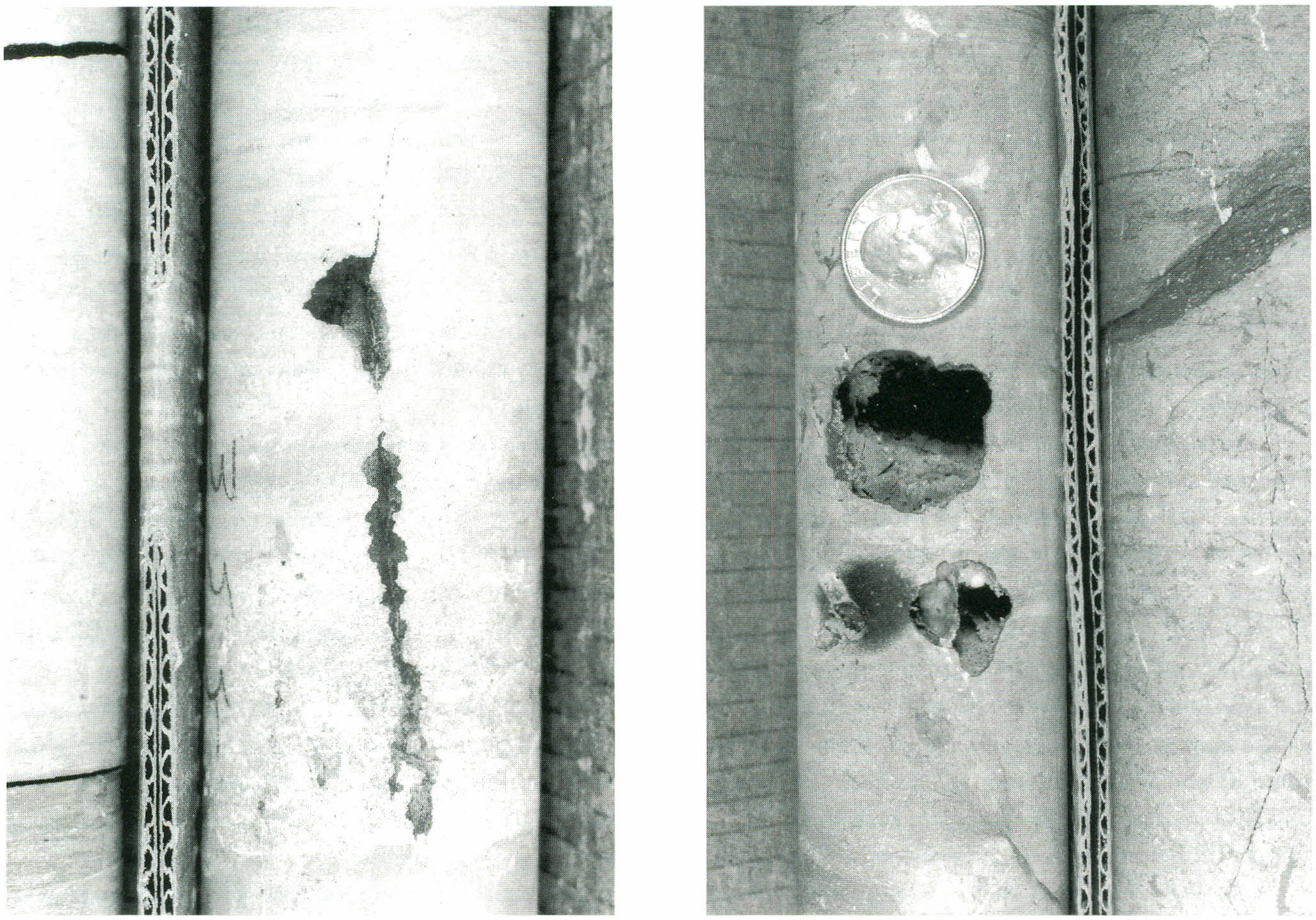

Figure 11. *Core from the Fort Apache Limestone Member in the #1 Alpine Federal hole south of Springerville in southern Apache County. Note distinct fossil hash and oil bleeding from vertical fractures in the left photo and vugs and wispy dark laminae in the right photo. (Quarter for scale). The core is 2 inches in diameter. See Figure 9 for location of the Alpine hole.*

State (Sec. 26, T. 19 N., R. 13 E.). Shows in the Berry well are coincident with good drilling breaks. Two of the shows are also coincident with good crossover (gas effect) on the neutron-density curves. The Gus Berry well, drilled in late 1999 and currently shut-in, is within the trend of the Oraibi trough in the northwestern part of the Holbrook Basin.

The petroliferous outcrops of the Martin Formation and Fort Apache Member along the Mogollon Rim south of the basin, together with shows of oil and gas in wells, document the presence of hydrocarbon source rocks and migration of oil and natural gas in the Holbrook Basin. Shows of oil and gas in other wells in the sparsely drilled Holbrook Basin were tabulated and described by Bahr (1962, p. 121), Peirce and Wilt (1970, Table D), Peirce and Scurlock (1972), and Petzet (1997, p. 85).

Production of more than 700 million cubic feet of 99.9 percent pure helium from Permian and Triassic strata northwest of Holbrook in the Pinta Dome area (Figure 9) and the recent discovery of carbon dioxide in Permian strata between St. Johns and Springerville (Rauzi, 1999) demonstrate that subsurface conditions are favorable for the generation and entrapment of industrial gas in the Holbrook Basin. The gas that was produced from the Holbrook Basin between 1960 and 1976 contained 8 to 10 percent helium, which was mixed largely with nitrogen. This is the richest known concentration of helium gas in the world (Dean and Lauth, 1961, p. 194; Spencer, 1983, p. 6). Gas, in the carbon dioxide discovery well drilled near St. Johns in 1994, analyzed by the U.S. Bureau of Mines, contained 90 percent carbon dioxide and 0.52 to 0.81 percent helium.

Several stratigraphic wells drilled to delineate potash in the Holbrook Basin encountered pressure within the sabkha-salt deposits of Permian age that was sufficient to blow gas containing 2.4 to 4.09 percent helium out of the hole. The Kern County Land #1 State (Sec. 2, T. 18 N., R. 24 E.), most notable for encounter of helium, blew gas containing 0.22 percent methane, 4.09 percent helium, and 95 percent nitrogen for 26 hours before it was brought under control. Other wells that encountered helium include the New Mexico and Arizona Land Company (NMA) #3 Fee (Sec. 28, T. 17 N., R. 22 E.), Arkla Exploration #22 NMA (Sec. 23, T. 17 N., R. 23 E.), Arkla Exploration #37 NMA (Sec. 25, T. 16 N., R. 22 E.), Arkla Exploration #68 NMA (Sec. 19, T. 16 N., R. 23 E.), Arkla Exploration #7 State (Sec. 10, T. 15 N., R. 23 E.), and the Arkla Exploration #10 NMA (Sec. 27, T. 16 N., R. 23 E.). The latter well blew gas that tested 2.4 percent helium at the Kerr-McGee lab at Navajo, Arizona. The helium-rich gas in these wells provides evidence of the migration of helium through this area and points to the potential for additional untapped reserves of helium in the Holbrook Basin.

The potential for hydrocarbons and industrial gases in the Holbrook Basin is considered good to very good. Evidence for this potential includes past and current production of hydrocarbons north of the basin in the Four Corners area, past production and recent discovery of industrial gas within the basin, shows of oil and gas in wells drilled throughout the basin, a surface seep of high-gravity oil south of the basin near Payson, and outcrops of petroliferous rocks of Devonian and Permian age all along the Mogollon Rim at the southern edge of the basin.

Geologic conditions in the Holbrook Basin are favorable for a variety of stratigraphic and structural traps including buried ridges and bioherms throughout the basin and in the Oraibi trough in the northwestern part of the area, zones of well-developed porosity and up-dip pinch outs all along the Mogollon slope, and bioherms, reefs, clastic buildups, and sand-lens development in proximity to buried topography throughout the basin and along the trend of buried shorelines to the east and west. Wells drilled in the southeastern part of the basin between Concho and Alpine, along the southwestern margin or shoreline of the late Paleozoic land mass, may encounter oil and gas trapped in bioherms, reefs, and clastic buildups associated with the buried shoreline.

Like the Cordilleran shelf, strata in the Holbrook Basin are essentially flat lying and largely under-pressured. Future wells should be drilled with unconventional, under-balanced techniques to prevent formation damage from drilling mud. Neutron-density curves should be run in all wells to identify under-pressured gas shows and reservoirs. Drill-stem tests should include long-term shut-in periods.

Most of the Holbrook Basin is a checkerboard of State Trust and fee land, with some public land in the central part. Large blocks of State Trust land are present in the southeastern part and large blocks of fee land are present in the central part of the basin. Drilling depths are shallow to moderate, ranging from less than 4,000 to 6,000 ft. Drilling density is about one well per 100 square miles.

Pedregosa and Bisbee Basins

The Pedregosa Basin of Paleozoic age includes all of Cochise and the southern half of Graham Counties. The Bisbee Basin of Cretaceous age, which generally overprints the older Pedregosa Basin, includes all of Cochise and Santa Cruz, the southern part of Pinal, and the western half of Pima Counties (Figure 12). The Pedregosa and Bisbee basins contain up to 25,000 ft of largely marine strata of Cambrian through Cretaceous age. This is the thickest accumulation of Paleozoic through Cretaceous rocks in the state (McKee, 1951, Plate 3D).

The thick section of Paleozoic rocks exposed in the Pedregosa Mountains in southeastern Arizona is representative of deposition in the Pedregosa Basin. This basin contains more than 2,000 ft of lower Paleozoic rocks of shelf or shallow marine origin separated by a regional unconformity from up to 8,000 ft of upper Paleozoic rocks of basin or deep marine origin. All of these rocks thin toward the west and north, toward the Defiance positive area in east-central Arizona, where there are potential stratigraphic and structural accumulations of oil and gas. Paleozoic rocks and regional unconformities in the Pedregosa Basin are similar in age and character to those in the Permian Basin of West Texas, a prolific hydrocarbon producer, where truncated strata beneath the regional uncon-

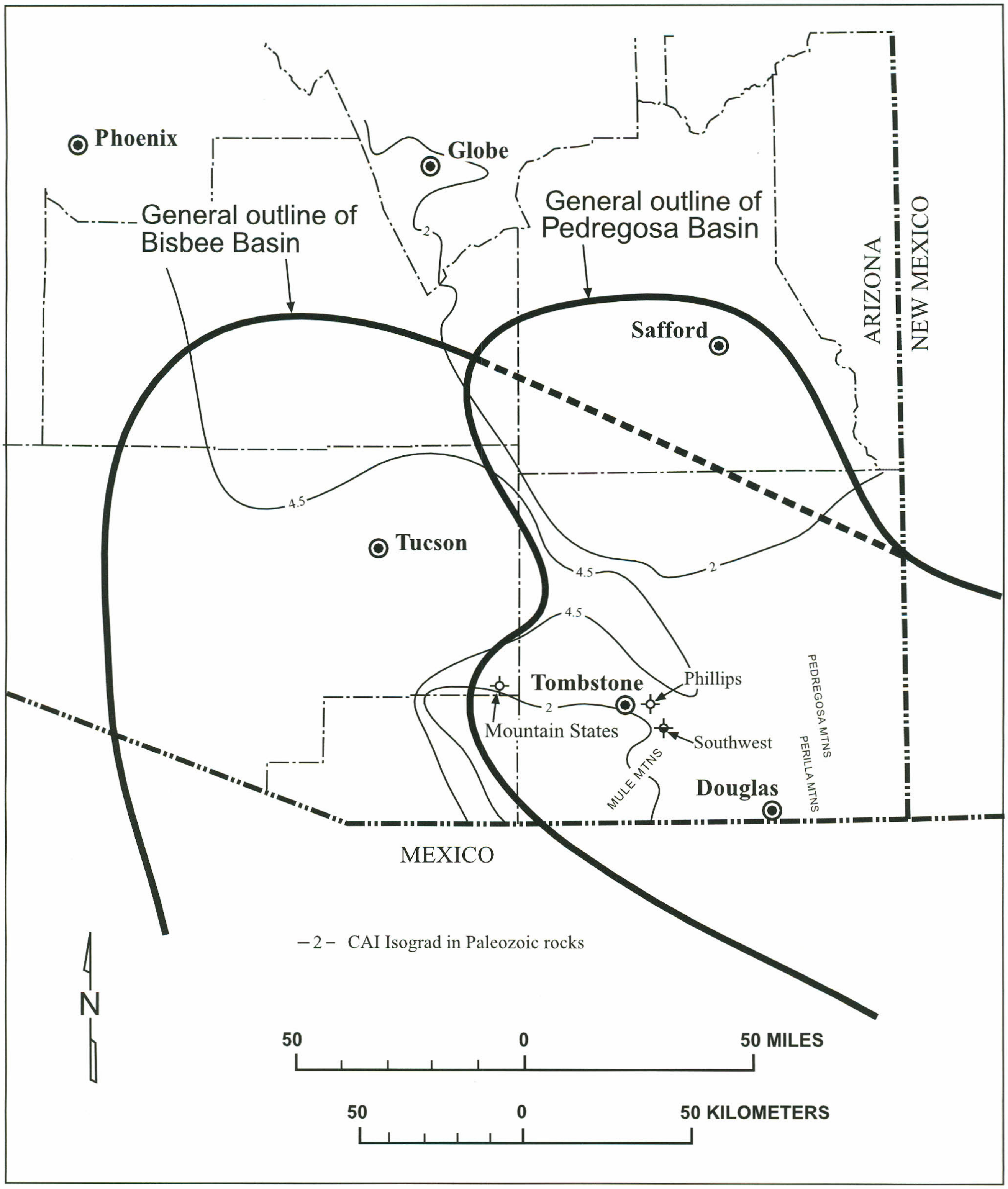

Figure 12. *General outline of the Pedregosa (Paleozoic) and Bisbee (Cretaceous) Basins showing the location of features discussed in the text. Conodont-alteration-index (CAI) isograds of Paleozoic rocks from Wardlaw and Harris, 1984, Figure 4.*

Figure 13. *Reef of Cretaceous age in the Mule Mountains. Rudistids are abundant in the massive bed (outlined), which is about 40 ft thick on the right. See Figure 12 for location of the Mule Mountains.*

formity form important hydrocarbon traps. Stream and lake deposits of Tertiary age, some of which include thick evaporite deposits, fill broad valleys between the mountains.

A thick section of Cretaceous rocks is exposed on both sides of the southern Sulphur Springs Valley—in the Mule Mountains to the west and the Perilla Mountains to the east. These strata, assigned to the Bisbee Group, represent deposition in the Bisbee Basin of more than 15,000 ft of Cretaceous strata of largely deltaic to shallow marine origin.

Lower Cretaceous marine rocks in the Mule Mountains are highly fossiliferous and contain numerous bioherms similar to those that produce oil in Texas and Mexico (Figure 13). The Lower Cretaceous rocks have potential for gas and oil accumulations in lenticular carbonate buildups and reefs where they are preserved in graben throughout southeastern Arizona.

Upper Cretaceous rocks in Mexico, about 15 miles south of Douglas, contain up to 15 coal seams (Obregon-Andria and Arriaga-Arredondo, 1991). These coal-bearing rocks may extend northward beneath the southern Sulphur Springs Valley (Elfrida Basin), where they would have good potential to yield coalbed methane in the vicinity of Douglas.

Evidence for hydrocarbons and potential hydrocarbon source rocks in the Pedregosa and Bisbee basins includes shows of oil and gas in wells (Thompson and others, 1978, Tables 2 and 3; Butler, 1989, Tables 2 and 3) and petroliferous rocks of Devonian and Cretaceous age in the Dragoon and Whetstone Mountains [Table 1 (14-15)]. Holm (1938) reported an oily material that seeped from Cretaceous sandstone at Walnut Spring in the early 1930s [Table 1 (20)]. Hydrocarbon shows were reported in Paleozoic strata in wells near Bowie, Douglas, and San Simon. In addition, color changes in conodonts show that the Paleozoic rocks in southeastern Arizona are thermally within the oil and gas window (Wardlaw and Harris, 1984).

Kenneth Smith, geologist with Continental Oil Company, reported scattered oil shows, poor-to-fair fluorescence and cut, and 450 ft of oil-cut mud in a drill-stem test in fairly porous limestone of Paleozoic age in the Southwest Oil Company #1 Davis-Clark well southeast of Tombstone (Sec. 5, T. 21 S., R. 24 E). The nearby Tombstone #1A State, drilled by Phillips Petroleum Company in Sec. 14, T. 20 S., R. 23 E., did not reach Paleozoic strata but did confirm the existence of reverse or thrust faulting of the strata penetrated by the Davis-Clark well. The structural relationships encountered in the Phillips well are similar to those in southwestern Wyoming and northern Utah where large quantities of hydrocarbons have been produced. This portion of the Pedregosa and Bisbee basins deserves serious evaluation for potential sub-thrust accumulation of hydrocarbons in strata of Cretaceous and Paleozoic age.

Mountain States Exploration drilled through about 1,000 ft of organic-rich, black shale of Cretaceous age in its #1A State well just west of the Whetstone Mountains in Sec. 29, T. 19 S., R. 18 E. The author collected sample cuttings of the black shale from the old location of the Mountain States well in 1993. These samples yield a faint cut fluorescence in 111-trichloroethane even after having been exposed to the elements for nearly 40 years. In 1958, Humble Oil Company reported gas shows in Permian strata in its #1 "BA" State in the southwestern New Mexico portion of the Pedregosa Basin.

High-gravity oil was produced in the 1920s and 1930s from several shallow, hand-dug postholes in a chicken yard in Willcox. More than 10,000 gallons of this oil were sold locally (Heylmun, 1978, p. 176). Heylmun (1980, p. 8) showed, however, that oil was stored in old masonry cisterns near the chicken yard and that all production from the postholes ceased within a few weeks after the masonry cisterns were replaced in the late 1930s.

The Pedregosa and Bisbee basins, like all of the other basins described in this report, remain largely untested and under drilled. Butler (1989, p. 83) pointed out that the drilling density in the graben-preserved strata of the Pedregosa and Bisbee basins is only one well for every 395 square miles.

Potential of the Pedregosa and Bisbee basins is considered fair to very good but with higher risk. Although the risk is higher, the potential recovery may be great. Interstate pipelines cross this part of Arizona and would provide a market outlet for any future discovery of natural gas. Large blocks of State Trust and private land are available for leasing throughout the area. Large blocks of public land are available in the northern part. Drilling depths are moderate to deep, ranging from 4,000 to 15,000 ft or more.

Yuma Basin

The Yuma Basin, in the southwestern corner of Arizona, includes all of the area south of Yuma to Mexico (Figure 14). The Yuma Basin, part of the Gulf of California embayment (Salton Trough), includes the San Luis and Fortuna basins of Mattick and others (1973). The Yuma Basin merges into the deep Altar Basin of Guzman (1981) to the south in Mexico. The Yuma Basin contains an exceptionally thick sequence of marine, estuarine, and nonmarine sediments of Tertiary age that thickens toward the south in the northern part of the Gulf of California (Sea of Cortez). Brennan (1989) concluded that these strata have high hydrocarbon potential in the eastern half of the Yuma Basin within the Barry M. Goldwater Aerial Gunnery Range.

In 1973, Exxon drilled an 11,400 ft well in the southern Yuma Basin (San Luis Basin) that did not reach the base of the Tertiary sediments. South of the Exxon well, in the northern part of the Gulf of California, Pemex drilled to a depth of 16,400 ft and did not reach the base of the Tertiary rocks. The Pemex well flowed 5.7 million cubic feet of gas per day at a depth of 13,500 ft and is currently shut-in as a commercial gas discovery. The producing interval in the Pemex well may extend northward into the Yuma Basin where oil and gas, having migrated up-dip, could be present in stratigraphic traps that formed where hydrocarbon-rich marine rocks onlap basement

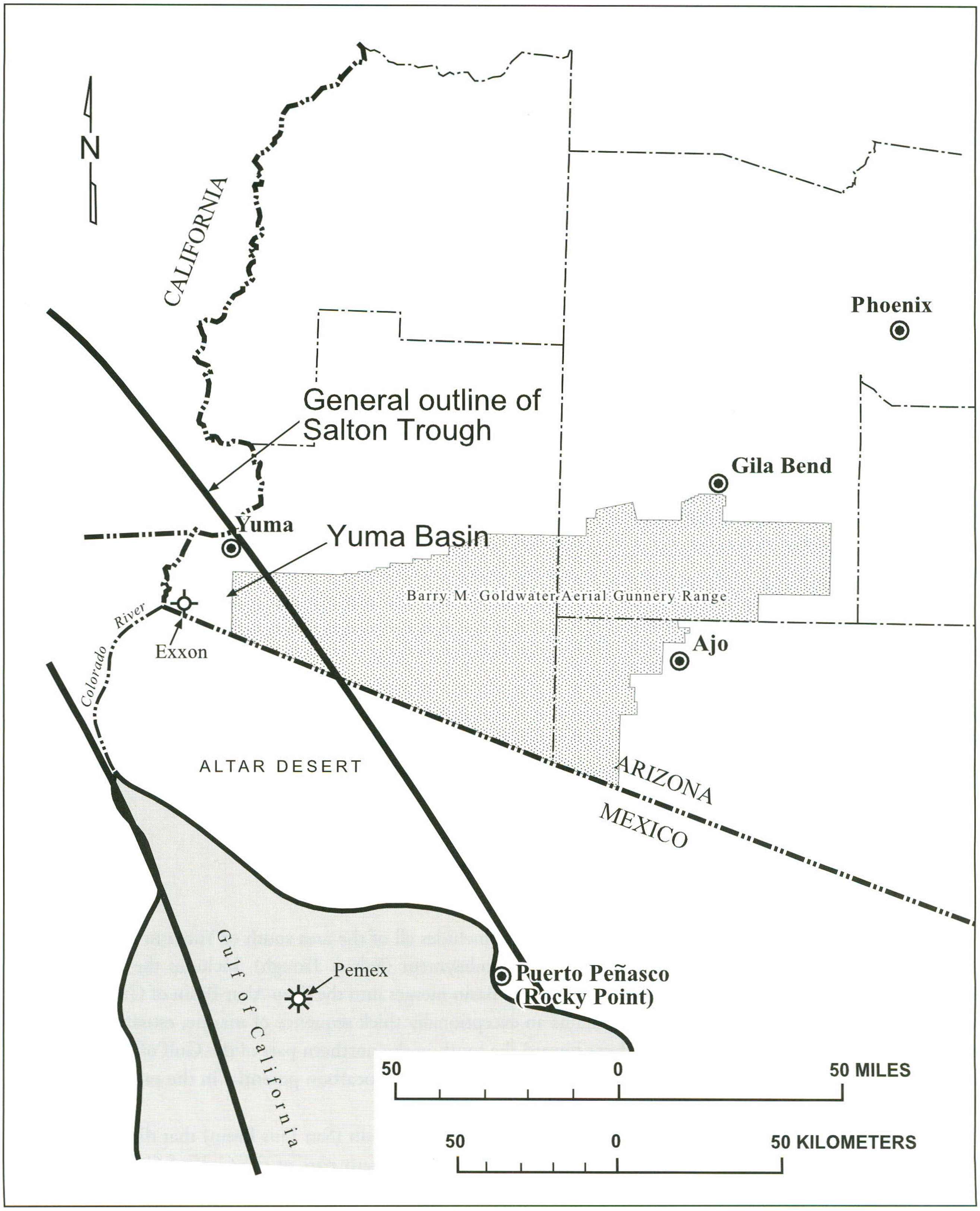

Figure 14. *Yuma Basin showing general outline of the Salton Trough and location of features discussed in the text.*

rocks or grade into impermeable continental strata. If the productive strata in the Pemex well are widespread, thin, distal turbidite sands, they could grade northward into linear, thick, proximal turbidite sands encased in mudstone in the Yuma Basin. The proximal turbidite sands could contain large volumes of gas under high pressure and have exceptional productive capability. Oil and gas migrating up-dip from the productive strata to the south may also be trapped in structures such as growth faults or faulted anticlines with small displacement.

Guzman (1981, p. 122-123) suggested that the hydrocarbon-rich Los Angeles and Ventura marine basins in southern California might have been in proximity to the Yuma Basin before the California basins moved northward along the San Andreas fault system. The Los Angeles Basin is one of the world's most productive. Under this scenario, oil and gas generated in the deep waters of the Los Angeles Basin migrated up-dip into secondary and other folds that were generated by movement within the San Andreas fault system. These hydrocarbon traps could still be present in the southern part of the Yuma Basin.

The hydrocarbon potential of the Yuma Basin is considered fair to good, especially in the deeper, sparsely tested southern parts of the basin and the completely untested eastern part of the basin beneath the Barry M. Goldwater Aerial Gunnery Range. Very few wells have been drilled to adequately test for the presence of linear proximal turbidite sands. State Trust, public, and private lands are available for leasing. Federal land in this area includes the Barry M. Goldwater Aerial Gunnery Range, which has good potential for discovery of oil and gas but is currently withheld from leasing and exploration. Drilling depths are moderate to deep, ranging from 4,000 to 20,000 ft or more.

Tertiary Basins

At least 14 Tertiary basins, primarily in southern and southwestern Arizona, have not been adequately tested for hydrocarbons. These basins are filled largely with sand, gravel, volcanic, lacustrine, and evaporite deposits of late Tertiary age that are preserved in the numerous down-faulted blocks of the Basin and Range Province (Figure 1). Correlation of Tertiary sedimentary units from basin to basin is difficult and most stratigraphic nomenclature is tentative. Eberly and Stanley (1978) identified a widespread unconformity that separates lower Tertiary strata, deposited in broad interior depressions, from upper Tertiary strata that were deposited in the Basin and Range graben. Presence of this unconformity was based on regional seismic profiles and a series of deep stratigraphic tests drilled by Humble Oil Company (now Exxon) in the 1970s.

Of the 14 Tertiary basins shown on Figure 1 and discussed here, three have more than 11,200 ft of strata, eight have more than 8,000 ft, and two have more than 6,400 ft. Some of the basins contain thick deposits of anhydrite and halite. The Luke and Red Lake basins contain a minimum of 10,000 ft of salt. Salt is also present in the Verde, Date Creek, and Safford basins. Anhydrite and gypsum are present in the Tonto, Tucson, Elfrida, and possibly the Paradise, Higley, Red Rock, and San Simon basins. Almost 6,000 ft of anhydrite and 60 ft of halite are present in the Picacho Basin. The Harquahala and Mohawk basins, in southwestern Arizona, contain more than 8,000 ft of strata that could include petroliferous limestone buried deeply beneath thick evaporite deposits. Petroliferous limestone crops out in the adjacent Gila Bend Mountains [Table 1 (19)].

Evidence for potential hydrocarbon source rocks in the Tertiary basins is as follows: reports of gray sand with globules of oil and black, oil-saturated shale in the Tannehill #1 Beardsley well northwest of Phoenix in Sec. 25, T. 4 N., R. 2 W. (Rauzi, 1991, p. 108); oil stains and slight fluorescence within evaporite strata in the Ivan Tenney #3 State well south of Safford (Sec. 36, T. 9 S., R. 27 E.); and organic-rich petroliferous limestone of Tertiary age that crops out near Tucson and in the Rincon Mountains in southeastern Arizona and in the Gila Bend Mountains in southwestern Arizona [Table 1 (16-19)]. The thick evaporite deposits of Tertiary age are also considered to be potential hydrocarbon source rocks. Evaporite deposits form in environments with high organic productivity and are commonly associated with major hydrocarbon reserves and production in many parts of the world (Kirkland and Evans, 1981). The evaporite deposits would also serve as impermeable seals to any hydrocarbons generated. Dark, biostromal and petroliferous carbonates of late Paleozoic age and organic-rich, black shale of Cretaceous age may also serve as a source of hydrocarbons where they are beneath or in fault contact with reservoir rocks of Tertiary age.

Heat associated with burial to depths of 8,000 to 10,000 ft or more and latent heat from mid-Tertiary metamorphic core complexes may have caused oil and gas to be generated from these potential hydrocarbon source rocks. Conditions would be especially favorable for hydrocarbon generation where reservoir rocks are in close association with organic-rich strata beneath the deeply buried evaporite deposits. No wells have yet completely penetrated the thick salt deposits in the Red Lake and Luke basins or the interbedded salt in the Date Creek Basin.

The diversely stratified Tertiary basins may include a variety of stratigraphic pinchouts, unconformities, and structural traps. Interbedded conglomerate, sandstone, volcanic rocks, and porous carbonates are potential reservoir rocks where they are encased or overlain by impermeable, organic-rich claystones, mudstones, carbonates, and evaporites. Oil or gas that migrates up-dip toward the mountain horst blocks could be trapped within the interfingering reservoir beds.

The Tertiary basins in southern and southwestern Arizona are similar to those in central Nevada, from which more than 20 million barrels of oil have been produced from basin-fill sedimentary and volcanic rocks. Oil produced from the Tertiary reservoirs in Nevada appears to have been derived from hydrocarbon source rocks of both Paleozoic and Tertiary age. Local heating by intrusive rocks may have caused oil to be generated in the Nevada Tertiary basins, as well as those in Arizona.

None of the deep Tertiary basins discussed in this report have been adequately tested. Very few deep wells have been drilled and no wells have completely penetrated the thick evaporite deposits. Because of this, the potential for a discovery of oil and gas in the Tertiary basins is considered to be fair. Potential is considered to be good where deeply buried petroliferous strata are beneath the thick evaporite deposits. Most land in the Tertiary basins is either fee or State Trust with lesser amounts of public. Drilling depths are shallow to deep, ranging from a few hundred feet to more than 12,500 ft in the deeper evaporite basins.

Conclusion

A wealth of evidence indicates that Arizona has potential for oil, natural gas, coalbed methane, helium, and carbon dioxide resources. The evidence includes current production of oil and natural gas, past production and recent discovery of the industrial gases helium and carbon dioxide, shows of oil, gas, and helium in wells, outcropping petroliferous rocks, oil seeps, and prospective areas with hydrocarbon source and reservoir rocks. Eight areas have fair to excellent potential (Figure 1). In addition, at least 14 Tertiary basins have evidence of source or reservoir rocks but have not been adequately tested.

The key to finding additional oil, natural gas, helium, and carbon dioxide in Arizona is simply to drill more wells to test the sparsely-drilled prospective areas. The major question now is, "who will make the next discovery in Arizona and when?"

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