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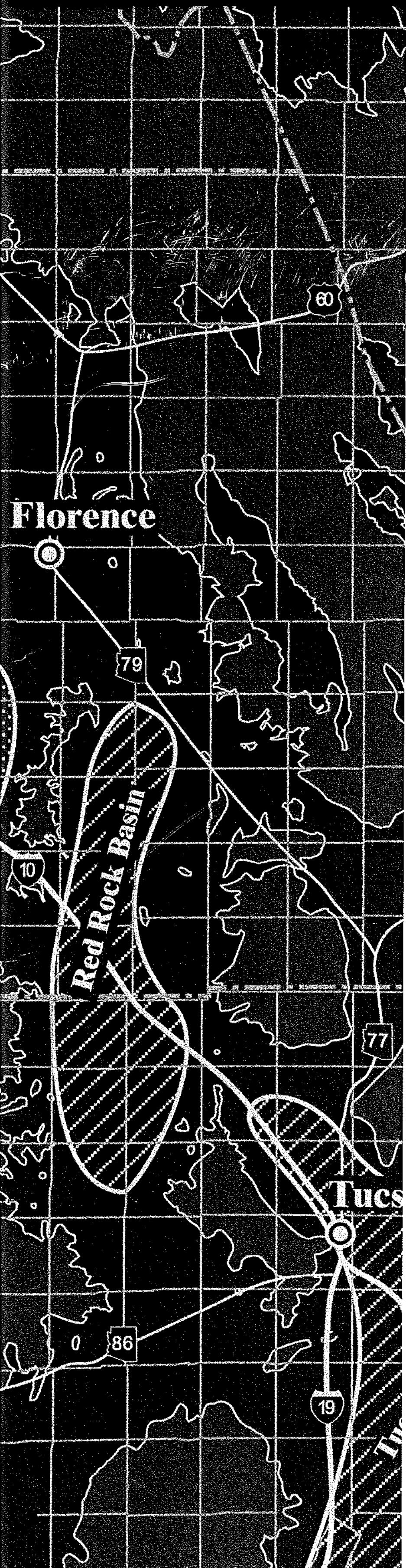

Arizona Has Salt!

Steven L. Rauzi

Circular 30

January 2002

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The Arizona Geological Survey (AZGS) informs and advises the public about the geologic character of Arizona in order to foster understanding and prudent development of the State's land, water, energy, and mineral resources. The geologic character of Arizona includes geologic hazards and limitations, energy and mineral resources, and the distribution and properties of rock formations. The AZGS also provides administrative and staff support for the Arizona Oil and Gas Conservation Commission (OGCC). The director of the AZGS is appointed by, and serves at the pleasure of, the Governor.

Members of the public are encouraged to visit the AZGS office and publication sales area, use the geology library and data files, and confer with staff geologists. The office is in the State of Arizona Regional Complex near downtown Tucson. If you are unable to visit the office, telephone or click on the website to get a better idea about what the agency does and what information and assistance are available.

Arizona Oil and Gas Conservation Commission

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Steven L. Rauzi
Oil & Gas Administrator

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Introduction

Background

Arizona has several deposits of subsurface salt (sodium chloride) that are thicker than the Grand Canyon is deep (Peirce, 1981a). These deposits are some of the thickest in the world (Peirce, 1989; Faulds and others, 1995, 1998).

Salt in Arizona is solution mined for industrial purposes near Phoenix and used to store liquefied petroleum gas (LPG) near Phoenix and Holbrook. Salt deposits near Phoenix and Kingman are being considered for the storage of natural gas. Several other basins have potential for the discovery and development of significant salt deposits.

Salt deposits in Arizona offer exceptional off-peak energy storage possibilities because of the location of interstate pipelines and railroads. Salt-solution caverns provide an economic alternative to surface storage in steel tanks. Arizona may be the only state in the west with salt bodies large enough for storage of LPG and natural gas between the main sources of supply and demand. The high deliverability of natural gas stored in salt caverns is a distinct advantage over storage in depleted oil and gas fields and aquifer reservoirs.

Purpose

H. Wesley Peirce (1981a) summarized the discovery and development of salt deposits in Arizona and discussed the potential for the existence of additional major deposits. The purpose of this report, which builds on Peirce's report, is to (1) identify and describe literature and the drilling and gravity data that define the major salt deposits, (2) document the relationship between gravity data and the major salt deposits and, (3) point to areas where additional salt deposits may be present. Known and potential salt deposits are shown on Figure 1. Another aspect of the report is to describe the existing storage and solution-mining facilities in the state and their relationship to railroads and pipelines. Areas with potential salt deposits also have potential for future development of storage-well and solution-mining facilities. All of the literature and the drilling and gravity data described in the report are available for review or purchase at the Arizona Geological Survey (AZGS).

Railroads and interstate pipelines trend across or pass near the major salt deposits in Arizona. Both of the existing LPG-storage facilities are served by the Burlington Northern Santa Fe (BNSF) railroad. Major railroads and interstate pipelines are shown in Figures 2 and 3.

Existing Facilities in Salt

Arizona hosts one solution-mining operation and two LPG-storage facilities. The solution-mining operation and one of the LPG facilities are west of Phoenix in the Luke salt deposit (Tertiary age) just east of Luke Air Force Base. The other LPG facility is located east of Holbrook in the Holbrook salt basin (Permian age) in southern Navajo and Apache Counties.

G.J. Grott formed the Southwest Salt Company and started solution-mining salt near Luke Air Force Base in the early 1970s. Morton Salt bought the facility in 1985. Four solution-mining wells have been drilled. Southwest Salt Company drilled three of the wells in 1968, 1970, and 1975. The wells drilled in 1968 and 1970 were plugged. The one drilled in 1975 is still active. Morton Salt drilled the fourth well in 1987.

Top of the salt at the Morton facility is 900 ft to 1000 ft below the ground surface. Morton uses fresh water to dissolve salt from the two active wells, which were drilled to a depth of about 3500 ft. The resulting brine is pumped into nine solar-evaporation ponds and harvested. The ponds hold more than 20 million gallons of brine and yield about 120,000 tons of salt each year (McGuire, 1999). The harvested salt is separated into different grades (coarse, extra coarse, fine, and industrial) before it is sent to either a pelleting press or bagging line. All of the salt harvested at the Morton facility is used for industrial purposes such as water treatment systems, making ice cream, and de-icing highways (McGuire, 1999; Sidener, 1999). One of the major customers is the nearby Palo Verde Nuclear Generating Plant where salt is mixed with water to make a more effective coolant.

AmeriGas operates the LPG-storage facility in the Luke salt just north of the Morton Salt facility. The AmeriGas facility consists of three storage wells originally drilled by California Liquid Gas Corporation (Cal Gas) between 1973 and 1977. AP Propane bought Cal Gas in 1987 and changed its name to AmeriGas in 1990. AmeriGas stores the LPG product (butane and propane) in specially constructed wells in which large caverns have been leached with fresh water deep inside the salt deposit. Top of the salt at the AmeriGas facility is about 1000 ft below the ground surface. The leached caverns are about 500 ft below the top of the salt, have an average radius of about 60 ft (maximum of about 175 ft), and extend from about

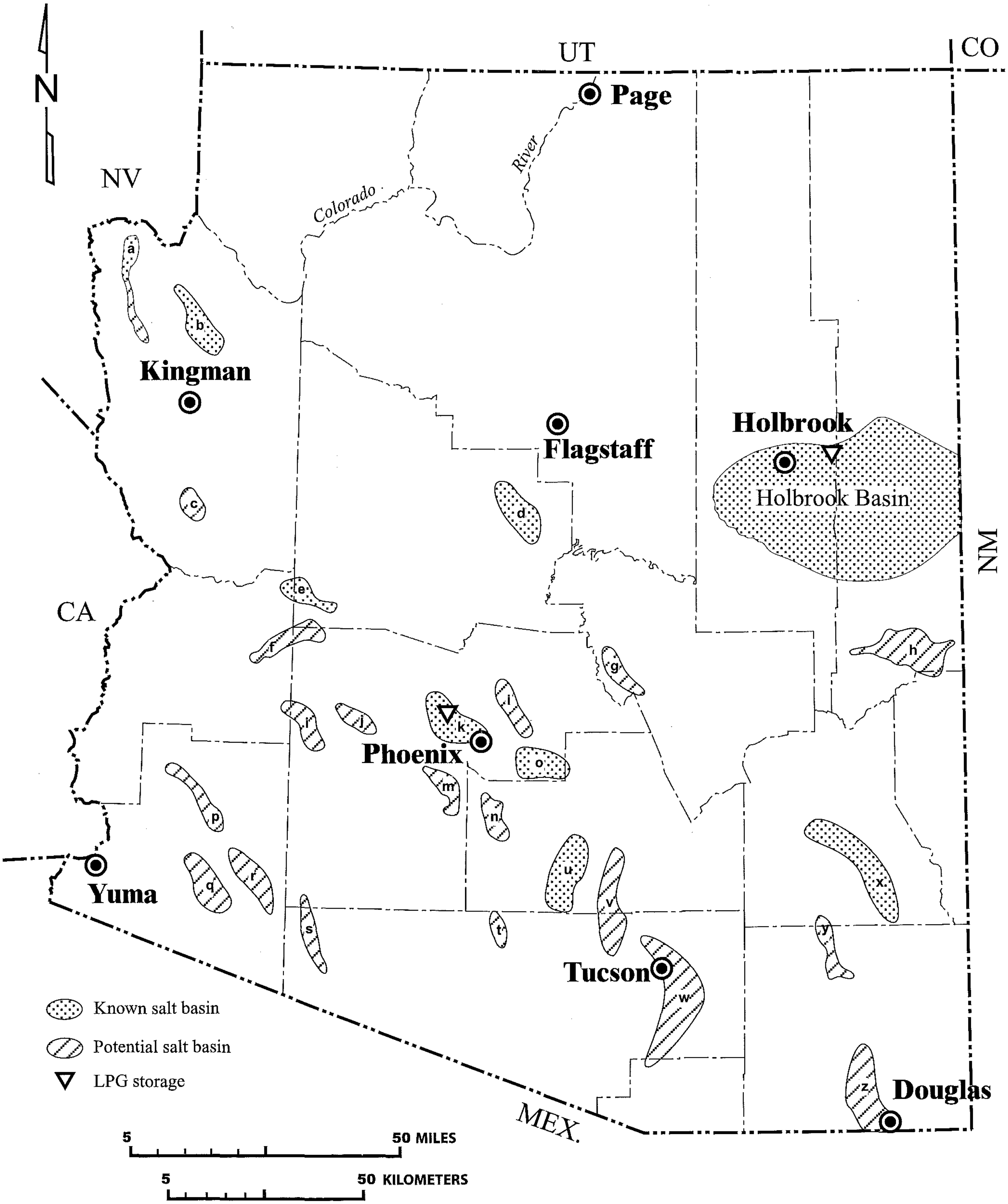

Figure 1. Known and potential salt basins in Arizona. (a) Detrital, (b) Red Lake, (c) Dutch Flat, (d) Verde, (e) Date Creek, (f) McMullen, (g) Tonto, (h) White Mtns, (i) Harquahala, (j) Tonopah, (k) Luke, (l) Paradise, (m) Rainbow, (n) Maricopa-Stanfield, (o) Higley, (p) King, (q) Mohawk, (r) San Cristobal, (s) Growler, (t) Santa Rosa, (u) Picacho, (v) Red Rock, (w) Tucson, (x) Safford, (y) Willcox, (z) Elfrida.

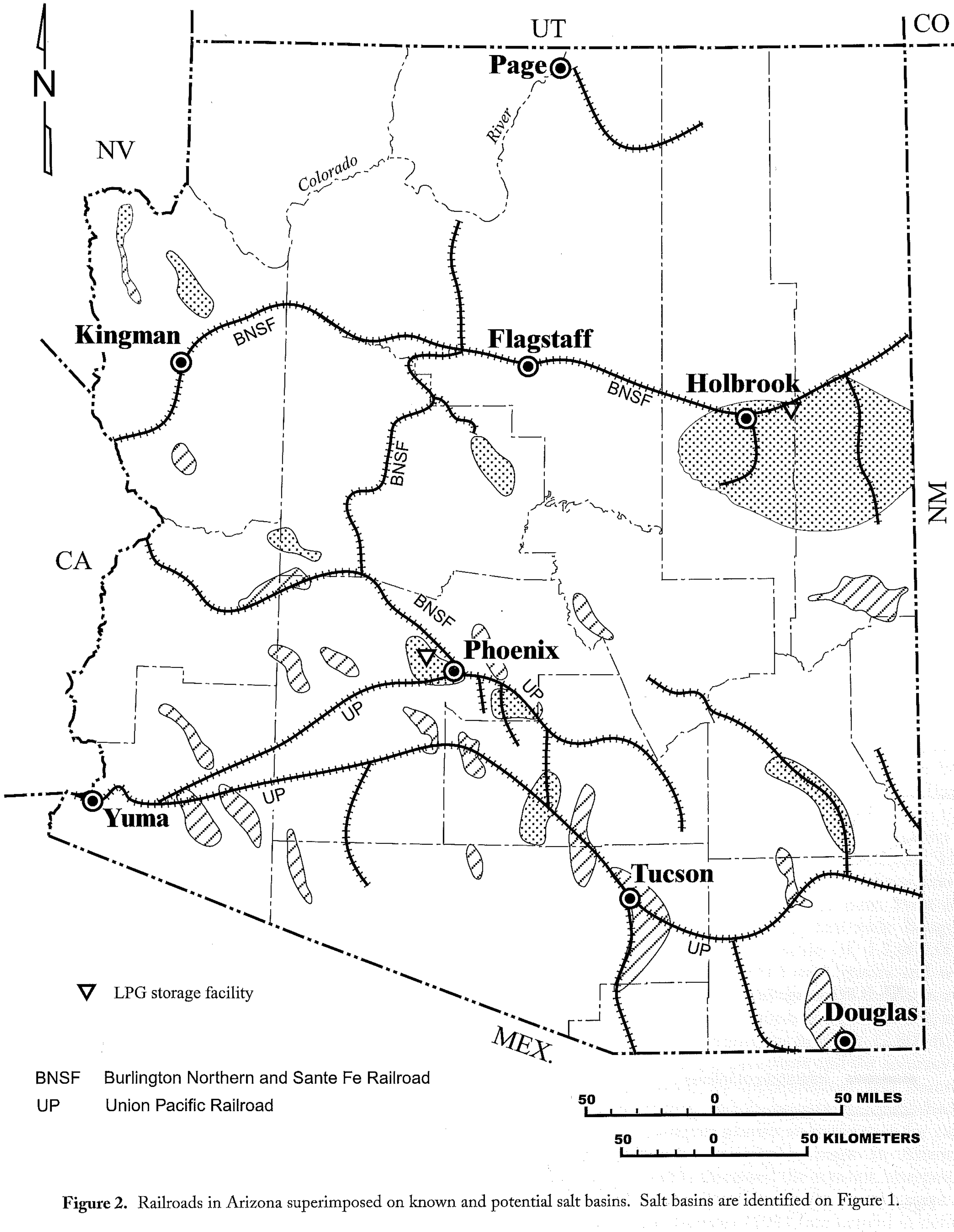

Figure 2. Railroads in Arizona superimposed on known and potential salt basins. Salt basins are identified on Figure 1.

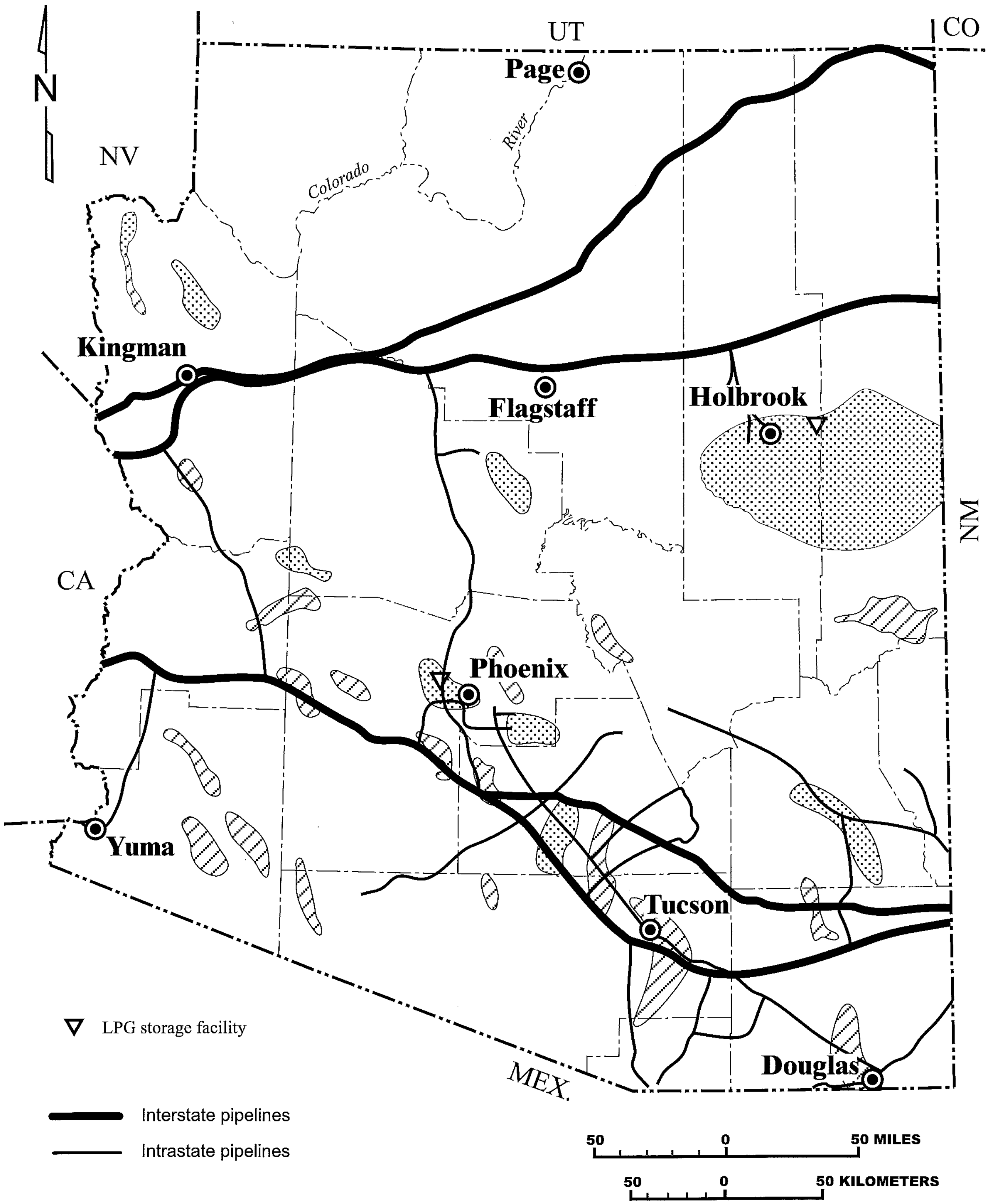

Figure 3. Natural gas pipelines in Arizona superimposed on known and potential salt basins. Salt basins are identified on Figure 1.

1550 ft to 3000 ft below the ground surface. Individual cavern volumes range from about 46 to 61 million gallons. Total cavern volume at the AmeriGas facility is about 156 million gallons. The AmeriGas facility is served by the BNSF railroad.

Ferrellgas operates the LPG-storage facility in the Holbrook salt basin. The Ferrellgas facility, about 20 miles east of Holbrook at Adamana, consists of 11 active storage wells originally drilled by the Suburban Companies and Williams Energy Company between 1971 and 1976. Ferrellgas bought the facility in 1986. Top of the salt at the Ferrellgas facility is about 870 ft below the ground surface. The caverns have been leached about 75 ft below the top of the salt, have an average radius of about 60 ft (maximum of about 118 ft), and extend from about 945 ft to 1040 ft below the ground surface. Individual cavern volumes range from about 7 to 11 million gallons. Total cavern volume at the Ferrellgas facility is about 86 million gallons. The Ferrellgas facility is served by the BNSF railroad and offers dedicated cavern storage to its customers.

Regulation

The U.S. Environmental Protection Agency (EPA) and the Arizona Department of Environmental Quality (ADEQ) regulate solution-mining wells in Arizona. The EPA and the Arizona Oil and Gas Conservation Commission (AOGCC) regulate class-II storage and disposal wells. Class-II wells are related to oil and gas activity and include wells used to dispose of fluids associated with the production of oil and natural gas, inject fluids for enhanced recovery, and store liquid or gaseous hydrocarbons.

The AOGCC is attached administratively to the AZGS in Tucson. AOGCC rules governing class-II storage and disposal wells are listed in Title 12, Chapter 7 of the Arizona Administrative Code (A.A.C.). These rules, A.A.C. R12-7-175 through R12-7-182, cover permitting, design, construction, and operation of wells used to store liquid or gaseous hydrocarbons and non-hydrocarbon liquids and gases. Among other things, these rules require at least 200 ft between caverns, at least 100 ft of clearance between caverns and neighboring property lines, safety flares at brine pits, and other safety features.

The U.S. Federal Energy Regulatory Commission (FERC) has jurisdiction over the interstate movement of natural gas. As a result, construction of facilities that store natural gas also require authorization from the FERC. Questions about solution-mining wells should be directed to the ADEQ. Questions about the AOGCC, its rules, or applications to drill storage or disposal wells in Arizona should be directed to the Oil and Gas Administrator at the AZGS.

Geologic Setting

Peirce (1985) identified and defined three physiographic regions in Arizona (Figure 4): (1) the southern Colorado Plateau in northern Arizona, (2) the Basin and Range in southern and southwestern Arizona, and (3) the Transition Zone, with elements of both, in central Arizona.

The Colorado Plateau is characterized by mostly flat-lying strata of Paleozoic to Mesozoic age, whereas the Basin and Range is characterized by relatively narrow mountains (ranges) of folded Precambrian or Paleozoic rocks separated by broad valleys (basins) filled with thick deposits of Tertiary age. The largely lacustrine and playa sediments in the broad valleys of the Basin and Range Province were derived from weathering of the adjacent range blocks.

The Transition Zone is characterized by deep canyons, high peaks, and numerous mesas, valleys, and small mountains. The Mogollon Rim is a high, steep escarpment that separates the Transition Zone from the southern edge of the relatively undisturbed Colorado Plateau. Extensive low-elevation, alluvial desert basins or valleys mark the change from the Transition Zone to the Basin and Range Province.

Information about the subsurface of the three physiographic regions comes primarily from gravity modeling, seismic surveys, and sparsely located drill holes. Seismic surveys are the most helpful in depicting the subsurface but are not as readily available as gravity data. Eberly and Stanley (1978); Hansen, Moulton, and Owings (1980); Faulds and others (1995); Kruger and Johnson (1994); Kruger, Johnson, and Houser (1995); and Kruger and others (1998) have published seismic lines across some of the deep Tertiary basins in the Basin and Range Province.

Peterson (1968) published a Bouguer gravity map of parts of Maricopa, Pima, Pinal, and Yuma Counties. This map was instrumental in the development of the solution-mining facility near the Luke Air Force Base. West and Sumner (1973) published the first state-wide Bouguer gravity map of Arizona at a scale of 1:1,000,000. Oppenheimer and Sumner (1980) used gravity and well data to construct a depth-to-bedrock map of the Basin and Range Province. They drew contours at 400 ft, 800 ft, and multiples of 1600 ft to a maximum depth of 12,800 ft. A discussion of their modeling procedure and the accuracy of the map were provided by Oppenheimer and Sumner (1981). Lysonski, Aiken, and Sumner (1981) published a complete residual Bouguer gravity anomaly map for each of the 1:250,000-scale topographic maps in Arizona. Aiken and others (1981) discussed the concept, interpretation, and uses of these maps. Gravity data on the maps of Lysonski, Aiken, and Sumner (1981) are helpful in defining the extent of the known salt deposits and suggesting

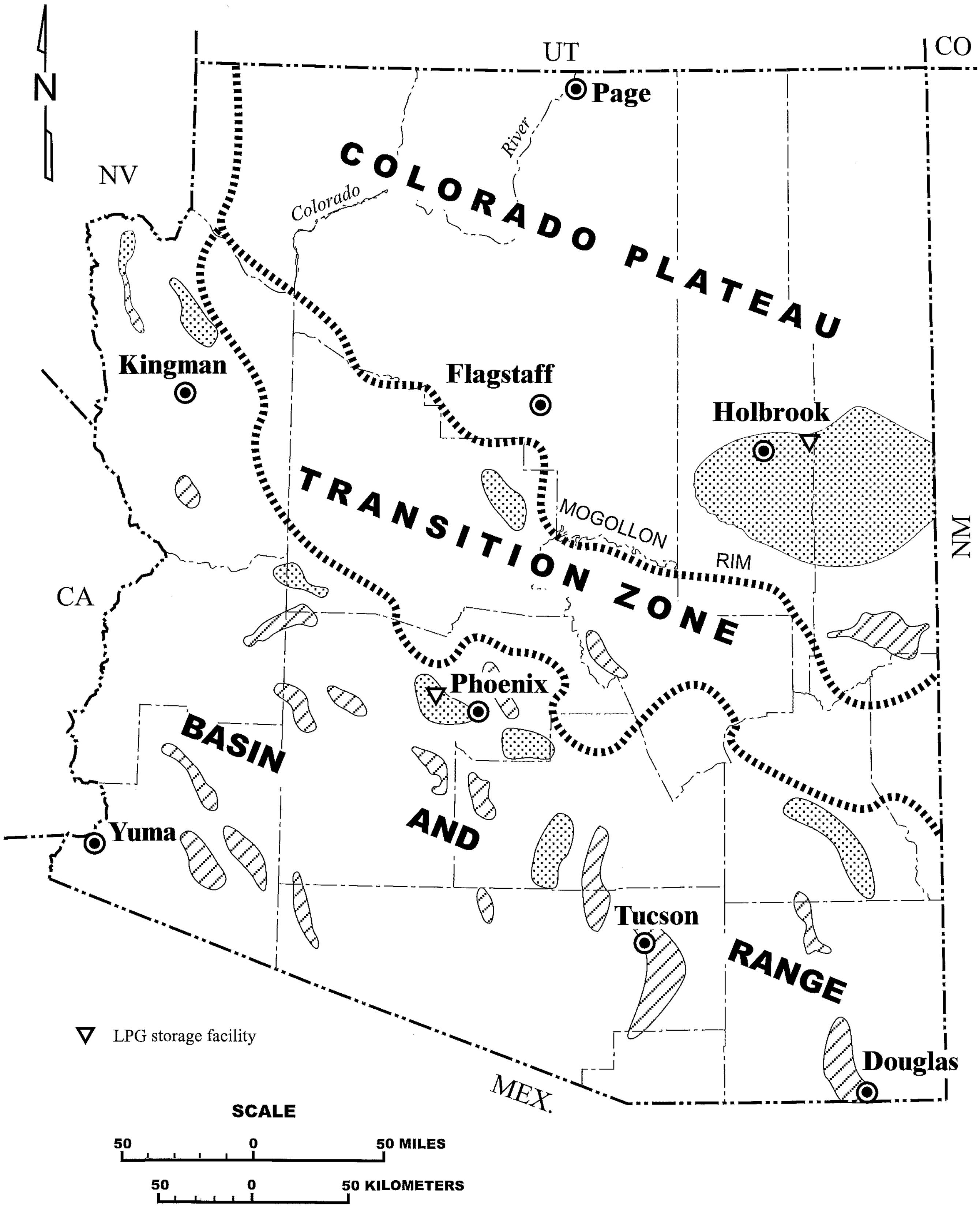

Figure 4. Physiographic provinces of Arizona (after Peirce, 1985) superimposed on known and potential salt basins. Salt basins are identified on Figure 1.

the location of potential salt deposits. Specific location data (Section, Township and Range) in the following sections are referenced to these maps, which are highly recommended as a supplement to this report. The Geologic Map of Arizona (Richard and others, 2000) includes the 4800 ft and 9600 ft depth-to-bedrock contours from Oppenheimer and Sumner (1980) in the Basin and Range Province and the 800 ft depth-to-bedrock contour for basins in the Transition Zone.

Several publications summarize drilling information in Arizona. Peirce and Scurlock (1972) and Scurlock (1973) compiled basic data for selected Arizona wells including formation tops, wireline logs run, and testing information. Rauzi (1999) compiled an index of samples that are available for wells drilled for oil and gas in Arizona. McGarvin and Trapp (1994) listed more than 4000 wells in the AZGS well-cuttings repository, which includes many holes drilled for water and other purposes. The AZGS maintains a series of 1:500,000-scale county-well-location maps of oil, gas, stratigraphic, geothermal, and selected water wells (Conley, Koester, and Rauzi, 1995a, 1995b, 1995c, 1995d,; Koester, Conley, and Rauzi, 1995a, 1995b, 1996a, 1996b). Rauzi (2001) compiled a statewide map and report of wells permitted by the AOGCC. Interstate pipelines are plotted on the statewide map. Well-location maps and reports are updated as new holes are drilled. Complete well files including samples, well logs, casing records, compiled data, and other information are available for most of the oil, gas, geothermal, and stratigraphic tests permitted by the AOGCC. Data sheets, some with lithologic and wireline logs, are available for the selected water wells on the county map series including many wells that are not plotted on the maps. The Arizona Department of Water Resources (ADWR) maintains records for more than 100,000 registered water wells in Arizona.

Known Salt Deposits

Salt, present in all of the physiographic regions in Arizona, is an abundant resource in several basins. The salt ranges in age from Permian on the Colorado Plateau to Tertiary in the Transition Zone and the Basin and Range Province. The thickest salt deposits are in the deep intermountain basins in the Basin and Range Province. The most extensive salt deposits are in the widespread strata of Permian age in the Colorado Plateau. The Tertiary salt in Maricopa County near Luke Air Force Base west of Phoenix and in Mohave County north of Kingman is at least 6000 ft thick and may be 8000 to 10,000 ft thick or more. These deposits cover tens of square miles. Even though the salt deposits in the Holbrook Basin are not as thick as the salt in the Basin and Range Province, they have an aggregate thickness of 655 ft southeast of Holbrook and cover a much larger area. Permian salt underlies more than 3500 mi^2 in southern Navajo and Apache Counties (Rauzi, 2000).

Blake (1890) was the first to describe the occurrence of rock salt in Arizona. He reported on outcrops in the Verde River Valley in central Arizona. Phalen (1919) described precipitated salts along the Salt River in central Arizona and outcrops along the Virgin River in Clark County, Nevada, and northwestern Arizona in addition to the outcrops in the Verde River Valley. Huddle and Dobrovolny (1945) published cross sections showing subsurface salt in the Holbrook Basin in east-central Arizona. This work was based on cable tool holes drilled for oil in the 1920s. Pierce and Rich (1962, p. 47-49) included the subsurface salt in the Holbrook Basin in their summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials. Bahr (1962) described salt dissolution features associated with the Holbrook anticline in the southwestern part of the Holbrook Basin. Peirce and Gerrard (1966) described the general geologic setting and stratigraphy of the evaporite deposits of the Holbrook Basin. They presented the broader aspects of evaporite distribution and deposition in east-central Arizona and attributed deposition of salt in the Holbrook Basin to intermittent restriction of marine waters. Blakey (1979, p. 128) attributed deposition of salt in the Holbrook Basin to sabkha and low-energy restricted marine conditions.

Peirce (1969; 1981a) and Koester (1971; 1972) summarized the major salt deposits in Arizona and discussed the development potential and possible origins of these resources. Koester reviewed significant drill holes in the various salt deposits in the Tertiary basins in the Basin and Range Province. Peirce (1972a) described the Red Lake salt deposit north of Kingman and concluded it was formed in a rapidly subsiding closed basin in late Tertiary time. Eaton, Peterson, and Schumann (1972) discussed the physical setting, delineation, and origin of the Luke salt deposit west of Phoenix. Eaton, Peterson, and Schumann (1970) postulated an arm of the sea as a source of the massive amount of salt in the Luke area but later (1972) discounted a marine origin based on bromine geochemistry and insoluble content. Mytton (1973) summarized the available geologic and hydrologic knowledge of salt in the Holbrook Basin with regard to its suitability for waste emplacement. He included a generalized lithologic log of the Luke salt. Peirce (1974) discussed the regional geologic setting of the thick evaporites in the Basin and Range Province and concluded they were of Late Tertiary age. He described a systematic drop in altitude and change in composition of the evaporite deposits in the separate continental basins in central Arizona. He attributed the massive salt at Luke to an integrated drainage system in which the Luke Basin was near the lower end of the system receiving chloride-enriched water. Peirce (1984, p. 218) considered the drainage of chloride-enriched water into the Luke Basin to be analogous to the chemical evolution of waters by sequential ponding and spillage to lower levels in the Atacama Desert in Chile. Dean and Tung (1974) discussed trace and minor elements in the anhydrite and halite deposits in the Holbrook Basin. Peirce (1976) discussed the tectonic significance of the thick evaporite deposits in the Basin and Range Province. He concluded that the evaporite deposits accumulated during late Miocene to Pliocene time and were indigenous to the basins in which they occurred. Eberly and Stanley (1978) showed the Luke salt deposit was Miocene in age based on a potassium-argon date of about 10.5 million years from a basalt flow overlying the salt. Johnson and Gonzales (1978) included four deposits in Arizona in their review of salt deposits and regional geologic characteristics important for potential storage of radioactive waste in the United States. Neal and Rauzi (1996) discussed the storage opportunities in Arizona salt. Faulds and others (1995, 1997) described the age, origin, and paleogeography of the Red Lake salt deposit in the Hualapai Valley north of Kingman. They reported the age of the salt as Miocene and determined it was deposited in a continental playa partially based on the texture and bromine content of the halite, dominance of halite, and oxygen and sulfur isotopes. They attributed the massive size of the salt deposit to rapid development of a deep basin, arid climate, interior drainage, proximity to a large uplifted region that supplied ample groundwater, and a readily available source of salt from marine sedimentary rocks of Permian age within the adjacent Colorado Plateau. They concluded that similar conditions prevailed all along or proximal to the southern and southwestern margin of the Colorado Plateau. Rauzi (2000) mapped the thickness and extent of Permian salt in the Holbrook Basin on the Colorado Plateau.

Martinez, Johnson, and Neal (1998); Neal, Colpitts, and Johnson (1998); and Neal (1999) described sinkholes, fissures, depressions, and other evaporite karst features associated with Permian salt in the Holbrook Basin. Peirce (1971; 1973; 1975; 1981b; 1987; 1989) provides additional information about salt deposits and potential storage sites in Arizona.

Colorado Plateau

Holbrook Basin

The Holbrook Basin covers about 8000 mi^2 in east-central Arizona in parts of Coconino, Navajo, and Apache Counties. Winslow, Sanders, Springerville, and Heber define the approximate northwest, northeast, southeast, and southwest extent of the basin, respectively. The BNSF railroad crosses the northern part of the area, through Winslow and Holbrook, and serves the Ferrellgas LPG-storage facility east of Holbrook at Adamana. Interstate pipelines cross the state just north of the area. Subsidiary pipelines extend south from the main line to Holbrook and Winslow.

Salt was first reported in the Holbrook Basin in the 1920s when it was encountered by cable tool holes drilled for oil and gas. Subsequent articles about the extent and regional geologic characteristics of the salt include Huddle and Dobrovolny (1945), Brown and Lauth (1958, Exhibit II), Pierce and Rich (1962), Peirce and Gerrard (1966), Mytton (1973), Johnson and Gonzales (1978), and Neal and Rauzi (1996). More recently, Rauzi (2000) used 223 wells including 135 wells cored for potash and 88 wells drilled for oil, gas, or LPG storage, to depict the extent and thickness of salt in the Holbrook Basin. Only 29 of the wells were drilled through the entire thickness of salt. Most were drilled into only the upper 100 to 300 ft of salt where potash minerals are present. A variety of wireline logs were run in the wells. The most useful curves in the salt section are the gamma ray, neutron, density, sonic, and resistivity logs. The spontaneous potential curve is not useful in delineating the salt.

Salt in the Holbrook Basin underlies about 3500 mi^2 in southern Apache and Navajo Counties (Figure 5). The salt attains a maximum aggregate thickness of 655 ft southeast of Holbrook in the Arkla Exploration Company #1 New Mexico and Arizona Land Company core hole. This hole, which is in Section 19, Township 16 North, Range 24 East (19-16n-24e), defines the approximate depositional center of the Holbrook salt basin (Rauzi, 2000, Plate 1).

Salt in the Holbrook Basin is part of the Supai Formation of Permian age. The Supai Formation there consists largely of sabkha deposits of red to reddish-brown clayey siltstone and halite interbedded with anhydrite, gypsum, and carbonate. Individual salt beds are commonly 1 to 5 ft thick but range in thickness from inches up to 30 ft and aggregate up to 655 ft. The halite grades laterally into anhydrite, gypsum, or mudstone. Anhydrite and gypsum extend beyond the limit of the halite deposits. Fine-grained clastic strata extend beyond the perimeter of the salt basin.

Potash is present near the top of the salt interval. The potash in the Holbrook Basin underlies about 600 mi^2 and ranges up to 38 ft thick (Rauzi, 2000, Plate 1). The potash

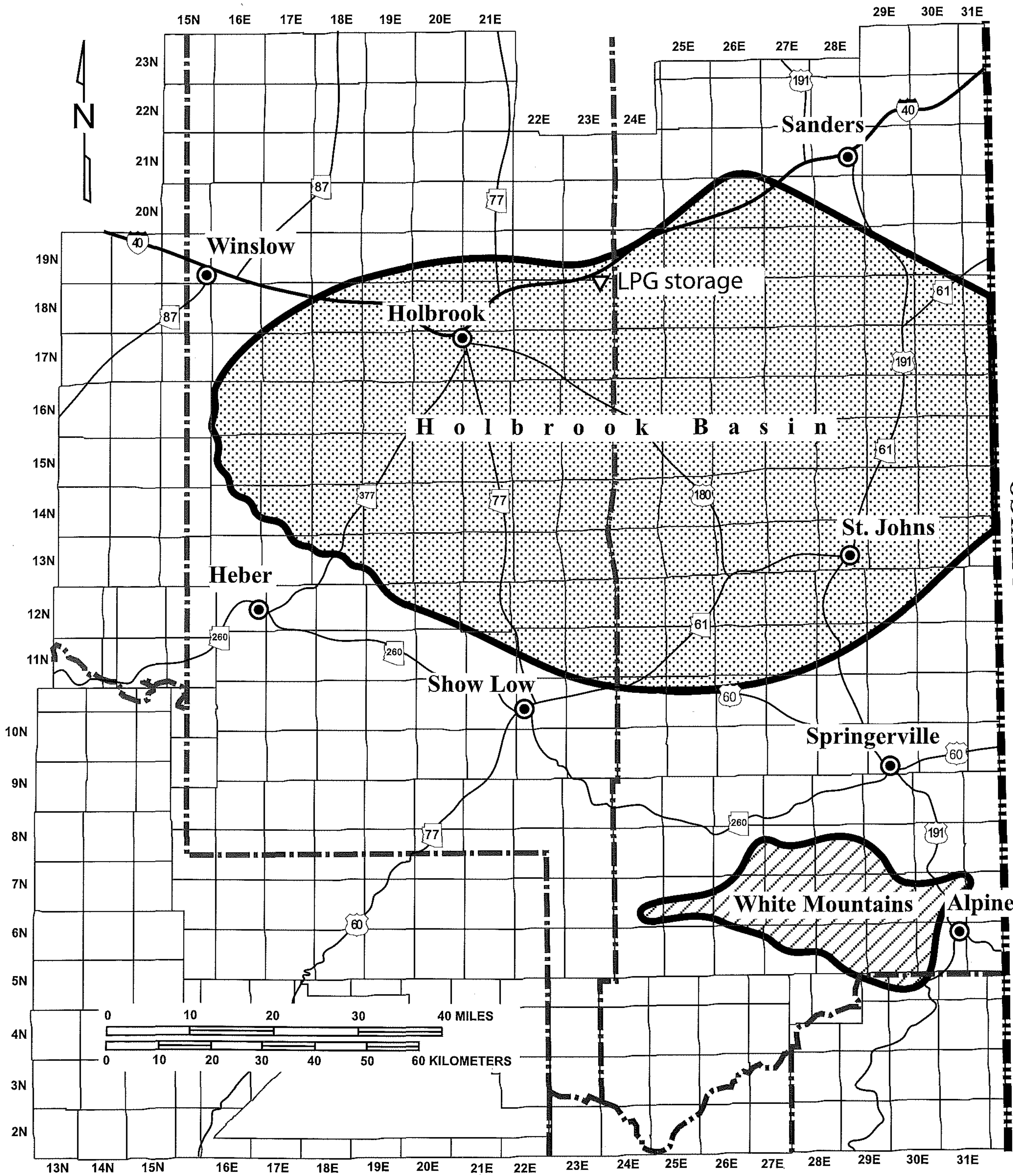

Figure 5. Holbrook salt basin (from Rauzi, 2000) and potential White Mountains salt basin (from Rauzi, 1996). See Figure 1 for legend.

minerals include sylvite, carnallite, and polyhalite. There has been no solution mining or commercial production of potash even though exploration drilling in the 1960s and 1970s indicated a potential of as much as 285 million tons of nearly 20 percent average grade K_2O.

Transition Zone

Verde Valley

The Verde Valley is in northeastern Yavapai County about 30 miles south-southwest of Flagstaff (Figure 6). This northwest-trending valley, about 30 miles long and 10 miles wide, is a half graben bounded on the southwest by the Verde fault. The Verde Valley, located within the Transition Zone, does not attain the great depth to bedrock that is common in the basins in the Basin and Range Province. Richard and others (2000) show the 800 ft depth-to-bedrock contour in the valley but not the 4800 ft contour. The well-location map of Yavapai County (Koester, Conley, and Rauzi, 1995b) lists five significant wells in the Verde Valley. These wells provide little useful information. Four of the wells are within the 800 ft depth-to-bedrock contour. Although no distinct trends are apparent on the residual gravity values (Prescott and Holbrook Sheets - Lysonski, Aiken, and Sumner, 1981), a small elongate gravity low is present within an area of widely spaced gravity contours just west of Camp Verde. Another elongate gravity low is present 10 miles north of Camp Verde. A natural gas pipeline extends eastward from the Maricopa Crossover into the northwestern part of the Verde Valley. No major railroads are present in the valley.

Blake (1890) published the first detailed description of salts, including halite, in the Verde Valley. The evaporite deposits described by Blake are associated with the mudstone facies of the lacustrine Verde Formation of Tertiary age and extend over an area of about 75 mi^2 in the southwestern part of the valley (Twenter and Metzger, 1963, p. 47). The evaporite deposits probably formed in isolated ponds bordering the restricted lake during dry periods. Halite is more common nearer the southwest-bounding fault. Nations (1974, p. 615) reported a composite thickness of more than 3100 ft for the Verde Formation. The maximum thickness of the Verde Formation has not been determined.

The salt mine described by Blake (1890) is about 1.5 miles southwest of Camp Verde in 1-13n-4e. The Verde Formation at the salt mine contains beds of sodium sulfate (thenardite, mirabilite, and glauberite) with thinly bedded halite. These deposits cover several acres in extent and reach a thickness of 60 ft or more. Gypsum is the chief mineral at a gypsum quarry in 11-13n-5e, about 6 miles east-southeast of the salt mine. Twenter and Metzger (1963, p. 76) reported that water from wells in the mudstone facies south of Camp Verde was small in quantity and very salty. In addition, salt was reported in two wells, the Verde Oil Company #1 in 14-13n-5e and a water well in 28-13n-5e. The Verde Oil #1 was drilled to a depth of 1625 ft in 1913. Verde Oil reported several beds of salt between 170 and 860 ft and water at 1000 ft that contained 33 percent sodium. Twenter reported evaporite minerals between 160 and 700 ft in the water well (Twenter and Metzger, 1963, p. 77). He reported salt, salty taste, and a white, crystalline crust forming on dry samples between 160 and 360 ft. The water well is about 3 miles southwest of the Verde Oil #1.

The salt mine and wells in the mudstone facies south of Camp Verde are just southeast of the elongate gravity low west of Camp Verde in the central to southeastern part of T. 14 N., R. 4 E. This gravity low may represent thicker deposits of salt along the Verde fault, which bounds the southwest margin the Verde Valley. Another gravity low is present 10 miles north of Camp Verde. The areal extent of evaporites in the northern part of the Verde Valley is not known and the limited subsurface information indicates that evaporite sediments did not extend that far north (Nations and others, 1981, p. 146). Even so, the elongate gravity low north of Camp Verde in the northeastern part of T. 15 N., R. 4 E. may represent a salt deposit formed in one of the isolated ponds bordering the restricted lake during dry periods. No deep holes have been drilled to verify the presence of the mudstone facies or discount the possibility of evaporite deposits and salt. ADWR records indicate that hundreds of domestic water wells have been drilled to depths of less than 300 ft in this part of the Township. The deepest well was drilled to a depth of only 930 ft in 1-15n-4e.

Basin and Range

Detrital Valley

Detrital Valley is a long, linear valley that trends northwesterly for about 40 miles between Dolan Springs and Lake Mead in northern Mohave County (Figure 7). The valley widens to about 15 miles at its southern end near Dolan Springs where it attains its maximum depth of at least 4800 ft (Richard and others, 2000). The well-location map of Mohave County (Koester, Conley, and Rauzi, 1996b) lists 19 significant wells in Detrital Valley. All are considerably north of the 4800 ft depth-to-bedrock contour west of Dolan Springs. Residual gravity values decrease steadily from Lake Mead into an elongate gravity low just southwest of Dolan Springs (Kingman Sheet - Lysonski, Aiken, and Sumner, 1981). Two interstate gas pipelines and a major railroad extend westerly through Kingman, about 25 miles south of Dolan Springs.

Detrital Wash flows northward through Detrital Valley into the Colorado River (now Lake Mead). North

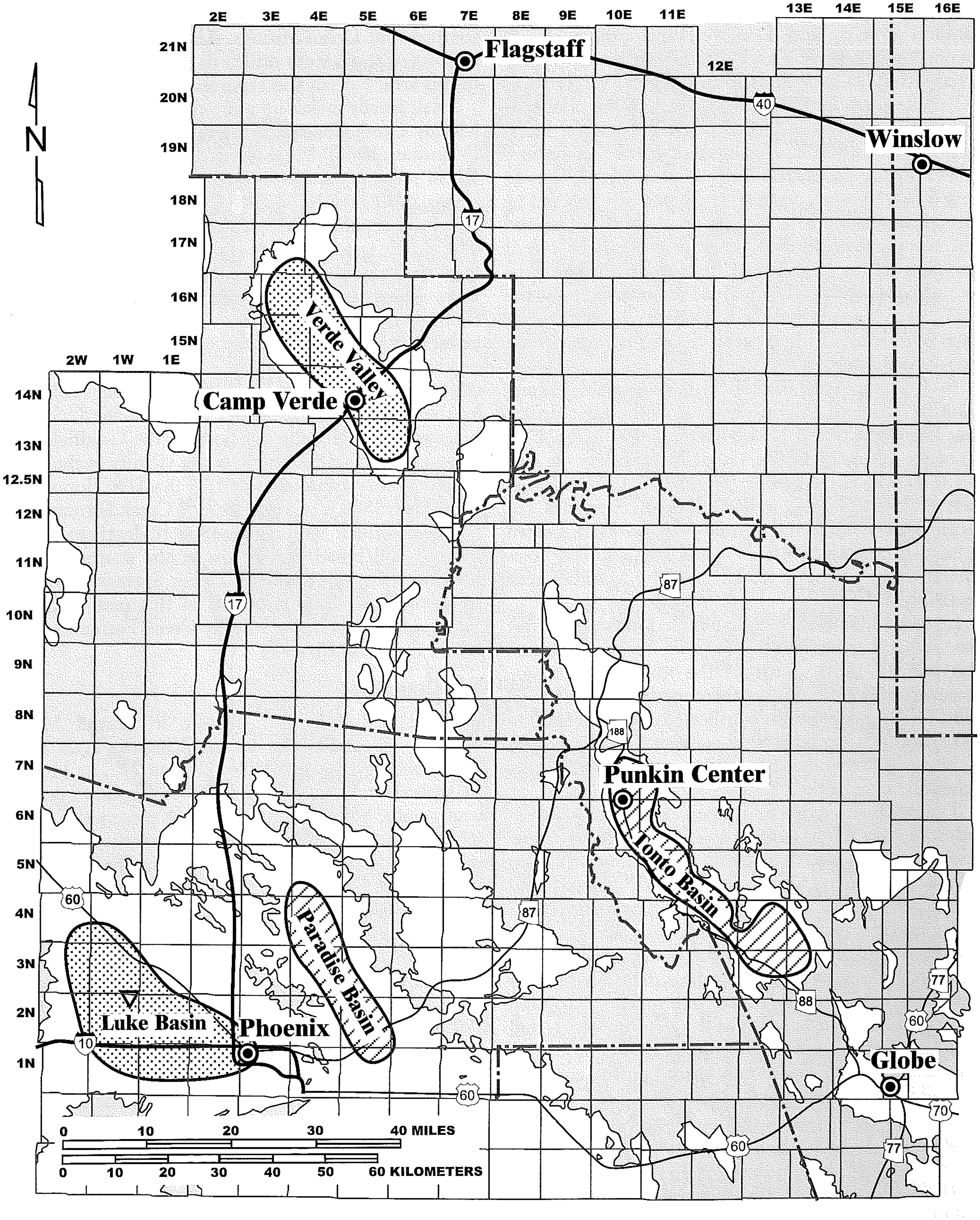

Figure 6. Verde Valley and Tonto Basin. Bedrock areas are shaded (from Richard and others, 2000). See Figure 1 for legend.

of the Colorado River, Phalen (1919), Longwell (1928), Mannion (1963), and Longwell and others (1965) described salt outcrops and several salt mines in the Tertiary Muddy Creek Formation along the Virgin River in Clark County, Nevada. These outcrops are now submerged beneath Lake Mead. Longwell (1936, p. 1423) described 400 to 500 ft of bedded anhydrite and gypsum on both sides of Detrital Wash south of the Colorado River. These gypsum outcrops, now partially covered by Lake Mead, extend 5 to 6 miles south of the river and form conspicuous outcrops that project above recent alluvium as far as 14 miles south of the river. The gypsum outcrops south of Lake Mead are referred to as the "Big Gypsum Ledges" on the Bonelli Bay 1:24,000-scale topographic map. Drilling data indicate that the gypsum grades laterally into salt to the south.

In 1957 and 1958, Goldfield Consolidated Mining Company reported salt in eight of 11 holes it drilled about 10 miles south of Lake Mead in T. 29 N., R. 21 W. Top of the salt ranged from 450 to 750 ft below the surface; thickness ranged from 500 to 600 ft and was as much as 750 ft in one well. Goldfield reported a salt deposit 3 miles long and 1 mile wide with an assured thickness of at least 500 ft. None of the Goldfield holes penetrated the complete thickness of the Muddy Creek Formation.

In 1995, U.S. Borax drilled three stratigraphic test holes about 5 miles south-southeast of the Goldfied holes and 10 miles north of the 4800 ft depth-to-bedrock contours at the southern end of the Detrital Valley. The Borax holes were drilled to depths of 1500 to 1800 ft and penetrated mostly gypsum and clay, but no salt, between 500 and 1500 ft. None of the Borax holes reached the base of the Muddy Creek Formation.

The residual gravity values decrease steadily southward from Lake Mead to form an elongate gravity low in the widest part of Detrital Valley just southwest of Dolan Springs (Kingman Sheet - Lysonski, Aiken, and Sumner, 1981). The spacing between the gravity contours converges to form two steep, east-facing gravity slopes between Lake Mead and the elongate gravity low. One is in the vicinity of the salt mass delineated by the holes drilled by the Goldfield Consolidated Mining Company. The other is south of the gypsum penetrated by the U.S. Borax holes—where the gravity contours are more widely spaced. The closely spaced gravity contours may represent right-stepping en echelon normal faults where a greater thickness of the lower Muddy Creek Formation, including salt, was deposited. The relatively large salt body associated with the northern of the two east-facing gravity slopes suggests that a relatively large salt body may be associated with the untested east-facing gravity slope south of the U.S. Borax holes.

No deep exploratory holes have been drilled in the deepest part of Detrital Valley depicted by the broad gravity low and the 4800 ft depth-to-bedrock contour southwest of Dolan Springs. ADWR records include at least seven water wells drilled to depths less than 1000 ft in this area. No salt was reported in the water wells.

Salt locally makes up more than 1600 ft of the lower Muddy Creek Formation north of the Colorado River (Mannion, 1963). Mannion described the deposition of salt in saline lakes that formed in local deeps in separate basins during early Muddy Creek time. Gypsum and anhydrite separate the salt deposits in the local deeps. The closely spaced gravity contours indicate at least two local deeps, probably associated with faulting, between Lake Mead and the deepest part of Detrital Valley southwest of Dolan Springs. Conspicuous outcrops of bedded gypsum separate the extensive outcrops of salt north of the Colorado River and the subsurface salt deposit associated with one of the local deeps delineated by the Goldfield holes. The gypsum in the U.S. Borax holes may separate the salt body in the Goldfield holes from another local salt body in the vicinity of the closely spaced gravity contours south of the U.S. Borax holes. More than 3800 ft of lower Muddy Creek Formation has not been drilled within the 4800 ft depth-to-bedrock contour and broad gravity low at the southern end of Detrital Valley southwest of Dolan Springs. There may be as much as 1600 ft of salt in this part of Detrital Valley, as there is in the Muddy Creek Formation north of the Colorado River.

Red Lake Salt

The Red Lake salt deposit, in central Mohave County, is about 30 miles north of Kingman in the northwest-trending Hualapai Valley (Figure 7). The Hualapai Valley is about 25 miles long and 10 miles wide. Four deep stratigraphic holes have confirmed the presence of massive salt just south of the Red Lake Playa near the center of the valley. The Red Lake salt takes its name from the playa. Kerr McGee Corporation drilled the first two holes in the Hualapai Valley to depths of 2608 ft and 2135 ft in 1958. El Paso Natural Gas drilled the third hole to a depth of 5994 ft in 1970. The El Paso hole cut about 4200 ft of essentially pure salt between 1796 and 5994 ft. TranAm Energy drilled the fourth hole to a depth of 2470 ft in 1989. None of the holes penetrated the base of the salt deposit. The thickest part of the salt mass may be associated with a pronounced gravity low on the Williams Sheet of Lysonski, Aiken, and Sumner (1981). The gravity low is about 10 miles southeast of the four drill holes in the southwestern part of T. 25 N., R. 15 W.

Koester (1971, 1972) summarized the drill-hole and gravity data in the Hualapai Valley. Peirce (1972a) described the shape, size, and age of the Red Lake salt and characterized the Hualapai Valley as a half graben hinged on the west with maximum displacement on the east. Seismic data confirm that the Hualapai Valley is a

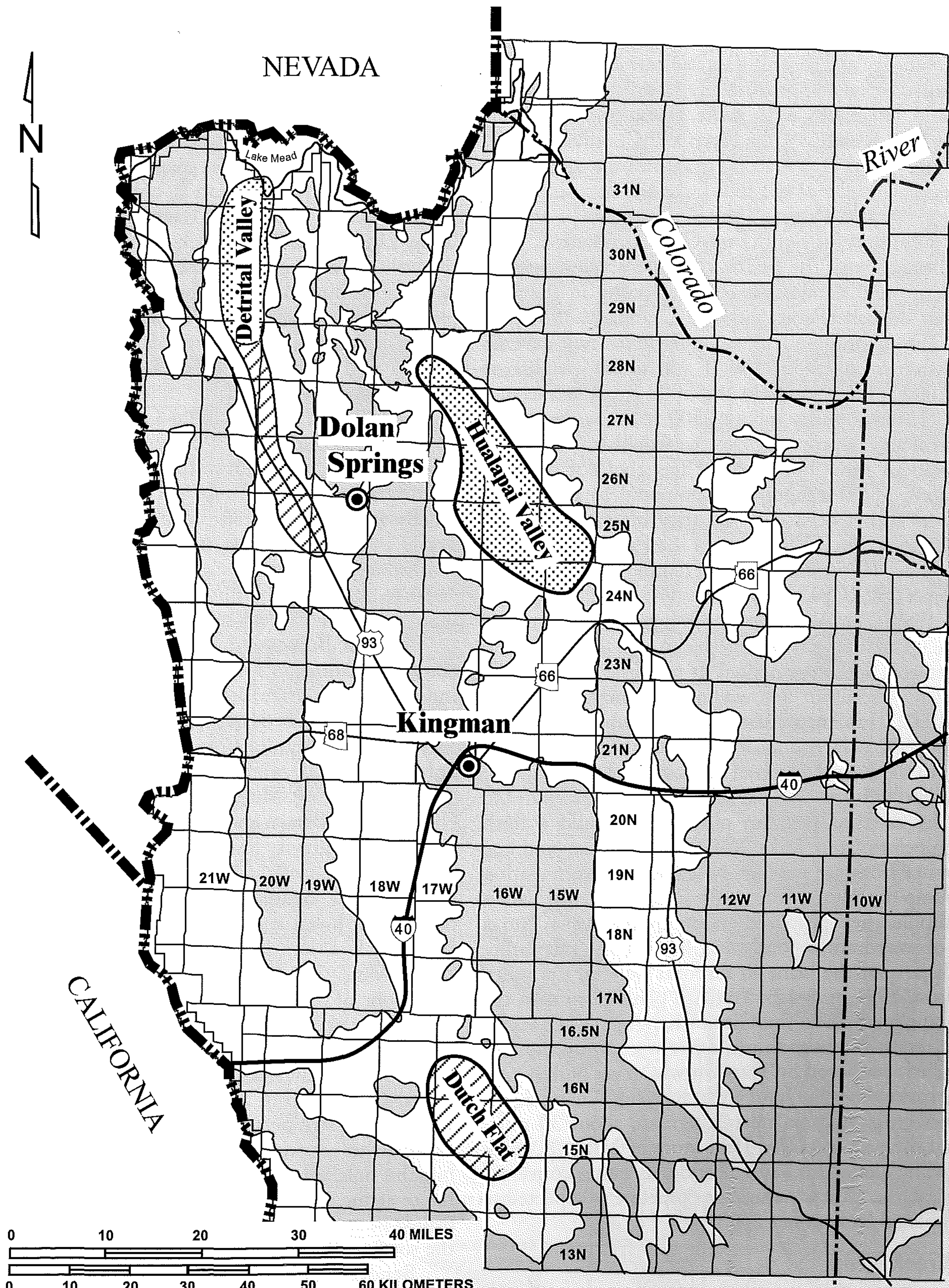

Figure 7. Detrital Valley, Red Lake salt (Hualapai Valley), and Dutch Flat. Bedrock areas are shaded (from Richard and others, 2000). See Figure 1 for legend.

half graben (Hansen, Moulton, and Owings, 1980). Top of the Red Lake salt is about 1500 ft below the ground surface. Gravity and seismic data indicate as much as 100 mi^3 of salt in a mass approximately 12 miles long, 5 miles wide, and as much as 2 miles thick (Gillespie and Bentley, 1971; Peirce, 1972a; Davis and Condradi, 1981). Faulds and others (1995, 1997) discussed the age, origin, and paleogeography of the Red Lake salt deposit.

In 1980, the Pataya Storage Company, a wholly owned subsidiary of Southwest Gas Corporation, filed an application with the FERC to construct and operate an underground natural gas storage facility in the Red Lake salt deposit (Pataya Storage Company, 1981 and 1982). Pataya proposed to solution mine two caverns with diameters of about 150 ft and usable heights of about 1000 ft between 4000 and 5000 ft below the surface of Hualapai Valley (about 2500 ft below the top of the salt). Pataya's proposed caverns would be capable of storing about three billion cubic feet (bcf) of working gas. Pataya noted a significant potential to expand its facility to 10 bcf of storage capacity by leaching additional caverns. The FERC denied the Pataya application in November 1985 citing a lack of demonstrated need for the project (FERC, 1985).

In 1989, TranAm Energy Group revived plans to construct a natural gas storage facility in the Red Lake salt deposit. TranAm presented its proposal to the public and town officials in a town meeting in Kingman in April 1991. TranAm released an environmental assessment in 1992 (Harrison, 1991). The TranAm plan was similar to the Pataya proposal in most respects except for the method of brine disposal and source of fresh water to leach the cavities. TranAm proposed to build a fresh water pipeline from Lake Mead to Kingman and use fresh water from the pipeline to leach the caverns rather than pump fresh water from wells in the Hualapai Valley. In addition, they proposed to pump the brine into a series of evaporation ponds and harvest the salt rather than dispose of the brine in disposal wells in the valley (Harrison, 1991, p. 9-12). TranAm planned to turn the water pipeline over to the City of Kingman after leaching but retain a right to future use of water from the line. The facility proposed by TranAm was never built.

A major railroad and two interstate natural gas pipelines cross Arizona near Kingman, about 30 miles south of the proposed Red Lake storage facility. A crude oil pipeline along this same corridor is being converted to natural gas. A new natural gas pipeline is expected to be completed by summer 2003.

Date Creek Basin

Date Creek Basin is about midway between Phoenix and Kingman in the northeastern corner of La Paz and southwestern Yavapai Counties (Figure 8). The Santa Maria and Bill Williams Rivers mark the northwestern boundary of the northwest-trending basin. Low hills of igneous rock mark the southeastern end. U.S. Highway 93 extends northwest just east of the basin. An interstate natural gas pipeline, the Havasu Crossover, trends northward through the Butler Valley, about 20 miles southwest of the Date Creek Basin. The closest railroad is about 30 miles to the east. The well-location maps of Yuma and La Paz Counties and Yavapai County (Conley, Koester, and Rauzi, 1995b; Koester, Conley, and Rauzi, 1995b) list seven wells in the Date Creek Basin. Rock salt was reported in one of the wells. Gravity data suggest the Date Creek Basin is a half graben hinged on the northeast with maximum displacement on the southwest. There is a pronounced gravity low at the northwestern end of the Date Creek Basin (Wynn and Otton, 1978; Prescott Sheet - Lysonski, Aiken, and Sumner, 1981).

In 1970, El Paso Natural Gas Company drilled a stratigraphic test, the #1 Bullard Wash Federal, to a depth of 3831 ft in 3-10n-10w, just east of the La Paz County line. The #1 Bullard Wash Federal, drilled in search of salt, penetrated predominately loose sand and gravel to 650 ft, volcanic tuff from 650 to 1550 ft, and sandstone with minor claystone and limestone from 1550 to 3831 ft. Gypsum, anhydrite, or salt were not reported in the El Paso hole.

In 1972, Brown and Thorp Oil Company deepened the El Paso hole to 5686 ft. Brown and Thorp reported mostly conglomerate, arkosic sandstone, and micaceous shale with minor beds of limestone from 3831 to 5630 ft and dark gray granite from 5630 to 5686 ft. Gypsum, anhydrite, or salt were not reported in the Brown and Thorp deepening. Mud salinity never exceeded 600 ppm chloride. The Brown and Thorp hole was drilled near the center of the gravity low in the northwestern end of the Date Creek Basin.

In 1979, Bendix Field Engineering Corporation drilled four holes in the Date Creek Basin as part of the National Uranium Resource Evaluation (NURE) program (McCaslin, 1980; Lease, 1981). Bendix reported salt in one of the holes, the PQ-5, which was drilled to a total depth of 5044 ft in 30-10n-10w, 5 miles southwest of the Brown and Thorp hole. The PQ-5 hole penetrated predominately sandstone and conglomerate to 2450 ft, red siltstone from 2450 to 4040 ft, and red siltstone with halite stringers from 4040 to 5044 ft. Bendix expected to encounter granite at approximately 4640 ft but the hole was still in the siltstone with interbedded halite at the total depth of 5044 ft. The PQ-5 hole was drilled in an area of closely spaced gravity contours along the southwestern edge of the gravity low.

Bendix drilled three other holes in the Date Creek Basin, the PQ-2, PQ-4, and PQ-6. The PQ-2 was drilled to a depth of 2621 ft in 26-9n-8w, 17 miles southeast of the Brown and Thorp hole. The PQ-4 was drilled to a depth of 5491 ft in 3-9n-9w, 9 miles south-

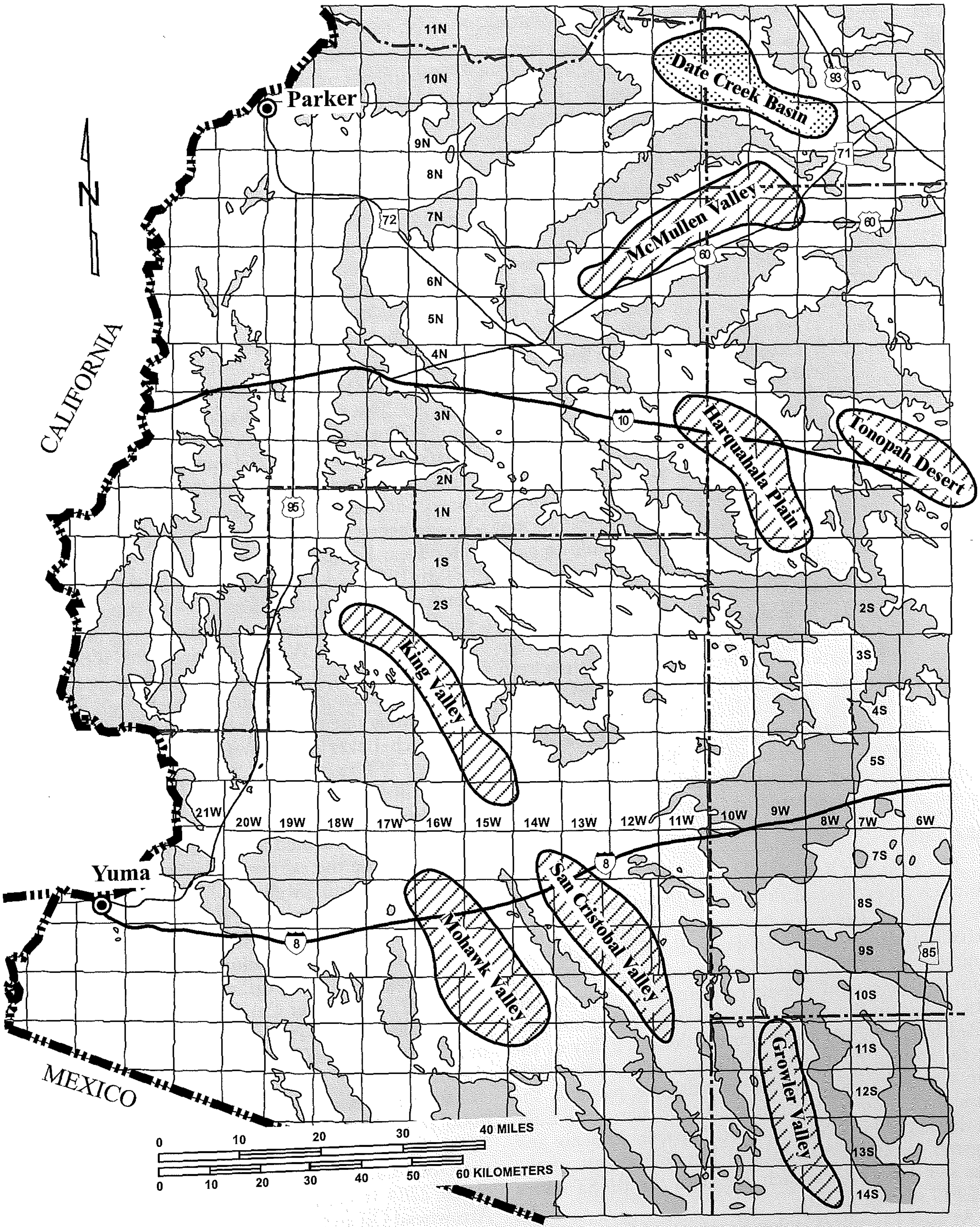

Figure 8. Date Creek Basin, McMullen Valley, Harquahala Plain, Tonopah Desert, and King, Mohawk, San Cristobal, and Growler valleys. Bedrock areas are shaded (from Richard and others, 2000). See Figure 1 for legend.

east of the Brown and Thorp hole. The PQ-6 was drilled to a total depth of 2998 ft in 31-11n-10w, 4 miles west-northwest of the Brown and Thorp hole. No salt or gypsum was reported in these holes. The PQ-2 and PQ-4 holes, at the southeastern end of the basin, penetrated biotite gneiss and volcanic rocks, respectively, at total depth. The PQ-6 hole, which experienced severe lost circulation below 2355 ft at the northwestern end of the basin, was still in conglomeratic sandstone at the total depth of 2998 ft.

The only hole that penetrated salt, the PQ-5, was drilled in an area of closely spaced gravity contours on the southwestern margin of the pronounced gravity low at the northwestern end of the Date Creek Basin. The PQ-5 penetrated at least 2450 ft of calcareous red siltstone with interbedded halite in the lower 860 ft. The closely spaced gravity contours probably represent a steeply dipping fault, a primary half-graben fault, along the southwestern edge of the basin. Rocks penetrated in the PQ-5 hole indicate that this basin-bounding fault formed an environment conducive to the deposition of siltstone and salt along the southwestern margin of the Date Creek Basin. The total thickness of salt is not known because the PQ-5, which was expected to be in granite at a depth of about 4600 ft, was still in interbedded siltstone and salt at total depth of 5044 ft. Strata in the PQ-5 hole suggest the presence of considerable salt, at least locally, along the entire southwestern margin of the Date Creek Basin in the southwestern half of T. 10 N., R. 10 W. The PQ-6 hole, 5 miles north of PQ-5, was not drilled deep enough to verify the extension of the interbedded salt in the PQ-5 hole into the southwestern corner of T. 11 N., R. 10 W. Additional drilling is needed to delineate the extent of the salt deposit penetrated in the PQ-5 hole.

Luke Salt

The Luke salt deposit is in central Maricopa County about 15 miles west of downtown Phoenix (Figure 9). The Luke salt basin got its name from the fact that it partially underlies Luke Air Force Base. Two solution-mining wells and three LPG-storage wells are located about 1 mile east of the air base near the approximate thickest part of the salt deposit. A stratigraphic hole was drilled in early 2001 to determine the suitability of the salt for storing of natural gas. The results of that hole were favorable. An interstate natural gas pipeline, the Maricopa Crossover, extends southward across the Luke salt deposit. The BNSF railroad between Phoenix and Flagstaff trends northwestward just to the east of the Luke salt deposit. A branch line from the BNSF serves the LPG storage facility.

At least 13 wells (Conley, Koester, and Rauzi, 1995a) and gravity data (Peterson, 1968; Phoenix Sheet – Lysonski, Aiken, and Sumner, 1981) have confirmed the presence of the massive Luke salt deposit. Although none of the wells have penetrated the entire thickness of the salt, a well drilled in early 2001 cut 4258 ft of salt. The gravity modeling of Oppenheimer and Sumner (1980) indicates the Luke salt was deposited in a basin with a depth of more than 11,200 ft to bedrock.

In 1953, Goodyear Farms drilled the #19-E water well to a depth of 2758 ft in 19-2n-1w, about 1 mile south of the Luke Air Force Base. Good cuttings samples were recovered from the Goodyear hole because it was drilled with cable tools. Anhydrite and gypsum were reported at about 1690 ft, water at 2054 ft, hot salt water at 2070 ft, and rock salt from 2318 to 2758 ft. The evidence indicates that the Goodyear hole dissolved rock salt between the water reported at 2054 ft and the salt water at 2070 ft. As a result, the top of the salt in the #19-E hole is close to a depth of 2060 ft (-865 ft). The Goodyear Farms #19-E was probably the first well to encounter solid rock salt in the western Salt River Valley. Two nearby water wells, drilled in 1959 and 1962, were plugged back because of brackish water or salt at total depth. These wells were located 4 miles northeast and 2 miles east, respectively, of the Goodyear Farms #19-E well.

In 1968, G.J. Grott drilled an exploration hole in the center of a pronounced gravity low (Peterson, 1968) on the basis of information from these early wells and discussions with H. Wesley Peirce of the AZGS (Grott, 1987). Grott's well, the #1 Roach-Baker in the southwest quarter of 2-2n-1w, was the discovery well for the solution-mining operation of Southwest Salt Company. The #1 Roach-Baker drilled over 3600 ft of solid rock salt between 880 ft and total depth of 4500 ft. Southwest Salt drilled a second and third well in 1970 and 1975. Morton Salt bought Southwest Salt's solution-mining facility in 1985, drilled a fourth well in 1987, and continues to mine the salt for industrial purposes. None of the solution-mining wells penetrated the base of the salt.

In 1973, Cal Gas drilled the first of three LPG-storage wells to a depth of 3200 ft about a half mile north of Southwest Salt's first solution-mining well, the #1 Roach-Baker. Cal Gas drilled two more wells in 1974 and 1977. All of the Cal Gas wells were drilled to a depth of about 3200 ft and penetrated more than 2000 ft of salt. None of the Cal Gas wells penetrated the base of the salt.

In 1988, Bob James drilled an oil test to a depth of 4000 ft in 19-2n-1w, about 5 miles southwest of the Southwest Salt #1 Roach-Baker and a half mile east of the Goodyear Farms #19-E. The Bob James well penetrated 2284 ft of salt from 1716 to 4000 ft. In 1992, Arrowhead Oil and Gas Ltd. drilled an oil test to a depth of 6650 ft in 23-2n-1w, about 3 miles south of the #1 Roach Baker hole and 4 miles east of the Bob James hole. The Arrowhead well is the deepest hole yet drilled

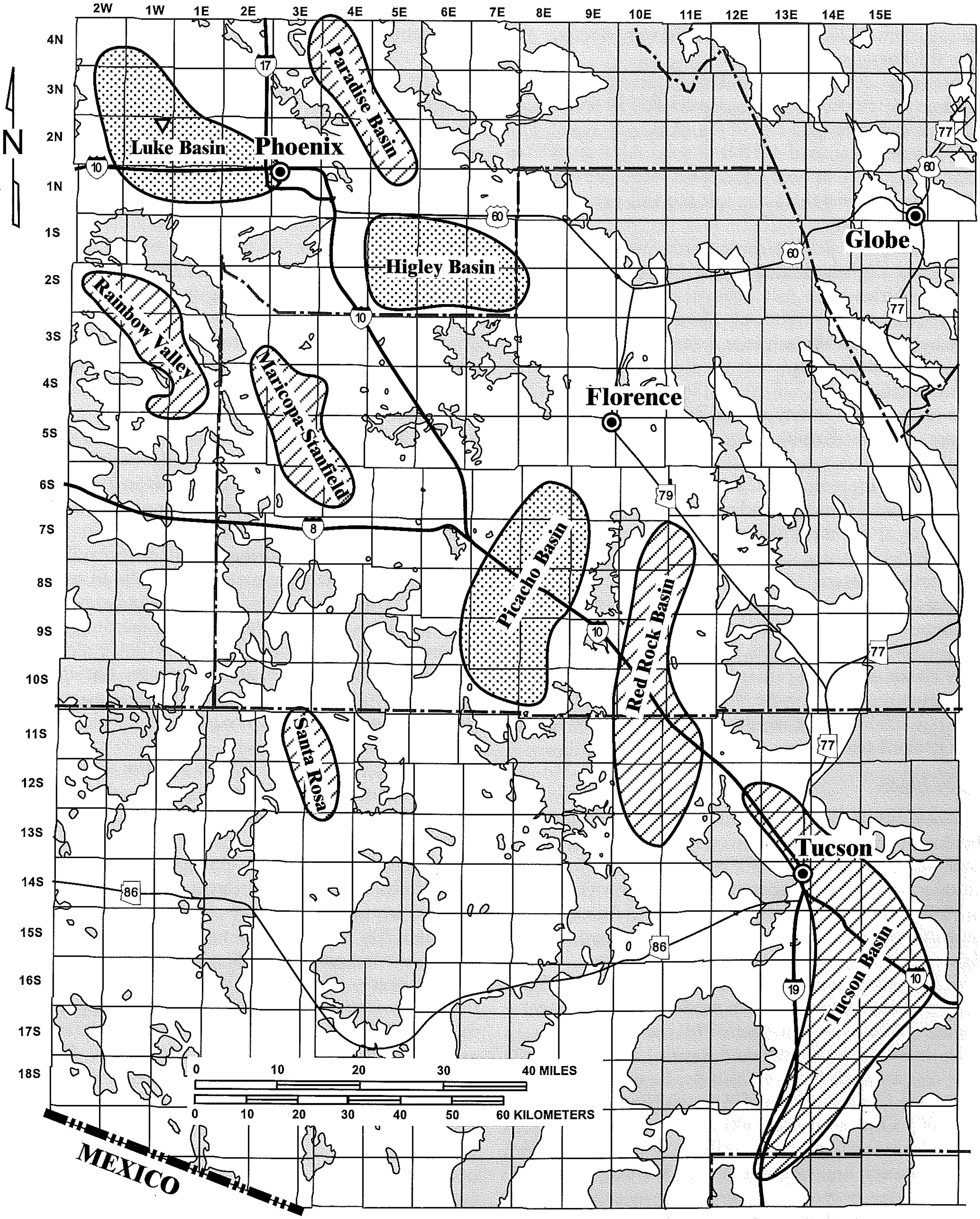

Figure 9. Luke salt, Paradise, Higley, Maricopa-Stanfield, Picacho, Red Rock, and Tucson basins, and Rainbow and Santa Rosa valleys. Bedrock areas are shaded (from Richard and others, 2000). See Figure 1 for legend.

into the Luke salt. The Arrowhead hole penetrated 4030 ft of salt from 2620 to 6650 ft but did not penetrate the entire thickness of the salt.

In early 2001, SunCor Development Company drilled a stratigraphic test to a depth of 5130 ft in 2-2n-1w, about a quarter mile east of the #1 Roach-Baker. The SunCor hole penetrated 4258 ft of solid salt from 872 to 5130 ft. The SunCor hole penetrated more salt than any well yet drilled into the Luke salt but did not penetrate the base of the salt.

The available drilling data clearly indicate that the Luke salt is slightly domed at the Morton Salt facility. The top of the Luke salt deposit at the Morton Salt facility is at a depth of 880 ft (+210 ft) in the #1 Roach-Baker hole. Top of the salt is at a depth of 1716 ft (-654 ft) 5 miles to the southwest at the Bob James well and at a depth of 2620 ft (-1572 ft) 3 miles to the south at the Arrowhead well. Gravity and seismic data suggest the salt mass is about 8 miles long, 5 miles wide, and over 1 mile thick.

Eaton, Peterson, and Schumann (1970; 1972) described the shape, size, and age of the Luke salt. They reported as much as 15 mi^3 of halite and interpreted the Luke salt deposit as a salt dome, pillow, or in situ evaporite prism. Koester (1971, 1972) described the Luke salt as a classic salt dome with characteristics similar to the salt domes along the Gulf Coast. Peirce (1972b; 1974) described evidence that the Luke salt was not a salt dome in the classic sense but rather formed in place as bedded salt with minimal, but some, flowage. Eberly and Stanley (1978) published a north-south seismic cross section through the Luke salt.

Higley Basin

The Higley Basin is about 20 miles southeast of Phoenix in southeastern Maricopa County (Figure 9). A lateral pipeline branches off of one of the main interstate natural gas pipelines and extends into the western part of the basin. A railroad crosses the basin. According to Oppenheimer and Sumner (1980), the depth of the Higley Basin is more than 11,200 ft to bedrock.

Information about the subsurface of the Higley Basin is revealed from gravity modeling (Mesa Sheet – Lysonski, Aiken, and Sumner, 1981) and data from 12 drill holes (Conley, Koester, and Rauzi, 1995a). Six of the drill holes are within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). One is on the 9600 ft contour. Wireline logs are available for five of the wells including gamma ray, caliper, density, and neutron curves. Cuttings are available for all but one.

In 1973, Geothermal Kinetics drilled two geothermal tests to depths of 9207 ft and 10455 ft in 1-2s-6e. These wells are just outside the southeastern limit of the 9600 ft depth-to-bedrock contour and about 4 miles east of a pronounced gravity low in the southwest quarter of T. 1 S., R. 6 E. The geothermal holes penetrated considerable gypsum and anhydrite from 2290 to 3850 ft, volcanic tuff from 7000 to 9000 ft, igneous rock from 9000 to 10,000 ft, and loose pebble and granule conglomerate from 10,050 to 10,400 ft. Mud salinity of 80,000 ppm chloride and considerable washout (large diameter hole recorded on the caliper curve) indicate salt in the evaporite interval.

In 1964, the U.S. Bureau of Reclamation (USBR) drilled a stratigraphic test to a depth of 1940 ft in 27-1s-6e. This hole is about 2.5 miles northwest of the two geothermal holes, near the 9600 ft contour, and 2.5 miles east of the gravity low. The USBR test penetrated interbedded gypsum and anhydrite from 1595 to 1660 ft and 1835 to 1885 ft. The USBR described a "strong salty taste and a white coating upon drying" in the lithologic description of the cuttings from the hole.

In 1968, the Roosevelt Water Conservation District (RWCD) drilled a water well 3 miles southwest of the geothermal tests to a depth of 2731 ft in 10-2s-6e. This hole is just outside the southern limit of the 9600 ft contour and 3.5 miles southeast of the gravity low. The RWCD hole penetrated the anhydrite-gypsum interval noted in the previously mentioned wells from 2235 to 2710 ft. "Thin halite beds," "salt or salty below 2500 ft," and "possibly went into halite" are annotated on the gamma ray-neutron log. The mud salinity recorded on the log header is 52,000 ppm chloride. The high mud salinity, low gamma ray values, and annotations of salt and salty on the gamma ray log indicate that this well penetrated salt.

The pronounced gravity low and the 9600 ft depth-to-bedrock contour delineate a significantly thicker sedimentary section about 8 miles long and 4 miles wide west of the Geothermal Kinetics, USBR, and RWCD drill holes. The anhydrite and gypsum in these three wells may represent the lateral equivalents of salt deposits in the thickest part of the basin represented by the 11,200 ft depth-to-bedrock contour of Oppenheimer and Sumner (1980). The gravity low (Mesa sheet - Lysonski, Aiken, and Sumner, 1981), in the southwestern part of T. 1 S., R. 6 E., may represent the depositional center of the basin where relatively thick and massive salt deposits may be present. Additional drilling is needed to verify and delineate the presence and size of the salt deposit.

Three other water wells of interest are located near the north and northwest limit of the 4800 ft depth-to-bedrock contour. The first well, in 26-1n-5e, is considerably northwest of the two geothermal tests, north of the 9600 ft contour, and just inside the northern limit of the 4800 ft contour. This water well, drilled to 1678 ft in 1964, penetrated gypsum from 1470 to 1680 ft. The second well, in 7-1s-7e, is north of the geothermal tests and just outside the northeastern limit of the 4800 ft contour. This water well was drilled to 2180 ft in 1966 and penetrated increasing amounts of gypsum from 1210 to 2180 ft. The third well, in 7-1n-6e, is about 3 miles north of the northern limit of the 4800 ft contour. It was drilled to a depth of 1150 ft. No lithologic information is available on this hole but it is located on a gravity ridge between the gravity lows in the Higley and Paradise Basins (Mesa Sheet - Lysonski, Aikens, and Sumner, 1981).

Picacho Basin

The Picacho Basin is about midway between Phoenix and Tucson in south-central Pinal County (Figure 9). Interstate 10 and a major railroad extend through the approximate center of the basin near the town of Eloy. Three interstate gas pipelines trend through the Picacho Basin more or less parallel to Interstate 10. The well-location map of Pinal County (Koester, Conley, and Rauzi, 1995a) lists 16 wells that reported gypsum, anhydrite, or salt in the Picacho Basin. Rock salt was reported in 11 of the wells. One of the wells in the northern part of the basin penetrated 820 ft of salt. Salty taste was reported in a well in the southern part of the basin. Gravity data suggest two depositional centers within the Picacho Basin, one north of Eloy and the interstate and one south (Tucson Sheet - Lysonski, Aiken, and Sumner, 1981).

Pool, Carruth, and Meehan (2001) used gravity data and information from 124 wells to study the hydrogeology of the Picacho Basin. They used structure contours and several geologic sections to show a thick accumulation of evaporites within a graben along the eastern part of the basin. The graben is smaller in areal extent than the physiographic basin and closely related to the gravity contours.

Kister and Hardt (1961, p. 83) reported a shallow gypsum and salt zone thickening into the northern part of the Picacho Basin. The depth of the gypsum-salt series ranged from about 500 ft to 700 ft in three wells in the southern part of T. 6 S., R. 7 E. Kister and Hardt described the deposition of salt in ephemeral lakes and concluded that gypsum and salt were likely present elsewhere and at different horizons throughout the Picacho Basin.

In 1963, the USBR drilled and cored a stratigraphic test to a depth of 1944 ft northeast of Eloy in 25-7s-8e. This hole is about 4 miles southeast of a gravity low (Tucson Sheet - Lysonski, Aiken, and Sumner, 1981) within the 4800 ft depth-to-bedrock contour in the northern part of the Picacho Basin. The USBR reported interbedded evaporites with scattered fine gravel between 1770 ft and total depth. The USBR cored gypsum and clay from 1934 to 1936 ft and "colorless, transparent, crystalline halite" from 1936 to 1944 ft.

In 1974, Geothermal Kinetics drilled a geothermal test to a depth of 8024 ft in 8-7s-8e, about 5 miles northwest of the USBR hole. This hole, which is just outside of the 9600 ft depth-to-bedrock contour, is about a mile southwest of the gravity low. The Geothermal Kinetics hole penetrated considerable anhydrite, gypsum, and salt from 1500 to 3700 ft, shale and clay from 3700 to 4200 ft, sandstone from 4200 to 5050 ft, and granite from 5050 to 8024 ft. At least 820 ft of salt was drilled from 1640 to 2950 ft. One salt interval was 520 ft thick. Mud salinity steadily increased from 2850 ppm chloride at 1500 ft to more than 240,000 ppm chloride at 2400 ft. Gamma ray, neutron, sonic, density, and resistivity logs are available for the Geothermal Kinetics hole. Given the 820 ft of salt in the Geothermal Kinetics hole and the association of gravity lows with either thick accumulation of sediments or massive salt there is a good probability that even thicker salt in the northern part of the Picacho Basin is associated with the center of the gravity low northeast of the Geothermal Kinetics hole in 4-7s-8e.

In 1972, Humble Oil & Refining Company (now Exxon Mobil) drilled a stratigraphic test to a depth of 10,179 ft just east of Eloy in 2-8s-8e. This hole is northeast of a broad gravity low within the 4800 ft depth-to-bedrock contour in the southern part of the Picacho Basin. The Humble hole penetrated mostly sand and gravel to 1250 ft, mostly claystone with thin intervals (aggregate 80 ft) of salt from 1250 to 2350, mostly anhydrite from 2350 to 8250 ft, mostly poorly-consolidated conglomerate from 8250 to 9060 ft, basalt from 9060 to 9600 ft, conglomerate from 9600 to 9880, and gneiss from 9880 to 10,179 ft. Gamma ray, neutron, sonic, density, and resistivity logs were run in the Humble Oil & Refining Company hole. According to Peirce (1973), the 6000 ft of anhydrite in the Humble hole might be the thickest sequence of anhydrite penetrated in the world.

The Humble hole is in an area of closely spaced gravity contours along the northeast side of a broad gravity low in T. 8-9 S., R. 7-8 E. The higher gravity values in the vicinity of the Humble hole may represent an anhydrite shelf that grades into thick salt deposits associated with the broad gravity low. The density of anhydrite is 2.95 gm/cc, whereas the density of salt is only 2.07 gm/cc. The USBR reported salty taste at a depth of 870 ft in a hole it drilled in 34-9s-7e, about 13 miles southwest of the Humble hole. The gravity low south of Eloy in the southeastern half of T. 9 S., R. 7 E. may represent a large mass of salt in the southern part of the Picacho Basin.

Safford Basin

The Safford Basin, in the northern part of the San Simon Valley, trends northwest through central Graham County in southeastern Arizona (Figure 10). The basin is about 60 miles long and 15 to 20 miles wide. A natural gas pipeline crosses the northern part of the basin at Safford. Two interstate pipelines cross the southern part of the

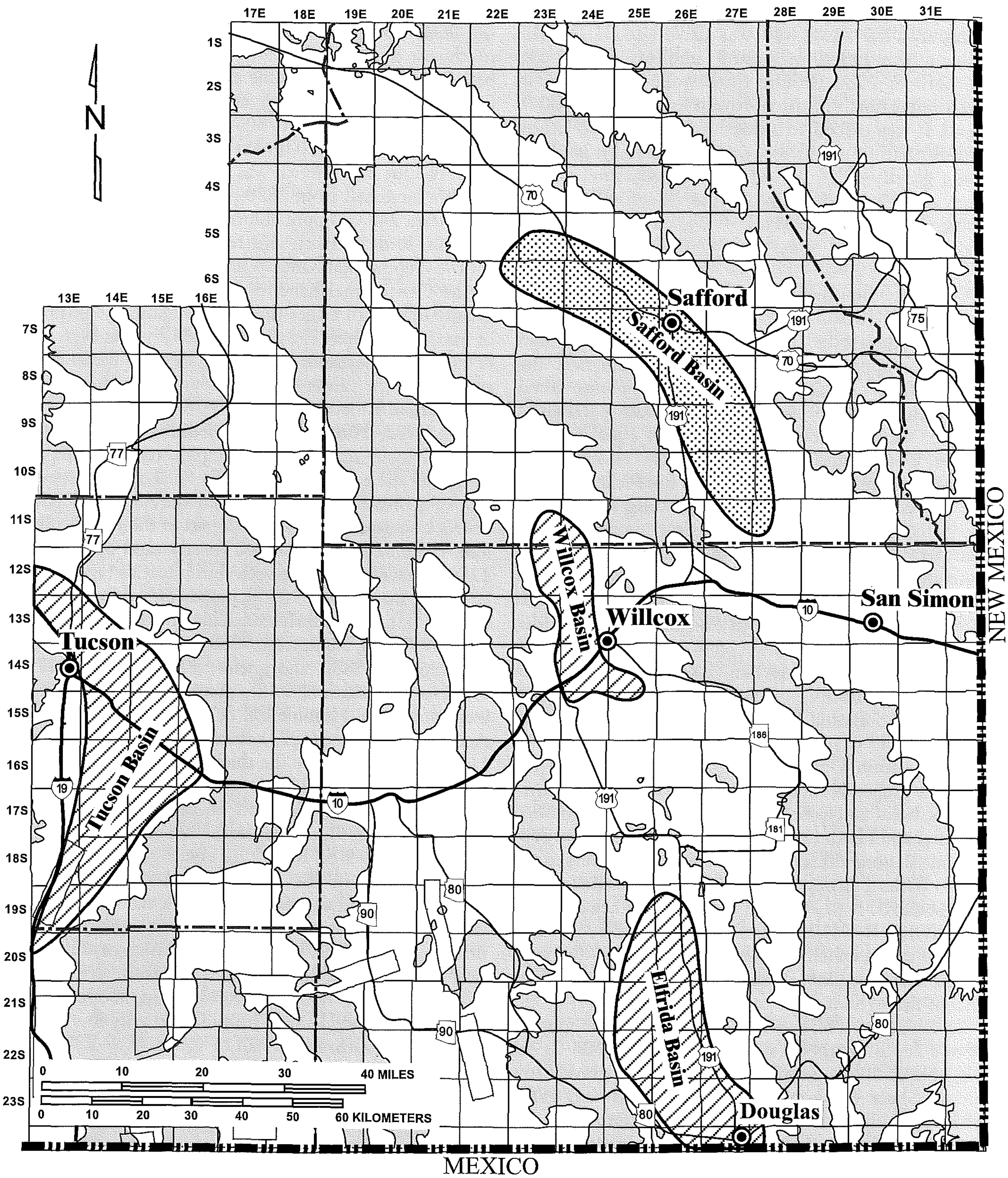

Figure 10. Tucson, Safford, Willcox, and Elfrida basins. Bedrock areas are shaded (from Richard and others, 2000). See Figure 1 for legend.

basin near San Simon. A north-trending crossover line along the western margin of the basin connects the pipelines near Safford and San Simon. A railroad crosses the length of the basin between Globe and Bowie. Knechtel (1938) described several early wells drilled in the basin. The well-location map of Graham and Greenlee Counties (Conley, Koester, and Rauzi, 1995d) lists at least 16 wells in the Safford Basin. Nine are within and one is on the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). According to Oppenheimer and Sumner (1980), the depth to bedrock is more than 9600 ft south of Safford. Gravity data suggest two potential salt masses in the Safford Basin (Silver City Sheet - Lysonski, Aiken, and Sumner, 1981). One of the two pronounced gravity lows is west of Safford. The other is between Safford and San Simon. Seismic data indicate the Safford Basin between Safford and San Simon is a half graben hinged on the northeast with maximum displacement on the southwest (Kruger and others, 1995).

Salt, salty water, and anhydrite were reported in many wells drilled in the Safford Basin. All of these wells surround the pronounced gravity lows in the northern and southern parts of the basin. No deep holes have been drilled in the center of the gravity lows. Koester (1971) referred to the northern gravity low, about 12 miles west of Safford in the southwestern part of T. 6 S., R. 24 E., as the Pima salt dome because of its close proximity to the town of Pima. The southern gravity low is about 8 miles southeast of Safford and trends southeastward from the southeastern part of T. 8 S., R. 26 E. to the western half of T. 9 S., R. 27 E.

Salt or salty water was reported in at least five wells around the northern gravity low west of Safford. Six feet of clean salt was reported at a depth of about 580 ft in the E.G. Rogers well, about 12 miles northwest of Safford in 5-6s-24e. The Rogers hole is 6 miles north of the gravity low. Gypsum and salt were reported from 760 to 930 ft in the Underwriters Syndicate #1 Mack, a deep oil test about 9 miles northwest of Safford in 13-6s-24e (Canfield, 1928; Knechtel, 1938). The Mack well is about 5 miles northeast of the gravity low. In 1957, Smithfield Canal Company reported thin to massive gypsum and anhydrite from 950 to 1550 ft and salt from 1000 to 1040 ft. The Smithfield Canal well, 4 miles northwest of Safford in 36-6s-25e, is 8 miles east of the gravity low. Highly saline water was reported in the A.R. Evans well 8 miles west-southwest of Safford in 14-7s-24e. The Evans hole is 3 miles southeast of the gravity low. Harris (1999, p. 74) reported slightly salty clay at a depth of 740 ft in the Whitmore #1, an oil test about 7 miles west of Safford in 6-7s-25e. The Whitmore hole is 4 miles east of the gravity low. The salt in these wells, surrounding a gravity low, may represent thin, perimeter salt pans that grade into thicker salt deposits toward the gravity low. The thickest salt deposits would be expected in the depositional center of the basin associated with the gravity low.

Salt or salty water is reported in several wells between the two gravity lows. The U.S. Geological Survey (USGS) reported minor to considerable salt encrustation from 1465 to 1780 ft and salinity of 168,200 ppm chloride in a well at the Safford Golf Course. The water at 1250 ft had 120,000 ppm of total dissolved solids. The golf course well, about 4 miles southwest of Safford in 22-7s-25e, is 7 miles southeast of the northern gravity low and 8 miles northwest of the southern gravity low. The Southern Pacific Company drilled a well in Safford that flowed warm salt water. Gypsum and anhydrite were reported below 800 ft and salty clay at total depth of 1820 ft. The Southern Pacific well, in 17-7s-26e, is about midway between the two gravity lows. Harris (1999, p. 74), describing samples from 250 to 2240 ft, reported gypsum below 1080 ft and disseminated salt crystals, clayey salt, and pure salt from 1570 to 2240 ft in a well about 4 miles southeast of Safford in 26-7s-26e. Koester (1971) reported cored salt from 2323 to 2339 ft in what may be a deepening of the hole described by Harris. This hole, variously known as the No Name, Alf Claridge, and Rex Barney well, is about 4 miles north of the southern gravity low.

Two deep oil tests were drilled just west and east of the southern gravity low between Safford and San Simon. West of the gravity low is the Phillips Petroleum Company #A1 Safford State, about 12 miles south of Safford in 16-9s-26e. The Phillips hole, drilled to a depth of 8509 ft, penetrated sand and conglomerate from the surface to total depth. No gypsum, salt, or clay was reported. The Phillips hole is 4 miles west of the center of the southern gravity low and just west of a rapid decrease in gravity values along the west end of the Safford Basin. The thick clastic deposits in the Phillips hole, drilled in the zone of maximum displacement along the southwestern margin of the Safford Basin, may grade rapidly into thick salt deposits in the center of the southern gravity low.

The Ivan Tenney holes are east of the gravity low. Tenney used cable tools to drill three holes about 15 miles southeast of the Phillips well in 36-9s-27e. Two of the holes were abandoned at shallow depths, 630 and 1090 ft, because of collapsed casing. The deepest hole, the #3 Tenney, was drilled to a depth of 3500 ft. Tenney reported anhydrite and clay from 1200 to 3500 ft, anhydrite and salt from 2140 to 2475 ft, and a small amount of salt water at 1240 ft in the deeper #3 Tenney. Harris (1999, p. 74) described composite samples from the three holes. He reported anhydrite and gypsum below 570 ft. The #3 Tenney hole is 4 miles southeast of the southern gravity low. The thick anhydrite with thin salt intervals in the Tenney well may represent a gypsum-anhydrite rim along the eastern margin of a long, linear salt playa represented by the southern gravity low. Thick salt deposits may be present in the center of the southern gravity low.

Oppenheimer and Sumner (1980) showed a depth to bedrock of more than 8000 ft in the southernmost part of the San Simon Valley between San Simon and the New Mexico line. The well-location map of Cochise County (Koester, Conley, and Rauzi, 1996a) lists 12 holes that were drilled in this part of the valley. No sample descriptions or, at best, very poor sample descriptions are available for most of the holes. However, gypsum and anhydrite were reported from 620 to 1060 ft in one of the holes, the Arzon #1 oil test, drilled to a depth of 8974 ft in 27-13s-30e. No evaporites were reported in a water well drilled to a depth of 2000 ft in 16-14s-31e, about 7 miles southeast of the Arzon hole. These holes are located in the center of the valley near San Simon and just north of an elongate gravity low associated with the 8000 ft depth-to-bedrock contour. No evaporites were reported in three deep oil tests drilled along the southwestern margin of the valley. In 1954, the Arizona Oil & Gas Development Company drilled one of the holes to a depth of 7580 ft in 36-14s-30e, about 2 miles southwest of the gravity low. No samples or sample descriptions are available for this hole. The other two holes were drilled by Portal Drilling Company to a depth of 5353 ft and L.A. Thomson to a depth of 5434 ft, in 9-16s-31e and 10-16s-31e, respectively, about 4 miles southwest of the southeastern end of the gravity low. No samples or sample descriptions are available above 2799 ft and below 3219 ft in the Portal hole and above 1800 ft in the Thomson hole.

Salt in the Tenney holes in the Safford Basin north of San Simon and gypsum and anhydrite in the Arzon hole near San Simon suggest that salt may be present south of San Simon even though no evaporites were reported in the deep holes drilled along the southwestern margin of the valley. The same conditions (ephemeral lake or salt playa) that resulted in the deposition of salt in the Safford Basin north of San Simon probably existed south of San Simon in the southernmost part of the San Simon Valley. As a result, salt deposits may be associated with the gravity low between San Simon and the New Mexico line in southwestern part of T. 14 S., R. 31 E. and eastern half of T. 15 S., R. 31 E.

Potential Salt Deposits

The abundance of salt in Arizona together with recognizable gravity anomalies associated with known salt deposits suggest that less explored basins and valleys may have potential for additional salt deposits. Salt of Permian age underlies about 3500 mi^2 in the Holbrook Basin on the Colorado Plateau. Massive salt deposits at least 6000 ft thick and possibly more than 10,000 ft thick have accumulated in the Hualapai Valley north of Kingman and the Luke Basin west of Phoenix. Faulds and others (1997) attributed the deposition of the massive salt deposits in the Basin and Range Province to a period of rapid subsidence and arid climate near the end of Miocene time (i.e. 15-12 Ma) that prevented the integration of regional drainage and led to a protracted period of interior drainage. They described the widespread evaporite deposits of Permian age on the Colorado Plateau as an abundant source of highly saline groundwater, which flowed into the newly developed basins in the Basin and Range Province. They concluded that the conditions that led to the voluminous deposition of nonmarine halite in the Hualapai Valley prevailed all along or proximal to the southern and southwestern margin of the Colorado Plateau.

Major salt deposits are associated with either gravity lows or closely spaced gravity contours in at least nine basins and valleys in the Basin and Range Province. These relationships suggest that pronounced gravity lows and closely spaced contours may represent salt deposits in basins and valleys where there is very little or no deep drilling information. The primary evidence used in locating these deposits in the following sections is the Bouguer gravity data of Lysonski, Aiken and Sumner (1981). Their gravity data is supplemented by the gravity modeling of Oppenheimer and Sumner (1980) and information from sparsely located deep drill holes. The following sections include reviews of available drilling and gravity data in the basins and valleys with pronounced gravity lows or closely spaced gravity contours and at least a 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). Even though not all of the basins and valleys in the Basin and Range Province are described, salt may be present in basins and valleys with less than a 4800 ft depth-to-bedrock contour and less pronounced gravity anomalies. In short, salt may be discovered in basins and valleys that are not described in this report.

Colorado Plateau

White Mountains

The White Mountains are in southern Apache County about 20 miles south of the southern edge of the well-known Holbrook salt basin (Figure 5). Rauzi (1996) pointed out the possible presence of a concealed evaporite basin beneath the White Mountains in east-central Arizona. Evidence for the possible White Mountain evaporite basin includes (1) a thick sabkha sequence of anhydrite and dolomite in the Alpine Federal core hole east of the basin, (2) numerous salt springs in the Gila and Salt River drainages west of the basin, and (3) a distinct gravity low between the two. The -26 milligal residual-gravity contour on the Clifton and St. Johns Sheets of Lysonksi, Aiken, and Sumner (1981) suggests an evaporite basin about 70 miles long and 55 miles wide totally concealed beneath the volcanic rocks of the White Mountains. Erosion of the westernmost edge of the concealed White Mountains salt basin may have contributed to the accumulation of the large salt deposits in the southern Basin and Range Province.

Transition Zone

Tonto Basin

The Tonto Basin trends northwesterly for about 40 miles in northeastern Yavapai County between Punkin Center and Globe (Figure 6). The basin is a graben with maximum displacement along the southwestern margin (Nations, 1990, p. 26). Like the Verde Valley to the northwest, the Tonto Basin is within the Transition Zone and does not attain the great depth to bedrock that is common in the basins in the Basin and Range Province. Richard and others (2000) showed an 800 ft depth-to-bedrock contour in the northern and southern ends of the slightly arcuate basin but not a 4800 ft contour. Richard (1999) described information from three wells in the Tonto Basin. Two are early oil and gas tests. One is at the south end of the 800 ft contour in the northern half of the basin. The other is at the north end of the 800 ft contour at the southern end of the basin. The third well, a water well drilled by the U.S. Forest Service, is between the two sub-basins defined by the 800 ft depth-to-bedrock contours. The Forest Service well encountered enough H_2S to cause a nearby campground to be evacuated temporarily (Likens, 1991). Residual gravity values form two gravity lows in the Tonto Basin (Mesa Sheet - Lysonski, Aiken, and Sumner, 1981). One is south of Punkin Center at the northern end of the basin. The other is at the very southern extent of the basin. No interstate gas pipelines or railroads are present in the vicinity of the Tonto Basin.

Lance and others (1962, p. 98) reported up to 300 ft of redbeds containing abundant gypsum near Punkin Center in the north end of the Tonto Basin. Nations (1990) reported as much as 900 ft of silty, gypsiferous mudstone. Of the three holes described by Richard (1999), the Sanchez-O'Brien oil test, near the center of the basin in 4-4n-12e, penetrated more than 1690 ft of mostly mudstone, siltstone and sandstone overlying Paleozoic and Precambrian units from 1810 to 3490 ft. The operator reported traces of anhydrite in the mudstone facies and a flow of brackish water (7900 ppm chloride) from 788 to 854 ft. No evaporites were reported in the other two holes, a shallow oil test 5 miles east of the Sanchez-O'Brien test, and a water well 5 miles southeast of the Sanchez-O'Brien test.

The presence of salt in Tertiary rocks in the Verde Valley to the northwest, abundant gypsum in the mudstone facies near Punkin Center, and brackish water in the Sanchez-O'Brien hole suggest the possible presence of salt in the subsurface of the Tonto Basin. The possible salt deposits may have formed in association with the gypsiferous mudstone facies within the areas outlined by the two gravity lows in the basin. These are located in the northern end of the basin in T. 5-6 N., R. 11 E. and the southern end of the basin in the southwest part of T. 4 N., R. 14 E.

Basin and Range

Dutch Flat

Dutch Flat is about 30 miles south of Kingman in southern Mohave County (Figure 7). It trends southeastward from Interstate 40 for about 30 miles, decreasing in width from about 20 miles at the northwest end near the freeway to only a few miles at the southeast end. Dutch Flat attains a maximum depth of at least 4800 ft (Richard and others, 2000) about 15 miles southeast of the freeway. The well-location map of Mohave County (Koester, Conley, and Rauzi, 1996b) lists two significant wells in Dutch Flat, both drilled in 1979 by Bendix Field Engineering Corporation as a part of the NURE program (McCaslin, 1980; Lease, 1981). Both of the Bendix holes, the PQ-9 and PQ-12, are just east of the 4800 ft depth-to-bedrock contour. Residual gravity values form two gravity lows, one near the center of Dutch Flat within the 4800 ft depth-to-bedrock contour and one near the north end of the flat where Interstate 40 turns to the southwest at the south end of the Black Mountains (Needles and Prescott Sheets - Lysonski, Aiken, and Sumner, 1981). The closely spaced gravity contours suggest that Dutch Flat is a half-graben with maximum fault displacement along the northwest and southwest margins. An interstate gas pipeline, the Havasu Crossover, extends through Dutch Flat and connects with the main east-trending line at the north end of the flat. A major railroad parallels Interstate 40 at the north end of the flat.

No gypsum, anhydrite, or salt were reported in the two Bendix holes. The PQ-9 was drilled to a depth of 5204 ft in 18-15n-16w, near the east end of the gravity low in the central part of Dutch Flat. The PQ-9 drilled through mostly fine- to coarse-grained clastic and volcanic rocks with a trace of clay before penetrating granite at 5190 ft. The PQ-12, about 3 miles north of the PQ-9 hole, was drilled to a depth of 1819 ft in 31-16n-16w, near the northeastern edge of the gravity low. The PQ-12 drilled through clastic and volcanic rocks before penetrating granite gneiss at a depth 1750 ft.

Dutch Flat is of more than passing interest because of its location between the salt deposits in Detrital Valley to the northwest and Date Creek Basin to the southeast. The closely spaced gravity contours along the southwestern and northwestern margins of Dutch Flat are similar to those in Detrital Valley and Date Creek Basin and probably represent primary half-graben faults where isolated sag ponds may have developed. Salt is associated with closely spaced gravity contours in both Detrital Valley and Date Creek Basin. As a result, even though no evaporites were reported in the two Bendix holes east of the 4800 ft depth-to-bedrock contour in the central part of Dutch Flat, salt may be present in fault-controlled sag ponds associated with the closely spaced gravity contours along the southwestern margin of Dutch Flat in the western half of T. 15 N., R. 17 W. and along the northwest margin in T. 16.5 N., R. 18-19 W.

McMullen Valley

McMullen Valley is about 80 miles northwest of Phoenix (Figure 8). This northeast-trending valley, about 35 miles long and 10 miles wide, extends across eastern La Paz, southwestern Yavapai, and northwestern Maricopa counties. U.S. Highway 60 and a railroad branch line extend northeastward across the southern part of the valley. The Harcuvar Mountains separate the northeastern end of McMullen Valley from Date Creek Basin to the north. Salt is present in Date Creek Basin. The northeastern part of McMullen Valley forms a basin within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). According to Oppenheimer and Sumner (1980), depth to bedrock in this part of the basin is more than 6400 ft. Lysonski, Aiken, and Sumner (Phoenix and Prescott Sheets, 1981) showed two gravity lows in the central to northeastern part of the basin.

The well-location map of Yuma and La Paz Counties (Conley, Koester, and Rauzi, 1995b) lists seven water wells in the southwestern part of McMullen Valley. Well-location maps of Maricopa County and Yavapai County (Conley, Koester, and Rauzi, 1995a; Koester, Conley, and Rauzi, 1995b) list nine selected water wells in the northeastern part of the valley. Six of the wells in the northeastern part of the valley are within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona. An interstate natural gas pipeline, the Havasu Crossover, trends northward through the southwestern end of the valley.

No evaporites were reported in any of the water wells drilled to depths of 1500 to 2000 ft in the northeastern part of McMullen Valley including the deepest well, a stratigraphic test, drilled to a depth of 4333 ft in 29-8n-9w. However, lakebed deposits with considerable clay were reported in most of these wells. Gypsum and other salts were reported in several of the wells in the southwestern part of the valley. Kam (1964, p. 25-27) reported alluvium from the surface to 100 ft, lakebed deposits from 100 to 1200 ft, and alluvial fan deposits from 1200 to 1405 ft in a water well drilled to a depth of 1432 ft in the southwestern part of the valley in 15-6n-12w. He reported gypsum crystals from 510 to 1180 ft, salt crystals from 890 to 900 ft, and some salt from 979 to 990 ft. He considered the gypsum to have been deposited in ephemeral lakes in which salts precipitated when the lake was on the verge of drying up.

More extensive salt deposits may yet be discovered in McMullen Valley. Gypsum and salt crystals are present in wells in the southwestern part of the valley and lakebed deposits in the northeastern part. Salt is present to the north in Date Creek Basin. Gypsum and anhydrite are present in Miocene deposits to the west in the northern end of the La Posa Plain. Massive salt deposits of Miocene age are present to the north at Red Lake (Faulds and others, 1997) and to the east at Luke (Eberly and Stanley, 1978). Evidence indicates that the Miocene was characterized by ephemeral lakes of long duration and a non-integrated drainage system in southern Arizona. Ephemeral lake and salt deposits may be present in the more than 2000 ft of untested Miocene strata within the 4800 ft depth-to-bedrock contours in the central to northeastern part of McMullen Valley. These deposits may be associated with the gravity lows in T. 7 N., R. 10-11 W. and T. 7-8 N., R. 9 W. Salt may also be associated with the closely spaced gravity contours along the northwestern and southeastern margins of McMullen Valley. Salt is associated with the closely spaced gravity contours just to the north in Date Creek Basin.

Harquahala Plain

The Harquahala Plain is in La Paz and Maricopa Counties about midway between Phoenix and the California state line (Figure 8). Interstate 10 extends through the approximate center of the plain, which forms a northwest-trending basin about 20 miles long and 5 miles wide within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). Two gravity lows are present in the southeastern part of the plain in western Maricopa County (Phoenix Sheet - Lysonski, Aiken, and Sumner, 1981).

Oppenheimer and Sumner (1980) showed that depth to bedrock in this part of the basin is more than 8000 ft. The well-location map of Yuma and La Paz Counties (Conley, Koester, and Rauzi, 1995b) lists one water well in the northern part of the Harquahala Plain. The well-location map of Maricopa County (Conley, Koester, and Rauzi, 1995a) lists nine selected water wells in the southern part of the plain. An interstate natural gas pipeline between California and New Mexico crosses the southern part of the plain. No railroads cross the Harquahala Plain.

No evaporites were reported in any of the water wells listed on the county well-location maps. No lithologic description is available for the deepest well, which was drilled to a depth of 2483 ft near the axis of the southern gravity low in 16-1n-9w. Clay was reported from 0 to 1380 ft in a well drilled to a depth of 1692 ft in 7-2n-9w, about 3 miles east of the axis of the northern gravity low. Gravity modeling by Oppenheimer and Sumner (1980) suggest that more than 5000 ft of strata beneath the Harquahala Plain remain untested. None of the holes were drilled deeply enough to test these strata, which, like the strata in Date Creek Basin to the north, could contain salt that was deposited in isolated playas or ephemeral lakes before an integrated drainage system was established through the Harquahala Plain. Salt could be present in these strata in the northern gravity low in T. 2-3 N., R. 10 W., and in the southern gravity low in the northern part of T. 1 N., R. 9 W.

Tonopah Desert

The Tonopah Desert is a broad plain in western Maricopa County about 50 miles west of Phoenix (Figure 8). Interstate 10 extends westerly across the southern part of the Tonopah Desert, which forms a northwest-trending basin about 12 miles long and 2 to 4 miles wide within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). Gravity data suggest that the basin underlying the Tonopah Desert is a half graben hinged on the northeast, with maximum displacement on the southwest. Two small gravity lows are present at the northwestern end of the basin (Phoenix Sheet - Lysonski, Aiken, and Sumner, 1981). The well-location map of Maricopa County (Conley, Koester, and Rauzi, 1995a) lists only two wells in the Tonopah Desert. One is a water well just inside the eastern limit of the 4800 ft contour; the other is an oil test just outside the western limit of the 4800 ft contour. No natural gas pipelines are present in the basin, but one crosses the state between California and New Mexico about 25 miles to the south. A railroad is about 10 miles southeast.

No sample description is available for the water well, which was drilled to a depth of 1090 ft in the southeastern part of the basin in 9-2n-6w. This hole is about 15 miles southeast of the gravity low in the northwestern end of the basin. Sand and gravel with considerable clay but no evaporites were reported in the oil test, which was drilled by Gemini Oil, Gas, and Mineral Company to a depth of 2040 ft near the southwestern margin of the basin in 27-2n-7w. The Gemini hole is about 12 miles southwest of the water well and 10 miles south of the gravity low in the northwestern end of the basin. Neither of these holes has tested the more than 2800 ft of strata beneath the Tonopah Desert interpreted by the modeling of Oppenheimer and Sumner (1980). Like the strata in the Harquahala Plain to the west, and McMullen Valley and Date Creek Basin to the north, the untested strata beneath the Tonopah Desert could contain salt that was deposited in isolated playas or lakes before an integrated drainage system was established through these basins. Salt may be discovered in the gravity low in the southwestern part of T. 3 N., R. 7 W.

Gravity contours in the Tonopah Desert converge along the southwestern margin of the basin. These closely spaced contours are similar to those in Date Creek Basin and are interpreted to represent a primary half-graben fault within which isolated sag ponds may have developed. Salt is associated with closely spaced gravity contours in the Date Creek Basin. Salt may be associated with the closely spaced gravity contours along the southwestern margin of the Tonopah Desert in T. 2-3 N., R. 7-8 W.

Paradise Basin

The Paradise Basin is about 15 miles northeast of Phoenix in east-central Maricopa County (Figure 9). The well-location map of Maricopa County (Conley, Koester, and Rauzi, 1995a) lists 16 wells in the Paradise Valley. Five are within and one is just outside the eastern limit of the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). Gravity lows are present at the northwestern and southeastern end of the basin (Mesa Sheet - Lysonski, Aiken, and Sumner, 1981). No interstate or lateral gas pipelines or railroads extend into Paradise Valley.

Paul H. Biery drilled the deepest well in the Paradise Basin, an oil test in 8-4n-4e, to a depth of 5396 ft in 1951. This hole is just north of a gravity low within the northern part of the 4800 ft contour. The Biery hole penetrated predominately fine to coarse sand and conglomerate from the surface to total depth. Anhydrite was first reported at 3150 ft. Abundant crystalline anhydrite in clusters and possibly bedded were reported in several intervals from 3730 to 4500 ft. Limestone was reported from 4500 to 4600 ft, basalt with traces of anhydrite and carbonate from 4600 to 4900 ft, and conglomerate from 4900 to 5396 ft. The basalt from 4600 to 4900 ft was dated at 22 million years (Peirce, 1984, p. 217). Mud salinity from 3900 to 5396 ft ranged from 600 to 100 ppm chloride. Salinity at total depth was 300 ppm chloride. The low salinity indicates that no salt was penetrated in the Biery hole even though anhydrite was reported below 3150 ft.

Glenn Oil Company drilled another deep oil test, about 6 miles southeast of the Biery hole, to a depth of 4159 ft in 1948. The Glenn Oil hole, in 2-3n-4e, is just southeast of the gravity low within the northern part of the 4800 ft contour. The sample description records mostly coarse-grained sand to pebble conglomerate to total depth. The character of the curves on the old Lane Electrolog suggests mostly coarse-grained sandstone to pebble conglomerate to 2350 ft, mostly conglomerate from 2350 to 3650 ft, and competent to highly fractured schist from 3650 ft to total depth. The absence of salt in cuttings or report of high salinity in the drilling mud indicates that salt is not present in the Glenn Oil Company hole.

The Biery and Glenn Oil holes bracket the northwestern gravity low within the 4800 ft depth-to-bedrock contour. Drilling and gravity data have shown that gravity lows in the Luke Basin to the west and the Higley Basin to the south represent depositional centers with thick accumulation of sediment and salt. Massive salt is associated with the gravity low in the Luke Basin. Similarly, the anhydrite reported in the Biery hole may grade laterally into salt along the axis of the gravity low. Salt could be present within the gravity low at the northwestern end of Paradise Basin in the southwestern part of T. 4 N., R. 4 E. No deep wells have been drilled in the gravity low at the southeastern end of Paradise Basin in T. 2-3 N., R. 5 E.

Rainbow Valley

Rainbow Valley (Waterman Wash area) is about 20 miles southwest of Phoenix in central Maricopa County (Figure 9). The northwest-trending valley is about 20 miles long and 10 miles wide and bordered by the Buckeye Hills to the north and Sierra Estrella Mountains to the northeast. Rainbow Valley is of interest because of its significant depth to bedrock and proximity to the massive Luke salt deposit north of the Buckeye Hills. Depth to bedrock in the central part of the valley is more than 9600 ft (Richard and others, 2000). Even though there are several shallow water wells in the valley, the well-location map of Maricopa County (Conley, Koester, and Rauzi, 1995a) lists only one hole, which is just southwest of the 4800 ft depth-to-bedrock contour in the central part of the valley. Gravity data indicate that Rainbow Valley is a half graben hinged on the southwest with maximum displacement on the northeast (Phoenix Sheet - Lysonski, Aiken, and Sumner, 1981). The closely spaced gravity contours along the northeastern edge of the valley are interpreted to indicate a major fault that separates Rainbow Valley from the Sierra Estrella Mountains. A gravity low is present just southwest of the fault in the central part of the valley. Two interstate gas pipelines extend through the long axis of the valley. A railroad crosses the southern end of the valley at Mobile.

White (1963) described strata in several holes drilled to depths of 1000 to 1500 ft in her study of groundwater conditions in the Rainbow Valley and Waterman Wash areas. She interpreted the lack of laterally extensive clay deposits and lakebeds deposits to indicate an integrated drainage through the area. No evaporite deposits were reported in any of the holes. Deeper deposits in Rainbow Valley, however, may have accumulated in isolated ponds and playas before an integrated drainage developed. Little subsurface control is available along the major half-graben fault that borders the northeastern edge of Rainbow Valley where the closely spaced gravity contours are similar to those in Detrital Valley and Date Creek Basin. Salt is associated with the closely spaced gravity contours in Detrital Valley and Date Creek Basin. Even though no evaporites were reported in any of the relatively shallow holes, salt may be discovered in fault-controlled sag ponds associated with the closely spaced gravity contours along the northeastern margin of Rainbow Valley in the southwestern parts of T. 2-3 S., R. 1 E. and 1 W. Salt may also be present in the more than 8000 ft of Tertiary strata that have not been drilled within the 9600 ft depth-to-bedrock contour and gravity low in the central part of Rainbow Valley in the eastern part of T. 3 S., R. 1 W.

Maricopa-Stanfield Basin

The Maricopa-Stanfield Basin is in northwestern Pinal County about 30 miles south of Phoenix (Figure 9). Much of the basin is in the Maricopa Ak Chin Indian Reservation. The northern part of the basin is in the Gila River Indian Reservation. The central part of the basin is marked by a pronounced gravity low (Ajo, Mesa, Phoenix, and Tucson Sheets - Lysonski, Aiken, and Sumner, 1981) about 15 miles long and 5 miles wide between the towns of Maricopa and Stanfield. This part of the basin is within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). The well-location map of Pinal County (Koester, Conley, and Rauzi, 1995a) lists at least 14 wells in the deeper part of the basin. All of these wells are within or near the 4800 ft depth-to-bedrock contour. Two interstate pipelines cross the basin; one trends northwest through the long axis of the basin, and the other trends east to west across the southern end of the basin. A railroad crosses the basin at Maricopa.

Gypsum, anhydrite, and water with high concentrations of sodium and chloride were reported in at least four holes drilled in the Maricopa-Stanfield Basin. These holes are located to the north, northeast, and southwest of the pronounced gravity low that marks the central part of the basin between Maricopa and Stanfield. No deep holes have been drilled in the center of the gravity low.

In late 1949 and early 1950, Robinson and Mason Drilling Company drilled an oil test to a depth of 3642 ft about 3 miles southeast of Maricopa in 36-4s-3e. They reported mudstone and gypsum between 800 and 1600 ft. The samples contained 70 to 50 percent gypsum from 800 to 1100 ft. No logs were run and no water analyses are available.

Hardt, Cattany, and Kister (1964) reported salty water in a well drilled to a depth of 416 ft about 4 miles west of Maricopa in 13-4s-2e. The total-dissolved-solids content of the water was 15,000 ppm. The sodium concentration was between 3930 and 3240 ppm; the chloride concentration was between 6160 and 4130 ppm. The high salinity in this well indicates the presence of salt in the basin.

In 1964, the USBR drilled a stratigraphic test to a depth of 1777 ft about 2 miles north of Maricopa in 9-4s-3e. They reported silty clay with gypsum from 660 to 1210 ft, gypsiferous silt with anhydrite masses from 1210 to 1490 ft, and sandy silt, sticky clay, and conglomerate with traces of crystalline gypsum from 1490 to 1690 ft. The gypsum comprised 50 to 60 percent of the sample from 1150 to 1160 ft and 1200 to 1210 ft and occurred in thin beds from 1210 to 1490 ft. They described the gypsum in this hole as disseminated, colorless, transparent, platy crystals, pods, and lens-like masses. The USBR drilled another stratigraphic hole to a depth of 1803 ft about 6 miles west of Stanfield in 21-6s-3e. They reported mostly sand and gravel from 0 to 1780 ft with gypsiferous silty sand from 760 to 790 ft.

The presence of salt in association with gravity lows in the Luke Basin to the north, Higley Basin to the northeast, and Picacho Basin to the southeast suggests that a significant salt deposit may also be associated with the pronounced gravity low in the Maricopa-Stanfield Basin. Salty water reported at shallow depth in a well west of Maricopa confirms the presence of salt north of the gravity low. Holes north and southeast of Maricopa and west of Stanfield confirm the presence of gypsum north, northeast, and southwest of the gravity low. The salt to the north and gypsum to the north, northeast, and southwest may grade laterally into a major salt deposit near the center of the pronounced gravity low in the central part of the Maricopa-Stanfield Basin near the center of T. 5 S., R. 3 E.

King, Mohawk, San Cristobal, and Growler Valleys

Richard and others (2000) showed deep basins with more than 4800 ft of valley-fill sediment above bedrock in at least four northwest-trending valleys in southwestern Arizona: King, Mohawk, San Cristobal, and Growler (Figure 8). Each is between 30 and 40 miles long, about 10 miles wide, and marked by distinct gravity lows (Ajo, Phoenix, and Salton Sea Sheets - Lysonski, Aiken, and Sumner, 1981). According to Oppenheimer and Sumner (1980), the depth to bedrock is more than 8000 ft in the Mohawk and southern King valleys and more than 6400 ft in southern San Cristobal Valley. An interstate gas pipeline trends northwesterly about 20 miles north of the King Valley. A railroad trends southwesterly between the King and San Cristobal valleys.

The King, Mohawk, and San Cristobal valleys are in Yuma County. The Growler Valley is in northwestern Pima and southwestern most Maricopa Counties. King Valley is northwest of San Cristobal Valley and is separated from that valley by the Gila River. The Mohawk and San Cristobal valleys are southeast of the Gila River. Growler Valley is southeast of San Cristobal Valley. All of Growler Valley and all but the northwesternmost parts of the Mohawk and San Cristobal valleys are within the Barry M. Goldwater Air Force Gunnery Range. All but the southeasternmost part of King Valley is within the Kofa National Wildlife Refuge and Yuma Proving Grounds. As a result, most of the available subsurface information comes from holes that have been drilled in the Gila River trough at the southeastern end of King Valley and the northwestern end of San Cristobal Valley. The well-location map of Yuma and La Paz Counties (Conley, Koester, and Rauzi, 1995b) lists 10 wells in southern King and northern San Cristobal valleys; no wells are listed in southern San Cristobal Valley or Mohawk Valley. No wells are listed in Growler Valley on the well-location map of Pima and Santa Cruz Counties (Conley, Koester, and Rauzi, 1995c). No deep holes have been drilled in any of the valleys. An oil test was drilled to a depth of 6767 ft in the Gila River trough between the King and San Cristobal valleys.

Harris reported gypsum in at least nine wells in the lower Gila River trough including seven holes between the King and San Cristobal valleys and two holes on the Yuma Proving Grounds in southeastern King Valley (Spencer and Harris, 1996). He reported gypsum from 280 to 1300 ft in the two holes in southeastern King Valley. The northern of the two holes in southeastern King Valley was drilled to a depth of 1450 ft in 29-5s-15w, just within the 4800 ft depth-to-bedrock contour and just southwest of the axis of a gravity low in the western half of T. 5 S., R. 15 W. Salt may yet be discovered in the gravity low in southeastern King Valley.

Two gravity lows are present at the northwestern end of King Valley. One is in the southeastern corner of T. 1 S., R. 18 W.; the other is in the southeastern corner of T. 2 S., R. 17 W. Records of the ADWR indicate that only four water wells are registered in northwestern King Valley. The deepest of the four holes was drilled to a depth of 1070 ft in 27-2s-17w, about 4 miles east of the axis of the southernmost of the two gravity lows. No evaporites were reported in any of the wells. However, no wells have tested the deeper strata for the presence of evaporites or salt in and between the two gravity lows in the northwestern part of the King Valley.

Harris reported gypsum from 280 to 760 ft in cuttings from five holes drilled in the Gila River trough between King and San Cristobal valleys (Spencer and Harris, 1996). The southernmost of the five holes was drilled to a depth of 1500 ft in northwestern San Cristobal Valley in 24-7s-14w. This hole is just north of the 4800 ft depth-to-bedrock contour and about 5 miles north of a gravity low in the southern half of T. 8 S., R. 13 W. The southwestern margin of the gravity low is marked by closely spaced gravity contours. The closely spaced gravity contours are interpreted to indicate that the northwestern San Cristobal Valley is a half graben hinged on the northeast with maximum displacement on the southwest. Salt is associated with primary half-graben faults and gravity lows in other basins in southern Arizona and may be associated with these features in the northwestern part of the San Cristobal Valley.

A broad gravity low is present in the southeastern part of the San Cristobal Valley in the northern part of T. 10 S., R. 11-12 W. The gravity contours are closely spaced in the southwestern part of T. 10 S., R. 12 W. ADWR records indicate that only one hole is registered in southern San Cristobal Valley. The hole was drilled to an unknown depth in 6-10s-12w, about 5 miles west of the axis of the gravity low. No other information is available for the hole. As a result, more than 6000 ft of strata, interpreted from the gravity modeling of Oppenheimer and Sumner (1980), remain untested in southeastern San Cristobal Valley. No holes have been drilled to test these deeper strata, which, like strata in Date Creek Basin to the north, could contain salt that was deposited in isolated playas or ephemeral lakes before an integrated drainage system was established through San Cristobal Valley. Salt may yet be discovered in the gravity low in the central part of San Cristobal Valley and in association with the closely spaced gravity contours along the southwestern margin of the valley.

Gravity data suggest that Mohawk Valley may be a half graben hinged on the southwest with maximum displacement on the northeast. ADWR records indicate that only one water well is registered in the northwesternmost end of the valley, just north of the Barry M. Goldwater Air Force Gunnery Range. No other holes are registered in the entire valley. The registered hole was drilled to a depth of only 500 ft in 6-9s-16w, about 8 miles west of the northwesternmost extent of the closely spaced gravity contours along the northeastern margin of Mohawk Valley. The lack of drilling and gravity modeling of Oppenheimer and Sumner (1980) suggest that more than 8000 ft of strata remain untested beneath the valley. No holes have tested the strata along the primary half-graben fault that defines the northeastern margin of Mohawk Valley. Salt may have been deposited in isolated ponds or salt flats bordering the bounding fault and may be present along the entire length of the northeastern margin of the valley between T. 8 S., R. 16 W. and T. 12 S., R. 12 W.

A distinct gravity low is present in Growler Valley in T. 13 S., R. 8-9 W. Salt may be associated with the gravity low. ADWR records indicate that only three shallow water wells are registered in Growler Valley. Two were drilled to depths of less than 50 ft north of the gravity low. The deepest hole was drilled to a depth of only 440 ft near the axis of the gravity low in 13-13s-9w. As a result, salt may yet be discovered in the more than 4800 ft of untested strata in the Growler Valley. These strata may have accumulated in ephemeral ponds and playas before an integrated drainage system was developed in the Growler Valley.

Santa Rosa Valley

Santa Rosa Valley is in north-central Pima County about 30 miles southwest of Casa Grande (Figure 9). The valley is entirely within the Tohono O'odham Nation. Santa Rosa Valley forms a north-trending basin about 12 miles long and 5 miles wide within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). Oppenheimer and Sumner (1980) interpreted the depth to bedrock in the northern part of the basin to be at least 8000 ft. Two gravity lows are present in the basin (Ajo and Tucson Sheets - Lysonski, Aiken, and Sumner, 1981). No wells are listed in Santa Rosa Valley on the well-location map of Pima and Santa Cruz Counties (Conley, Koester, and Rauzi, 1995c). The nearest pipeline and railroad are about 25 miles to the northeast.

Heindl and Cosner (1961) described at least 11 shallow water wells in Santa Rosa Valley. The deepest is only 590 ft. No evaporites were reported in any of the wells but none were drilled deep enough to confirm the presence of evaporites in the more than 7000 ft of untested strata in the northern part of the valley. These deeper deposits may have accumulated in isolated ponds and playas before an integrated drainage system developed through Santa Rosa Basin. Salt may be discovered in these deposits in the gravity low in the western part of T. 11 S., R. 4 E. and the gravity low in the northwestern part of T. 13 S., R. 4 E.

Red Rock Basin

Red Rock Basin trends northward across the Pima-Pinal County boundary about midway between Casa Grande and Tucson (Figure 9). Interstate 10 extends through the approximate center of the basin near the town of Red Rock. The northern part of the basin is entirely within southern Pinal County. The southern part of the basin, known as Avra Valley, is mostly within Pima County. The well-location maps of Pima and Santa Cruz Counties and Pinal County (Conley, Koester, and Rauzi, 1995c; Koester, Conley, and Rauzi, 1995a) list eight wells in the Red Rock Basin. Five are in the northern part of the basin and three are in the southern part, as defined by the 4800 ft depth-to-bedrock contours. None of the wells are within the 9600 ft depth-to-bedrock contour in the southern part of the basin. Tucson Water (2000) listed static-water-level measurements from 154 wells in Avra Valley. Most of these are far less than 1000 ft deep. Two gravity lows are present in Red Rock Basin (Tucson Sheet - Lysonski, Aiken, and Sumner, 1981). One is coincident with the 4800 ft depth-to-bedrock contour north of Red Rock. The other is coincident with the 9600 ft contour south of Red Rock in the northern part of Avra Valley. Three interstate gas pipelines and a major railroad trend through the basin more or less parallel to Interstate 10.

Evaporites were reported in only one of the five shallow wells drilled in the northern part of the Red Rock Basin. These wells penetrated mostly sand, gravel, sandy clay and clay. The deepest is a water well drilled to a depth of 1410 ft in 29-9s-10s, near the southeastern end of the northern 4800 ft depth-to-bedrock contour. Gypsum and clay were reported from 1000 to 1090 ft in another water well drilled to a depth of 1090 ft in 20-9s-10e, about 4 miles southeast of the gravity low in the northern part of the basin.

The deepest of the three wells in the southern part of Red Rock Basin was an oil test drilled with cable tools by Eloy Development Association in the late 1940s. The Eloy hole was drilled to a depth of 4950 ft in 6-12s-11e, just north of the 9600 ft depth-to-bedrock contour. A few samples from 575 to 600 ft and a fairly complete set of samples from 2100 to 4800 ft from the Eloy hole were sent to the USGS Ground Water Branch in Tucson in 1953. The USGS reported impure gypsum at 2190 ft, fine to medium sand from 2190 to 2720 ft, mostly sand, silt, clay, and gypsum from 2720 to 2900 ft, sand, silt, clay, and anhydrite from 3193 to 3813 ft, and hard clayey silt and tuff from 3813 to 4800 ft. No evaporites were reported in the other two holes drilled in the southern part of Red Rock Basin. One is an oil test drilled by Berry Mineral Development to a depth of 3212 ft in 27-11s-10e. The other is a water well drilled by Arizona Public Service to a depth of 2509 ft in 15-10s-10e. The Berry hole is 4 miles west of the Eloy hole and just west of the 4800 ft contour. The Arizona Public Service well is 10 miles northwest of the Eloy hole, just inside the northern extent of the 4800 ft depth-to-bedrock contour.

The presence of salt in close association with a gravity low in the Picacho Basin, adjacent to the west, suggests that salt may also be associated with the two gravity lows in Red Rock Basin. The deep oil test has confirmed the presence of gypsum and anhydrite at the north end of the gravity low south of Red Rock in the southern part of the basin. Gypsum and anhydrite in the deep oil test may grade laterally into salt within the southern gravity low in T. 12 S., R. 10-11 E. No wells have been drilled deep enough to establish the presence of gypsum, anhydrite, or salt in the gravity low north of Red Rock in the northern part of the basin. The closely spaced gravity contours southeast of the northern gravity low suggest that the northern gravity low may represent a half graben with maximum displacement on the southeast. The association of salt with gravity lows in several basins and with closely spaced gravity contours in Date Creek Basin and Detrital Valley suggests that salt may also be associated north of Red Rock with the northern gravity low in the east half of T. 8-9 S., R. 10 E. and the closely spaced gravity contours along the west end of T. 9 S., R. 11 E.

Tucson Basin

The Tucson Basin extends from eastern Pima County into northernmost Santa Cruz County (Figure 9). The basin widens to about 20 miles just south of Tucson where it attains a maximum depth of more than 9600 ft (Richard and others, 2000). The well-location map of Pima and Santa Cruz Counties (Conley, Koester, and Rauzi, 1995c) lists nine wells within the 4800 ft depth-to-bedrock contour. Two of the wells are within the 9600 ft contour. One penetrated igneous bedrock at 12,000 ft just southeast of Tucson. Tucson Water (2000) listed static-water-level measurements from 654 wells in the Tucson Basin. Most of these are far less than 1000 ft deep. Residual gravity contours converge to form four gravity lows in the Tucson Basin (Nogales and Tucson Sheets - Lysonski, Aiken, and Sumner, 1981). One is north of Tucson, just west of Oro Valley; three are between Tucson and the Santa Cruz County line. Two interstate gas pipelines and a major railroad trend northwesterly through the basin at Tucson.

The deepest hole in the Tucson Basin is a stratigraphic test drilled to a depth of 12,571 ft by Humble Oil & Refining Company (now Exxon Mobil) in 1972. The Humble hole, in 5-16s-15e, penetrated mostly fine to coarse clastic rocks to 7200 ft, volcanic with minor clastic rocks from 7200 to 10,000 ft, conglomerate from 10,000 to 12,000 ft and igneous basement from 12,000 to 12,571 ft. Gypsum stringers, interbedded gypsum and anhydrite, and scattered anhydrite inclusions were present from 1850 and 3900 ft. A 10 ft anhydrite bed was present at 7100 ft.

Anderson (1987, p. 10) assigned the extensive deposits of gypsiferous and anhydritic clayey silt and mudstone in the central, down-faulted part of the Tucson Basin to the middle Tinaja beds, which he attributed to accumulation in a closed basin during the beginning of large-scale block faulting. Anderson's study was based on more than 500 water-supply and test wells. However, because few of the wells penetrated deeply into the lower and middle Tinaja beds, much of their thickness is unexplored. As a result, the four gravity lows in the Tucson Basin may coincide with isolated ponds where salt may have accumulated in the middle Tinaja beds during dry periods. The ponds, or possible salt pans, would have formed in local depositional centers within the closed Tucson Basin.

The northernmost gravity low is just west of Oro Valley in the center of T. 12 S., R. 13 E. To the south, a gravity closure is located in the northeastern corner of T. 16 S., R. 14 E., just west of the deep Humble hole. Gypsum and anhydrite in the Humble hole, on the eastern edge of the extensive evaporite deposits described by Anderson, may grade westward into salt within the gravity closure. The broadest gravity low in the central graben is east of Sahuarita and Green Valley in T. 17-18 S., R. 14 E. This gravity low may represent the lowest center of deposition in the Tucson Basin and may coincide with significant salt deposits in the middle Tinaja beds. The southernmost gravity low, just east of Arivaca, trends northeast through the central part of T. 19 S., R. 13 E. All of these gravity lows have potential to contain salt.

Willcox Basin

Willcox Basin is about midway between Tucson and the New Mexico line in the northern part of Sulphur Springs Valley (Figure 10). Most of the basin is in northern Cochise County. The basin, named after the Willcox Playa, ranges from 2 to 7 miles wide within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). The well-location maps of Graham and Greenlee Counties and Cochise County (Conley, Koester, and Rauzi, 1995d; Koester, Conley, and Rauzi, 1996a) list at least 16 wells in the Willcox Basin. Gypsum was reported in only two of the holes. No evaporites were reported in any of the holes within the 4800 ft depth-to-bedrock contour. Residual gravity contours form a broad, elongate gravity low across the northern part of the basin between Willcox and the Graham County line and a smaller gravity low in the southern part of the basin between Willcox and Cochise (Silver City Sheet - Lysonski, Aiken, and Sumner, 1981). An interstate natural gas pipeline trends westerly through the basin about 4 miles north of Willcox. A major railroad crosses the southern end of the basin at Willcox.

Gypsum was reported in two deep oil tests south of Willcox in the southern part of the Willcox Basin. In 1949, Waddell Duncan drilled one of the holes, the #1 Lawson, to a depth of 2702 ft in 4-14s-25e. The #1 Lawson is about 12 miles southeast of the gravity low between Willcox and the Graham County line and 5 miles northeast of the gravity low between Willcox and Cochise. Sand, clay, and gypsum were reported in the #1 Lawson from 249 to 980 ft. Traces of gypsum were reported to total depth. In 1931, Benedum Trees drilled the other hole to a depth of 3298 ft in 19-15s-26e, about 10 miles southeast of the Waddell Duncan #1 Lawson hole. Some gypsum was reported in the Benedum Trees hole from 180 to 355 ft and 1435 to 1598 ft.

No evaporites were reported in the deepest hole drilled in the Willcox Basin. In 1951, Waddell Duncan drilled the deepest hole, the #1 McComb, to a depth of 6865 ft in 23-13s-24e. The #1 McComb was drilled on the eastern edge of the basin about 3 miles northwest of Willcox and 7 miles southeast of the gravity low between Willcox and the Graham County line. The #1 McComb penetrated mostly coarse-grained alluvial and volcanic material with some clay and thin carbonate.

No evaporites were reported in two deep holes drilled on the northwestern end of the Willcox Basin in southern Graham County. In the 1930s, the Hooker Ranch drilled one of these holes to a depth of 1985 ft in 6-11s-23e, about 7 miles northwest of the gravity low between Willcox and the Graham County line. The Hooker Ranch hole penetrated mostly clay and gravel. In 1965, Ram Oil Company drilled the other hole to a depth of 1823 ft in 2-11s-22e, about 2 miles west of the Hooker Ranch hole. The Ram Oil hole also penetrated mostly clay and gravel.

The Willcox Basin is of interest because of its proximity to the Safford Basin to the east. Salt is present in the Safford Basin. Even though very little gypsum was reported in only two holes in the southernmost end of the Willcox Basin, salt could be associated with the two gravity lows in the basin. One of the gravity lows is between Willcox and Cochise in the southwestern part of T. 14 S., R. 24 E. No deep holes have been drilled on this gravity low. The other, and more pronounced, gravity low is between Willcox and the Graham County line in the eastern part of T. 12 S., R. 23 E. Almost 100 water wells are registered with the ADWR along the axis of this gravity low. The deepest, in 15-12s-23e, is only 1510 ft deep. The lack of deep drilling and gravity modeling of Oppenheimer and Sumner (1980) suggest that more than 3000 ft of strata remain untested in the gravity low between Willcox and the Graham County line.

Elfrida Basin

Elfrida Basin, in southern Cochise County in the southern part of the Sulphur Springs Valley (Figure 10), trends southward for about 45 miles between Pearce and the southern border of Arizona at Douglas. Small volcanic hills border the basin on the north. Even though the basin is about 20 miles wide, only the western half is within the 4800 ft depth-to-bedrock contour on the Geologic Map of Arizona (Richard and others, 2000). The well-location map of Cochise County (Koester, Conley, and Rauzi, 1996a) lists 14 wells in the basin, two of which encountered gypsum and anhydrite within the 4800 ft depth-to-bedrock contour. Residual gravity contours form a broad gravity low across the western part of the basin (Douglas Sheet - Lysonski, Aiken, and Sumner, 1981). An interstate gas pipeline trends northwest through the center of the basin. A railroad spur extends into Douglas at the southern part of the basin.

Coates and Cushman (1955) reported gypsum outcrops at the northern and southern ends of the Elfrida Basin. Gypsum has been reported in at least two wells near the center of the basin. The gypsum outcrops at the south end of the basin, just east of Douglas, have been worked in the past, mostly for local use.

Gypsum with fine sand was reported from 990 to 1012 ft in a water well drilled to a depth of 1012 ft near the center of the basin in 1-21s-25e. This well is about 5 miles northwest of McNeal. In 1953, E.R. Allen drilled the deepest hole in the basin, the #1 Davis, to a depth of 5450 ft in 25-21s-25e, about 4 miles southwest of McNeal. Allen reported gypsum lenses from 650 to 2000 ft and scattered gypsum from 2000 to 2810 ft. The Allen oil test is about 4 miles south of the water well in Section 1. Both of these holes are about 4 miles west of the closely spaced gravity contours that may represent a half-graben fault along the eastern edge of the deep, western half of the basin between Elfrida and Douglas. Salt is associated with closely spaced gravity contours in Detrital Valley and Date Creek Basin. Gypsum at either end of Elfrida Basin and in the two wells near the center of the basin may grade into potential salt deposits in the vicinity of the closely spaced gravity contours between Elfrida and Douglas. Salt may also be present southwest of the Allen oil test in the gravity low in the northeastern part of T. 22 S., R. 25 E.

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