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Evaluation and proposed study of potential ground-water supplies, Gallup area, New Mexico

By

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Recommendations for a ground-water exploration program in the vicinity of Gallup, New Mexico

By

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Abstract

The ground-water potential of 5 areas in central-western New Mexico within 85 miles (135 km) of Gallup, N. Mex. was evaluated by reviewing the published literature, inspecting aerial and space photographs, and interviewing ranchers and personnel employed by well-drilling and mineral-exploration companies by telephone.

The San Andres Limestone and underlying Glorieta Sandstone of Permian age are the oldest aquifers capable of yielding water of a quality suitable for municipal use. Extreme local variations in hydraulic conductivity and water quality reflect a karstic topography developed on the San Andres Limestone prior to burial by Upper Triassic sediments. The San Andres Limestone and Glorieta Sandstone form an important aquifer in the Grants-Bluewater area where yields of as much as 2,200 gallons per minute (140 l/s) have been obtained. Yields from wells completed in the San Andres-Glorieta aquifer on the Chaco slope and in the Gallup sag-Mogollon slope on the northeast and southeast flanks, respectively, of the Zuni uplift will be much less than those prevailing in the Grants-Bluewater area. Water quality in the San Andres Limestone and Glorieta Sandstone deteriorates with distance away from the axis of the Zuni uplift.

Sandstones of Triassic, Jurassic, and Cretaceous age are potential aquifers wherever they are present. Yields to wells tapping these aquifers are generally less than 200 gallons per minute (13 l/s) due to the relatively low hydraulic conductivity.

Wells tapping alluvium of Late Cenozoic age along the Rio San Jose and Puerco River and interbedded volcanics and alluvium elsewhere in the area generally yield less than 100 gallons per minute (6 l/s) of water.

Tributaries of the Rio San Jose that have eroded canyons into Paleozoic and Mesozoic rocks east of the Continental Divide and south of the eastern part of the Zuni uplift have been repeatedly displaced and (or) covered by Quaternary volcanic rocks. The exact location, extent, and depth of buried alluvium in the Late Tertiary valleys is unknown. Water enters the volcanic rocks as rainfall and snowmelt and probably passes quickly into and through the underlying alluvium into Jurassic and Cretaceous strata.

The Gallup Sandstone in the lower part of the Mesaverde Group and the San Andres Limestone and Glorieta Sandstone (combined) are potential sources of water in the North Plains-Malpais area.

Sustained yields of 500 to 800 gallons per minute (30 to 50 l/s) can be expected from wells completed in the Gallup Sandstone of Cretaceous age in areas west and north of the Zuni uplift. Properly completed wells tapping the Dakota Sandstone of Cretaceous age and the Westwater Canyon Sandstone Member of the Morrison Formation of Jurassic age locally yield 100 to 250 gallons per minute (6 to 15 l/s) north and east of Gallup. Additional supplies of ground water could be developed from these aquifers. However, arrangements to purchase or lease the water would probably need to be made before these resources could be exploited.

Approximately 3,000 gallons per minute (190 l/s) of ground water is being pumped from the Westwater Canyon Member of the Morrison Formation at two uranium mines located about 12 miles (20 km) northeast of Gallup in the Church Rock mining district. The water is pumped into settling ponds at the surface. Effluent from the ponds is allowed to flow into arroyos draining into the Puerco River. Some of the waste water will be used in an ore-processing mill that is expected to be constructed near the mines. However, additional waste water will probably be available from other mines that reportedly will be located in the same mining district. Water salvaged from the current mining operations and (or) pumped from abandoned uranium mines constitutes the most readily available and dependable source of new ground-water supplies for the city of Gallup. The water contains dissolved uranium but is otherwise of better quality than that now available in the municipal supply.

The quality of water produced from wells tapping aquifers of several geologic ages within the areas studied frequently wxceeds the standards for human consumption recommended by the U.S. Puboic Health Service. Treating water to improve the quality rather than seeking alternate sources of less mineralized water may be the only practical solution to this problem.

Ownership, control, and (or) regulation of the ground water are factors of utmost importance in this area and should be considered in planning any ground-water exploration program.

Introduction

Purpose of this report

The U.S. Bureau of Reclamation is conducting feasibility studies of the Gallup area in order to determine whether or not ground water of suitable quality is available in quantities sufficient to supply the anticipated future demands of the city at a cost competitive with other sources. To help meet these objectives, the U.S. Bureau of Reclamation requested the U.S. Geological Survey to determine the potential for occurrence and development of ground water of suitable quality and quantities in nearby areas and to propose a comprehensive exploration program to evaluate the most promising sites.

Gallup and the surrounding area

The city of Gallup, county seat of McKinley County, is located on Interstate Highway 40 in central-western New Mexico about 28 mi (45 km) west of the Continental Divide (fig. 1). Gallup is the center of trade for an area of about 15,000 mi^2 (38,850 km^2) in eastern Arizona and western New Mexico inhabited predominantly by Indians. The population of Gallup was 14,596 at the time of the 1970 census (U.S. Bureau of the Census, 1970). In addition to the normal business from the trade community, the economy of Gallup is heavily dependent upon trade with tourists who are attracted by several nearby Indian Reservations and by the arts and crafts manufactured by Indians and sold by merchants in Gallup or at nearby trading posts.

Large deposits of uranium, and oil and gas have been found to the north and east of the city (Averitt, 1972; Butler, 1972; and Pritchard, 1972). Development of these abundant natural resources is expected to further stimulate the economy. Two new uranium mines have been opened in the Church Rock area about 12 miles (19 km) northeast of Gallup in the past few years. Additional mines are expected to be constructed in the near future as the rate of exploitation of known reserves of uranium is increased (Hatzlett, 1969; and Fitch, 1974). At least six coal-gasification plants, now in the advanced stages of planning, are expected to be constructed in this decade in the Burnham-Bisti area north of Gallup (fig 1) in the proximity of the large reserves of strippable Upper Cretaceous coal (Sears, 1925 and 1934; Sears, Hunt and Dane, 1936; Shomaker, Beaumont, and Kottlowski, 1971; Shomaker, 1974; Byrne and Cook, 1974; and U.S. Bureau of Reclamation, 1974, Exhibit 1-1, p. 1-2).

Need for additional water

The municipal water system in Gallup is being operated at or near capacity. Eleven wells now in operation are capable of a total sustained yield of approximately 3.7 million gallons per day (14,005 m^3/d). The capacity to produce water at an increased rate for short periods is extremely limited. The ground water now available for domestic use contains approximately 1,000 milligrams per litre (mg/l) of dissolved solids. The upper limit of dissolved solids recommended by the U.S. Public Health Service (1962) is 1,000 mg/l. Additional supplies of better quality ground water are needed to meet existing and expected demands on the municipal system. The Yah-ta-hey well field (Mercer and Cooper, 1970; and U.S. Bureau of Reclamation, 1973) is currently being expanded and can be expected to meet projected needs for about 10 to 15 years, but perhaps less than that, if the growth in the population and trade stemming from development of uranium and coal resources occurs as anticipated.

Scope and methods of investigations

This report is necessarily of a preliminary or reconnaissance nature, and, as such, is limited in scope. The literature and readily available unpublished geologic and hydrologic data were thoroughly reviewed. Low and high altitude aerial and space photographs were inspected in the hope of detecting structural lineaments or paleostream patterns which may control the occurrence of ground water. Well drillers and mineral exploration companies were contacted by telephone to obtain qualitative information relating to the occurrence of previously unknown water-bearing strata and to shows of water of larger-than-expected magnitude in known aquifers.

English to metric conversion factors

Most numbers in this report are given in English units followed by metric units in parentheses. The conversions to metric units were made as follows:

English		Multiplied by	Metric	
Unit	Abbreviation		Unit	Abbreviation
Acre	acre	0.4047	Hectare	ha
Acre-foot	acre-ft	.0012335	Cubic hectometre	hm^3
Foot	ft	.3048	Metre	m
Gallons per minute	gpm	5.45	Cubic metres per day	m^3/d
Do	do	.06309	Litres per second	l/s
Gallons per day	gpd	.003785	Cubic metres per day	m^3/d
Inch	in	2.54	Centimetre	cm
Mile	mi	1.6093	Kilometre	km
Square mile	mi^2	2.59	Square kilometre	km^2

Chemical concentrations are given only in metric units, milligrams per litre (mg/l). For concentrations less than 7,000 mg/l, the numerical value is about the same as for concentrations in the English unit, parts per million (ppm). The altitudes, elevations, distances, depths, and volumes given in this report are often either estimated or generalized so as to be descriptive of a large area. Accordingly, the values stated are often rounded to the nearest hundred units. The values are also converted from English units to metric units and given in parentheses following the original value. The metric units are rounded to the nearest 5 units. However, when the magnitude of the value in English is either small or expressed with obvious precision, an attempt has been made to keep the metric conversion consistent.

Areas studied

The potential for developing ground-water resources in each of five areas outlined in figure 1 was evaluated. The areas and the names given to them for purposes of this report are: (1) the Gallup-Tohatchi-Church Rock area encompassing approximately 1,300 mi^2 (3,365 km^2) located between the Chuska Mountains on the north and the Zuni Mountains at the south; (2) Zuni Southwest area, approximately 1,050 mi^2 (2,720 km^2) lying along the southwestern flank of the Zuni Mountains; (3) the North Plains-Malpais[1/] area, a broad, shallow topographic depression covered by volcanic rocks including about 700 mi^2 (1,815 km^2) located to the south of the southern end of the Zuni Mountains; (4) the Grants-Bluewater area, encompasses about 300 mi^2 (775 km^2) centered around the city of Grants; and (5) the Mesa Chivato-Cebolleta Mountains, an elliptical area containing about 400 mi^2 (1,035 km^2) extending for approximately 35 mi (55 km) northeast of Mount Taylor.

1/ Malpais, "....a region of rough and barren lava flows." (Gary, McAfee, and Wolf, 1972. p. 428).

Previous investigations

West (1957, 1959, and 1961) and Mercer and Cooper (1970) have studied the ground-water resources of the Gallup and Gallup-Tohatchi areas, respectively. Shomaker (1971) prepared a thorough and exhaustive study of the water resources of Fort Wingate Army Depot and adjacent areas. The unpublished dissertation by Berry (1959) is virtually the only comprehensive source of subsurface hydrologic information for the relatively deeper part of the San Juan basin. A study of the Grants-Bluewater area by Gordon (1961) forms the basis for the conclusions and recommendations pertaining to the Grants-Bluewater area of this report. Some information pertaining to many wells drilled by companies exploring for and (or) mining uranium from Jurassic strata in the Grants mineral belt in southeastern McKinley County (fig. 1) is available in Cooper and John (1968). Reports by Cooley, Akers, and Stevens (1964); Cooley, Harshbarger, Akers, and Hardt (1969); Davis, Hardt, Thompson, and Cooley (1963); Edmonds (1967); Harshbarger and Repenning (1954); Kister and Hatchett (1963); and McGavock, Edmonds, Gillespie, and Halpenny (1966) relate primarily to the Navajo Indian Reservation north and west of Gallup but include part of the Gallup-Tohatchi-Church Rock area. The principal aquifers and ground-water resources along Interstate Highway 40 from Gallup to Laguna are summarized in a brief article by Cooper and West (1967).

The city of Gallup has been concerned about the availability of an adequate supply of ground water for many years. Reports prepared by several consultants including Hatfield Engineering Co. (1969), Burnett and Hatfield (1957), Banner and Associates (1957), Allgood Engineering Co. (1969), Gordon Herkenhoff and Associates (1959, 1961a, 1961b, and one undated report), and Kenneth W. Larsen and Associates (1971) retained by the city of Gallup, and one report prepared by a private individual acting on his own volition (Dean, 1963), all dealing with sources and (or) supplies of water for Gallup have been reviewed by the U.S. Bureau of Reclamation (1973, p. 7-13).

The possibility of diverting water from the San Juan River in northwestern New Mexico to supply the city of Gallup has been evaluated by the U.S. Bureau of Reclamation (1966 and 1973). The feasibility of obtaining water supplies from reservoirs that could possibly be constructed on Black Creek within the Navajo Indian Reservation, Apache County, Arizona, and (or) Whitewater Arroyo near Cheechilgeetho, McKinley County, New Mexico, has been evaluated in a reconnaissance study by the U.S. Bureau of Reclamation (1963). Southwest Research Institute (1971) recommended a plan for improving the quality of water produced from the Yah-ta-hey well field by desalting the water with an electrodialysis plant.

The regional structure of central-western New Mexico has been described in a number of reports by Kelley (1950, 1951, 1955a, 1955b, 1957, and 1967). A detailed analyses of the fracture systems in the Zuni uplift and the Colorado plateau has been made by Kelley and Clinton (1960).

The literature describing the geologic history, structure, and stratigraphy of the area is exceedingly voluminous. Articles deemed to be useful in outlining the geologic history and framework of the region and the geohydrology of the five areas studied are cited in the selected references. Summary reports in the Geologic Atlas of the Rocky Mountain region, United States of America (Mallory, 1972) were particularly useful in gaining an understanding of the regional geology.

Acknowledgments

Appreciation is expressed to the many well drillers, mining geologists, and engineers employed by private companies and State and Federal agencies, ranchers and others who provided information, opinions, and counsel that would not otherwise have been available. The U.S. Bureau of Reclamation provided the financial support for this evaluation of potential ground-water aquifers.

Physiography

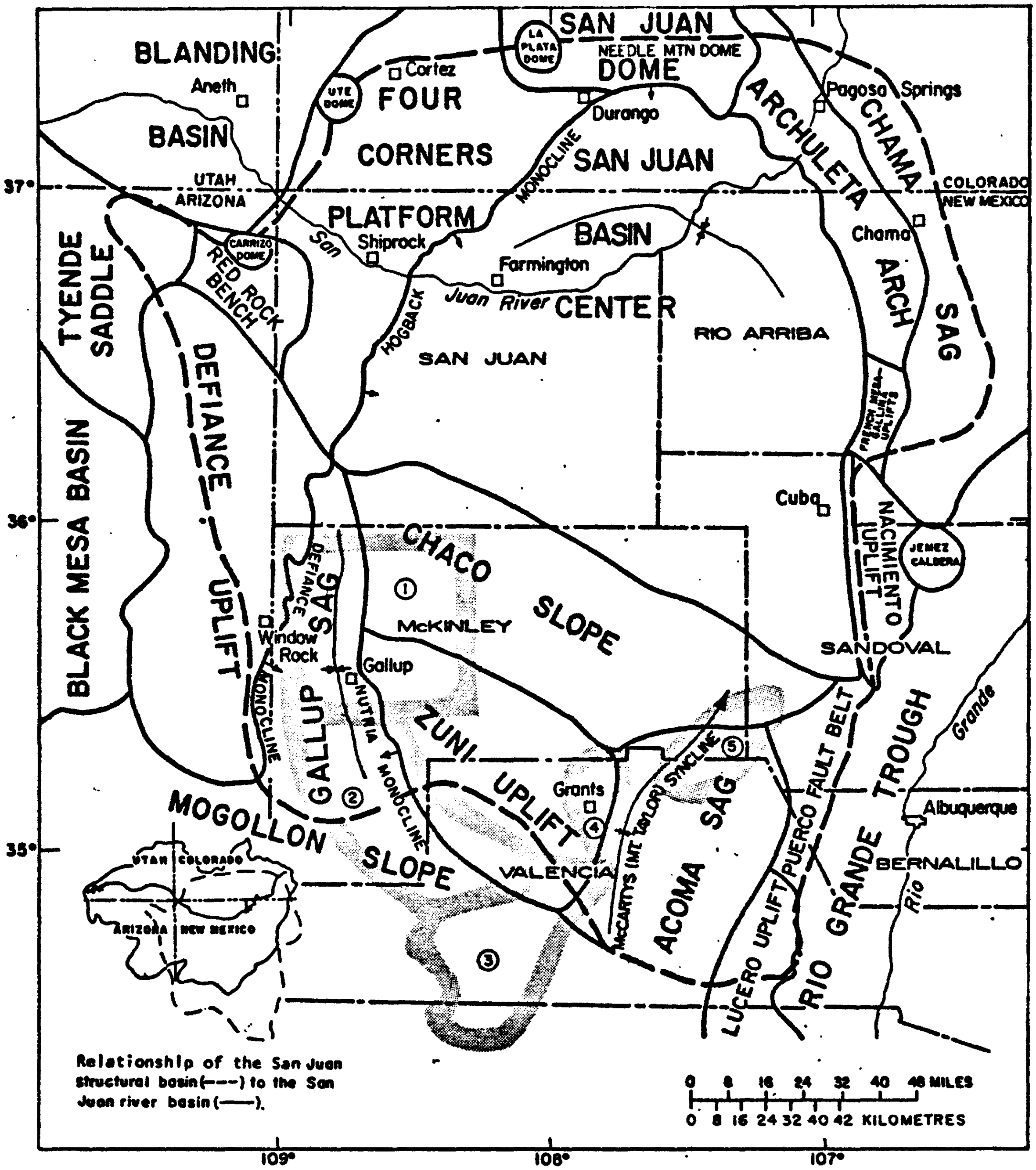
Landforms

The area studied lies within the Navajo and Datil sections of the Colorado Plateau physiographic province (Fenneman, 1931, and 1962; and Hunt, 1956, fig. 1, and 1974, fig. 15.1). Cenozoic deformation, erosion and volcanism have produced a starkly beautiful landscape dominated by the Chuska and Zuni Mountains located northwest and southeast of Gallup, respectively, and Mount Taylor northeast of Grants. Throughout much of the area colorful exposures of red sandstones, siltstones, and shales of Permian, Triassic, and Jurassic age enhance the beauty of the otherwise drab and sparsely vegetated mesas, cuestas, buttes, and hogbacks. Mount Taylor rises to an altitude of 11,389 ft (3,471 m), much higher than the related volcanic field capping Mesa Chivato and Cebolleto Mountains to the northeast at altitudes of approximately 8,000 ft (2,440 m).

Local topographic relief of more than 1,000 ft (305 m) in central-western New Mexico is not unusual. Altitudes range from about 6,500 ft (1,980 m) near Gallup and Grants, on the west and east side of the Continental Divide, respectively, to 11,389 ft (3,471 m) at Mount Taylor. The shape of the surface and the relief are controlled by a combination of local and regional structure and the character of the rock. The less resistant strata, generally shales and siltstones, are easily eroded and underlie the valleys and slopes. The more resistant sandstone beds and lava flows form the upper surface of the buttes and mesas. Prominent hogback ridges are formed by resistant sandstone beds along the steeply dipping Nutria monocline on the north and northwestern flank of the Zuni uplift (Edmonds, 1961; and Read, Smith, Fitzsimmons, and Werts, 1967, p. 100-101).

Volcanic rocks generally younger than those in the Mount Taylor field have been extruded from several centers and an unknown number of fissures scattered along a belt trending southwestward from Mesa Chivato across the southeastern end of the Zuni Mountains to Trechado at the southwestern margin of the North Plains (figs. 1, 2, and 3). Younger pahoehoe flows follow the valleys excavated during the latest cycle of erosion and, in several places, form a black, virtually unweathered malpais terrain (Nichols, 1946; Lindsey, 1951; and National Park Service, 1969).

Remnants of an older regional erosional surface are preserved in the Zuni and Chuska Mountains and beneath the lavas of Mesa Chivato, Mesa Prieta, and Lucero Mesa. Streams now draining the region flow at levels 600 to 700 ft (185 to 215 m) below the older Zuni erosion surface (Bryan and McCann, 1938, p. 11; Wright, 1946, p. 435-444; McCann, 1938; and Moench and Schlee, 1967, p. 54). Present stream gradients are approximately one-half of the 25 to 30 ft/mi (5 to 6 m/km) westward slope of the middle Pliocene Zuni surface (Fitzsimmons, 1959, p. 115). The distance between the present-day surface and the Zuni erosional surface provides some measure of the rate of erosion in central-western New Mexico and an insight into the relief to be expected on land surfaces hidden by late Cenozoic volcanic rocks.



EXPLANATION

Boundary of structural components

Approximate boundary of San Juan structural basin

Axis of syncline

Monocline

Adopted from Kelley (1950, p. 102, 1955, p. 23, and 1957, p 44).

Area Evaluated

① -Gallup-Tohatchi-Church Rock
② -Zuni Southwest
③ -North Plains-Malpais
④ -Grants-Bluewater
⑤ -Mesa Chivato-Cebolleta Mountains

Figure 2.--Physiographic components of the San Juan structural basin in northwestern New Mexico.

Surface drainage

The Puerco River, an ephemeral stream and part of the Colorado River drainage system, passes through Gallup. Areas lying east of the Continental Divide are drained by the Rio San Jose and Rio Puerco, which are intermittent tributaries of the Rio Grande. The two "Puerco" streams draining the west and east slopes of the Continental Divide are distinguished by the respective choice of English and Spanish words for rivers. ("Puerco"--A Spanish word meaning "dirty", probably referring to the heavy load of silt carried during periods of substantial flow.)

Ephemeral washes of the Chaco River, an ephemeral tributary of the San Juan River, drain an area north of Gallup. The San Juan River, approximately 85 mi (135 km) to the north, is the only perennial stream of any significance in the area.

Excluding the San Juan River, surface-water flow in the vicinity of Gallup is not adequate for development of more than a small supplemental water supply.

Climate

The climate of the area surrounding Gallup is semiarid with precipitation varying from about 8 in (20 cm) annually in the lower elevations to 20 in (50 cm) in the Zuni and Cebolleta Mountains and 30 in (75 cm) near the summit of Mount Taylor. Evaporation rates greatly exceed precipitation throughout the area (New Mexico State Engineer, 1956a).

The mean annual temperature of Gallup is approximately 50°F (10°C). Daily temperature fluctuations of 30° to 40°F (17° to 22°C) are common. Maximum temperatures seldom exceed 100°F (38°C) during the summer. Minimum temperatures occasionally fall below 0°F (-18°C) in the winter.

Geology

Geologic history and generalized stratigraphy

The following account of the geologic history of western New Mexico is adapted primarily from Hilpert (1969, p. 28-31. A generalized stratigraphic section representative of central-western New Mexico and the general hydrologic characteristics of the strata yielding water to wells are summarized in table 1. More detailed descriptions of the stratigraphy, of the regional aquifers and of those of only local occurrence or importance, considered essential to an understanding of the geohydrology of the 5 areas evaluated, are incorporated within the analysis of the individual areas. For more detailed descriptions of the stratigraphy, ground-water quality, and aquifer characteristics of other specific areas, the reader is referred to those reports cited in the selected references.

Table 1.--Generalized stratigraphic section and water-bearing characteristics of aquifers in central-western New Mexico

[Adapted and (or) modified from West (1959), Gordon (1961), Cooper and John (1968), Mercer and Cooper (1970), and Shomaker (1971).]

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Erathem	System	Series	Group	Stratigraphic Unit	Thickness feet	Thickness metres	Generalized lithology	Generalized hydrologic characteristics	Remarks
Cenozoic	Quaternary	Holocene		Alluvium	0- 200	0- 60	Valley-fill deposits of unconsolidated silt, clay, sand, and gravel.	Yields adequate quantities of water for stock and domestic supplies at many places and for irrigation locally. Yields are erratic.	Water is generally potable but usually is hard and contains a high proportion of sulfate ion (SO_4^{--}).
		Holocene and Pleistocene		Basalt	0- 200(?)	0- 60	Dense to vesicular black basalt, extruded as lava flows of varying thickness and extent.	Yields adequate quantities of water for stock and domestic supplies at many places.	Extensive flows in North Plains "malpais" area.
				Alluvium	0- 100(?)	0- 30	Valley fill deposits of sand, gravel, silt, and clay.	Yields adequate quantities of water for stock and domestic supplies at many places and for irrigation in favorable localities in valley.	Pre-Holocene alluviated valleys in North Plains "malpais" area are generally untested.
		Pleistocene		Landslide debris	(?)	(?)	Unconsolidated surficial deposits consisting mainly of Chuska Sandstone in Chuska Mountains and Chinle Formation in Grants area.	Small amount of water yielded to springs in Chuska Mountains. Unknown in Grants area.	--
				Pediment	(?)	(?)	Veneer of unconsolidated gravel and sand deposited on stream-cut terrace surfaces.	Not known to yield any water. Deposits are usually very thin.	--
	Tertiary	Pliocene (?)		Chuska Sandstone	0-1,000+	300+	Gray to grayish-white, massive, crossbedded sandstone with some interbedded siltstone and shale.	Yields water to springs in the Chuska Mountains. No known wells penetrate this sandstone.	Outcrops only in the Chuska Mountains.
		Pliocene and Miocene		Basalt and other extrusive and intrusive igneous rocks	0-5,000+	0-1,500+	Extrusive and intrusive rocks of basaltic, andesitic and rhyolitic composition. Sheet flows, cinder cones, dikes, welded tuffs, ash falls, pumice, breccia, and vesicular basalts complexly interbedded.	Ground water encountered in small quantities in mineral exploration wells. Springs form at base of basalt flows (Cooper and John, 1968, p. 36-37).	Largely confined to Mount Taylor-Mesa Chivato area (Moench and Schlee, 1967, p.26-27.

Table 1.--Generalized stratigraphic section and water-bearing characteristics of aquifers in central-western New Mexico - Continued

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Erathem	System	Series	Group	Stratigraphic Unit	Thickness feet	Thickness metres	Generalized lithology	Generalized hydrologic characteristics	Remarks
Mesozoic	Cretaceous	Upper Cretaceous	Mesaverde	Menefee Formation					
				Allison Member	600- 800	180- 245	Chiefly light-gray to white, lenticular sandstone interbedded with light-gray shales and thin coal seams.	Low permeability but sandstones do yield small amounts of water to wells. Not considered a large supply source.	Upper Cretaceous sedimentary rocks were deposited during several regional transgressions and regressions of marine seas. Consequently sediment characteristic of continental, swamp, shoreline, and marine environments are represented.
				Cleary Coal Member	50- 300	15- 90	Predominantly alternating beds of tan and brown sandstones, claystone, mudstone, with interbedded coal and scattered beds of ironstone and limestone concretions.	Sandstones yield small amounts of water to domestic and stock wells.	
				Point Lookout Sandstone including Hosta Tongue	0- 300	0- 90	Massive light-gray to yellow, fine to medium-grained sandstone.	Yields moderate water supplies to domestic and stock wells.	Deposited in a variety of near-shoreline marine environments in a regional transgressive-regressive sequence.
				Crevassee Canyon Formation					
				Gibson Coal Member	0- 175	0- 55	Chiefly light-gray clay, irregular light-gray sandstone and coals.	Sandstones yield small amounts of water to domestic and stock wells. Limited aquifer due to wedging out and interfingering of sandstone beds.	--
				Bartlett Barren Member	0- 400	0- 120	Similar to Gibson Coal Member but has very little coal.	Sandstones yield small amounts of water to stock and domestic wells.	--
				Dalton Sandstone Member	0- 200	0- 60	Massive, clean, white to buff, medium to coarse-grained sandstone	Data on water-bearing characteristics are sparse but a few wells obtain moderate amounts of water from this unit. May be potentially good aquifer.	Deposited in a variety of near-shoreline marine environments in a regional transgressive-regressive sequence.
				Dilco Coal Member	0- 300	0- 90	Chiefly irregular buff to gray medium-grained sandstone, light-gray clay, and lenticular coal beds and carbonaceous shales.	Sandstones yield small amounts of water to domestic and stock wells.	--
				Gallup Sandstone	150- 500	50- 150	Predominantly a light-gray to buff, fine to coarse-grained sandstone interbedded with gray siltstone and mudstone; and minor amounts of coal.	Yields small to large amounts of water to wells in the area. Major source of water for the city of Gallup.	Deposited in a variety of near-shoreline marine environments in a regional transgressive-regressive sequence.
				Mancos Shale	450- 700	135- 215	Chiefly dark-gray mudstone and sandy siltstone with scattered thin beds of sandstone.	Generally not water bearing.	A marine shale that intertongues with other Upper Cretaceous sediments on a regional scale.
		Upper and Lower(?) Cretaceous		Dakota Sandstone	30- 250	10- 75	Light-gray to buff, fine to coarse-grained sandstone with some interbedded siltstone and coal.	Yields small to moderate amounts of water to wells. May be in hydraulic communication with the underlying Westwater Canyon Sandstone Member of the Morrison Formation. One of the major aquifers in the area.	Some local uranium minerelization. A composite unit deposited in a variety of environments. Includes fluvial, lagoonal, and near-shore marine sediments.

Table 1.--Generalized stratigraphic section and water-bearing characteristics of aquifers in central-western New Mexico - Continued

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Erathem	System	Series	Group	Stratigraphic Unit	Thickness feet	Thickness metres	Generalized lithology	Generalized hydrologic characteristics	Remarks
Mesozoic	Jurassic	Upper Jurassic		Morrison Formation					Morrison Formation beveled and truncated to south by post-Jurassic-pre-Late Cretaceous erosion (Smith, 1959).
				Brushy Basin Shale Member	0- 200	0- 60	Variegated sandy shale	Generally not water bearing.	Sandstones are host for uranium deposits in Laguna area.
				Westwater Canyon Sandstone Member	0- 250	0- 75	Chiefly a white to red, coarse to medium-grained sandstone.	Yields small to moderate amounts of water to wells. One of the major aquifers in the area.	Produced in Yah-ta-hey water field operated by city of Gallup. Major host for uranium ore in central-western New Mexico. Wedges out toward southern part of area.
				Recapture Shale Member	0- 400	0-120	Dark reddish-brown to green sandstone and shaley mudstone.	Generally not water bearing.	Intertongues with and wedges out southward into the Cow Springs Sandstone.
			---	Cow Springs Sandstone and Bluff Sandstone of San Rafael Group, undivided [Equivalent in part to the Zuni Sandstone of Dane and Bachman (1957) reproduced as figure 3 of this report.]	50- 425	15-130	Chiefly gray to light-yellowish gray, fine to medium-grained, crossbedded sandstone with some interbedded siltstone.	Very few wells tap the formation but the few that do yield small amounts of water.	The Bluff Sandstone is a tongue of the more extensive eolian Cow Springs Sandstone that was deposited on the flank of the Mogollon highland. In southwestern McKinley County, the Cow Springs Sandstone is stratigraphically equivalent to the Todilto Limestone, Summerville Formation, Bluff Sandstone, and the lower part of the Morrison Formation. (Harshbarger, Repenning, and Irwin, 1957, p. 48-51 and 1958, p. 111).
			San Rafael	Summerville Formation	0- 200	0- 60	Moderate reddish-brown sandstone and sandy siltstone.	Generally not water bearing	
				Todilto Limestone	0- 75	0-20	Gray thin bedded limestones and reddish-brown sandy shale.	do.	Host for uranium deposits in Grants area.
				Entrada Sandstone	50- 350	15-110	Reddish-brown, fine-grained sandstone and siltstone.	Low permeability restricts the water-bearing capacity.	Eolian in part.

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Table 1.--Generalized stratigraphic section and water-bearing characteristics of aquifers in central-western New Mexico - Continued

Erathem	System	Series	Group	Stratigraphic Unit	Thickness feet	Thickness metres	Generalized lithology	Generalized hydrologic characteristics	Remarks
Mesozoic	Triassic	Upper Triassic	Glen Canyon	Wingate Sandstone					
				Lukachuki Member[1/]	0- 360	0-110	Chiefly a reddish-brown, fine-grained crossbedded sandstone.	Yields small amounts of water to domestic and stock wells.	Depositional characteristics of eolian environment (Cooley, 1959).
				Rock Point Member	0- 100	0- 30	Silty sandstones interbedded with sandy siltstone.	Unknown	Depositional characteristics of fluvial environment (Cooley, 1959).
			Dockum	Chinle Formation					
				Owl Rock Member	0- 40	0- 10	Chiefly an interbedded light-gray limestone and reddish-brown shale.	Generally not water bearing.	Lower units of the Chinle Formation rest unconformably on the Moenkopi Formation or upper Paleozoic rocks. Predominatly fluvial deposits.
				Petrified Forest Member					
				Upper part	800- 900	245-275	Chiefly reddish-brown siltstones and mudstones with interbedded fine-grained sandstones.	do.	--
				Sonsela Sandstone Bed	20- 175	5- 55	Predominantly light-orange to gray, poorly sorted sandstones, conglomerate and interbedded siltstone and mudstone.	Yields small amounts of water to wells. Water quality is generally unsuitable for domestic use.	--
				Lower part	250- 750	75-230	Reddish-brown to purple and light-gray to white silty sandstone and interbedded varicolored siltsone and mudstone.	Generally not water bearing.	--
				Shinarump Member	0- 130	0- 40	Moderate orange and yellowish-gray sandstone, in part conglomeratic with interbedded siltstones and mudstones.	Yields small amounts of water to stock and domestic wells.	
		Middle(?) and Lower Triassic		Moenkopi(?) Formation	0- 100	0- 30	Chiefly a reddish-brown sandy shale and interbedded siltstone.	Generally not water bearing.	Unconformably underlies the Chinle Formation and unconformably overlies the San Andres Limestone and other Permian rocks.

1/ Now recognized as the Iyanbito Member of the overlying Upper Jurassic Entrada Sandstone (Green, 1974).

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Table 1.--Generalized stratigraphic section and water-bearing characteristics of aquifers in central-western New Mexico - Concluded

Erathem	System	Series	Group	Stratigraphic Unit	Thickness feet	Thickness metres	Generalized lithology	Generalized hydrologic characteristics	Remarks
Paleozoic	Permian	Leonardian		San Andres Limestone	0- 250	0- 75	Light-gray, microcrystalline, thin- to massive-bedded limestone. Locally may be pink to orange in color. Karstic topography developed at unconformity below Triassic beds.	Hydraulically connected to underlying Glorieta Sandstone. Major aquifer in Grants-Bluewater area where it is a source of irrigation water although yields and quality are erratic. Elsewhere yields generally range from 50 to 150 gpm (3 to 9 l/s).	Thins to north regionally across area of study. Not present in northern McKinley and Sandoval counties.
				Glorieta Sandstone	100- 350	0-110	Predominantly a thick-bedded to massive, well-sorted, light-gray to buff, fine-grained sandstone. Generally tightly cemented.	Hydraulically connected to overlying San Andres Limestone. Correlated by Baars (1962, 1972) with Coconino Sandstone to west. Major aquifer in Grants-Bluewater area. Dependable source of small yields of water in much of central-western New Mexico.	
				Yeso Formation					
				San Ysidro Member	50- 300	15- 90	Very fine-grained, orange to red sandstone and claystone with some anhydrite and limestone in lower part.	Generally does not yield water.	
				Meseta Blanca Member	150- 500	50-150	Very fine-grained, silty, micaceous, light-brown to reddish-brown sandstone.	Yields a small amount of water for domestic and stock use. Water quality generally poor.	Correlated with De Chelly Sandstone by Baars (1962 and 1972).
		Wolfcampian		Abo Formation	500- 800	150-245	Dark brick-red to reddish-brown arkosic sandstone and siltstone, with numerous layers of conglomerate in lower part.	Generally not water bearing but may yield a small amount of very poor quality water.	
	Pennsylvanian	Upper(?) Pennsylvanian		Unknown	0- 500+	0-150+	Arkose, arkosic conglomerate, thin limestones and shale.	Probably contains impotable water. Untested.	Thin to absent in the immediate vicinity of the Zuni Mountains, and over a broad area southwest of the axis of the present Zuni uplift (fig. 3; and Kelly, 1967, and Mallory, 1972, fig. 4).
Precambrian	Precambrian			Igneous and Metamorphic rocks	-	-	Granite, gneiss, metarhyolite, schist, and greenstone.	Fractured and jointed in outcrops. However, the fractures are undoubtedly closed and permeability correspondingly reduced at depth in the subsurface.	-

Sedimentary rocks older than the Pennsylvanian Period are not present in central-western New Mexico. Information derived from sparse well control and projections from outcrops elsewhere in the Colorado Plateau and southern Rocky Mountains suggests that the Precambrian rocks were eroded to a near peneplain by the beginning of the Paleozoic Era. Marine seas appear to have invaded the area several times during the early and middle Paleozoic but rocks representing these events have been removed by post-Mississippian erosion (Foster, 1957; Momper, 1957; Smith, 1957; Hilpert, 1969; and Kent, 1972).

The antecedents of the Zuni and Defiance uplifts emerged as a broad upwarp during the Palezoic. These positive structural features have persisted intermittently with modifications to the present and have had a considerable influence on sedimentation in central-western New Mexico. Clastics eroded from the ancestral Zuni-Defiance uplift were deposited into marine seas in adjacent areas. Eventually the Zuni-Defiance highlands were worn down and buried during a broad regional subsidence. Flood-plain deposits of the Lower Permian Abo and Yeso Formations were succeeded by the shoreline dune and beach sands of the Glorieta Sandstone and the marine carbonates and sandstones of the San Andres Limestone as shallow middle Permian seas inundated much of the central North American continent.

In Late Permian and Early Triassic time the region was uplifted and a karstic topography was developed on the San Andres Limestone. This period of erosion was followed by regional subsidence as northwestern New Mexico became a broad plain. The terrigenous clastics of the Dockum Group were deposited on this relatively stable surface by streams draining to the north from adjacent highlands to the south. The Sonsela Sandstone Bed, a prominent medial conglomeratic sandstone within the widespread Petrified Forest Member of the Chinle Formation, forms an aquifer of local importance in central-western New Mexico (Cooley, 1959; and Stewart, 1972). Relatively stable conditions persisted on into Late Triassic and Early Jurassic time. The Wingate Sandstone and Entrada Sandstone were deposited, primarily by eolian processes, on the older flood plains as the highland areas were worn to low relief. The Lukachuki Member of the Wingate Sandstone has recently been recognized as being more closely related to the overlying Entrada Sandstone. Green (1974) has renamed this unit the Iyanbito Member of the Entrada Sandstone thus designating the boundary between the Jurassic and Triassic at the top of the Rock Point Member of the Wingate Sandstone.

The hinge line of the broad uplifted Mogollon highlands moved progressively northward throughout the Jurassic to a position approximately at the latitude of Grants by Early Cretaceous time and included the ancestral Zuni-Defiance structures (Kelley, 1967, p. 30). A broad, shallow basin and flood plain lay to the north of the old Mogollon and Zuni-Defiance structural uplifts. The general location of the zone between the highlands to the south and the basinal areas to the north profoundly influenced depositional patterns during the Jurassic (Hilpert, 1969, p. 29). The upper part of the Entrada Sandstone and the Todilto Limestone, Summerville Formation, Bluff Sandstone, and Morrison Formation were deposited in this basin or on the adjacent flood plains. The basin was apparently above sea level except for brief intervals during the deposition of the Summerville Formation and possibly the Todilto Limestone.

The Bluff Sandstone is considered by Harshbarger, Repenning, and Irwin (1957 and 1958) to be a tongue of the Cow Springs Sandstone. This unit has been given formational recognition because of the widespread lateral extension northward and eastward into western New Mexico from the thick, massive eolian Cow Springs Sandstone in northern Arizona. The lowermost and uppermost Cow Springs is also the lateral equivalent to the Summerville Formation and lower part of the Morrison Formation, respectively. Intertonguing relationships between the Summerville and Morrison have also been described by Harshbarger, Repenning and Irwin (1957 and 1958).

The Westwater Canyon Sandstone Member of the Morrison Formation is one of the major hosts for uranium and coincidentally one of the better aquifers in northwestern New Mexico. This fluvial sandstone is approximately 300 ft (90 m) thick near the Arizona-New Mexico border but thins eastward to 100 to 250 ft (30 to 75 m) on the east side of the San Juan basin. South of the latitude of Albuquerque, the Westwater Canyon Member thins to extinction, mostly as a result of nondeposition but partly due to pre-Dakota erosion.

In Late Jurassic or Early Cretaceous time both the ancestral Mogollon and Zuni-Defiance highlands and the basin margin were tilted to the north and beveled to form an extensive coastal plain. The Mancos sea encroached from the southeast and northeast as the region gradually subsided. The transgressive Dakota Sandstone progressively oversteps beds to the southwest ranging in age from the (Jurassic) Morrision Formation to the (Permian) Abo Formation. The generally well-cemented Dakota Sandstone resists erosion and forms prominent cliffs and ledges. The distinctive yellow-brown color of the weathered Dakota contrasts sharply with the varicolored shales in the underlying Morrison Formation and the drab grey of the overlying Mancos Shale. The Dakota Sandstone, a relatively poor aquifer, can be traced both at the surface and in the subsurface for hundreds of miles throughout western New Mexico and the adjacent states (Pike, 1947; Young, 1960 and 1973; Best, 1973; Owen, 1973; Landis, Dane, and Cobban, 1973; and Campbell, 1973).

Cretaceous strata of western and northwestern New Mexico are several thousand feet thick and consist of a thick sequence of alternating lagoonal, estuarine, deltaic, littoral, and neritic sandstones with interbedded shales and siltstones, paludal coals and claystones, and continental fluvial and eolian sandstones, siltstones, and shales. These complexly interbedded and intertongued strata were deposited as shallow seas repeatedly transgressed westward from or retreated eastward to the Western Interior Seaway that by Late Cretaceous time, extended from the Arctic Ocean to the Gulf of Mexico (Kent, 1972; and McGookey, 1972). The San Juan structural basin as known today did not exist. Most probably the shoreline resembled that of the modern day northern coast of the Gulf of Mexico. Terrigenous clastics were supplied by streams draining highlands located to the west. Widespread layers of volcanic ash, present as bentonitic or kaolinitic beds within marine and transitional rocks, are indicative of igneous activity in the highland areas during the Cretaceous Period.

Among the Upper Cretaceous strata, the Gallup Sandstone, a basal sandstone in the Mesaverde Group, is one of the most dependable and productive aquifers in western and northwestern New Mexico and, as such, warrants particular attention. The Gallup Sandstone is a regressive sandstone deposited along a northwestward trending shoreline that was prograding northeastward into the Mancos sea. Coastal barrier strand plain or delta front sandstones of the Gallup Sandstone intertongue with and (or) grade seaward (northeastward) into offshore mudstones of the Mancos Shale and intertongue landward (northwestward) with the paludal mudstone, fluvial channel sandstones, and minor coalbeds of the lower part of the Mesaverde Group. The major facies, depositional environments and stratigraphic correlations of the Gallup Sandstone have been described in detail by Molenaar (1973 and 1974).

The Mesozoic Era closed as the Rocky Mountain region was broken into numerous individual basins associated with adjacent uplifts (Kent, 1972; and Robinson, 1972). Many of the present-day landforms including the Defiance, Zuni, Lucero, Nacimiento, and San Juan uplifts were probably shaped at this time. Other structural features related to this age of tectonism include the Defiance and Nutria monoclines, the Acoma and Gallup sags, the McCartys syncline, and the numerous other smaller flexures, folds, faults, and fractures present throughout western and northwestern New Mexico.

Volcanic activity increased concurrent with mountain building and, as a consequence, extrusive and (or) intrusive igneous rocks are often associated with the basin-filling continental sediments. The extensive volcanics of the Datil Formation on and south of the Mogollon slope, the Mount Taylor volcanic field, the numerous intrusive and extrusive volcanic rocks along the Rio Grande trough, and the dikes, sills, necks, and flows around the periphery of the San Juan basin were formed during late Tertiary and Quarternary time (Hunt, 1956, figs. 26, 33, and 37; and Hilpert, 1969, p. 30). The younger Pleistocene and Holocene volcanism near the southeastern end of the Zuni uplift in the vicinity of Grants may coincide with the latest regional upwarping of the Colorado Plateau.

Regional structure

Structural components

The areas evaluated are located along the southwestern margin of the San Juan basin in a region dominated by the Defiance and Zuni uplifts (fig. 2). The structural boundaries between the San Juan basin and the marginal Chaco slope and Gallup and Acoma sags are rather indistinct and arbitrarily placed for descriptive purposes (Kelley and Clinton, 1960, p. 21 and 76-80). The Mogollon slope forms the southern border of the Colorado Plateau and is adjacent to the Basin and Range province of Arizona and New Mexico. The present form of most of the structural components is Laramide or younger in age. However, the Zuni and Defiance uplifts are part of a much older regional structural lineament (Slawson and Austin, 1962, p. 26; and Kent, 1972).

Zuni uplift

The Zuni uplift is a southeasterly trending uplift located along the southern margin of the San Juan structural basin between Gallup and Grants. This doubly faulted plunging anticline is oval shaped and asymmetrical with the steeper flank on the southwest (Grose, 1972, fig. 4). On the northeastern flank, late Paleozoic and Mesozoic beds dip away from the Precambrian granite and metamorphic core at angles of only 3 to 10 degrees, while along the southwestern flank of the Zuni uplift they dip southwestward at angles of 5 to 20 degrees. The angle of westerly dip increases progressively northwestward along the Nutria monocline. Strata are in nearly vertical positions locally in the vicinity of Gallup (Edmonds, 1961; and Kelley and Clinton, 1960, p. 44). Mount Sedgwick with an altitude of 9,256 ft (2,281 m) is the highest point in the Zuni Mountains. Structural relief in the Zuni uplift is greater than 5,000 ft (1,525 m) (Fitzsimmons, 1959, p. 112). The Zuni uplift is highly faulted and has a complex structural history (Kelley and Clinton, 1960, p. 44; Kelley, 1965; and Goddard, 1966).

Defiance uplift

The Defiance uplift is a north-trending fold about 30 mi (50 km) wide and 100 mi (160 km) long located along the border between New Mexico and Arizona (fig. 2). The western margin of the San Juan basin in the vicinity of Gallup is determined by the position of the Defiance uplift. The steeply dipping, sinuous Defiance monocline on the eastern flank and staggered crestal axes of minor superimposed folds give an asymmetric shape to this anticlinorium (Kelley and Clinton, 1960, p. 42; and Kelley, 1965, p. 28). Chuska Peak, altitude 8,793 ft (2,680 m), is at the southern end of one of the larger folds within the Defiance uplift (Cooley, Harshbarger, Akers, and Hardt, p. A 26; and fig. 1). The structural relief along the eastern margin of the uplift is greater than 7,000 ft (2,135 m).

Gallup sag

The Gallup sag is a comparatively narrow elongate northward plunging syncline located between the Defiance and Zuni uplifts (Kelley, 1957; and Kelley and Clinton, 1960, p. 78). At the latitude of Gallup, the syncline is sharply defined on the east by the Nutria monocline and on the west by the Defiance monocline. The Gallup sag plunges northward at about 60 ft/mi (11 m/km) into the San Juan basin where it blends into the regional dip northeast of Newcomb. Similarly, the southernmost extension of the Gallup sag merges into the gently northward dipping strata on the Mogollon slope. Several small but sharply defined anticlinal and synclinal flexures near Gallup modify the otherwise simple structure of the Gallup sag.

Acoma sag

The asymmetrical Acoma sag (Kelley, 1951, p. 125) is bounded by the Zuni uplift and by the Lucero uplift and Puerco fault belt on the west and east, respectively (fig. 2). McCartys (Mount Taylor) syncline is located within the Acoma sag near the western margin. The northern end of the Acoma sag is arbitrarily placed at the northern end of the northward plunging McCartys syncline, the major structural trend within the Acoma sag. Similarly, the southern boundary of the Acoma sag is arbitrarily chosen north of several small anticlines and synclines on the Mogollon slope near the southern end of Mesa del Oro.

Mogollon slope

The Mogollon slope is located south of other structural components marginal to the San Juan basin in central-western New Mexico and north of the Basin and Range province (fig. 2). The boundary between the Mogollon slope and the Basin and Range province is obscured by thick accumulations of volcanics and sediments derived from the volcanics (Fitzsimmons, 1959, p. 114).

South of the Gallup and Acoma sags, the Mogollon slope has the appearance of a structural saddle between synclines to the north and rocks that dip southward into the Basin and Range province under a thick accumulation of volcanic rocks. The limited information available suggests that the Mogollon slope becomes a structural terrace intermediate between the steeply southwestward dipping beds on the southwest flank of the Zuni uplift and the Basin and Range province (Foster, 1957, p. 65, fig. 3; Bayley and Muehlberger, 1968; J. C. MacLachlan, and others, 1972; and King, 1969).

The Mogollon slope, or parts of it, influenced the distribution of sediments in central-western New Mexico during the early Paleozoic. Later, after foundering during the Permian, it became a primary source of Late Triassic and Jurassic terrigenous clastics (McKee, and others, 1956, pl. 8; Fitzsimmons, 1959, p. 115; and Stewart, Poole, and Wilson, 1972, p. 93 and 99.

Chaco slope

The Chaco slope, defined by Kelley, 1950, p. 102; and Kelley and Clinton, 1960, p. 76, is a crude rectangular area approximately 40 mi (65 km) wide extending in a southeasterly direction a distance of about 110 mi (175 km) between the Gallup sag and Defiance uplift to the west and the Acoma sag and Puerco fault belt on the east (fig. 2). The trend of the Chaco slope is parallel to the Zuni Mountains along the southern margin of the San Juan structural basin. Prevailing regional dips of rocks in the subsurface on the Chaco slope are about 1 degree to the north and (or) northeast. The position of the boundaries of the Chaco slope with adjacent structural components are placed primarily on slight changes in the dip of strata and are difficult to distinguish. The structural relief across the width of the Chaco slope is approximately 2,500 ft (760 m).

Faults and fractures

Episodic Laramide and post-Laramide differential uplift, local and regional warping, and normal faulting have produced the larger structural elements briefly described above, the numerous folds, flexures, faults, and an extensive fracture system present throughout central-western New Mexico. In addition to the late Mesozoic and Cenozoic tectonism, rocks in this general region were deformed previously by several intervals of pre-Laramide diastrophism. Events of major importance were: (1) post-Mississippian uplift of the ancestral Defiance and Zuni structures and removal of older Paleozoic rocks not removed previously as a result of earlier orogenies, (2) epeirogenic upwarping during Late Permian and Early Triassic time, and (3) northward tilting of an ancestral Zuni-Defiance region that includes the present Mogollon slope and Zuni uplifts during the Late Jurassic. Younger structures may have followed zones of weakness developed in the rocks during the earlier diastrophic events. However, most of the pre-Laramide joints and small folds, faults, and flexures have been hidden by a cover of Late Cretaceous and younger sedimentary and volcanic rocks.

Kelley and Clinton (1960) have analyzed and described the fracture and fault system of the Colorado Plateau in detail. Present-day and older geologic structures are one of several important factors controlling the general occurrence of ground water and deposition of secondary uranium minerals. Descriptions of the areally important structures are found in nearly all articles related to these subjects. Reports that contain descriptions and (or) the position of structural components that may be useful in future studies of the ground-water resources in central-western New Mexico include the following: Cooper and John, 1968; Berry, 1959; Gilkey, 1953; Gordon, 1961; Hilpert, 1969; Hunt, 1938; Kelley, 1950, 1951, 1955a, 1955b, 1957, 1963, and 1967; Mercer and Cooper, 1970; Moench and Schlee, 1967; Santos, 1970; Sears, 1925 and 1934; Sears, Hunt, and Dane, 1936; Shomaker, 1971; Slack, 1973; Slawson and Austin, 1962; Smith, 1954 and 1957; Stoehr, 1959; West, 1959 and 1972; and maps by Goddard, 1966; Green and Pierson, 1971; Moench, 1963a, 1963b, 1964a and 1964b; Moench and Puffett, 1963a and 1963b; Moench, Schlee, and Bryan, 1965; O'Sullivan and Beaumont, 1957; Santos 1966a and 1966b; Santos and Thaden, 1966; Schlee and Moench, 1963a and 1963b; Smith, 1958; Smith and others, 1958; Thaden and Ostling, 1967; Thaden, Merrin, and Raup, 1967; Thaden and Santos, 1963; Thaden, Santos, and Ostling, 1966 and 1967; and Thaden, Santos, and Raup, 1967.

A review of the literature indicates that the structural fabric in central-western New Mexico is dominated by northeastward and northwestward regional orientations of joints, flexures, folds, and monoclines. This relatively simple pattern is modified, interrupted, and otherwise complicated by structures with easterly or northerly trends. Kelley and Clinton (1960, p. 2, 88, and 96) postulate that the dominant structure alignments were developed during 2 phases of Laramide deformation. The northeasterly and northerly trending structures originated from stresses aligned in an easterly to southeasterly direction. The northwesterly trending folds and uplifts were formed in response to northeasterly oriented regional stresses. Laughlin, Brookins, and Causey (1972, p. 1544) refer to two principal structural lineaments that intersect in the vicinity of the southeastern end of the Zuni Mountains. One is a northwesterly trending lineament, defined by Slawson and Austin (1962), extending northwestward from a point southeast of the Sacramento Mountains in southern New Mexico through the Zuni Mountains into northwestern Utah. The other, a northeasterly trending lineament, is presumably delineated by a line of Tertiary and Quaternary volcanic rocks extending northeastward from a volcanic center in central-eastern Arizona through the Mount Taylor volcanic region to the volcanic rocks in the vicinity of Taos and Raton, N. Mex., and Trinidad, Colo. (Cohee, 1962).

The northwesterly trending structural grain parallel to the Zuni Mountains is superimposed on a less emphatically defined north-south alignment of the Defiance uplift (Kelley and Clinton, 1960, fig. 2). The Zuni and Defiance uplifts are apparently related to geologically very old features that, at various times, either controlled sedimentation or were sources of sediment. A pronounced nonconformity separates Permian and (or) Pennsylvanian sedimentary rocks from the underlying Precambrian igneous and metamorphic complexes in both uplifts.

The area most disturbed by faulting and fracturing in central-western New Mexico is located immediately east and northeast of the Zuni uplift (Kelley and Clinton, 1960, fig. 7). The fault pattern north and northwest of Grants is both semi-radial and tangential to the principal northwesterly trend of the Zuni uplift. Nearly all of the faults are normal. Vertical displacement along most of the faults is relatively small; however, several of the larger faults may have as much as several hundred feet of throw and can be traced for tens of miles.

Outside of a few local areas, the influence of the well developed regional joint pattern and the numerous faults and folds on the occurrence of ground water is still unknown. Potential aquifers of Mesozoic age generally contain abundant clay minerals. Therefore, the well developed fractures observed at the surface would be normally expected to be "healed" at depth and the hydralulic conductivity diminished correspondingly. Flows of water from fractures in the Jurassic Westwater Canyon Member of the Morrison Formation observed by the author in actively mined stopes in an uranium mine approximately 1,400 ft (425 m) below the regional potentiometric surface were only a few gpm, suggesting that this premise may be valid for this area. Ground water moving through the San Andres Limestone has probably enlarged openings along fractures and faults cutting the soluble carbonate rock. An analysis of both pre-Laramide as well as Laramide and younger fault and fracture systems could be an important exploration tool to use in locating supplies of ground water in the San Andres Limestone.

Geohydrology of selected areas

Gallup-Tohatchi-Church Rock

The Gallup-Tohatchi-Church Rock area includes approximately 1,300 mi^2 (3,365 km^2) in northwestern McKinley County, New Mexico (fig. 1). The city of Gallup is located in the central-southern part of the area. The settlement of Tohatchi is located a few miles west of Highway 666 in the central-northern section of the area. The community of Church Rock is situated about 8 mi (13 km) east of Gallup immediately north of Highway 66 (Interstate 40). The Church Rock uranium mining district is located near Pinedale about 10 mi (16 km) northeast of Church Rock (fig. 1). The arbitrarily placed boundaries of the Gallup-Tohatchi-Church Rock area includes part of the Navajo Indian Reservation. A large amount of land outside of the Navajo Reservation but within the designated Gallup-Tohatchi-Church Rock area is also owned by the Navajo Tribe. Fort Wingate is located in the southeastern part of the area.

The Gallup-Tohatchi-Church Rock area lies almost entirely within the Navajo section of the Colorado Plateau province of Fenneman (1931 and 1962). Late Cenozoic erosion of sequences of alternating resistant sandstones and soft easily eroded shales has produced a landscape of moderate relief composed of benches, mesas, buttes, and cuestas. Altitudes range from more than 8,700 ft (2,650 m) in the Chuska Mountains on the northwest to less than 6,000 ft (1,830 m) in the bottom of the ephemeral washes northeast of Tohatchi (fig. 1). Although the area is devoid of perennial streams, many of the arroyos carry large flows of water during infrequent intense storms. The southern part of the area is drained by the ephemeral Puerco River or tributaries to this stream. Most of the northern part of the area is drained by normally dry washes tributary to the ephemeral Chaco River. Many of the small valleys were partly filled with clay, silt, and fine sand during a previous geomorphic regimen. Many of the present channels are deeply entrenched in the older alluvium (Cooper and Mercer, 1970, p. 29).

The Gallup-Tohatchi-Church Rock area is located at the junction of several elements marginal to the San Juan structural basin (fig. 2). Most of the area falls within the Gallup sag or on the Chaco slope. The Zuni uplift projects into the area from the southeast. East of Gallup, the steeply dipping Jurassic and Cretaceous strata on the Nutria monocline, the structural zone intermediate between the Gallup sag and the Zuni uplift, are referred to locally as the "Hogback" (fig. 3). The axis of the northward plunging Gallup sag trends northerly passing through the area a few miles west of Gallup and parallels Highway 666 (Kelley, 1967; and Cooper and Mercer, 1970, fig. 7). Structural relief on top of the Gallup Sandstone along the axis of the Gallup sag between Gallup and Tohatchi is approximately 1,400 ft (425 m) (Cooper and Mercer, 1970, fig. 7). At a distance of a few miles from the axes of the Gallup sag and the Zuni uplift, the prevailing regional dip is to the northeast into the center of the San Juan basin at inclinations generally less than 5 degrees. Chapman, Wood, and Griswold, Inc. (1974, sheet 1) has mapped two subparallel faults trending northeastward through the Church Rock mining district. The longest fault, referred to locally as the "Pipeline fault," extends from sec. 4, T.15 N., R.17 W. to projected sec. 16, T.17 N., R.15 W., a distance of approximately 15 miles (25 km). The magnitude and direction of displacement along the "Pipeline fault" is unknown. Other faulting noted on geologic maps of the area is relatively minor in comparison.

Sedimentary rocks ranging in age from Permian to Quarternary are exposed at the north end of the Zuni Mountains. Mesozoic strata form a prominent cuesta that extends eastward from Rehobeth to beyond Coolidge on the north side of Highway 66 (Interstate 40) at the eastern edge of the area. Upper Cretaceous rocks are exposed over most of the area in gentle cuestas and strike valleys. The entire Mesozoic section is exposed in a steeply eastward dipping section along the Defiance monocline and in the Defiance uplift in the northwestern part of the area. In the Chuska Mountains, more than 1,000 ft (305 m) of Upper Tertiary Chuska Sandstone rests unconformably on the Mesozoic rocks (Harshbarger and Repenning, 1954). A few scattered Tertiary intrusions have been mapped west of Chuska Peak in the extreme northwestern part of the area (fig. 3).

The Permian San Andres-Glorieta aquifer thins to less than 200 ft (61 m) north of Gallup. In addition, the carbonate facies, the most productive part of the aquifer, wedges out in northern McKinley County (Baars, 1962, figs. 17 and 18). Depths to the San Andres-Glorieta aquifer will range from about 3,500 ft (1,060 m) near Gallup to more than 5,300 ft (1,615 m) north of Tohatchi. The depth, generally low transmissivity, and expected high concentrations of dissolved solids eliminates the San Andres-Glorieta aquifer as a potential source of water for municipal use in this area.

In general, rocks older than the Jurassic Westwater Canyon Member of the Morrison Formation are not considered to be capable of yielding the desired quantity and quality of water.

More than 7,000 ft (2,135 m) of sedimentary rocks ranging in age from Permian through Quaternary are present in the northern part of the area. "Granite wash" and Precambrian metamorphic rocks were penetrated at depths of 6,898 ft (2,103 m) and 7,053 ft (2,150 m), respectively, in an oil test well drilled in sec. 29, T.19 N., R.17 W. At the time of abandonment, the test well was plugged back to a depth of 2,500 ft (760 m) and converted to a water well. Water flows from the Gallup Sandstone and Dakota Sandstone and Westwater Canyon Member of the Morrison Formation in this well under artesian pressure at a reported rate of approximately 750 gpm (50 l/s) (Cooper and Mercer, 1970, table 2). Water from the combined aquifers contains less than 400 mg/l dissolved solids. The major constituents are sodium, bicarbonate, and sulfate as is typical of water from the Mesozoic rocks in this area. Undesirable quantities of dissolved iron, frequently found in water produced from the same aquifers in other nearby localities, are not present in this well (Cooper and Mercer, 1970, table 6).

The Gallup, Dakota, and Westwater Canyon aquifers have been considered by many investigators to be the principal sources of relatively large amounts of water for this general area. As part of a continuing investigation of the water resources of the Gallup area, the city of Gallup, the New Mexico State Engineer, and the U.S. Geological Survey cooperated in evaluating the potential of the Cow Springs Sandstone, the Westwater Canyon Member of the Morrison Formation, the Dakota Sandstone, and the Gallup Sandstone in the Gallup-Tohatchi area during 1967-69, inclusive. The results of this areal study, including the drilling and testing of the Muñoz 1 and Muñoz 1A exploratory wells in sec. 17, T.16 N., R.18 W., have been reported by Cooper and Mercer (1970). The Muñoz 1A test well is now part of the Yah-ta-hey well field, a major source of the municipal water supply for the city of Gallup.

The deepest aquifer tested in the Muñoz 1 well, the Cow Springs Sandstone, yielded less than 2 gpm (.1 l/s) of water containing in excess of 3,000 mg/l dissolved solids. The test confirmed earlier regional assessments of the potential of this unit (Cooper and Mercer, 1970, p. 47).

The Westwater Canyon Member and the Dakota Sandstone are approximately 190 ft (60 m) and 160 ft (50 m) thick in the Muñoz wells, respectively. The Westwater Canyon Member and the Dakota Sandstone are hydraulically connected in the vicinity of Gallup. A few miles farther to the east, they become separated by the eastward-thickening Brushy Basin Shale Member of the Morrison Formation (Marvin, 1967, fig. 1; and Kittel, Kelley, and Melancon, 1967, fig. 2).

The Westwater Canyon Member yielded water containing 800 to 1,100 mg/l dissolved solids (Cooper and Mercer, 1970, p. 29 and table 5). The dissolved-solids content of the water produced from the Dakota Sandstone in the Muñoz 1 well ranged from 666 to 1,050 mg/l. In addition to high concentrations of sodium, bicarbonate, and sulfate, the water contained more than 33 mg/l of dissolved iron (Cooper and Mercer, 1970, p. 52 and table 5). After several years of production, the Muñoz 1A well was subsequently plugged back to the base of the Gallup Sandstone in a partially successful attempt to reduce the content of dissolved iron in the water supply.

The combined yield from the Westwater Canyon Member and the Dakota Sandstone was less than 100 gpm (6 l/s). The aquifer characteristics of the Gallup Sandstone (including the Dalton Sandstone Member of the Crevasse Canyon Formtion), the Dakota Sandstone, and the Westwater Canyon Member of the Morrison Formation were evaluated as one unit, the "multiaquifer system" of Cooper and Mercer (1970, p.83), in the Muñoz 1A well in the Yah-ta-hey well field. The transmissivity of the "multiaquifer system" was determined to range between 250 and 296 ft^2/d (23 to 27 m^2/d). The storage coefficient was computed to be 3.1×10^{-3} (Cooper and Mercer, 1970, p. 90). Mercer and Lappala (1972, p. 19-23) computed transmissivity values ranging from 145 ft^2/d to 350 ft^2/d (13 to 33 m^2/d) for the Dalton and Gallup aquifers combined in the city of Gallup Erwin 1 well, sec. 7, T.16 N., R.18 W., about 1.5 mi (2.4 km) west of the Muñoz 1A well. The storage coefficient for the combined Dalton and Gallup aquifers in the Erwin 1 well was determined to be 3.0×10^{-5}.

The Gallup Sandstone, the most productive aquifer in the Gallup-Tohatchi-Church Rock area, is currently the major source of water for the city of Gallup. The Gallup Sandstone varies from less than 200 ft (60 m) to more than 500 ft (150 m) in thickness (Molenaar, 1973 and 1974). Approximately 515 ft (160 m) of the section penetrated in the Muñoz 1 well was assigned to the Gallup Sandstone by Cooper and Mercer (1970, p. 55). However, Mercer and Lappala (1972, p. 12) subsequently reassigned the upper part of the Gallup Sandstone in the Muñoz 1 well to the overlying Dalton Sandstone Member of the Crevasse Canyon Formation, thus reducing the thickness of the Gallup Sandstone to about 360 ft (110 m).

The Gallup Sandstone crops out in the city of Gallup where it forms narrow, steeply dipping ridges along the Nutria monocline (the "Hogback") east of Gallup. The Gallup Sandstone is also exposed along the east margin of the Defiance uplift west and northwest of the city. Depths to the top of the Gallup aquifer range from about 1,700 ft (520 m) in the Yah-ta-hey well field about 6 mi (10 km) north of Gallup to approximately 1,200 ft (365 m) in the northeastern part of the area east of Tohatchi.

The Gallup Sandstone, together with the overlying Dalton Sandstone Member of the Crevasse Canyon Formation, constitutes the most productive aquifer system in close proximity to the city of Gallup. Information from uranium test wells and the existing stock and domestic wells inventoried by Cooper and Mercer (1970, table 2) suggest that the yields of approximately 800 gpm (50 l/s) measured in the Yah-ta-hey well field are typical of the production rates to be expected from this aquifer system north and east of Gallup in the Gallup-Tohatchi-Church Rock area. The water produced from the Gallup and Dalton aquifers in the Yah-ta-hey well field contains from 400 to nearly 2,200 mg/l of dissolved solids. Water containing less than 1,000 mg/l dissolved solids should be available from the Gallup and Dalton aquifers nearly everywhere within the area provided care in the selection of the productive zones is exercised.

The Grants mineral belt extends northwestward from the Smith Lake, Ambrosia Lake, and Laguna mining districts into the Church Rock mining district located in the southeastern part of the Gallup-Tohatchi-Church Rock area (fig. 1). Sandstones of the Westwater Canyon Member of the Morrison Formation are the principal host rock for uranium in the Church Rock mining district. The Westwater Canyon Member is approximately 300 ft (90 m) thick in the vicinity of Church Rock. The thickness of the Dakota Sandstone varies from 70 ft (20 m) to 200 ft (60 m) depending on the placement of the boundary between the Dakota and the overlying Mancos Shale. The Dakota Sandstone and Westwater Canyon Member are separated by less than 75 ft (25 m) of interbedded shale, sandstone and siltstone of the Brushy Basin Member of the Morrison Formation. The Westwater Canyon Member is probably in hydraulic communication with the Dakota Sandstone and the sandstone beds in the lower part of the Mancos Shale. At least some of the uranium ore bodies are localized along the northeast-trending "Pipeline" fault (Hazlett, 1969; and Chapmand, Wood and Griswold, Inc., 1974, sheet 1). The influence of the "Pipeline" fault and other faults and fractures on the hydrology of this area is unknown. Very small amounts of water were observed flowing from fractures in the United Nuclear Northeast Church Rock mine, sec. 35, T.17 N., R.16 N., situated about 1,400 ft (425 m) below the potentiometric surface. However, the effect of the hydraulic communication between aquifers on a regional scale in relation to the pumping of water from a local area may be of some significance to the occurrence of ground water in this area.

During the mining of ore from the Westwater Canyon Member, "long-holes" are drilled at the end of newly driven stopes, haulageways, or drifts to explore for and define the ore body and to drain the ground water from the rock. Removal of the water from the sandstone facilitates stoping and greatly increases the strength of the rock (Gay, 1963, pp. 245 and 246; and Hohne, 1963, p. 247). Gay (1963, p. 245) reports that, in the "Grants district," "ground-water flowage gradually declines in most mines to less than one-third of the maximum amount as development nears completion." A diminished yield over a period of time should be expected to occur in this manner in a horizontal drain.

Approximately 3,000 gpm (190 l/s) of ground water is now being pumped from the Westwater Canyon aquifer in two uranium mines located in sec. 35, T.17 N., R.16 W., about 12 mi (20 km) northeast of Gallup in the Church Rock mining district. The water generally contains less than 400 mg/l dissolved solids; sodium and bicarbonate are the most abundant constituents. Except for the content of dissolved uranium, the waste water is of much better quality than the water now produced from the Cretaceous aquifers near Gallup (table 2).

Table 2.--Dissolved and suspended chemical constituents in water from uranium mines and wells in the vicinity of Church Rock, McKinley and San Juan Counties, New Mexico

Sample number	Name of well or mine	Location	Aquifer	Depth of producing interval or sampling point from land surface in metres (feet): Top	Depth of producing interval or sampling point from land surface in metres (feet): Bottom	Date (year, month, day)	Time of day (2400 clock)	Yield estimated l/s (gpm)	Source of water
1	Continental Oil Company Crownpoint Water Well 1	NW¼NW¼ sec.20 T.17 N., R.12 W.	Westwater Canyon Member, Morrison Formation (Jurassic)	654 (2,145)	714 (2,341)	74- 6- 8	1610	11 (180)	Well head
2	United Nuclear Corporation Northeast Church Rock well	NW¼SE¼ sec.35, T.17 N., R.16 W.	do.	472 (1,550)	503 (1,650)	71- 3-23	1430	1.25 (20)	Domestic and industrial water supply well
3	do.	NW¼SE¼ sec.35, T.17 N., R.16 W.	do.	472 (1,550)	503 (1,650)	71- 3-23	1430	1.25 (20)	do.
4	United Nuclear Corporation Northeast Church Rock mine	NW¼SE¼ sec.35, T.17 N., R.16 W.	do.	442 (1,450	457 (1,500)	71- 3-23	1545	< .06 (<1)	Mine seepage collected in mine
5	do.	NW¼SE¼ sec.35, T.17 N., R.16 W.	do.		457 (1,500)	73-11-13	1000	.06 (1)	do.
6	do.	NW¼SE¼ sec.35, T.17 N., R.16 W.	do.		518 (1,700)	73-11-13	1100	.09 (1.5)	do.
7	do.	NW¼SE¼ sec.35, T.17 N., R.16 W.	do.	457 (1,500)	549 (1,800)	73-11-13	1500	126 (2,000)	Seepage effluent pumped from mine shaft
8	Kerr McGee Corporation Sec. 35 Church Rock mine	NW¼NE¼ sec.35, T.17 N., R.16 W.	do.		549 (1,800)	73-11-13	1600	95 (1,500)	do.
9	El Paso Natural Gas Company Burnham Gasification Water Supply Well 1	NE¼SW¼ sec.3, 1/ T.23 N., R.14 W.	do.	1,518 (4,980)	1,585 (5,200)	73- 8-27	1430	22 (350)	Flow from well head

Sample number	Silica dissolved (SiO_2) mg/l	Iron dissolved (Fe) mg/l	Manganese dissolved (Mn) mg/l	Calcium dissolved (Ca) mg/l	Magnesium dissolved (Mg) mg/l	Sodium dissolved (Na) mg/l	Potassium dissolved (K) mg/l	Bicarbonate dissolved (HCO_3) mg/l	Carbonate dissolved (CO_3) mg/l	Carbon dioxide dissolved (CO_2) mg/l	Alkalinity as $CaCO_3$, Total mg/l	Sulphate dissolved (SO_4) mg/l	Chloride dissolved (Cl) mg/l
1	18	0.0	-	1.9	0.0	120	1.1	244	12	0.5	220	55	5.3
2	-	-	-	-	-	-	-	218	24	-	-	35	3.6
3	15	.50	0.02	2.0	2.6	110	0.7	216	37	-	143	32	3.5
4	-	-	-	-	-	-	-	-	-	-	-	38	-
5	15	.01	0	2.1	0.0	120	1.1	223	25	.3	225	33	4.8
6	16	.04	0	2.4	.0	110	.7	201	32	.3	218	32	2.5
7	17	.02	0	2.2	.3	120	1.4	215	31	.3	228	45	5.2
8	17	.02	0	11	8.4	130	1.6	220	21	.4	215	110	3.6
9	43	.01	.16	39	.5	250	2.5	166	0	2.1	136	490	17

Table 2.--Dissolved and suspended chemical constituents in water from uranium mines and wells in the vicinity of Church Rock, McKinley and San Juan Counties, New Mexico - Continued

Sample number	Fluoride dissolved (F) mg/l	Nitrite + Nitrate dissolved as N mg/l	Phosphorous dissolved orthophosphate as P mg/l	Orthophosphate dissolved (PO_4) mg/l	Residue Total dissolved solids calculated from sum of determined constituents mg/l	Residue Total dissolved solids calculated from sum of determined constituents T/ac-ft	Hardness dissolved as $CaCO_3$ (Ca,Mg) mg/l	Noncarbonate hardness dissolved mg/l	Percent sodium %	Sodium adsorption ratio (SAR)	Specific conductance, micromhos at 25°C
1	0.3	0.05	0.13	0.40	334 345[2/]	0.47	4	0	98	25	545
2	-	-	-	-	-	-	-	-	-	-	513
3	.6	.1	.02	.06	326[2/] 310	-	16	0	94	12	499
4	-	-	-	-	-	-	-	-	-	-	503
5	.2	.08	.03	.09	312	0.42	5	0	98	23	508
6	.2	.33	.03	.09	296	.40	6	0	97	20	493
7	.2	.21	.04	.12	329	.45	7	0	97	20	550
8	.3	.18	.03	.09	412	.56	62	0	82	7.2	663
9	1.0	.03	.14	.43	925	1.26	99	0	84	11	1,390

Sample number	pH	Water temperature °C	Density at 20°C	Alpha gross dissolved as U natural µg/l	Alpha gross suspended as U natural µg/l	Beta gross dissolved as Cs 137 pCi/l	Beta gross suspended as Cs 137 pCi/l	Beta gross dissolved as Sr^{90}/Y^{90} pCi/l	Beta gross suspended as Sr^{90}/Y^{90} pCi/l	Radium-226 dissolved radon method (Ra^{226}) pCi/l	Uranium natural dissolved (U) µg/l	Residue total filtrable mg/l	Residue total non-filtrable mg/l	Latitude	Longitude
1	8.9	37	-	<5.4	3.7	3.0	2.5	2.4	2.0	0.05	<0.4	360	60	35°41'34"N	108°08'23"W
2	9.0	-	-	-	-	-	-	-	-	-	-	-	-	35°39'26"N	108°30'28"W
3	8.8	-	-	-	-	-	-	-	-	-	-	-	-	35°39'26"N	108°30'28"W
4	-	-	-	-	-	-	-	-	-	-	-	-	-	35°39'26"N	108°30'28"W
5	9.1	-	-	1,070	.8	57	4.4	48	4.1	.62	264	420	3	35°38'26"N	108°30'28"W
6	9.2	-	-	110	< .4	12	.9	9.6	.8	.09	31	300	<1	35°39'26"N	108°38'28"W
7	9.2	-	-	2,000	3,000	150	1,100	120	860	8.1	1,210	340	490	35°39'26"N	108°30'28"W
8	9.0	-	-	-	-	-	-	-	-	-	-	-	-	35°39'30"N	108°30'27"W
9	8.1	61	-	<9.3	< .4	3.9	< .4	4.8	< .4	.24	.07	880	1	36°15'28"N	108°19'22"W

Table 2.--Dissolved and suspended chemical constituents in water from uranium mines and wells in the vicinity of Church Rock, McKinley and San Juan Counties, New Mexico - Concluded

Sample number	Remarks
1	Collected by J. W. Shomaker during pump test of newly completed well. Static water level, 103 m (338 ft) from land surface. Boron, 70 µg/l. Dissolved uranium by fluorometric extraction, 0.09 µg/l. Land surface datum estimated to be 2,096 m (6,875 ft) above mean sea level.
2 and 3	Collected by W. A. Mourant from tap in washroom near mine shaft. Well drilled and completed December 1967. Casing with 0.121 m (4.75 in) inside diameter was set to depth of 503 m (1,650 ft). Lowermost 30 m (100 ft) has torch-cut slots. Casing not cemented. Water from Dakota Sandstone and other aquifers may be commingled with water from the Westwater Canyon Member. The well ie equipped with an oilfield type cylinder pump operated by a pump jack with a 25 horsepower electric motor. Pump is set at 486 m (1,596 ft), has a 0.8 m (32 in) stroke, and yields 1.26 l/s (20 gpm) when the leathers are good. Initial water level was 122 m (400 ft) below land surface when drilled in December 1967 and was 274 m (900 ft) below land surface in January 1969--the last time that the pump was removed for maintenance. Storage is provided by two 38 m^3 (10,000 gal) metal tanks and flows by gravity through plastic and galvanized pipes to the buildings and trailers. The water is not treated prior to consumption.
4	Collected by W. A. Mourant from seepage from roof of "549 m" ("1,800 ft") drift at 457 m (1,500 ft) level. Sandstone is well fractured and friable. Most water was entering mine workings around roof rock bolts but there were also numerous flows of about 0.13 l/s (2 gpm) issuing from fractures in the sandstone.
5	Collected by W. L. Hiss from a drill hole at end of C-3 drift about 610 m (2,000 ft) southwest of the mine shaft. Near station 15-205+48 ft. Water clear.
6	Collected by W. L. Hiss from a drill hole near No. 1 vent hole in A-1 drift. Water clear.
7	Collected by W. L. Hiss from end of waste water discharge line at settling pond. Water had gray color and was very turbid. Mild clay odor. Suspended solids reported to be unusually high due to included muck from air shaft being driven.
8	Collected by W. L. Hiss from end of sump discharge line. Water was clear with no odor. Mine shaft completed but active mining had not yet commenced.
9	Collected by W. L. Hiss and J. W. Shomaker. Well was allowed to flow at about 22 l/s (350 gpm) for several hours prior to collecting the sample. Land surface datum 1,751 m (5,746 ft) above mean sea level.

1/ Projected section, township, and range.
2/ Total dissolved solids determined by evaporation at 180°C.

The waste water now is pumped to the land surface and into settling ponds. After most of the suspended particulate material has precipitated, the water is allowed to flow from the ponds into normally dry arroyos that are tributaries of the Rio Puerco. A uranium mill reportedly will be constructed in the same area in the near future and will utilize some of the waste water in processing ore. However, another mine will be sunk in a nearby area in the near future. Waste water will also be pumped from this mine and other mines that may be sunk in this area and contribute to the total available water that could possibly be salvaged. Ownership and availability of the waste water is uncertain and probably is a matter of small concern to be resolved before the water could be put to beneficial use.

An abandoned uranium mine, also completed in the Westwater Canyon Member, is located about 8 mi (15 km) northeast of Gallup near a paved road, a natural gas pipeline right-of-way, and high voltage electrical power lines. Periodic measurements of the water level in the shaft of this abandoned mine were made for several years by personnel from United Nuclear Corp. Subsequently, a continuous water-level recording instrument was installed by the U.S. Geological Survey in order to monitor the long-term effects of pumping on the aquifer (fig. 4). The head in the Westwater Canyon aquifer has declined at a rate of approximately 1.85 ft/mo (0.56 m/mo) indicating the reduction in the hydraulic head caused by dewatering of the active mines in the Church Rock mining district. Substantial quantities of water might also be produced from this abandoned mine for use by the city of Gallup if the rights to this resource could be obtained.

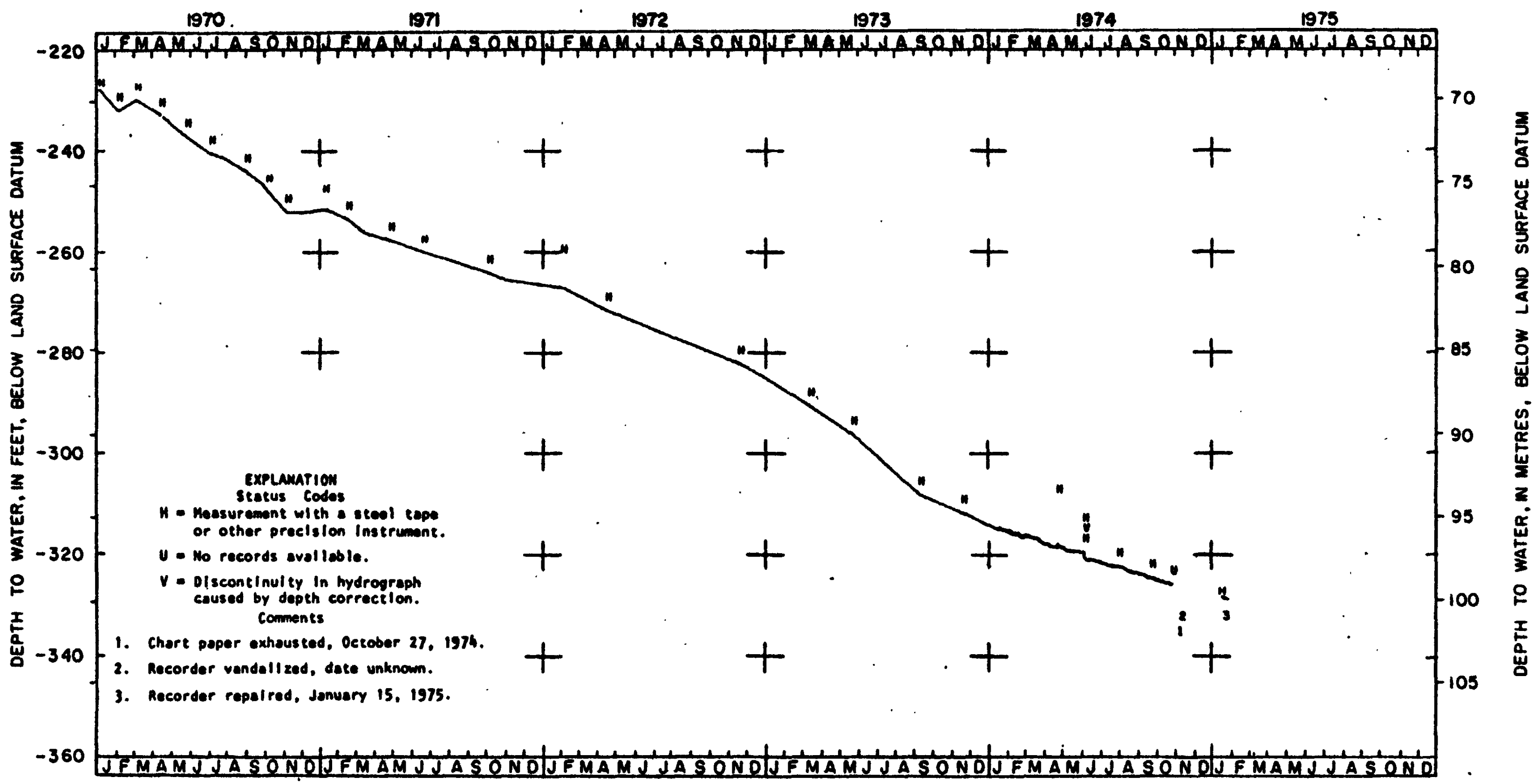

Figure 4.--The water level observed in the shaft of the abandoned United Nuclear Corp. Northeast Church Rock Mine, SE¼NW¼NE¼ sec. 17, T.16 N., R.16 W., McKinley County, New Mexico. [Water level prior to start of dewatering in October 1968 during sinking of new uranium mine shaft in sec. 35, T.17 N., R.16 W. reported to be 144 ft (44 m). Water level measured from land surface datum estimated from a topographic map to be 6,810 ft (2,076 m).]

Zuni Southwest

An area encompassing approximately 1,050 mi^2 (2,750 km^2) oriented in a northwesterly direction parallel to the axis of the Zuni Mountains in southwestern McKinley and northwestern Valencia Counties, New Mexico, is referred to as the Zuni Southwest area for purposes of this report. The Zuni Southwest northern boundary is located about 6 mi (10 km) south of Gallup and is common with the southern boundary of the Gallup-Tohatchi-Church Rock area. The southwestern boundary adjoins the northwestern boundary of the North Plains-Malpais area, approximately 55 mi (90 km) southeast of Gallup. The northeastern boundary trends subparallel to the outcrop of the Paleozoic rocks along the southwestern flank of the Zuni Mountains. The position of the southwestern boundary was chosen arbitrarily at a distance far enough southwest of the Zuni Mountains so as to include most of the Gallup Sandstone west of the axis of the Gallup sag.

Altitudes within the area range from 6,400 ft (1,950 m) near Manuelito along the Puerco River to above 8,000 ft (2,350 m) along the Zuni Mountains northeast of Ramah (fig. 1). The southeastern boundary is located along the Continental Divide at altitudes of approximately 7,700 ft (2,345 m). Thinly vegetated cuestas, mesas, and buttes dominate the terrain in the southeastern part of the area where local relief frequently exceeds 500 ft (150 m). The landscape is much more subdued in the northern part of the area. The ephemeral Whitewater Arroyo and Rio Pescado head in the uplands near the Zuni Mountains and flow to the west or west-southwest to join larger tributaries of the Little Colorado River.

Much of the land is within the Zuni and (or) Navajo Ramah Indian Reservations. Additional land near or contiguous with the reservations have been acquired by either the Zuni or Navajo tribes. A small amount of land near the Zuni Mountains is within the Cibola National Forest.

Structurally, the area is situated on the west flank of the Zuni uplift and northern edge of the Mogollon slope (fig. 2). The asymmetrical, north-plunging axis of the Gallup sag is aligned subparallel to the Zuni uplift approximately 6 mi (10 km) from the eastern edge of the area. Minor anticlinal folds located near the northern and southeastern ends of the Zuni Southwest area complicate an otherwise simple structural pattern (Kelley, 1967).

Rocks ranging in age from Permian to Cretaceous are exposed in the steeply dipping strata uplifted along the southwestern flank of the Zuni Mountains. These strata attain a maximum thickness of approximately 5,000 ft (1,525 m) along the axis of the Gallup sag. Jurassic and Upper Cretaceous rocks outcrop over much of the Zuni Southwest area (fig. 3). Upper Tertiary terrigenous clastics blanket the Upper Cretaceous and Mesozoic strata in the vicinity of Cheechilgeetho. Quaternary basalts have spilled over the Continental Divide and covered alluvium in formerly active streams.

Much of the geology is similar to that described in more detail in the sections on the North Plains-Malpais or Gallup-Tohatchi-Church Rock areas.

Rocks older than the Permian Glorieta Sandstone probably contain water much too highly mineralized for human consumption. The Glorieta Sandstone and the hydraulically connected San Andres Limestone overlying it have a combined thickness of approximately 500 ft (150 m) near Ramah. The San Andres Limestone thins markedly to the north and is only about 100 ft (30 m) thick in the vicinity of Gallup (Baars, 1962, fig. 18). The thickness of the Glorieta Sandstone varies from 200 (60 m) to 300 ft (90 m) within the Zuni Southwest area (Baars, 1962, fig. 17).

Water produced from the Ramah Mutual Help Water Supply Well in sec. 17, T.10 N., R.15 W., Valencia County, completed by the U.S. Public Health Service, contains approximately 400 mg/l dissolved solids. The mineral content of the water in the San Andres-Glorieta aquifer will increase with distance from the outcrop in the Zuni Mountains. Water produced from this aquifer generally will contain 500 to 1,000 mg/l dissolved solids with calcium, sodium, bicarbonate, and sulfate being the most abundant constituents. Undesirable quantities of iron usually will be present.

Wells completed in the San Andres-Glorieta aquifer in the Zuni Southwest area will probably yield about 100 gpm (6 l/s). Artificial stimulation of the wells should increase the yield, possibly to as much as 400 gpm (25 l/s). A karstic topography similar to that found on the San Andres paleo-surface in the Zuni Mountains probably is present in the subsurface northeast of the axis of the Gallup sag. The transmissivity of the San Andres may have been either increased or decreased locally due to the effect of solution, depending on whether or not the cavities have been filled by younger sedimentary material--chiefly terrigenous clastics from the Chinle Formation.

The depth to the San Andres-Glorieta aquifer from the land surface differs widely from place to place because of the structural and topographic configuration of the area. The San Andres Limestone was penetrated in wells located in sec. 35, T.11 N., R.19 W., sec. 27, T.8 N., R.15 W., and sec. 17, T.10 N., R.15 W., at depths of 871 ft (265 m), 3,140 ft (955 m) and 2,596 ft (790 m), respectively.

At the north end of the Zuni Southwest area the San Andres-Glorieta aquifer has not been evaluated. An oil-test well drilled in sec. 19, T.15 N., R.19 W., about 8 mi (13 km) west of Gallup, penetrated the Glorieta Sandstone at a depth of about 3,485 ft (1,060 m). A drill-stem test of the Glorieta Sandstone indicated that the hydraulic conductivity of this aquifer at this locality is very low. Wells tapping zhe San Andres-Glorieta aquifer in the vicinity of Pinehaven will probably yield approximately 100 gpm (6 l/s) of water containing about 500 mg/l of dissolved solids. Fracturing of the aquifer by local flexures and movement along the Nutria Monocline may have enhanced the transmissivity locally.

The Sonsela Sandstone Bed in the Petrified Forest Member of the Chinle Formation, the Wingate Sandstone, and the Cow Springs Sandstone yield small quantities of water of generally marginal to unsuitable quality. These aquifers are tapped locally for both domestic and stock supplies, but will not yield water of suitable quality in sufficient quantities to be considered as a source of water for municipal use.

The Westwater Canyon Member of the Morrison Formation thins southward to extinction along a line extending through Pinehaven and Manuelito (Saucier, 1967, fig. 2) and, therefore, cannot be considered as a source of water in the Zuni Southwest area.

Both the Dakota Sandstone and Gallup Sandstone either outcrop or are found at shallow depths over much of the Zuni Southwest area. The Gallup and Dakota aquifers are locally important sources of ground water for domestic and stock use. Yields from wells tapping these aquifers on (or near) the Ramah Navajo Indian Reservation reported by Dewilde (1971, table 2) are relatively low and range from 10 to 25 gpm (.6 to 2 l/s). The water quality generally is good, with dissolved solids usually less than 500 mg/l.

Many wells drilled near the outcrops of the Dakota and Gallup aquifers are dry or yield only small amounts of water. Selection of well sites where geohydrologic conditions are more favorable and the use of improved drilling and well construction practices probably would enhance the yield of wells that tap these two aquifers. Properly completed wells tapping the Gallup and Dakota aquifers in the Gallup sag south of Gallup should yield 100 to 300 gpm (6 to 20 l/s) of water containing 500 to 1,500 mg/l of dissolved solids. The water may, however, also contain undesirably high concentrations of dissolved iron.

Depths to the two aquifers in the northern part of the Zuni Southwest area vary widely. The Gallup is commonly found at depths of 300 to 500 ft (90 to 150 m) or less. The Dakota and Gallup aquifers are separated by approximately 700 ft (215 m) of Mancos Shale. The city of Gallup now produces water from the Gallup Sandstone from wells drilled in and near the city (West, 1957, 1959, and 1961a). Wells tapping the Gallup and Dakota aquifers in the Gallup sag south of the Gallup are potentially important large sources of ground water.

North Plains-Malpais area

The North Plains-Malpais area includes approximately 700 mi^2 (1,815 km^2) of sparsely inhabited ranch land situated south of the southern end of the Zuni Mountains in central Valencia and northern Catron Counties, New Mexico (fig. 1). The area is bounded on the northwest, west, and southwest by the Continental Divide. The southern boundary has been arbitrarily placed near the southern limit of the North Plains. The eastern boundary is parallel to State Highway 117 and western slopes of the uplands and mesas along the western boundary of the Acoma Indian Reservation. The northern terminus of the North Plains-Malpais area abuts the southern boundary of the Grants-Bluewater area. The city of Gallup is located about 60 miles (95 km) to the northwest. A proposal has been made to include the northeastern part of the area within the National Park System as a national monument (National Park Service, 1969, p. 29). However, this part of the area is now apparently managed by the Bureau of Land Management as an Outstanding National Area under the Classification and Multiple Use Act of September 19, 1964 (National Park Service, 1969, p. 25; Cohea, 1974).

Trechado is located at the southern end of the area on State Highways 117 and 36. The Ramah Navajo Indian Reservation extends southward into the western part of the area. A large part of the remaining land is owned by the State or Federal governments.

Access to the northern, eastern, and southern perimeters of the area is provided by State Highways 53, 117, and 36, respectively. The name "Malpais" is quite appropriate because multiple Quaternary lava flows have formed a rugged expanse of terrain. The landscape of the younger volcanic rocks on the northeastern one-third of the area, in particular, is frequently composed of a seemingly chaotic maze of pressure ridges and mounds, collapsed pits and tubes, crevasses, tilted blocks, and sinuous pahoehoe flows covered with aa and lava blocks. In many places, this rugged topography cannot be traversed with vehicles of any type. A few unimproved roads leading to ranches are the only means of overland access in a very large fraction of the entire area.

The North Plains-Malpais area is a broad, shallow asymmetrical topographic basin open to the northeast (fig. 1). The axis of the basin is located immediately east of the Quaternary volcanic rocks and trends northeastward from T.4 N., R.13 W. to T.8 N., R.10 W (fig. 3). Altitudes range from approximately 7,700 ft (2,350 m) along the Continental Divide to 6,600 ft (2,010 m) at the northeastern end, about 10 mi (16 km) south of San Rafael. A few of the scattered cinder cones in the northwestern part of the area may rise to elevations of about 300 ft (90 m). Elsewhere, the topographic relief of the undulating surface is relatively low (fig. 1).

Surface drainage is by unnamed ephemeral streams that are parallel or subparallel to the topographic axis. The lava fields are characterized by an absence of surface drainage. A large closed topographic depression, located about midway across the basin on the asymmetrical axis in the center of T.6 N., R.11 W., apparently interrupts the surface drainage (fig. 1). Several small closed depressions in the southwestern part of the area trap water and become lakes during periods of high rainfall. The visible ephemeral drainage system eventually joins the Rio San Jose southeast of Grants.

At the northeast of the North Plains-Malpais area, rocks of Permian through Jurassic age dip at angles of generally less than 10 degrees to the southwest away from the Zuni Mountains (fig. 3). West of the Continental Divide, Cretaceous sedimentary rocks are exposed in broad cuestas and mesas. Jurassic and Cretaceous rocks outcrop on Cebolleta Mesa and the other associated mesas and cuestas along the eastern edge of the area. Quaternary alluvium and Tertiary volcanic rocks cover Cretaceous strata within and adjacent to the southern part of the area.

Nearly all the North Plain-Malpais area is covered by Quaternary basalts. Although more than 40 cinder and composite volcanoes have been mapped, the bulk of the lava erupted through fissures. Most of cinder cones, spatter cones, fissures, and faults are aligned in a northeasterly direction. An alignment of some of the volcanoes, dikes, and fissures subparallel to the northwesterly trend of the Zuni Mountains is evident but much less obvious (Kelley and Clinton, 1960, fig. 2). The volcanic features are aligned in trends parallel to the two dominant regional structural trends.

The volcanic rocks in the northern part of the area have been mapped and described by Nichols (1936, 1938, 1939a, 1939b, and 1946); National Park Service (1969); Hatheway (1969); Causey (1970); and Hatheway and Herring (1970). Other recent work by Laughlin, Brookins, and Carden (1972); Laughlin, Brookins, and Causey (1972); Laughlin, Brookins, Kudo, and Causey (1971); Carden and Laughlin (1974); and Renault (1969 and 1970) has been concentrated on the petrology and geochemistry of the volcanics.

Episodic eruptions of volcanic rocks probably commenced in the southwestern part of the area during earliest Quaternary time but may have started near the close of the Tertiary Period (Hatheway, 1969). Most of the lava was ejected quiescently through fissures, although scattered cinder cones are bold evidence of pyroclastic activity.

The centers of volcanic activity appear to have shifted progressively northeastward throughout the Quaternary, culminating with the McCartys Basalt (Nichols, 1946; and Carden and Laughlin, 1974). McCartys Crater, a low shield volcano surmounted by a small cinder cone located in sec 28, T.7 N., R.11 W., approximately 23 mi (37 km) south of the junction of Highway 66 (Interstate 40) with Highway 117 was the source of the McCartys Basalt. Lava from this volcano flowed northward into the Rio San Jose, then eastward down the valley a distance of about 4 mi (6 km). The fresh, unweathered appearance of the McCartys Basalt suggests an even younger age than the 400 to 1,200 years reported by Nichols (1946, p. 1056) and the National Park Service (1969, p. 5).

The series of progressively younger eruptions have, in effect, "shingled" the surface underlying the volcanic rocks with a succession of thin, overlapping flow units. Hatheway and Herring (1970, p. 316) measured the gradient of the surface beneath the Bandera flow and McCartys Basalt and found it to be less than one degree. The McCartys Basalt flowed on a surface with an average slope of "only 0°21'" (Hatheway and Herring, 1970, p. 317).

The location and extent of streams developed on the Zuni erosional surface is unknown and apparently cannot be readily determined by examination of aerial photographs. Perhaps extensive field mapping on foot or horseback or from a helicopter would be helpful in delineating the major channels—if any existed. The complexity of the flows and unknown location of fissures and lava tubes would probably preclude the use of electrical resistivity techniques. Dewilde (1971, p. 45) has encountered similar difficulty in locating the stream channels buried by Quaternary volcanic rocks.

The maximum alluviation of any stream valley now buried beneath the volcanic rocks would probably be less than the relatively thin Quaternary alluvium in the Rio San Jose valley. Dewilde (1971, p. 4 and 5) in describing a valley buried by Quaternary volcanic rocks on the Ramah Navajo Indian Reservation, notes that, "The alluvium of an ancient buried streambed is comprised of sand and gravel(?), usually reported as 'yellow quicksand' on driller's logs." The maximum thickness of alluvium given by Dewilde (1971, table 2) is 100 ft (30 m). Attempts were made to determine the validity of reports by ranchers and well-drillers of "alluvium" or "gravels" beneath the volcanic rock, without much success. (One person's "gravel" is another's "sand" and "thick" and "thin" are meaningless expressions unless they can be related to quantitative values.) Erosion of Mesozoic rocks already composed principally of relatively fine-grained clastics would be expected to yield even finer material as alluvium. A source of rocks that would yield pebbles and gravel is virtually nonexistent.

After the onset of volcanism, streams would probably have been disrupted and diverted progressively northeastward by each new eruption. Stream valleys of any significance must have been excavated prior to this time. Dewilde in his description of buried stream valleys, referring to wells drilled in T.6-7 N., R.13-14 W., notes that "East of the Continental Divide, logs of wells on the reservation indicate that the basalt and alluvium are drained." This suggests that attempts to develop large supplies of water from the alluvium in late Tertiary streambeds hidden beneath the Quaternary basalts would be futile.

The thickness of the volcanic rocks over much of the North Plains-Malpais area is unknown. A few shallow stock wells bottomed in alluvium or Mesozoic strata have been drilled along the margins of the flows and (or) in localities where the basalts are known to be relatively thin (Dewilde, 1971, table 2). More than 590 ft (180 m) of basalt was penetrated in a well drilled in sec. 2, T.7 N., R.11 W. near the eastern edge of the volcanics (Hatheway and Herring, 1970, p. 305). Speculations on the thickness of the Quaternary basalts are largely based on driller's logs from the scattered stock wells and limited field observations along the relatively thinner edges of the flows. Studies of the depth of the larger cracks, the depth of collapse depressions, the thickness of the edge of the flows around kipukas, and by comparison of the relationships between adjacent or superimposed flows have provided additional information (Nichols, 1946, p. 1053). Few wells have been drilled in the central and western areas near eruptive centers where the volcanic rocks may reach the maximum thickness. Inferences based on the observations that the individual flows are often spread over large areas, due to initial low viscosities of the molten lava, and descriptions of thicknesses from well logs or field data suggest that the Quaternary basalts are all generally less than 1,000 ft (305 m) thick except near the volcanoes, fissures, and other sources of the flows where greater thicknesses should be expected.

The North Plains-Malpais area is located between the sharply uplifted Zuni Mountains on the north and the Mogollon slope to the south. Permian and Triassic beds dip to the southwest and south away from the Zuni Mountains and are concealed beneath the younger Quaternary basalts. Cretaceous rocks in the vicinity of Trechado and Adams Diggings at the southern end of the North Plains-Malpais area dip gently to the north under a cover of the older volcanic rocks (oral commun., G. O. Bachman, January 10, 1975). Field geologists who have mapped the area for oil companies suggest that a broad northward-plunging syncline is located between Adams Diggings and Hickman. The relation of this fold to the southern extension of the McCartys syncline (fig. 2), if any, is unknown. If the reported syncline is an extension of, or is aligned with, the McCartys syncline, then it appears that the topographic axis of the area is located on the westward limb of a major regional fold (Cohee, 1962).

Glimpses of the underlying sedimentary rocks are provided at Little-hole-in-the-wall, in northern T.8 N., R.11 W., Cerritos de Jaspe, in northeastern T.8 N., R.12 W. and northwestern T.8 N., R.11 W., and at an unnamed ridge west of Cerro Encierro, near the southeast corner of T.8 N., R.12 W. (Hatheway, 1969; and fig. 3). The Permian Yeso, Abo, and Glorieta Formations are exposed in cuestas at the first two localities. Hatheway and Herring (1970, p. 302) report that the rocks exposed west of Cerro Encierro "....appear to belong to the same general series of Permian rocks." They also indicate that the Permian rocks in the three exposures "strike about N. 40° W. and dip moderately to the southwest" away from the uplifted Zuni Mountains.

No evidence of a structural downwarping in the center of the North Plains-Malpais area similar to that associated with the Mt. Taylor volcanic rocks has been reported in the literature. Presumably the magnitude of dip southwestward away from the Zuni Mountains gradually decreases toward the south. At some undetermined location the rocks become horizontal; still farther to the south, the direction of dip is reversed and becomes northerly, reflecting the influence of the Mogollon slope. Most probably the structural axis of the syncline trends in a northwesterly direction through the center of the North Plains-Malpais area. The center of interior drainage located in T.6 N., R.11 W. may be a surface manifestation of the intersection of the projected McCartys syncline and the axis of the syncline between the Zuni uplift and the Mogollon slope.

The occurrence and movement of ground water in the North Plains-Malpais area is controlled, to a large extent, by the lithology, structural attitude, position, and distribution of strata hidden beneath the Quaternary basalt flows. The subcrop pattern of the Paleozoic and Mesozoic rocks probably can be extrapolated from the peripheral exposures. The subcrop of the Permian and Triassic rocks should follow the structural contour of the Zuni uplift. The north-westerly strike of these rocks south of Paxton should become abruptly northerly in the vicinity of San Rafael as the strata loop around the southeastern end of this plunging anticline (Gordon, 1961, pl. 1). Farther to the south, the Jurassic and Cretaceous rocks should extend laterally without perceptible structural displacement from the mesas and cuestas on the periphery of the area to comparable positions beneath the volcanic rocks. The topographic relief of approximately 800 ft (245 m) from the top of Cebolleta Mesa to the ephemeral stream drainage below is similar to that in the Rio San Jose valley. If the surface beneath the Tertiary basalts on the top of Cebolleta Mesa represents the Zuni erosional surface, then the relief present and general configuration of the land surface suggests that the area was sculptured by normal erosional processes operative in central-western New Mexico prior to the eruption of the Quaternary volcanic rocks.

Sedimentary rocks ranging in age from Permian to Quaternary having a total thickness of approximately 5,000 ft (1,525 m) are present beneath the Quaternary basalts in the central and western parts of the North Plains-Malpais area. The stratigraphic section penetrated in the Ramah Navajo Indian School Water Supply Well 1, SW¼ sec. 27, T.8 N., R.15 W. is probably typical for the area. This well was bottomed in the Permian Glorieta Sandstone and data given for older formations are extrapolated from other wells and nearest outcrops. Projection of data from oil-test wells and outcrops into the area indicates that rocks of Cambrian through Pennsylvanian age are absent.

Local thin deposits of "granite wash," alluvial material derived from the underlying granitic Precambrian basement, may represent the oldest sedimentary rocks. The Permian Abo and Yeso Formations with an aggregate thickness of approximately 1,400 ft (425 m) overlie the Precambrian basement complex and (or) the "granite wash." These units are expected to yield only very small amounts of water, much too highly mineralized for domestic use, and are not considered aquifers with a potential worthy of further evaluation.

The Glorieta Sandstone is a light-gray to yellowish-gray, fine-grained, quartzose sandstone. This unit is probably at least 300 ft (90 m) thick (Baars, 1962, fig. 17). The overlying San Andres Limestone is composed of interbedded, dense, hard limestone and clean, tightly cemented, quartzose sandstone. The San Andres is about 200 ft (60 m) thick (Baars, 1962, fig. 18). Karstic features observed in and near the outcrops in the Zuni Mountains were not noted in the Ramah Navajo Indian School Water Supply Well 1.

The San Andres Limestone and Glorieta Sandstone are hydraulically connected and together they constitute one of the best aquifer systems in the area. Wells tapping the complete thickness of the San Andres-Glorieta aquifer can be expected to yield approximately 100 gpm (6 l/s). Artifical stimulation of the aquifer by hydraulic fracturing and treatment with acid will probably increase the yield several fold. Depth to water will be approximately 1,000 ft (305 m) and the depth to the top of the San Andres should range from 3,000 to 3,500 ft (915 to 1,065 m) below land surface. The regional flow pattern of water in the San Andres-Glorieta aquifer is unknown.

The water probably contains 500 to 1,000 mg/l of dissolved solids with calcium, sodium, sulfate, and bicarbonate being the most abundant dissolved constitutents. The water may also contain undesirable quantities of dissolved iron. Water produced from the Ramah Navajo Indian School Water Supply Well 1 contains approximately 700 mg/l of dissolved solids. Iron and manganese were present in 5.3 mg/l and 0.009 mg/l quantities respectively in one sample analyzed shortly after the well was completed.

The Triassic Chinle Formation, ranging in thickness from 1,500 to 1,700 ft (455 to 520 m), overlies the San Andres Limestone of the Petrified Forest Member in the Chinle (Stewart, Poole, and Wilson, 1972, plate 3). The Sonsela Sandstone Bed is about 150 ft (45 m) thick in the Ramah Navajo Indian School Water Supply Well 1 but appears to have a very low porosity and permeability. The water contained in the Sonsela Sandstone Bed probably exceeds the upper limits for dissolved solids permitted by Public Health Service standards. This unit is not considered to be a potential aquifer in this area.

The Chinle Formation is overlain, in succession, by the Triassic Wingate Sandstone, the Jurassic Cow Springs Sandstone (equivalent in part to the Zuni Sandstone shown in figure 3), and the Cretaceous Dakota Sandstone. These units should be approximately 200 (60 m), 175 (55 m), and 75 (25 m) ft thick, respectively. The Westwater Canyon Member of the Jurassic Morrison Formation is not present this far south. The Wingate, Cow Springs, and Dakota aquifers, individually, seldom yield more than 50 gpm (3 l/s) of water. The dissolved constituents in water in these aquifers generally exceeds the maximum dissolved solids content permissible for human consumption. These aquifers are not considered to be suitable as a source of water in this area.

Approximately 500 ft (150 m) of Mancos Shale overlies the Dakota Sandstone. Sandstone beds in the lower part of the Mancos Shale would probably yield adequate supplies of good quality water to stock wells in western part of the North Plains-Malpais area. However, yields from these aquifers would undoubtedly be much too small for development as a source of water for the city of Gallup unless the production was combined with that of another aquifer.

The Gallup Sandstone overlies and intertongues with the upper part of the Mancos Shale. This aquifer has a total thickness of about 450 ft (135 m) in the western part of the area (Molenaar, 1973 and 1974). About one half of the Gallup Sandstone is composed of massive to irregularly bedded, fine to medium-grained, light-brown or pinkish quartzose sandstone and can be considered as water bearing. The Gallup Sandstone also includes sandy shales, siltstones, carbonaceous shales, and thin beds of coal.

The Gallup Sandstone is the most frequently tapped aquifer system on the Ramah Navajo Indian Reservation (Dewilde, 1971, p. 5). Yield from this shallow aquifer is not expected to be more than 50 gpm (3 l/s). However, the water should contain less than 500 mg/l dissolved solids. Depths to the top of the Gallup Sandstone will be generally less than 1,000 ft (305 m). Static water levels will range from 400 to 700 ft (120 to 215 m) below land surface (Dewilde, 1971, pl. 2). The Gallup Sandstone and the sandstone aquifers near the base of the Mancos Shale in the western part of the North Plains-Malpais area merit further study as a potential source of water for the city of Gallup.

Quaternary basalts and alluvium probably overlie the eroded Gallup Sandstone, Mancos Shale, and Dakota Sandstone in the central and western parts of the area. If these units are drained as stated by Dewilde (1971, p. 5), then they do not warrant further consideration as a source of water. Apparently water originating as rainfall and snowmelt must pass quickly through the volcanic rocks and thin underlying alluvium into the permeable sandstones of the Upper Cretaceous strata.

A potentiometric map prepared by Dewilde (1971, pl. 2) indicates that water moves through the Gallup Sandstone to the southwest out of the western and central parts of the North Plains-Malpais area. This ground water probably eventually contributes to the flow of the Little Colorado River.

Yields from shallow wells tapping the alluvium in the ephemeral stream valleys in the eastern part of the area are reported to be generally less than 25 gpm (2 l/s). The water is of good quality and suitable for domestic use. Ground water in the alluvium in the eastern and northern parts of the area probably enters sandstones in the Jurassic and Cretaceous rocks and moves east, northeast, and north. This ground water probably eventually contributes to the flow of either the Rio Salado or Rio San Jose, tributaries of the Rio Grande.

Pumping of large quantities of water from the eastern part of the North Plains-Malpais area could intercept and divert water that would, under prior conditions, flow into either the Bluewater underground basin and (or) the Rio Grande basin.

Grants-Bluewater

The Grants-Bluewater area encompasses approximately 300 mi^2 (775 km^2) within Tps.9-13 N. and Rs.9-11 W. inclusive, in north-central Valencia and southeastern McKinley Counties (figs. 1 and 3). This water-productive area is, for practical purposes, coincident with the Bluewater Underground Water Basin declared by the New Mexico State Engineer in 1956 (New Mexico State Engineer Office, 1958; Gordon, 1961, p. 77; Hudson and Borton, 1970, p. 4 and 88). The town of Grants, near the center of the area, is approximately 60 mi (95 km) southeast of Gallup.

The area is located in valleys cut by the Rio San Jose and its tributaries. It lies between the east end and northwest flank of the plunging Zuni uplift to the southwest and Mount Taylor and the Cebolleta Mountains on the northeast. Altitudes of the developed part of the area, including the communities of Bluewater, San Rafael, and Milan, and the town of Grants, range from about 6,300 ft (1,920 m) to about 6,800 ft (2,075 m). Local relief in many localities exceeds 1,500 ft (455 m).

Rocks ranging in age from the Permian Abo Formation to Holocene alluvium and basalt are exposed within the Grants-Bluewater area (fig. 3). Between Grants and Bluewater, Paleozoic and Mesozoic strata dip gently toward the north and northeast onto the Chaco slope and into the San Juan basin. South of San Rafael, the same strata dip eastward more sharply into the McCartys syncline, a component of the Acoma sag.

A well drilled in sec. 8, T.12 N., R.10 W., about 3 mi (5 km) northeast of Bluewater, penetrated 2,442 ft (744 m) of Triassic, Permian, and Pennsylvanian rocks above Precambrian schist and gneiss (West, 1972, p. D 5). Similar thicknesses of sedimentary rocks are probably present in the vicinity of Grants and San Rafael.

The principal aquifer in the Grants-Bluewater area is formed by a combination of the San Andres Limestone and the underlying Glorieta Sandstone. The transmissivity of the San Andres Limestone is much greater than that of the Glorieta Sandstone. However, water is transmitted into the San Andres from the Glorieta Sandstone as the head in the overlying San Andres Limestone is reduced, and the two units are generally treated as one aquifer in central-western New Mexico. Regionally, the San Andres Limestone thins northward and disappears along a lobate west-trending line running through central McKinley and northern Sandoval Counties (Baars, 1962, p. 205). In addition to the regional thinning of the San Andres, the carbonate rock was extensively removed by solution in the area during the post-Leonard pre-Late Triassic erosion cycle. The San Andres Limestone-Glorieta Sandstone, undivided, is 236 ft (72 m) thick in The Anaconda Co. disposal well 1, sec. 8, T.12 N., R.10 W., near the northern end of the Grants-Bluewater area. However, only about 9 ft (3 m) of limestone is present in the section penetrated in this well.

The Quaternary alluvium and basalt that underlie the valleys of the Rio San Jose and its tributaries also constitute a significant aquifer in the Grants-Bluewater area. The alluvium and interbedded basalt flows range in thickness from 100 to 140 ft (30 to 43 m). A maximum thickness of approximately 30 ft (9 m) of alluvium was deposited prior to the flows of basalt (Gordon, 1961, p. 37).

Water in the San Andres-Glorieta aquifer flows to the southeast parallel to the course of the Rio San Jose under a gradient of 1 to 10 ft/mi (.2 to 2 m/km). Water in the alluvium-basalt aquifer also flows to the southeast in response to the regional drainage but with a gradient of about 20 ft/mi (4 m/km). However, the potentiometric surfaces representative of the hydraulic head in the two aquifers are dissimilar. The potentiometric surface for water in the alluvium and basalt compares more closely to the configuration of the topography than does the corresponding potentiometric surface for the San Andres-Glorieta aquifer (Gordon, 1961, pl. 2; and West, 1972, pl. 1).

Water in the San Andres-Glorieta aquifer apparently leaks upward into the overlying alluvium-basalt aquifer from near Grants southeastward. Under natural conditions, water from both aquifers probably discharges from springs into the Rio San Jose about 8 mi (13 km) southeast of Grants (Gordon, 1961, pl. 2; and West, 1972, p. D 5).

Sandstones in the Chinle Formation yield adequate quantities of water of suitable quality for domestic and stock use throughout much of the area. Yields of several hundred gallons per minute (gpm) are obtained in some localities where the water has been used for irrigation. Additional supplies of poor quality water could probably be developed from wells tapping sandstone beds in the Chinle Formation. The effect of production of water from the Chinle Formation on other aquifers is unknown but vertical hydraulic communication with the underlying San Andres-Glorieta aquifer and the overlying alluvium-basalt aquifer should be relatively good due to the extensive system of faults, fractures, and joints.

Rocks older than the Permian Glorieta Sandstone contain water that is much too highly mineralized to be considered for municipal use. Water produced from the Yeso Formation in the Anaconda Co. disposal well, sec. 8, T.12 N., R. 10 W., contained approximately 4,000 mg/l of dissolved solids.

Numerous normal faults cut the rocks in the area. Displacement along most of the faults ranges from a few feet to a few tens of feet. However, several prominent north-to-northeast-trending faults radiating from the Zuni uplift have throws of several hundred feet and can be traced for tens of miles (fig. 3; Gordon, 1961, pl. 1 and p. 48-50; and Kelley, 1967). Faults and associated joint and fracture systems may have a pronounced effect on the local occurrence and movement of ground water in the Grants-Bluewater area. Displacement of relatively impervious material into juxtaposition with aquifers may retard or prevent the flow of water depending on the amount of stratigraphic offset. Conversely, some faults and fracture zones may increase the transmissivity of the strata and thus become local conduits within an aquifer system.

The transmissivity of the San Andres Limestone has been locally increased by solution resulting from ground water moving through the fractured zones. Regional solution of the San Andres Limestone and formation of a karstic surface during exposure of the Permian rocks prior to deposition of the Triassic Chinle Formation has also altered the transmissivity of this important aquifer. In some places, the San Andres has been removed completely. In other places, fine-grained terrigenous clastics of Triassic or younger age have filled solution cavities and reduced the previously higher hydraulic conductivity. However, wherever the solution cavities remain open and the San Andres Limestone is intact, the transmissivities are quite large. Reeder (in Gordon, 1961, pp. 58, 104, and 105), reports a range of transmissivities of 410,000 to 3,200,000 gpd/ft (55,000 to 430,000 ft^2day^{-1}; 5,000 to 40,000 m^2day^{-1}) and specific capacities varying from 49 to 1,100 gpm/ft (6.5 to 147 ft^2min^{-1}; 0.6 to 14 m^2min^{-1}) for several wells completed in the San Andres Limestone. Values of the specific capacity given by Reeder for one well completed in the alluvium and another well tapping the Glorieta Sandstone were smaller than the smallest reported value for the San Andres Limestone. Yields from wells that tap both the major aquifers, in the valley between Bluewater and Milan, range from 500 to 2,200 gpm (30 to 140 l/s).

The water of the best chemical quality in both the San Andres-Glorieta and alluvium-basalt aquifers is found in a narrow belt extending southeastward from near Bluewater to Milan. Concentrations of dissolved solids in this narrow belt generally range from 300 to 900 mg/l. Elsewhere, the water in the two aquifers is more highly mineralized and concentrations greater than 2,000 mg/l of dissolved solids have been reported.

Water levels declined 18 to 45 ft (5 to 14 m) during the period 1946-57 as a consequence of the withdrawal of ground water for irrigation, industrial, and municipal use. However, since 1957, the water levels in the basin have risen about 20 ft (6 m) and become relatively stable (Gordon, 1961, p. 45; Hudson and Borton, 1970, p. 91; and Stevens, and others, 1972. The increase and stabilization of the hydraulic head in the basin probably reflect long-term changes in demand on the aquifer system.

Wells yielding large quantities of water of desirable quality for municipal use can be obtained only in the narrow valley between Bluewater and Milan. Heavy demands for water are now being made on the aquifers in this area. Because this is a declared underground water basin, additional water can be withdrawn only by obtaining permission from the New Mexico State Engineer or by purchasing existing water rights. Either action by the city of Gallup would require permission from appropriate regulatory agencies to divert water outside of a declared water basin and from the Rio Grande drainage system to the Colorado River drainage system.

Mesa Chivato-Cebolleta Mountains

The Mesa Chivato-Cebolleta Mountains area contains approximately 400 mi^2 (1,035 km^2) and is located about 80 mi (130 km) east of Gallup in southeastern McKinley, southwestern Sandoval, and northeastern Valencia Counties (figs. 1 and 3). The long axis of the elliptically shaped area extends northeastward along the trend of the Cebolleta Mountains from Mount Taylor to the Rio Puerco, a distance of about 70 mi (115 km). A part of the Cibola National Forest is within the western part of the area. The southwestern two-thirds of the area is located in the Grants mineral belt between two of the largest uranium mining districts in the United States--Ambrosia Lake, on the west, and Laguna, on the east.

The Mesa Chivato-Cebolleta Mountains area occupies the northeastern corner of the Datil section of the Colorado Plateau physiographic province (Fenneman, 1931 and 1962). Mesa Chivato and other mesas that together comprise the "pedestal" under Mount Taylor all rise to an altitude of about 8,000 ft (2,440 m). The plains surrounding the mesas range in altitude from 6,000 to 6,700 ft (1,830 to 2,040 m). Mount Taylor dominates the geomorphic setting with an altitude of 11,389 ft (3,471 m). Ephemeral streams loop northeastward around Mesa Chivato and the northern part of the Cebolleta Mountains to join the Rio Puerco west of Cabezon Peak. The southern and eastern flanks of the Cebolleta Mountains are drained by arroyos or ephemeral streams that are tributaries of either the Rio San Jose or Rio Puerco (fig. 1).

The Mesa Chivato-Cebolleta Mountains area lies within the extreme southeastern and northern ends of the Chaco slope and Acoma sag, respectively (fig. 2). The axis of the McCartys syncline plunges northward beneath Mount Taylor, Mesa Chivato, and the western part of the Mount Taylor volcanic field. The maximum structural relief over a width of 20 mi (32 km) along the McCartys syncline is about 1,500 ft (460 m) (Shomaker, 1967, p. 197). Maximum dip toward the axis of the McCartys syncline is generally less than 5 degrees. The prevailing northward regional dip is generally less than 2 degrees but is interrupted by small flexures with greater angles of dip. Normal faults with relatively small throws are commonplace.

The eruption of the Mount Taylor volcano probably commenced in late(?) Miocene time coincident with and (or) after the major crustal disruptions in western New Mexico. Mount Taylor is located in or near the axis of the McCartys syncline and thus may be related to deep-seated crustal movements. The Cebolleta Mountains northeast of Mount Taylor are studded with more than 200 younger volcanic centers (Baker and Ridley, 1970, p. 107). Some of the vents are comparatively unaffected by erosion and remain standing as imposing features, several hundred feet above the surface of the mesas. Sheet basalt and andesite flows from the vents poured out upon and covered the middle Pliocene Zuni-Ortiz pediment surface surrounding Mount Taylor (Mesa Chivato surface of Moench and Schlee, 1967, p. 54). Prior to the erosion of the Rio Puerco valley, the flows and interbedded volcanic ash apparently extended farther eastward and once were continuous with the lava cap on Mesa Prieta (Dutton, 1885). Basalt dikes, undoubtedly related to the sheet flows, are prevalent in the Mount Taylor volcanic field. The dikes trend north, paralleling the strike of most of the faults in the region. Similarly, the vents are aligned in north or northeasterly directions parallel to the regional strike of joints mapped by Kelley and Clinton (1960, fig. 2).

Obsidian from Grants Mesa and La Jara Mesa, west and southwest of Mount Taylor, respectively, and perlite from Grants Mesa have been dated at 3.2 ± 0.3 m.y. (million years). A sample of sanidine-bearing perlite from Mount Taylor was dated at about 2.6 m.y. (Bassett, Kerr, Schaeffer, and Stoenner, 1963). The volcanic rocks yielding these dates apparently are from some of the more recent extrusions in the Mount Taylor volcanic complex but are distinctly older than the McCartys Basalt and other late Holocene flows in the Rio San Jose valley.

There is a wide range in thickness of the Tertiary and Quaternary volcanics. A well drilled in sec. 7, T.13 N., R.5 W., McKinley County, penetrated 543 ft (165 m) of interbedded basalt and volcanic ash (Cooper and John, 1968, p. 37). Wells drilled during the search for uranium in the general area of the Cebolleta Mountains are reported to have penetrated several thousand feet of volcanics. However, these reports are unusual and, indeed, may be exaggerated. Obviously, reports of abnormally thick sections obtained from wells that have penetrated sections within and parallel to any of the numerous dikes cutting the sedimentary rocks will have distorted the data. The volcanic rocks were extruded upon a middle Pliocene tableland topography. A variable but somewhat predictable thickness of volcanic rock should have resulted from the irregular configuration of the buried paleo-surface.

Most of the rainfall and (or) snowmelt entering the extensive exposures of extrusive igneous rocks probably percolates quickly through these rocks and either recharges the underlying Cretaceous aquifers or moves laterally to the edges of the volcanic field to emerge as spring flow (Cooper and John, 1968, p. 37). Lateral movement of water may be, in a few places, restricted by dikes. Locally, impervious beds of volcanic ash or unfractured basalt or andesite may retard downward movement of water. Depending on the composition, fracturing, texture, and configuration of the volcanic flows and intrusions, and on the configuration of the pre-volcanic rock surface, water may be perched locally on impervious strata. Wells tapping the perched zones might have high initial yields, but such yields would probably diminish quickly until a balance between production and recharge were attained. The quality of the water contained in the volcanic rocks is generally quite good. Unfortunately, it is unlikely that the volume of water present in the complex of volcanic rocks is sufficient to provide the sustained yield of several million gallons per day that will be required by the city of Gallup.

Oil and gas-test wells have been drilled to the Precambrian basement at depths of approximately 6,200 ft (1,890 m) in sec. 2, T.13 N., R.4 W., and sec. 10, T.13 N., R.3 W., Sandoval County, near the eastern boundary of the Cebolleta Mountains, and in sec. 14, T.14 N., R.8 W., McKinley County, about 6 mi (10 km) west of Chivato Mesa. The sequence of sedimentary rocks within the McCartys syncline and the northwestern part of the area is estimated to be approximately 8,000 ft (2,440 m) thick.

Sandstones and shales of the Cretaceous Dakota Sandstone, Mancos Shale, and Mesaverde Group are exposed on the flanks of the Cebolleta Mountains and presumably underlie the Mount Taylor volcanic complex. Alteration, deformation, and (or) disruption of the Cretaceous sedimentary rocks by the younger intrusives appears to be relatively insignificant wherever the relationships are observable. Hunt (1938) has theorized that introduction of the volcanic material by progressive magmatic stoping minimized these effects. One can probably safely assume that the Jurassic and older sedimentary rocks are also relatively unchanged by the volcanic intrusions.

However, the concentration of dissolved constituents in the water contained in rocks older than the Jurassic Morrison Formation undoubtedly greatly exceeds the maximum limits permissible for human consumption. Although the Jurassic Bluff Sandstone is approximately 300 ft (90 m) thick, yields from this aquifer do not generally exceed 10 gpm (0.6 l/s) and the water is usually too highly mineralized to be desirable for human consumption (Cooper and John, 1968, p. 25). Berry (1959, pl. 8) indicates that total dissolved solids in the Jurassic Entrada Sandstone in this area generally exceeds 5,000 mg/l. The carbonate lithofacies in the San Andres Limestone is very thin to absent. The San Andres-Glorieta aquifer, productive in the Grants-Bluewater area, is expected to have a relatively low transmissivity here and to yield moderately mineralized water that would be unsuitable for human consumption.

In ascending order the Jurassic Westwater Canyon Member of the Morrison Formation and the Cretaceous Dakota Sandstone, Gallup Sandstone, Dalton Sandstone Member of the Crevasse Canyon Formation, and the Point Lookout Sandstone are all potential aquifers in this area.

The Westwater Canyon Member is a varicolored, coarse to medium-grained, poorly sorted, well-cemented sandstone. The nature of the trough cross-stratification suggests that the sandstone was apparently deposited over a widespread flood plain by easterly or northeasterly flowing streams in the vicinity of Grants and Ambrosia Lake (Moench and Schlee, 1967, p. 18). The thickness of the Westwater Canyon Member probably averages about 150 ft (30 m) but is extremely variable as should be expected from the depositional environment.

Despite generally unfavorably reservoir characteristics, the Westwater Canyon Member of the Morrison Formation is one of the most important aquifers underlying the Mesa Chivato-Cebolleta Mountains area. Properly completed wells tapping the Westwater Canyon aquifer should yield 50 to 150 gpm (3 to 9 l/s). The Westwater Canyon Member is the principal host rock for extensive deposits of uranium in the Ambrosia Lake mining district north of Grants. Water produced from the Westwater Canyon aquifer may contain undesirably high concentrations of radium and other radionuclides but otherwise is expected to contain less than 1,000 mg/l of dissolved solids. Typically, the main dissolved constituents are calcium, sodium, bicarbonate, and sulfate.

The Cretaceous Dakota Sandstone unconformably overlies the Brushy Basin Member of the Jurassic Morrison Formation in the Mesa Chivato-Cebolleta Mountains area. The thickness of the Dakota Sandstone varies from 50 to 150 ft (15 to 45 m) due to the unconformable nature of the lower contact and to intertonguing with the overlying Mancos Shale. The Dakota Sandstone mainly is composed of light-gray to buff, generally thick-bedded, fine to coarse-grained, crossbedded sandstone. The sandstones and siltstones in the Dakota Sandstone are generally well cemented with silica and (or) carbonate. Shale, siltstone, conglomerate, and coal are interbedded and (or) intertongued with the more massive sandstone beds. Frequent local horizontal and vertical changes in lithology result in corresponding large variations in hydraulic conductivity.

Even under favorable geologic conditions, properly constructed wells tapping the Dakota Sandstone in this area will probably yield less than 50 gpm (3 l/s). The chemical quality of the water will generally be marginal for domestic consumption. In addition to a relatively high concentration of sulfate, bicarbonate, and sodium, water produced from the Dakota Sandstone may contain undesirably high concentrations of radionuclides (Cooper and John, 1968, p. 30).

In the Mesa Chivato-Cebolleta Mountains area, the Gallup Sandstone is composed of a prominent upper sandstone, 60 to 125 ft (20 to 40 m) thick, a thinner and regionally less persistent lower sandstone ranging in thickness from a few feet to as much as 75 ft (25 m), and a medial tongue of the Mancos Shale with an average thickness of about 90 ft (25 m). The sandstones are composed of fine to medium-grained quartz sand, are massive to thin-bedded, and in many places have low-angle crossbedding. The buff-to-gray sandstone beds commonly are poorly to moderately cemented, and generally form less prominent outcrops than the older Dakota Sandstone.

No wells are now known to be producing from the Gallup Sandstone on Mesa Chivato or in the Cebolleta Mountains. Yields of as much as several hundred gpm from the Gallup Sandstone are reported to have been encountered locally during the drilling of uranium-test wells in the northern part of the area and in the area north and west of San Mateo (fig. 3). The Gallup is tapped by a small-capacity well in the community of Marquez, east of Mesa Chivato, Sec. 31, T.13 N., R.4 W. (Cooper and John, p. 48 and 57). The water now being produced from the Gallup Sandstone in this area is generally of poor quality and only marginally suitable for domestic consumption (Cooper and John, 1968, table 3; and Berry, 1959, pl. 12).

The Dalton Sandstone Member of the Crevasse Canyon Formation ranges in thickness from 35 to 200 ft (10 to 60 m) and is generally medium to coarse-grained, composed of white-to-buff, massive sandstone (Cooper and John, 1968, p. 33). Because of the rapid lateral variations in lithology and the intertonguing relationships of the Dalton Sandstone Member with other members of the Crevasse Canyon Formation, the hydraulic characteristics of this aquifer probably vary widely and would be difficult to predict. The limited information available suggests that the yield and quality of water produced from the Dalton range from a few to several hundred gpm and from several hundred to several thousand mg/l of dissolved solids, respectively.

The Point Lookout Sandstone varies from 75 to 300 ft (25 to 90 m) in thickness. Except for the arkosic composition, the gross lithology and physical stratigraphy resembles that of the Gallup Sandstone. Compared to the Gallup Sandstone, the Point Lookout Sandstone is less mature, i.e., it contains more clay, the grains are more angular and less well sorted, and it has less porosity. Therefore, the hydraulic conductivity of the aquifer is probably significantly lower than that of the Gallup Sandstone. Yields reported from the Point Lookout aquifer seldom exceed 25 gpm (2 l/s). However, properly constructed and completed wells at geologically favorable locations might yield several times as much water. The small amount of information available suggests that the water in the Point Lookout aquifer in the Mesa Chivato-Cebolleta Mountains generally contains from 400 to 1,000 mg/l of dissolved solids.

In increasing order, approximate depths to the most prospective aquifers on Mesa Chivato near the center of T.13 N., R.5 W. are: Point Lookout Sandstone, 700 ft (215 m); Dalton Sandstone Member, 1,200 ft (365 m); Gallup Sandstone, 1,800 ft (550 m); Dakota Sandstone, 3,300 ft (1,005 m); and Westwater Canyon Member, 3,600 ft (1,100 m), respectively. Penetration of the basalt flows and igneous intrusions may require the use of special techniques when drilling wells in this area.

Wells open to all of the most favorable Jurassic and Cretaceous aquifers in the Mesa Chivato-Cebolleta Mountains area will probably yield less than 500 gpm (30 l/s) of water that, at best, is of a quality so poor as to be only marginally suitable for domestic consumption.

Ambrosia Lake

Uranium is now being mined from the Westwater Canyon Member of the Morrison Formation within the zone of saturation in the Ambrosia Lake mining district. Millions and perhaps billions of gallons of waste water is discharged yearly as the mines are dewatered (Cooper and John, 1968, p. 38-42). Production of waste water can be expected to increase as the intensity of the mining increases and as new mines are developed in the saturated zone of the Westwater Canyon aquifer. A small fraction of the water pumped from the mines is used in the uranium ore processing mills. Most of the waste water is channeled into a formerly dry arroyo that carries the effluent southward out of the Ambrosia Lake area and into San Mateo Creek, a tributary of the Rio San Jose (Cooper and John, 1968, p. 40).

The ground water pumped from the uranium mines is slightly radioactive and occasionally exceeds the recommended limit for safe drinking water (Cooper and John, 1968, p. 28 and 40-42). The total of dissolved constituents found in water produced from the Westwater Canyon aquifer in the Ambrosia Lake mining district ranges from less than 300 to more than 1,400 mg/1. Most of the water sampled by Cooper and John (1968, table 3) contained less than 700 mg/1 of total dissolved solids.

Reports from industry sources indicate that known uranium reserves and reserves expected to be found in the Grants mineral belt will support uranium mining in the Ambrosia Lake and Laguna mining districts for many years. The large quantities of water pumped from the mines as they are dewatered now constitute a dependable supply that could be salvaged and used for beneficial purposes after only minimum treatment to remove undesirable dissolved and suspended constituents. After mining ceases, the abandoned mines will comprise a large underground collection system. High capacity pumps could then be installed in the abandoned shafts and water produced as needed.

Permission to divert the water from the Rio Grande drainage basin probably would have to be obtained before the water could be exported from the Ambrosia Lake mining district to Gallup.

Ownership of land and (or) water

Much of the land included within the five areas evaluated is either owned by private individuals and companies and (or) the Navajo and Zuni Indian Tribes, or is reserved by the Federal Government for the Navajo and Zuni Indians (U.S. Bureau of Land Management, 1971-74). Ownership of a tract of land within the areas studied may often be complicated due to ownership of the surface, subsurface, and minerals, respectively, by different parties. Only relatively small areas of land favorably situated for development of relatively large supplies of ground water are held by either the State or Federal government. The use of water within the Grants-Bluewater basin is controlled by the New Mexico State Engineer. The ownership of the land surface, the subsurface, water and (or) water rights, and the legal control of the use of water are factors that should properly be considered prior to implementing more comprehensive programs for ground-water exploration and development.

Conclusions and recommendations

The San Andres-Glorieta aquifer of Permian age is the oldest unit considered capable of yielding water of desirable and (or) marginal quality in the quantities required for a municipal supply, and it has the highest reported well yields in the Grants-Bluewater basin. Existing production and the drilling of additional wells is regulated by the New Mexico State Engineer in this area.

The San Andres-Glorieta aquifer is a potential source of water for the city of Gallup south and southwest of the Zuni Mountains in the North Plains-Malpais and Zuni Southwest areas of this report. Without artificial stimulation of wells, the San Andres-Glorieta aquifer system should yield 100 gpm (6 l/s) of water containing 500 to 1,000 mg/l dissolved solids from depths ranging from 2,000 to 3,500 ft (610 to 1,700 m). Artificial stimulation by acidization and hydraulic fracturing of wells tapping the aquifer system could increase the yields several fold. The post-Permian karstic topography evident in the Zuni Mountains and Grants-Bluewater area is not prominently developed in the subsurface at distances only a few tens of miles from the outcrop of these strata.

Alluviated stream valleys buried by Quaternary volcanic rocks in the North Plains-Malpais area cannot be easily delineated. In some parts of the area the alluvium in the buried stream valleys is known to be dry. Water entering the volcanic rocks as rainfall or snowmelt probably passes rapidly into and through the underlying thin alluvium into the subcropping Jurassic and Cretaceous sandstones. Therefore, further exploration for large water supplies that were anticipated to be in the alluvium that was buried by volcanic rocks in the North Plains-Malpais area does not seem to be warranted by the available geologic evidence.

Wells tapping alluvium of late Cenozoic age in the Rio San Jose and (or) Puerco River valleys and interbedded volcanic rocks and alluvium elsewhere in the area generally yield less than 100 gpm (6 l/s) of water having a wide range in quality. The prospects of finding adequate supplies of uncommitted water from this source are negligible.

Triassic, Jurassic, and Cretaceous strata are present throughout much of the area in the vicinity of Gallup. Unfortunately, most of the prominent and widespread sandstones that comprise a substantial part of the aggregate thickness of the Mesozoic strata have extremely low hydraulic conductivities and (or) contain water that greatly exceeds the maximum concentration of dissolved solids suitable for domestic consumption.

Water from rainfall and snowmelt entering the thick, extensive late Tertiary and Quaternary volcanic rocks capping the Mesa Chivato-Cebolleta Mountains apparently escapes as spring flow along the edges of the mesas and buttes or passes into underlying Cretaceous sandstones. Wells tapping the Cretaceous rocks in the Mesa Chivato-Cebolleta Mountains will yield as much as several hundred gallons per minute in some localities. However, at many places the water is much too highly mineralized for human consumption.

The widespread Gallup Sandstone is the best aquifer known in the vicinity of Gallup. Sustained yields of 500 to 800 gpm (30 to 50 l/s) can be expected from wells completed in this aquifer west and north of the Zuni Mountains. Where present, the overlying Dalton Sandstone Member of the Crevassee Canyon Formation is also highly productive. The quality of the water in the Gallup and Dalton aquifers varies widely. Large supplies of water containing from 500 to 1,000 mg/l dissolved solids could be developed and produced from the Gallup and Dalton aquifers over a large area within the Gallup sag north of the city of Gallup. The feasibility of obtaining the rights to develop this resource at a reasonable cost should be pursued as a means of alleviating the present shortage of water.

The Gallup Sandstone and sandstones in the lower part of the Mancos Shale underlie the Quaternary alluvium and volcanic rocks in the western part of the North Plains-Malpais area. Yields of the few relatively shallow wells tapping these aquifers do not exceed 50 gpm (3 l/s). The quality of the water produced is, however, comparatively good with dissolved solids generally less than 500 mg/l. These aquifers in this area merit further evaluation as a potential source of water for the city of Gallup.

The Westwater Canyon Member of the Morrison Formation, one of the principal uranium-bearing units in the Grants mineral belt is present north of the latitude of Grants. Uranium is now being mined from the Westwater Canyon Member within the zone of saturation in the Ambrosia Lake and Church Rock mining districts. Very large quantities of water are being pumped to the surface from the mines as they are dewatered during the active mining phase. Some of the water is used in the uranium ore processing mills but most is simply discharged into formerly dry arroyos. The ground water pumped from the Westwater Canyon aquifer in the Ambrosia Lake mining district generally contains less than 700 mg/l dissolved solids. It is slightly radioactive and occasionally exceeds the limits recommended by the U.S. Public Health Service for safe drinking water. Water pumped from the Westwater Canyon aquifer in two mines near Church Rock generally contains less than 400 mg/l dissolved solids. This water also contains variable amounts of radiochemical constituents but is otherwise of much better quality than that now being consumed by the inhabitants of the city of Gallup.

Industrial sources of information indicated that known reserves and reserves expected to be discovered in the Grants mineral belt will sustain mining for many years. The large quantities of water pumped from the mines as they are dewatered now constitute a dependable supply that could be salvaged and used for beneficial purposes after only minimum treatment to remove undesirable dissolved and suspended constituents. After mining ceases, the abandoned mines will comprise a large underground collection system. High capacity pumps could then be installed in the abandoned shafts and water pumped from the mines as needed. Permission to divert the water from the Rio Grande drainage basin probably would have to be obtained before the waste water could be salvaged and exported from the Ambrosia Lake mining district to Gallup. However, waste water from the Church Rock mining district is being discharged into tributaries of the Puerco River, a drainage system that passes through the city of Gallup, and thus may be available under existing State laws and Interstate agreements.

Water salvaged from the current mining operations and (or) pumped from abandoned uranium mines constitutes the most readily available and dependable source of new ground water of relatively high quality for the city of Gallup. The legal right to utilize this water should be acquired if at all possible.

The total ground-water resources available in the Westwater Canyon aquifer and the characteristics of the aquifer should be determined as soon as possible. This is especially important since large quantities of ground water are now being wasted in the current mining processes. An evaluation of the aquifer system could be accomplished by: (1) monitoring the long-term effects of pumping in the aquifer by continuing to observe the water levels in the shaft of the abandoned Church Rock Mine located in sec. 17, T.16 N., R.16 W., (2) determining and maintaining a record of the quantity of water pumped from the aquifer, (3) relating the observed declines to the quantity of water pumped, (4) constructing a mathematical model of the Westwater Canyon aquifer system in this region and simulating the behavior of the aquifer under various conditions, and (5) verifying the mathematical model by pumping water from the abandoned Church Rock mine and observing the response of the aquifer system to the imposed stresses. Further recommendations for both conservation and use of the water available should be made following the construction of a mathematical model that accurately represents the Westwater Canyon aquifer.

The quality of water produced from aquifers of several geologic ages within the vicinity of Gallup frequently does not meet the standards for human consumption recommended by the U.S. Public Health Service. The possibility of treating the water to improve the quality rather than searching for new sources of water should be evaluated as a practical method of obtaining supplies of potable water in this area.

Ownership, control, and (or) regulation of the ground water are factors of major importance in this area. These elements should be considered in planning any ground-water exploration program.

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