Geology and Ground Water in the Central Part of Apache County, Arizona

By J. P. AKERS

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By J. P. Akers

ABSTRACT

The central part of Apache County, Ariz., includes an area of about 3,300 square miles between the Navajo Indian Reservation to the north and U.S. Highway 60 to the south. Sedimentary rocks in the area range from Pennsylvanian to Quaternary in age and from 2,000 to more than 6,000 feet in thickness. The strata were tilted to the northeast, and part of the Upper Triassic and all the Jurassic and Lower Cretaceous rocks were eroded away before strata of Late Cretaceous age were deposited. Basaltic lava flows and cinder cones, representing four general periods of eruption in late Miocene to Quaternary time, are widespread in the southern part of the area.

Pennsylvanian and Permian rocks overlie basement rocks of granite and diorite and include the Supai Formation, the Coconino Sandstone, and the Kaibab Limestone. The Supai Formation is 1,000 to 2,000 feet thick and consists of interbedded red and brown mudstone, siltstone, sandstone, limestone, and evaporites. It contains water of very poor quality outside Apache County. The Coconino Sandstone is 200 to 250 feet thick and consists of light-gray fine- to medium-grained sandstone. It contains water suitable for domestic use in the south and water unsuitable for most purposes in the north. The Coconino Sandstone underlies all central Apache County in the subsurface. The yellowish-gray to dark-gray Kaibab Limestone is present in the southern two-thirds of the area and is 0 to 350 feet thick. It contains water where it is fractured and combines with the Coconino Sandstone to form a single hydrologic unit that yields from 6 to 74 gpm (gallons per minute) of water per foot of drawdown.

An unconformity separates the Permian rocks from the overlying Triassic rocks, which comprise the Moenkopi and Chinle Formations and the Wingate Sandstone. The Moenkopi Formation is 35 to 250 feet thick and consists of intercalated brownish-red siltstone, sandstone, and conglomerate. It contains salty water in some areas but is dry in most. The Chinle Formation is 0 to 1,550 feet thick and unconformably overlies the Moenkopi. The Chinle consists of multicolored claystone, mudstone, siltstone, sandstone, and conglomerate. Some of the sandstone units yield small amounts of water, usually of a quality unsuitable for domestic use. The Wingate Sandstone is about 250 feet thick and is present only in the extreme northeastern corner of the area. It consists of intercalated, reddish-brown sandstone and siltstone and does not contain water.

The Upper Cretaceous rocks comprise the Dakota Sandstone, from 50 to 115 feet thick; the Mancos Shale, about 150 feet thick; and the Mesaverde Group, as much as 200 feet thick. These rocks consist of yellowish-gray, light-green, and

reddish-brown sandstone and carbonaceous siltstone. Some of the sandstone units contain water of suitable quality for domestic use, and wells in these units yield from 10 to 1,000 gpm.

Sedimentary rocks of Eocene(?) age are about 800 feet thick and unconformably overlie Cretaceous rocks. They consist of light-brown and medium-red conglomerate, sandstone, and siltstone. These sedimentary rocks contain small amounts of water suitable for domestic use and yield from 10 to 25 gpm in the Springerville area. The Datil Formation of Miocene(?) Tertiary age consists of more than 800 feet of sedimentary rocks, which are composed largely of volcanic fragments. The Datil Formation does not contain water in the one small area where it crops out.

The Bidahochi Formation of Pliocene age consists of 0 to 800 feet of white, green, and brown claystone, mudstone, and sandstone. Locally it yields from 10 to 50 gpm of water suitable for domestic use.

Quaternary rocks consist of as much as 500 feet of alluvium, sand, gravel, travertine, cinders, and lava. The alluvium along the large drainages contains water that differs in quality from place to place. In most areas where it occurs, the lava contains water generally suitable for domestic use.

The Coconino Sandstone and Kaibab Limestone, the best aquifers in the area, receive recharge directly from precipitation where they crop out south of the area near the Mogollon Rim and indirectly from overlying Cretaceous rocks and lava of Tertiary and Quaternary age. The water moves northward toward points of natural and artificial discharge. Water in the Coconino and Kaibab occurs under confined and unconfined conditions. The water in the northern half of the area is probably contaminated by highly mineralized water that leaks upward from the Supai Formation.

The other main aquifers—Cretaceous rocks, Bidahochi Formation, and lava—are recharged locally, and the water they contain moves downgradient along the contact with underlying impermeable rocks toward points of natural discharge.

INTRODUCTION

PURPOSE, COOPERATION, AND ACKNOWLEDGMENTS

The need for adequate information on source, occurrence, quantity, quality, movement, and use of ground water has become increasingly apparent in Arizona during the last two decades. Because such information is basic to the establishment of sound policies governing exploitation of ground-water resources, the Arizona State Legislature in 1939 appropriated funds to begin the study of the ground-water basins in the State. The present study, begun in June 1956, was made by the U.S. Geological Survey in cooperation with the Arizona State Land Department. Special thanks are given to the ranchers, farmers, drillers, and other citizens of Apache County who granted permission to work on their property and who contributed from their knowledge of the area.

LOCATION AND ACCESSIBILITY

The area investigated covers about 3,300 square miles in northeastern Arizona and is entirely in Apache County. The area is bounded on the east by the Arizona-NewMexico State line, on the west by the Navajo-Apache County line, on the north by the Navajo Indian Reservation, and on the south by U.S. Highway 60 (fig. 1).

U.S. Highways 60, 66, 260, and 666 and State Route 61 provide excellent access to the communities in the central part of Apache County, and secondary and ranch roads provide fair-weather access to nearly any spot in the area. The Atchison, Topeka and Santa Fe Railroad parallels U.S. Highway 66, but there is no railroad station in Apache County.

FIELDWORK

The original geologic and hydrologic data were plotted on aerial mosaics at a scale of 1:32,680 and transferred to the Army Map Service topographic base map at a scale of 1:250,000. An inventory of the wells and springs was made, and most of them were visited. Wherever possible, water levels in the wells were measured, either

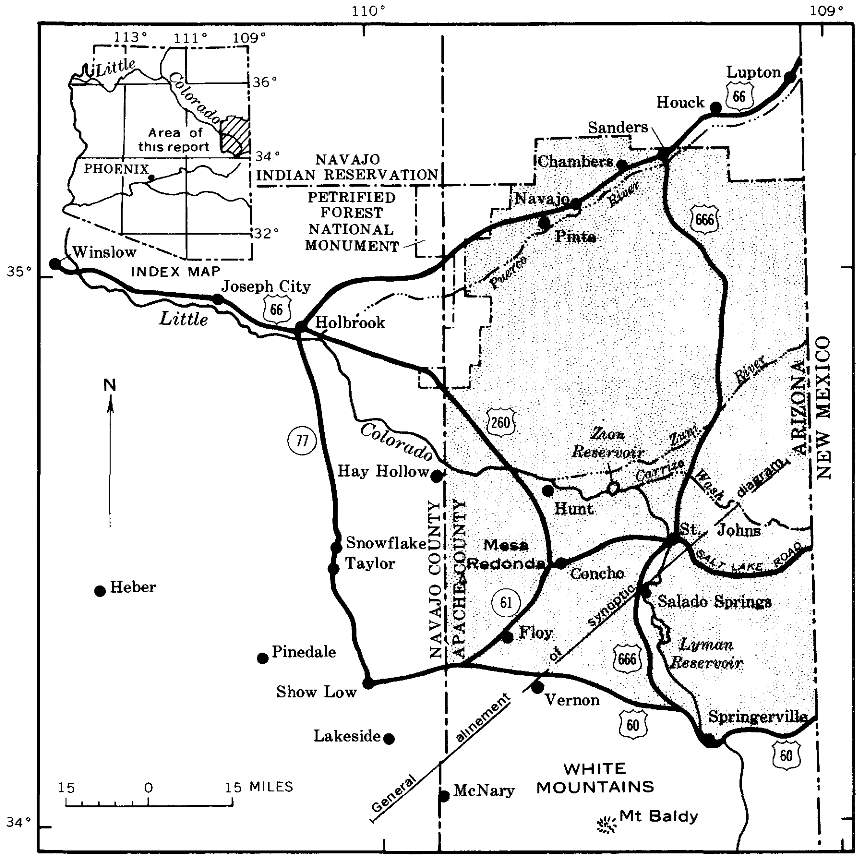

FIGURE 1.—Map showing central part of Apache County and adjacent areas.

by tape or electrical probe, but for some wells the hydrologic data were obtained from the owners or drillers. Controlled pumping tests were made on two wells near St. Johns, and the data obtained from these tests are given in the section entitled "Ground water."

The discharge of the larger springs was measured, and that of some smaller springs and seeps was estimated. Most stream discharge measurements were obtained from records of the Surface Water Branch of the U.S. Geological Survey.

The altitudes of many wells were obtained from U.S. Geological Survey topographic maps; others, mostly in the area south of St. Johns, were obtained by surveying altimeters.

Profiles of the structural sections (pl. 1) were compiled from altitudes obtained by surveying altimeters and from altitudes of bench marks established by Federal and State agencies. The thicknesses of the strata were determined from well logs and stratigraphic sections.

During the investigation, water samples were collected for chemical analysis; although a water sample was not collected from each well, those collected are probably representative of the aquifers locally. Chemical analyses were made by the Geological Survey. Some of the data presented (table 5) were taken from chemical analyses obtained by Harrell and Eckel (1939).

WELL-NUMBERING SYSTEM

The location of wells visited in the field were plotted on aerial mosaics of the U.S. Soil Conservation Service, which assigned numbers to the individual 15-minute quadrangles. Wells within the quadrangles were numbered in the sequence in which they were visited in the field. The position of a well within a quadrangle is designated by the number of miles it lies west and south of the northeast corner. Thus, a well referred to in the text as 237–1(9.65×3.45) would be well 1, 9.65 miles west and 3.45 miles south of the northeast corner of quadrangle 237. Oil-test wells are similarly numbered, but the number representing the sequence in which the wells were visited is followed by the letter "T." For example, a wildcat well drilled 15 miles northeast of St. Johns on the Zuni anticline is numbered 217–1T(14.3×3.4). Springs are designated by the letter "S," as in 237–S4(9.15×14.50).

PREVIOUS INVESTIGATIONS

The ground-water conditions in the central part of Apache County were described briefly in a regional report by Harrell and Eckel (1939), and some of their data are included in this report. Ground-water investigations in two adjoining areas—the Snowflake-Hay Hollow area (Johnson, 1962) and the Navajo Indian Reservation (Harshbarger and others, 1953; Akers and Harshbarger, 1958)—provided data on geology, the occurrence of ground water, and chemical quality of water.

The geology of several areas in the central part of Apache County is the subject of several University of Texas unpublished masters' and doctoral theses. The geologic map (pl. 1) of the area east of U.S. Highway 260 and State Route 61, south of Wahee Wash, and north of U.S. Highway 60 is, in part, modified from maps accompanying these theses (Crutcher, 1956; Green, 1956; Maar, 1956; O'Brian, 1956; Rehkemper, 1956; Robertson, 1956; Rutledge, 1956; Sirrine, 1958; Smith, 1956; Underwood, 1956; Woodyard, 1956).

The Triassic stratigraphy of the central part of Apache County is described in detail in an unpublished master's thesis by M. E. Cooley (1957).

GEOGRAPHY

PHYSIOGRAPHY

The central part of Apache County is in parts of the Navajo and Datil sections of the Colorado Plateaus physiographic province (Fenneman, 1931). It is part of the structural subdivision called the Mogollon slope (Kelley, 1955), a broad homocline that extends from the Mogollon Rim on the south to Black Mesa basin and the Defiance uplift on the north. The regional dip of the strata is northeast, and the general slope of the land surface south of the Little Colorado River is to the north. In the northern part of the area the land slopes south to the Little Colorado River and northwest to the Puerco River from a high that extends diagonally southwestward across the area between the two rivers. The altitudes range from 5,200 feet at the junction of the Little Colorado River and the Apache-Navajo County line to more than 7,800 feet in the extreme southeastern part of the area. Generally, the altitudes along the Arizona-New Mexico State line are above 6,500 feet, whereas in the rest of the area the altitudes usually range from about 5,300 to 5,800 feet.

The southern part of central Apache County is characterized by an irregular topography formed by lava-capped mesas, cinder cones, and deep canyons (fig. 2). The area includes the northern flank of the White Mountains, which are in the Datil lava field. The middle and northwestern parts of the area consist of badlands, broad valleys, retreating escarpments, and extensive flat, mesalike highlands whose summits show general accordance and levels of ancient erosion surfaces carved on soft underlying sedimentary rocks. The northeastern part of the area, except along the Puerco River, is a broad, relatively flat sandy plain generally above an altitude of 6,500 feet.

FIGURE 2.—Quaternary cinder cone along U.S. Highway 60 about 6 miles north of Springerville. Dark rock in foreground is blocky lava of Quatenary age.

CLIMATE

The climate and precipitation of central Apache County vary considerably with altitude. The Mogollon Rim and the high volcanic centers of the White Mountains form a barrier to the moisture-bearing winds. As a result, the southern part of the area receives more precipitation than the northern part. The weather station in the southern part of the area at Springerville has an altitude of 6,964 feet, an annual mean temperature of 48.7°F, and an average annual precipitation of 12.11 inches; the station at St. Johns has an altitude of 5,730 feet, an annual mean temperature of 52.4°F, and an average annual precipitation of 11.59 inches; the station at the Petrified Forest National Monument has an altitude of 5,460 feet, an annual mean temperature of 65.6°F, and an average annual precipitation of 8.87 inches.

The climatic conditions as recorded by the U.S. Weather Bureau since 1912 at St. Johns are typical of most of the area. Rain measuring 0.10 inch or more falls on an average of 32 days a year, and about 50 percent of the annual rainfall takes place during July, August, and September. Snowfall occurs from November to May and averages 21.6 inches a year or about 15 percent of the total precipitation. July is the warmest month with an average temperature of 73.1°F, and January is the coldest month with an average temperature of 32.3°F. The maximum recorded temperature was 104°F in July 1923, and the minimum was 22° below zero in January 1937. The average dates of the first killing frost on October 8 and the last on May 12 give a growing season of 146 days.

Most of the winter precipitation is a low-energy type, and a relatively large amount percolates into the soil and may eventually reach the ground-water reservoir. Most of the summer rains fall in high-energy storms of short duration resulting in rapid runoff and little recharge. The protective cover of vegetation and soil at the higher altitudes tends to restrict rapid runoff and gives more chance for recharge to ground water.

DRAINAGE

The Little Colorado River is the master stream, and its level is the base level for all other streams in the region (pl. 1). Rising in the high forested White Mountains, the stream flows north to St. Johns and thence generally northwest to the county line. The stream is perennial above and intermittent below St. Johns. From Springerville to the Navajo-Apache County line, about 85 river miles, the average gradient is 20 feet per mile. The Little Colorado River drains an area above the U.S. Geological Survey's stream gaging station at the junction of the river and U.S. Highway 260. The drained area covers 6,280 square miles, of which about 870 square miles is in New Mexico, and has altitudes ranging from 11,500 feet at Mount Baldy to about 5,200 feet at the Navajo-Apache County line.

The average annual discharge of the Little Colorado River above Lyman Reservoir in the 17-year period 1940–57 is 18.7 cfs (cubic feet per second), or 13,540 acre-feet per year, and the median of yearly discharge is 14 cfs, or 10,100 acre-feet (U.S. Geol. Survey, 1959). The average annual discharge for the 21 years in the periods 1929–33 and 1940–57 near Hunt below Zuni River is 19.0 cfs or 13,760 acre-feet per year, and the median of yearly discharge is 12 cfs or 8,700 acre-feet. Table 1 shows the average annual discharge, maximum discharge, and minimum discharge of the Little Colorado River at selected gaging stations in the central part of Apache County.

TABLE 1.—*Average annual discharge, maximum discharge, and minimum discharge of the Little Colorado River at selected gaging stations in the central part of Apache County, Ariz.*

[Data from U.S. Geol. Survey Water-Supply Paper 1513]

Station	Drainage area (square miles)	Years of record	Average annual discharge (cfs)	Maximum discharge (cfs)	Minimum discharge (cfs)
Above Lyman Reservoir, below Coyote Creek	747	1940–57	18.7	16,000	0
St. Johns	940	1929–33 1935–39	7.52	2,100	0
Near Hunt above Zuni River	3,680	1940–50	6.72	1,100	0
Near Hunt below Zuni River	6,280	1929–33 1940–57	19.0	8,000	0

The main tributaries of the Little Colorado River in the central part of Apache County are Coyote Creek, Carrizo Wash, and the Zuni River from the east, and Big Hollow and Concho Creek from the south. The Puerco River, another main tributary, cuts across the northern part of the area and joins the Little Colorado River at a point about 2 miles from Holbrook. Smaller tributaries are Beaver Dam Draw and Milky Wash from the north and Oso Draw from the south. Only Coyote Creek contributes perennial water, which is obtained from springs issuing from lava, and its base flow is probably less than 1 cfs. In central Apache County the tributaries on the south and west side of the Little Colorado River have steeper gradients and are shorter than those on the north and east side. The average gradient of the tributaries from the south is about 58 feet per mile compared with about 43 feet per mile for the tributaries from the north. The difference in gradient has resulted from the northeastward tilting of the beds on the Mogollon slope.

The Little Colorado River and its tributary streams are subject to flash flooding in the rainy season, and a dry wash may become a torrent in a matter of minutes. During these floods the water incises deeply into the soft formations along the stream courses and becomes heavily laden with sediment. Studies made by the U.S. Bureau of Reclamation (1955) show that in the 44 years beginning in 1908 about 22,700 acre-feet of sediment has been deposited above Zion Dam 8 miles upstream from Hunt.

In contrast with its tributaries which have formed many arroyos, the Little Colorado River has formed arroyos in only a few places. Between Lyman Dam and a point 4 miles upstream from St. Johns and also near Springerville the river flows in a shallow channel less than 5 feet deep. In this stretch, the channel is less than 50 feet wide and is bordered by willows, cottonwoods, and salt grass. Here, the river is perennial because it is sustained by large springs. The resultant dense vegetal cover has retarded stream erosion which is so prevalent in other parts of central Apache County.

Many small areas of interior drainage occur in isolated localities on the lava-capped platforms south of St. Johns and Concho and in the highlands between the Zuni River and Puerco River. These areas generally are small circular depressions, less than a mile in diameter, and contain ephemeral lakes.

Zion and Lyman Dams, large earthen structures, have been built across the Little Colorado River, and Concho Dam, a small earthen structure, has been built across Concho Creek. The original dam at Zion Reservoir was built in 1902–05 but was destroyed by a flood when almost completed; a second dam at the same site was finished in

1908. The reservoir had a capacity of 12,896 acre-feet and a surface area of 2,048 acres in 1908, but silting had reduced the capacity to 760 acre-feet by 1952. Continued silting has so reduced the capacity that the reservoir is no longer usable.

The other large dam forms Lyman Reservoir about 20 miles upstream from Zion Dam and about 9 miles due south of St. Johns. It washed out in 1915 and was rebuilt in 1920. The capacity of the reservoir is 20,600 acre-feet, and the drainage area above the reservoir is about 790 square miles. The maximum storage between the years 1940 and 1957 was 25,500 acre-feet in May 1941. In recent years the reservoir has been dry several times because runoff was low and the water was released for irrigation.

VEGETATION

Most of central Apache County is in the upper Sonoran floral life zone, which at this latitude is between 4,000 and 7,000 feet in altitude, and receives an average annual precipitation of between 12 and 18 inches (Sumner, 1945). The part above 7,000 feet is in the Transition zone.

The Sonoran zone is characterized by piñon, pine, juniper, scrub oak, and sagebrush. Piñon, pine, and juniper are the only indigenous trees in large areas in Apache County, and they grow mainly in well-drained rocky or sandy soil. A few scrub oaks grow in shady places on the north sides of cliffs. Sagebrush plains and dry wastelands cover large areas where there is insufficient soil moisture to support piñon and juniper. Phreatophytes—such as cottonwood, tamarisk, and willow—grow along washes which have shallow underflow.

Ponderosa pine is predominant in the Transition zone. Between Springerville and Show Low, a few Ponderosa pine, remnant of a lower extension of the Transitional zone, grow on a ridge in the Carrizo Creek drainage basin near the Arizona-New Mexico State line.

Most of the soil formed on cinders is tight and is devoid of trees, although it contains good stands of grass. The habitat of the various range grasses and forage shrubs—as related to topography, soil, and geologic formations—is shown in figure 3.

INDUSTRY AND POPULATION

Cattle raising is the most important occupation in the area, although considerable farming is done near Springerville, St. Johns, and Hunt. In 1955 about 15,900 acres was under cultivation; the crops were mostly alfalfa and grains (Barr, 1956, table 6).

Lumbering and other associated industries are also important to the area. A sawmill at Eager just south of the report area processes

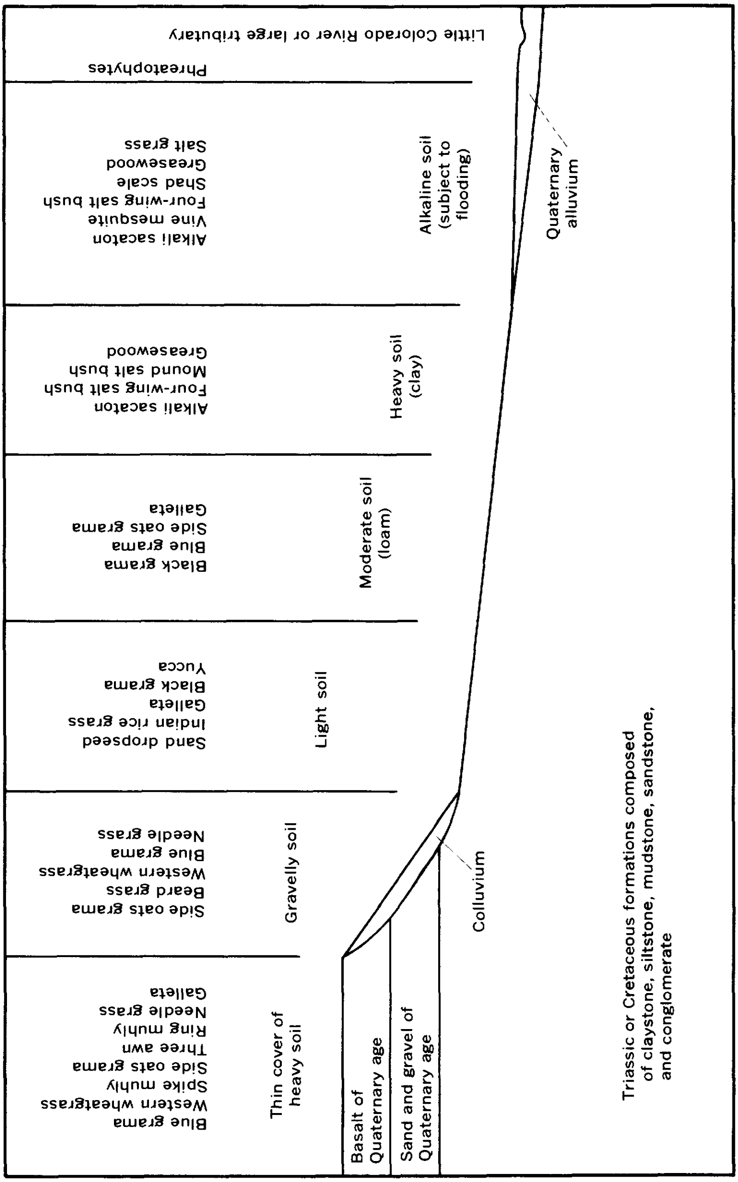

Chart compiled by Paul Ellsworth, U.S. Soil Conservation Service, and J. P. Akers

FIGURE 3.—Typical habitat of range grasses and forage shrubs, as related to topography, soil, and geologic formations in the central part of Apache County, Ariz.

timber cut in Ponderosa pine and spruce forests in the White Mountains, and a planing mill and box factory are in operation at St. Johns.

During 1955–57 a few tons of uranium ore was produced from the Chinle Formation near Hunt and east of St. Johns, but mines were inactive in 1962. Some development work was done recently on a manganese deposit in the Chinle Formation north of the St. Johns-Salt Lake road near the Arizona-New Mexico State line, but the grade of the ore discouraged exploitation.

In recent years several wildcat wells have been drilled because of increased interest in oil and gas exploration in the central part of Apache County. Most of the wells were drilled on anticlines located by surface mapping, but some were drilled on the basis of data obtained by geophysical methods. Shows of oil were reported in several wells, but up to 1960 no production had been obtained. Several wells in the northern part of the area near Navajo produce gas containing a high percentage of helium from the Coconino Sandstone.

The population of Apache County averages less than three persons per square mile, but in the area of this report the average probably is even less. The only communities of any size are Springerville, which has a population of 714 persons, and St. Johns, which has a population of 1,291 persons, according to preliminary estimates based on the 1960 census. The rest of the population lives at widely scattered ranches and at tourist centers along U.S. Highway 66.

GEOLOGY

GEOLOGIC HISTORY

Deposition in the central part of Apache County during the Paleozoic Era was controlled on the west by the Cordilleran geosyncline, which extended from Canada to Mexico through southwestern Utah and southern Nevada, and on the north by a positive area, the Defiance dome (McKee, 1951). The area is partly on the southern part of the Defiance dome (fig. 4), which is underlain by a residual mountain mass composed mostly of pink granite of Precambrian age.

A relatively stable shelf area extended between the geosyncline and the positive area. Seas from the geosyncline periodically encroached upon the shelf, and several thousand feet of marine and nearshore marine deposits accumulated on the shelf. These deposits thin and pinch out eastward against the flank of the positive area; so, deposits older than Late Pennsylvanian are not represented in central Apache County.

Conditions of deposition remained relatively stable until Middle Pennsylvanian or Early Permian time when the Uncompahgre-San Luis uplift occurred, affecting east-central Utah, southern Colorado,

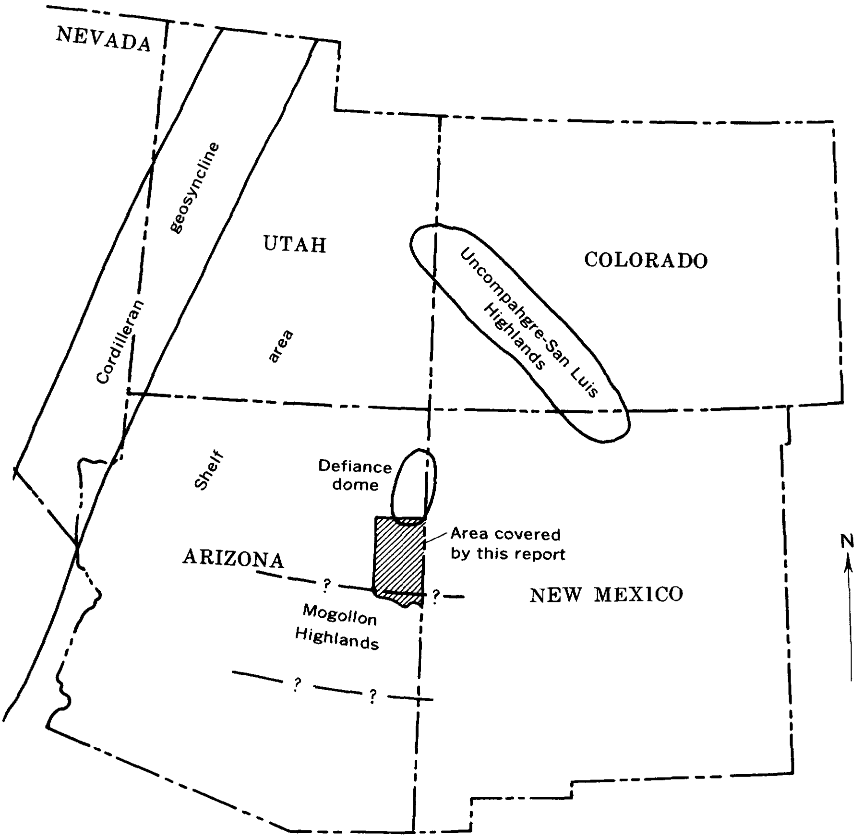

FIGURE 4.—Map showing approximate locations of highland areas and the Cordilleran geosyncline in Paleozoic and part of Mesozoic time.

and north-central New Mexico. The positive areas thus formed furnished sediments to surrounding low areas during remaining Paleozoic time. The Defiance dome remained positive during this time, but there is no evidence that it furnished much sediment to the basins.

By Early Permian time either flood-plain building in the depositional basin or broad, gentle regional uplift had caused retreat of the seas toward the Cordilleran geosyncline, and the continental red beds and evaporites of the upper part of the Supai Formation were deposited. These sediments buried the Defiance dome, perhaps for the first time. Advancing eolian sands, represented by the Coconino Sandstone, covered the red beds later in Early Permian time.

Apparently, slight uplift occurred in the Defiance dome north of the report area just prior to the last transgression of the Cordilleran seas in Paleozoic time. This uplift is reflected in the distribution, thickness, and lithology of the Kaibab Limestone of Leonard age.

The Kaibab thins out in an irregular arc extending from the eastern edge of Winslow to Show Low Creek and then northeastward across most of central Apache County (fig. 5). Nearness to a landmass is suggested in areas near the edge of the arc where the Kaibab becomes more sandy and includes numerous lenses and beds closely resembling the Coconino Sandstone.

Conditions controlling deposition at the beginning of the Mesozoic Era were somewhat different from those of late Paleozoic time. The Cordilleran geosyncline was still present to the west, and a part of the Defiance dome remained higher than the surrounding terrain (McKee, 1954, p. 76–77). However, recurrent uplift occurred in the areas to the northeast, and a new highland area, the Mogollon Highlands (Harshbarger and others, 1957, p. 44), began to form in east-central Arizona. The uplift was gentle at first but later increased, starting vigorous erosion of the highland areas and deposition of the Moenkopi Formation of Early and Middle(?) Triassic age.

The sediments forming the Moenkopi Formation were transported through wide valleys formed between the Defiance dome and the Uncompahgre-San Luis Highlands to the north and the Mogollon Highlands to the south. The valleys joined at the western edge of the Defiance dome to form a broad flood plain extending west-northwestward to the margins of the Cordilleran geosyncline. The earliest Moenkopi deposition began in the geosyncline, and later deposition moved eastward to form an overlapping sequence up the flood plain and valleys. The central part of Apache County is relatively near the southern source area in the southern valley, and the sedimentary rocks representing the Moenkopi in this area are the youngest in the formation.

Deposition in the low areas and erosion of the high areas caused a general leveling of the Defiance dome and continued throughout Early Triassic time and perhaps into the Middle Triassic, after which the Moenkopi sediments were subject to widespread erosion. This erosion carved channels into the Moenkopi Formation and set the stage for Late Triassic deposition.

A broad depositional basin replaced the former valleys when vigorous renewed uplift took place in Late Triassic time in the Uncompahgre-San Luis Highlands and the Mogollon Highlands. The Mogollon Highlands became more prominent as a result of this uplift, and they were extended westward into central Arizona. The depositional basin between these highlands extended to the Cordilleran geosyncline. In his thesis Cooley (1957) showed that an integrated stream system existed in the basin during deposition of the coarse-grained Shinarump Member of the Chinle Formation of Late

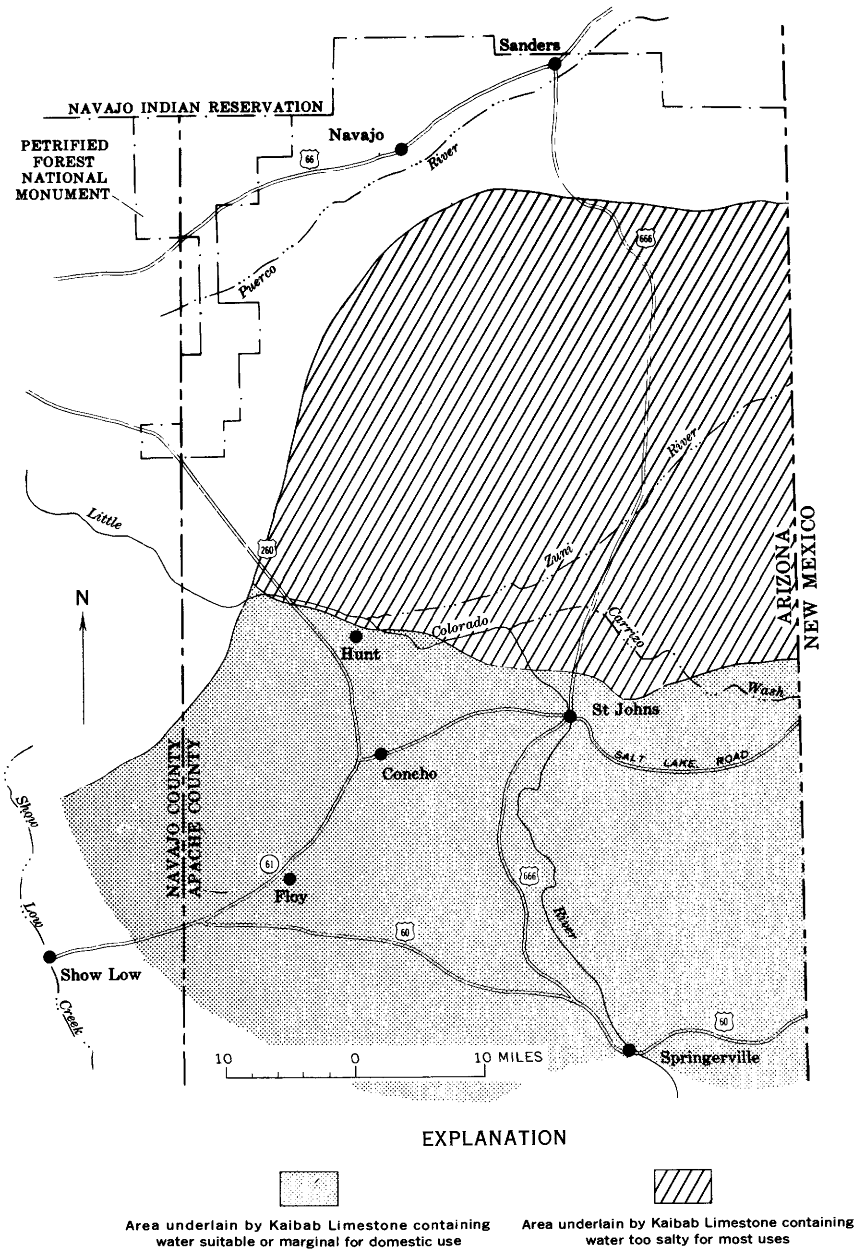

FIGURE 5.—Map of the central part of Apache County, Ariz., and adjacent areas showing generalized distribution in the subsurface of the Kaibab Limestone and the quality of water the Kaibab contains.

Triassic age. Streams near the Mogollon Highlands in central Apache County were entrenched and flowed northeastward until they joined the main stream, which flowed northwestward through broad, flat lowlands enroute to the geosyncline.

The configuration of the depositional basin remained nearly the same during the deposition of the Petrified Forest Member of the Chinle Formation. The fine-grained material suggests, however, that the stream velocities were greatly reduced. The depositional basin was altered before the Owl Rock Member of the Chinle Formation was deposited. The change is reflected on the isopach map of the Chinle Formation (fig. 6) and by the pinch out of the Owl Rock Member in the St. Johns-Zuni Pueblo area. Figure 6 shows that the axis of the depositional basin had shifted from northwest to northeast and that the Owl Rock deposition was restricted to an area approximately coinciding with the present Navajo Indian Reservation.

The shift began while the Cordilleran geanticline was formed in place of the geosyncline (Eardley, 1951, p. 21–23). The geanticline became a barrier which dammed the northwest drainage and caused rather extensive bodies of still water to form. The limestone and calcareous siltstone units in the Owl Rock Member of the Chinle Formation and the overlying Rock Point Member of the Wingate Sandstone were deposited in these bodies of water.

During the latest Triassic time, the basin remained unchanged (Harshbarger and others, 1957, p. 25); but through-flowing streams drained southwestward, possibly through a gap between the rising Cordilleran geanticline and the Mogollon Highlands.

Jurassic rocks are not present in the central part of Apache County, and the history of the Jurassic in this area is not known. However, Harshbarger and others (1957, p. 44) showed that an uplift, called Mohavia by Eardley (1951, pl. 13), bridged the gap between the Cordilleran geanticline and the Mogollon Highlands in Early Jurassic time and became an important source for Upper Jurassic sediments. The arrangement of positive areas during this time resulted in the formation of a wide trough that extended northward into a marine basin in northern Arizona and southern Utah. Central Apache County is to the south of the marine basin, and there is no evidence that marine sediments were deposited during the Jurassic Period in the area. Jurassic rocks in this area probably formed from fluviatile and eolian sediments similar to those in the southern part of the Navajo Indian Reservation.

Renewed uplift in the Mogollon Highlands, probably in Early Cretaceous time, slightly tilted the previously deposited formations, and pre-Late Cretaceous erosion removed the entire Jurassic in central Apache County.

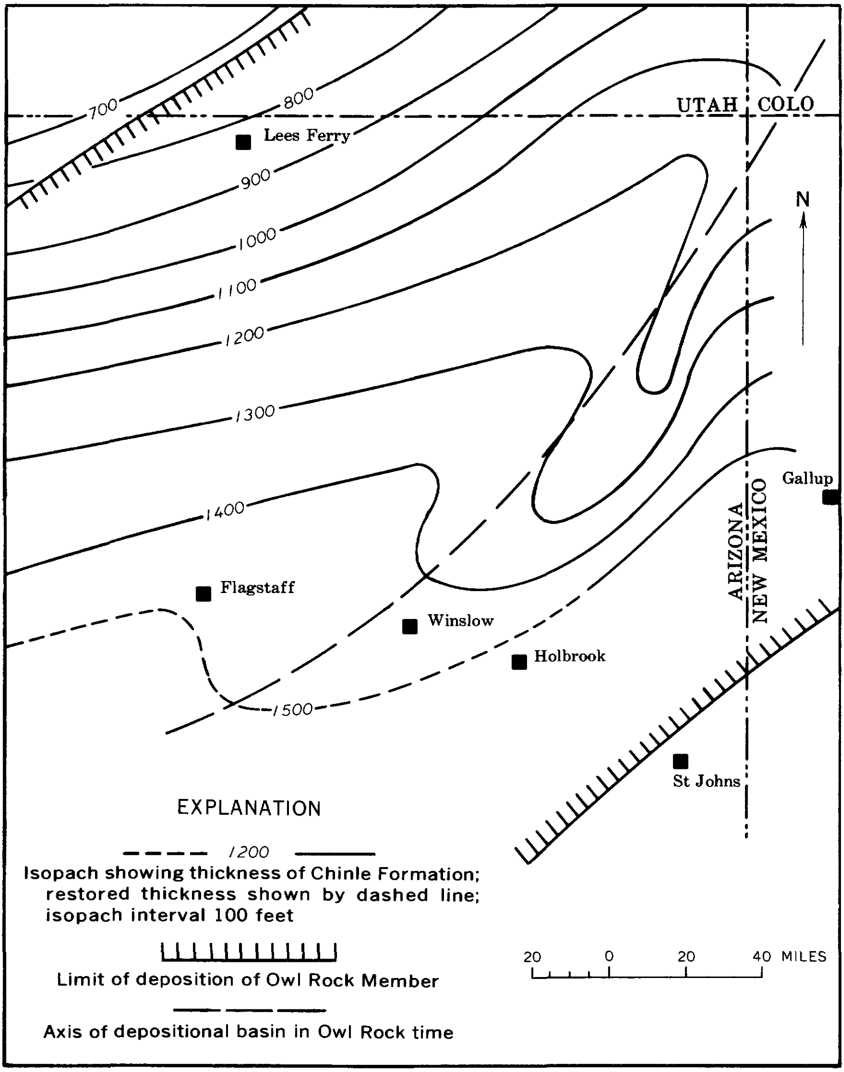

FIGURE 6.—Isopach map of the Chinle Formation in northeastern Arizona, showing limit of deposition of the Owl Rock Member of the Chinle Formation and axis of depositional basin in Owl Rock time. After Akers, Cooley, and Repenning (1958) and Cooley (1959).

This period of erosion ended with the deposition of the fluviatile basal unit of the Dakota Sandstone at the edge of a sea advancing from the northeast in Late Cretaceous time. This advance was one of several advances and retreats of Late Cretaceous seas which resulted in a succession of continental shale, sandstone, and coal beds intertongued with marine shale and sandstone beds. These deposits are represented by the Dakota Sandstone, the Mancos Shale, and the

Mesaverde Group. The final retreat probably took place during renewed uplift in the Mogollon Highlands at a time concurrent with the Laramide orogeny, which outlined the present structure in the Colorado Plateaus.

The Cretaceous deposits were overridden by coarse materials eroded from the uplifted areas. These coarse materials are mainly of early Tertiary age and are shown on the geologic map (pl. 1) as sedimentary rocks of Eocene(?) age. Volcanic activity in nearby areas resulted in deposition of the volcanic sediments of late(?) Tertiary age which gradationally overlie the Eocene(?) sedimentary rocks. Subsequently, erosion of these and older deposits began and continued until late Miocene time when changing structural conditions resulted in the formation of a rather extensive lake in which the lower member of the Bidahochi Formation was deposited in Pliocene time. In late Miocene to middle Pliocene time there was active volcanism in the San Francisco, Hopi Buttes, and White Mountains volcanic fields, and large quantities of volcanic rock were effused. In the San Francisco and White Mountains volcanic fields, this volcanism continued intermittently into Recent time. Some of the middle Pliocene flows of the Hopi Buttes field, the middle volcanic member of the Bidahochi Formation, are preserved in the northwest part of the report area.

Bidahochi Lake was drained in late Pliocene time, and the mainly fluviatile sediments of the upper member of the Bidahochi were brought in from eastern and southeastern sources and deposited by a stream system from which the present Little Colorado River drainage has developed.

After the deposition of the Bidahochi Formation, erosion, which initiated the early drainage patterns of the Little Colorado River, began in central Apache County. The several stages of development in the valley of the Little Colorado are represented by erosion surfaces which have been assigned to the Black Point (Gregory, 1917; Childs, 1948; Cooley, 1958a) and Wupatki surfaces (Childs, 1948; Cooley, 1958a). Near the Little Colorado River the Black Point surfaces were planed more than 300 feet, and the Wupatki surfaces were formed between 10 and 150 feet above the present river level. The Black Point surfaces were formed during late Pliocene and early Pleistocene time, and the Wupatki surfaces were formed during middle and late Pleistocene time (Childs, 1948; Cooley, 1958a).

The early streams on the Black Point surfaces drained to the north and centered beneath the northward projecting lobes of lava east of Hay Hollow, east of Concho, and east of St. Johns. Adjustment of the late Black Point streams to the lava flows accounts, in part, for the present position of the Little Colorado River, Carrizo Wash, and tributary streams draining the White Mountains area.

In central Apache County and elsewhere in the Little Colorado River drainage area, a general period of regional downcutting occurred between the planation of the Black Point and Wupatki surfaces. A lava flow in the valley of the Zuni River has preserved conditions that occurred between the formation of these erosion surfaces. Locally, however, along the northern and northeastern borders of the White Mountains volcanic field, downcutting of this period is not clearly differentiated because after the valleys were formed, they were filled with resistant layers of lava. Thus, several deposits of gravel, shown on the geologic map (pl. 1), in the St. Johns area represent late Black Point erosion and deposition on that surface. One such deposit in Richville Valley is between the Bidahochi Formation and the younger lava flow of Tertiary and Quaternary age.

The deposits overlying the Wupatki surfaces, shown on the geologic map (pl. 1), have been preserved as well-defined river terraces or as gentle slopes or pediments that outline the sides of the present flood plain of the Little Colorado, Puerco, and Zuni Rivers and other streams tributary to the Little Colorado. The material overlying the Wupatki surfaces consists of gravel near the Little Colorado River and silty or gravelly sand in other areas, and it is similar in lithology to the sediments on the Black Point surfaces.

The surface distribution of the geologic formations is shown in plate 1, and their age, lithologic description, thickness, and water-bearing properties are summarized in table 2.

STRATIGRAPHY

SEDIMENTARY ROCKS

Sedimentary rocks in the central part of Apache County range from Pennsylvanian to Quaternary in age, but rocks of the Jurassic System are missing. Rocks older than Crataceous are tilted to the northeast and have been beveled by erosion so that, in general, the older rocks crop out to the south. The rocks consist of sandstone, siltstone, mudstone, claystone, limestone, conglomerate, bedded pyroclastic material, unconsolidated sand and gravel, and evaporites and are from 2,000 to 6,000 feet thick. Granite, diorite, or quartzite of probable Precambrian age underlie the sedimentary rocks.

PENNSYLVANIAN AND PERMIAN ROCKS

Sedimentary rocks older than the Kaibab Limestone of Permian age are not exposed in the central part of Apache County. Oil-test wells, however, have penetrated about 1,900 feet of older rocks in the subsurface. These older rocks are the Supai Formation of Pennsylvanian and Permian age and the Coconino Sandstone of Permian age.

TABLE 2.—*Generalized section of sedimentary rocks in the central part of Apache County, Ariz.*

System	Series	Group or formation	Thickness (feet)	Lithologic and water-bearing character
Quaternary	Recent and Pleistocene		0–500	Alluvium, sand, gravel overlying river terraces, travertine, cinders, and lava. Contains water.
		—Unconformity—		
Tertiary	Pliocene	Bidahochi Formation	0–800	White to light-brown sandstone with minor beds of siltstone and white ash, and light-brown to greenish-gray claystone, mudstone, and siltstone with a few beds of bentonite. Includes lava in the northern part of the area. Contains water.
		—Unconformity—		
	Miocene(?)	Datil Formation	800+	Greenish-gray and reddish-gray mudstone, siltstone, sandstone, and conglomerate composed largely of volcanic fragments. Does not contain water in area of this report.
	Eocene(?)	Sedimentary rocks	800±	Light-brown to medium-red conglomerate, sandstone, and siltstone. Contains many pebbles and cobbles of quartzite, jasper, granite, gneiss, schist, and limestone. Contains water in Springerville area.
		—Unconformity(?)—		
Cretaceous	Upper	Undifferentiated: Mesaverde Group	200+	Yellow, light-green, and reddish-brown siltstone, sandstone, and conglomerate interbedded with gray siltsone and coal. Some sandstone beds contain water.
		Undifferentiated: Mancos Shale	150+	Yellowish to dark-gray siltstone with minor thin beds of yellow to light-brown fine- to medium-grained sandstone. Does not contain water.
		Undifferentiated: Dakota Sandstone	50–115	Yellowish-gray to light-brown sandstone with lenticular beds of conglomerate, carbonaceous siltstone, and coal. Contains water.
		—Unconformity—		
Triassic	Upper	Wingate Sandstone	250	Reddish-brown intercalated siltstone and sandstone beds. Does not contain water.
		—Unconformity—		
		Chinle Formation	0–1, 550	Multicolored claystone, mudstone, siltstone, sandstone, conglomerate, and limestone. Some sandstone units contain water, usually of poor quality.
		—Unconformity—		
	Middle(?) and Lower	Moenkopi Formation	35–250	Brownish-red intercalated siltstone, sandstone, and conglomerate. Contains water of very poor quality in some areas.
		—Unconformity—		
Permian	Lower	Kaibab Limestone	0–310	Yellowish-gray to dark-gray cherty and silty fossiliferous limestone with a few fine-grained sandstone beds. Contains water where sufficiently fractured.
		Coconino Sandstone	200–400	Light-gray to white, fine- to medium-grained sandstone. Major aquifer in area; contains salty water in some areas.
Permian - - - Pennsylvanian		Supai Formation	1, 000–2, 000	Red and brown mudstone, siltstone, sandstone, and limestone interbedded with evaporites. Some units contain salty water.
		—Unconformity—		
Precambrian		Basement rocks		Pink coarsely crystalline granite and diorite. Not known to contain water.

SUPAI FORMATION

The Supai Formation consists of interbedded red and brown sandstone, siltstone, mudstone, and limestone and of evaporite beds containing white to greenish-gray anhydrite, gypsum, and halite. The evaporite beds are present only in the upper 1,000 to 1,500 feet of the formation. The evaporite beds are probably equivalent to the Yeso Formation and the underlying red beds to the Abo Sandstone in western New Mexico.

The thickest known section of the Supai Formation, more than 2,600 feet thick, was penetrated by a wildcat well about 14 miles south-southwest of Holbrook in Navajo County. It is thinner in Apache County. In wildcat well 217–1T (14.3 × 3.4), 15 miles northeast of St. Johns, 1,600 feet of the Supai was penetrated. Its equivalents, the Abo Sandstone and Yeso Formation, are 1,640 feet thick in a wildcat well drilled about 20 miles east-southeast of St. Johns in Catron County, N. Mex.

The age of the Supai Formation has been considered by many workers (Noble, 1922; Huddle and Dobrovolny, 1945; Hughes, 1950, unpub. master's thesis; Winters, 1951; and Jackson, 1951), who agreed that the deposits are partly Pennsylvanian and Permian. Huddle and Dobrovolny (1945) stated that the Supai in central and northeastern Arizona probably ranges in age from Des Moines (Middle Pennsylvanian) to Leonard (Lower Permian).

The Supai Formation is not utilized as an aquifer in the central part of Apache County mainly because of its depth, but many of the sandstone beds within the Supai Formation, especially those near the top, are capable of storing and transmitting water and probably contain water in most of the area. However, the Supai Formation includes numerous beds of evaporite deposits, and south of Holbrook drillers have reported obtaining salt water from it. Therefore, water in the Supai probably would be too salty for most uses and, where it is under artesian pressure, might rise in wells to contaminate fresh water in the overlying formations. Near the Mogollon Rim, water in the upper sandstone beds in the Supai is under water-table conditions and is fresh.

PERMIAN ROCKS

COCONINO SANDSTONE

The Coconino Sandstone underlies the entire area. It does not crop out in central Apache County, although it is on the surface to the west between Holbrook and Snowflake. The sandstone is uniform in composition and consists of very pale orange to almost pure white quartz grains that are fine to medium, well sorted, and subangular to rounded. The quartz grains are clear and frosted and are bonded with firm to weak siliceous or calcareous cement. Where exposed, the Coconino characteristically displays large-scale wedge-trough crossbedding, considered typical of eolian deposits. It is extensively jointed in most outcrops, and partings generally along the crossbedding planes increase the permeability of the formation.

Logs of wells show that the Coconino Sandstone is about 250 feet thick in Carrizo Valley and about 200 feet thick in the Lupton area near U.S. Highway 66. It thickens toward the northwest to about 450 feet near Holbrook and toward the southwest to about 600 feet near Snowflake. Wildcat well 259–1T(5.0 × 6.0), about 11 miles east of Springerville, penetrated 205 feet of Coconino Sandstone.

Because the Coconino Sandstone has not yielded fossils diagnostic of age, its age has been established as Early Permian on the basis of its stratigraphic position between the Supai Formation, ranging from Middle Pennsylvanian to Lower Permian in age, and the Kaibab Limestone of Early Permian age. The Coconino Sandstone can be correlated in wells with the Coconino Sandstone of the Holbrook-Snowflake area and with surface exposures of the upper part of the De Chelly Sandstone on the Defiance Plateau. It is probably continuous in the subsurface to the east with the Glorieta Sandstone, which crops out in the Zuni Mountains northeast of the report area. The name Coconino is used in this report because the sandstone in the central part of Apache County is similar to the Coconino Sandstone to the west.

The Coconino Sandstone is the major aquifer in the southern part of the area and furnishes water to most of the deep wells. However, many drillers' references to "Coconino" actually refer to similar water-bearing sandstone beds in the overlying Kaibab Limestone. Rock closely resembling the Coconino Sandstone crops out in two areas about 3 miles east of Hunt; but these outcrops are underlain by beds of Kaibab Limestone, which in turn are underlain by the Coconino Sandstone. The same sequence of limestone and sandstone is reported in logs of wells drilled in Hunt, Concho, St. Johns, and near the Arizona-New Mexico State line. Sandstone beds in the Kaibab Limestone also are exposed in the Heber-Pinedale area (fig. 1).

KAIBAB LIMESTONE

The entire thickness of the Kaibab Limestone is not exposed in central Apache County but is known from logs of drilled wells. In fact, the formation crops out only in five small areas at the crests of anticlines. The most extensive outcrop and the most complete section are at the crest of the Cedar Mesa anticline, 4½ miles south of St. Johns (pl. 1), where 75 feet of limestone forms part of the walls of a small gorge along the Little Colorado River. Three stratigraphic units are recognizable in the Kaibab in this locality (fig. 7). The middle unit is separated from the upper and lower units by unconformities, which have a relief of 10 feet. The upper unit is composed of thin and thick flat beds of dense aphanitic to crystalline yellowish-gray to dark-gray magnesian limestone containing abundant marine fossils. The limestone, not including the silicified fossils, is 98 percent soluble (L. F. Brady, oral commun., 1960). The middle unit consists of about 10 feet of very calcareous siltstone and fine- to coarse-grained sandstone. This unit probably represents material deposited under nearshore conditions, as it contains small-scale crossbedding, angular granules of jasper and milky quartz, and has mud cracks on some bedding surfaces. The lower unit consists of thin- to thick-bedded dense dark-gray aphanitic limestone.

Two small exposures of the Kaibab Limestone are at the crest of small anticlines on either side of the Little Colorado River about 3 miles east of Hunt. Two sedimentary units are recognizable in the exposure north of the river. The upper unit consists of 15 feet of white to very pale orange sandstone composed of fine to medium well-sorted quartz grains. The lower unit consists of 15 feet of silty to sandy, yellowish-gray limestone which weathers to a pitted and "pockety" surface. Only the sandstone unit is exposed south of the river. The remaining two exposures, on the St. Johns anticline east of the Cedar Mesa anticline and on the Antelope Valley anticline northeast of Springerville, consist of light-gray sandy limestone.

FIGURE 7.—Three units in the Kaibab Limestone exposed at the crest of the Cedar Mesa anticline 4½ miles south of St. Johns, Ariz. Limestone (ls), siltstone and sandstone (si).

The Kaibab Limestone is 310 feet thick in well 237–1(10.0×3.4) 3 miles south of St. Johns, and 175 feet thick in a wildcat well 217–1T(14.3×3.4) 15 miles north-northeast of St. Johns. It is 0 to 80 feet thick in Hunt Valley and is not present at Snowflake.

The Kaibab Limestone in the Grand Canyon area has been divided into three members—Alpha, Beta, and Gamma—by McKee (1938) and has been assigned by him to the Leonard. Subsurface study indicates the limestone is continuous with the San Andres Limestone in west-central New Mexico. The Kaibab Limestone exposed in the Cedar Mesa anitcline contains "* * * quite a number of (invertebrate) species that are found in common with the Alpha member of the Kaibab, but several of the most distinctive Kaibab species are not found at all at the St. Johns' locality, where they are replaced by other forms that are unknown elsewhere" (N. D. Newell, written commun., 1960). The Kaibab Limestone in this area probably is the same age as the Kaibab to the west and the San Andres Limestone to the east, but it no doubt represents a different zoogeographic province.

The Kaibab Limestone is water bearing in most of the area where it is below the regional water table, and it furnishes water to some wells.

PRE-MOENKOPI UNCONFORMITY

The pre-Moenkopi unconformity, marked by an erosion surface of considerable relief, separates rocks of Permian and Triassic age in the central part of Apache County, as it does everywhere in the Colorado Plateaus. In the Cedar Mesa anticline the basal units of the Triassic Moenkopi Formation were deposited on the Kaibab Limestone, which had a karst topography. Some of the scours and potholes carved in the Kaibab are as much as 20 feet deep. They are filled with coarse angular rubble derived mainly from the Kaibab. The same conditions prevail north of the Little Colorado River east of Hunt, except that the scours and potholes were perhaps not as deep. In other areas the pre-Moenkopi relief was from 6 to 8 feet. Where the unconformity is exposed near Holbrook, it is an almost flat erosion surface which truncates the crossbeds of the Coconino Sandstone.

The time represented by this erosion interval is greater in the St. Johns area than it is to the northwest in southwestern Utah. McKee (1954, p. 24) showed that the Moenkopi Formation in the Navajo country is equivalent to only that part of the Moenkopi above the Virgin Limestone Member in southwestern Utah, and Poborski (1954, p. 993) presented evidence showing that the members of the Moenkopi above the Virgin Limestone Member may be Middle Triassic in age. Only the youngest member (Holbrook) of the Moenkopi Formation in the Navajo country is present in central Apache County. Thus, in central Apache County the time represented by the hiatus includes the Late Permian and probably most of the Early Triassic, whereas in southwestern Utah the time represented by the hiatus includes the Late Permian and only part of the Early Triassic.

TRIASSIC ROCKS

The Triassic rocks, chiefly the Chinle and Moenkopi Formations, cover most of central Apache County and have been eroded into badlands, which in many areas are devoid of soil or vegetation. The maximum preserved thickness of these rocks in the report area is about 1,600 feet. They are composed principally of siltstone and mudstone which, for the most part, are not water bearing. Some sandstone beds in these formations discharge ground water to a few small springs and yield minor quantities of water to drilled wells. The siltstone and mudstone beds confine the ground water in the underlying Kaibab Limestone and Coconino Sandstone.

MOENKOPI FORMATION

McKee (1954) named two members of the Moenkopi Formation in the valley of the Little Colorado River between Cameron and Holbrook. These are, in ascending order, the Wupatki and Moqui Members, which underlie the Holbrook Member previously named by Hager (1922). The members of the Moenkopi Formation overlap from southern Utah toward the southeast in the valley of the Little Colorado River. The extreme eastern edges of the Wupatki and Moqui Members extend only into the northwestern edge of central Apache County, whereas the Holbrook Member is present in the entire area (fig. 8).

Wupatki and Moqui Members

The basal member, the Wupatki, at the western edge of central Apache County is chiefly a reddish-brown sandstone less than 30 feet thick. The sandstone is silty and is composed of very fine and fine-grained sand which is bonded by a moderately firm calcareous cement. The Moqui Member consists of about 20 feet of mudstone, siltstone, and some silty very fine to fine-grained sandstone. The member is thin to thick bedded, and the layering is lenticular. Lenticular and nodular masses of gypsum and casts of salt crystals have been observed in the Wupatki and Moqui Members. Solution of salts in the sediments may have detrimentally affected ground water in the Moenkopi Formation and, in places, in the underlying Coconino Sandstone.

Holbrook Member

The type section for the Holbrook Member of the Moenkopi Formation is near Holbrook, where it consists of about 50 feet of pale-red, pale-yellowish-brown, and yellowish-gray lenticular sadnstone and

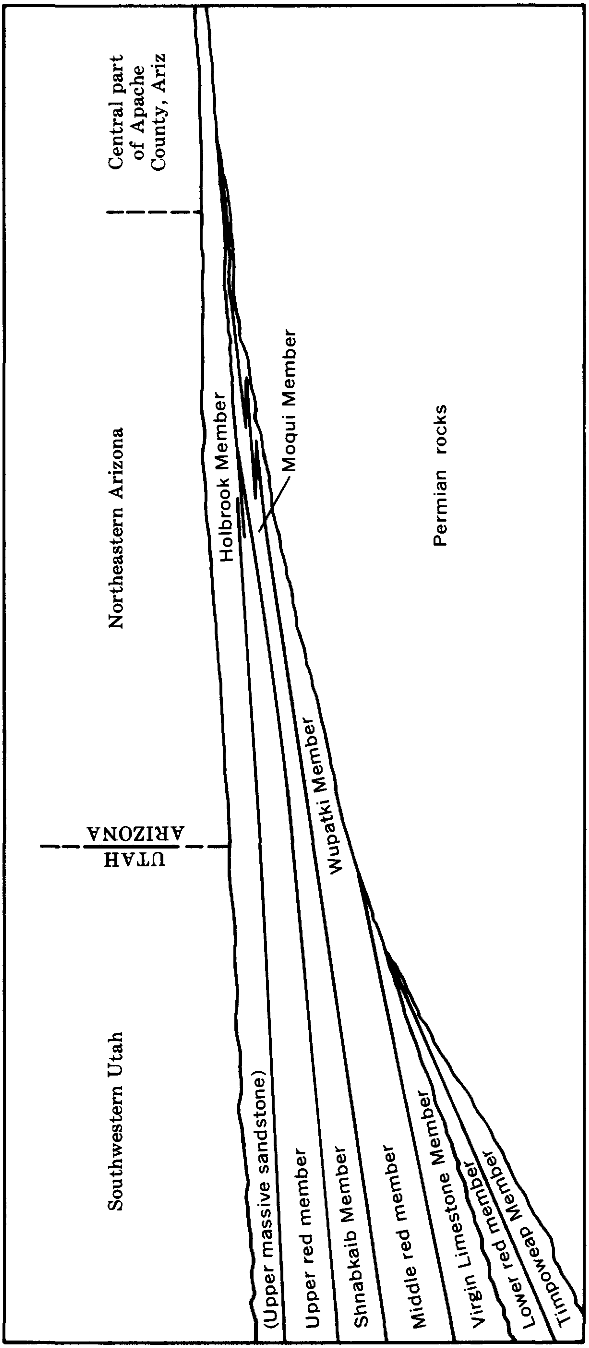

FIGURE 8.—Diagrammatic sketch showing relation of the Holbrook Member to the other members of the Moenkopi Formation in southwestern Utah and northeastern Arizona. Modified from McKee (1954, p. 24).

conglomerate intercalated with pale-reddish-brown mudstone and siltstone lenses. The sandstone units are composed of poorly sorted very fine to medium-grained quartz and biotite and other black accessory minerals firmly bonded with calcareous cement. The conglomeratic units are composed of angular to rounded limestone and of chert pebbles and mud pellets in a fine to very coarse sand matrix. Small- to medium-sized crossbeds of the trough type deposited at a low to medium angle are common in the sandstone and conglomerate units. The member weathers to form a ledgy cliff.

In the central part of Apache County the lithology of the Holbrook Member is similar to that of the type section. Near the junction of U.S. Highway 260 and the Little Colorado River the member consists of more than 100 feet of lenticular and wedge-shaped units of sandstone, conglomerate, and siltstone. A 15- to 20-foot thick conglomeratic sandstone unit is conspicuously exposed here and has been confused with the Shinarump Member of the Chinle Formation, although it occurs in the middle of the Holbrook Member. This sandstone unit is also present in a large area south and southwest of Hunt. In some areas west-southwest of Concho the sandstone unit contains subangular to rounded chert and quartzite pebbles as much as an inch in diameter. In other places near the Navajo-Apache County line east of Snowflake, the unit is a gray sandstone composed of well-sorted fine- to medium-grained quartz. The sandstone unit unconformably overlies older units in the Holbrook Member of the Moenkopi Formation.

The Holbrook Member contains several distinctive units in the report area. In one exposure 5 miles west-southwest of Hunt there is a resistant 3-foot unit composed entirely of angular granule-sized particles of olive-colored limestone. In the same area some of the siltstone units are purplish blue in contrast with the predominant red and brown colors of the Moenkopi Formation. These blue units closely resemble some of the blue mudstone units of the Petrified Forest Member of the Chinle Formation, and they weather to soft loose material very much like many of the silty units of the Chinle Formation.

The thickness of the Moenkopi Formation in the central part of Apache County is not uniform because the top and bottom of the formation are erosional unconformities. The formation is 95 feet thick in well 237–1(10.0×3.4), and 3 miles east, in the crest of the Cedar Mesa anticline, it is 40 to 80 feet thick. The Moenkopi is more than 185 feet thick in well 215–1T(8.3×14.7) about 5 miles northwest of Concho, from 150 to 200 feet thick in wells in the Hunt Valley, and from 125 to more than 200 feet thick in helium wells in the Pinta dome area near Navajo, Ariz.

No fossils have been found in the Moenkopi Formation in the central part of Apache County, but in several adjacent areas the formation contains fossils which most workers believe to be Triassic (Shimer, 1919, p. 492–497; Brown, 1933, p. 4; Welles, 1947, p. 242; Peabody, 1948, p. 300). The fossil remains are from vertebrates, and they occur in the upper part of the formation.

Brown's (1933, p. 4) study of a palatal impression of an amphibian found southeast of Winslow led him to believe that this form was most similar to forms from the "Lower and Middle Triassic of other countries." More recently, Welles (1947) presented faunal evidence showing that the younger members of the Moenkopi are probably Middle Triassic. Thus, the Moenkopi in this report is referred to as Lower and Middle(?) Triassic, although in the central part of Apache County it may all be of Middle Triassic age.

PRE-CHINLE UNCONFORMITY

The pre-Chinle unconformity has been recognized in an area of 80,000 square miles (Gregory, 1950) and has been described in many reports (Darton, 1925; Longwell, 1928; Gregory, 1917, 1950, and 1951; McKee, 1936 and 1954; Akers and others, 1958). Darton (1925, p. 119) regarded this break as not denoting a "notable unconformity or time break," whereas Gregory (1950, p. 64) stated that the unconformity "demonstrates a feature of major importance in the history of the Triassic."

In some areas, such as in Monument Valley and near Lees Ferry, the erosion surface has a relief of about 200 feet. In the Defiance Plateau the entire Moenkopi Formation and Kaibab Limestone are missing in some areas. In central Apache County channels as much as 50 feet deep occur locally along the erosion surface and are filled by sandstone and conglomerate of the Shinarump Member of the Chinle Formation. In places, the channels form "traps" for ground water, and a few springs and seeps issue along the basal contact.

CHINLE FORMATION

Exposures of the Chinle Formation are widespread in the valley of the Little Colorado River downstream from Springerville and in the valleys of the larger tributaries to the Little Colorado River. The formation forms the famous Painted Desert in the Petrified Forest National Monument and consists of a thick series of colorful lenticular beds of claystone, siltstone, sandstone, and conglomerate.

The Chinle Formation was named by Gregory (1917), who recognized four members in the Navajo Indian Reservation. He informally called the members divisions A, B, C, and D. Division A was separated from the Chinle Formation and transferred to the Wingate

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Sandstone by Harshbarger and others in 1957. Stewart (1957) named division B the Owl Rock Member after exposures near Owl Rock in Monument Valley. Gregory (1950) renamed division C the Petrified Forest Member of the Chinle Formation because the member is well exposed in the Petrified Forest National Monument. In part of Apache and Navajo Counties the Petrified Forest Member is subdivided into an upper part and a lower part, separated by the prominent Sonsela Sandstone Bed (Akers and others, 1958, p. 93). Division D has not been formally named, but it has been referred to as the "lower red member" (Akers and others, 1958). Another member, however, occupying almost the same stratigraphic position but differing in lithology, was described and named the Mesa Redondo Member by Cooley (1958b). The Shinarump formerly was a separate formation, but Stewart (1957) reclassified it as the basal member of the Chinle Formation.

The members of the Chinle Formation grade into and intertongue with the underlying and overlying members, and the contacts between them are arbitrarily chosen on the basis of gross lithology. These gradational and intertonguing relations are complex, especially in the lower members, and it is difficult to map the several members separately. Because of the discontinuous distribution and close intertonguing and gradational relations between the Shinarump Member and the lower and middle units of the Mesa Redondo Member of Cooley (1958b), they are mapped as one unit. For the same reason, the upper part of the Mesa Redondo Member of Cooley (1958b) is included with the Petrified Forest Member. The Sonsela Sandstone Bed is a conspicuous marker bed separating the upper and lower parts of the Petrified Forest Member in part of the area, but where the Sonsela Sandstone Bed is absent, the contact between the upper and lower parts is vague. For this reason, the Sonsela Sandstone Bed is shown on the geologic map, but the upper and lower parts of the Petrified Forest Member are not differentiated. The contacts bounding the Owl Rock Member are more easily recognized, and the Owl Rock Member is mapped separately where it is exposed.

The entire Chinle Formation is not exposed anywhere in the report area, but data from measured sections and well logs show that there is 1,550 feet of the formation in the Zuni River valley near U.S. Highway 666 (Cooley, 1958b). The Chinle section thins abruptly in a south-southwest direction across Apache County and is absent near McNary (fig. 1.).

The Chinle Formation is regarded as Late Triassic in age by practically every worker familiar with the formation, but not all agree on the epoch to which it belongs. Von Huene (1926) expressed the belief that the Chinle Formation contains a fauna representing both the Middle and Upper Triassic. The weight of paleontological evidence presented by Branson (1927) and Branson and Mehl (1929, p. 17–18) indicates a Middle Triassic age, but Camp (1930, p. 4), Daugherty (1941, p. 42), Colbert (1950, p. 64), and others presented evidence suggesting a Late Triassic age. The formation is considered Upper Triassic in this report.

Shinarump Member

The Shinarump Member of the Chinle Formation consists of yellowish-gray to very pale orange sandstone, conglomerate, mudstone, and siltstone. All the units in the member are lenticular, and the texture is extremely variable. In some places sandstone or conglomerate is prevalent, whereas in others, siltstone or mudstone predominates.

The sandstone is composed of fine to coarse subrounded to subangular fairly well to poorly sorted quartz grains in firm to weak calcareous, siliceous, or ferruginous cement. Accessories are black minerals and weathered feldspar. The conglomerate consists of well-rounded pebbles and cobbles, ranging in size from ⅛ to 8 inches in diameter, of chert, quartzite, jasper, and occasionally of granite and schist in a sand matrix. The average size of the pebbles is 1 to 1½ inches in the Cedar Mesa anticline and ¾ to 1 inch near Hunt. In some areas the sandstone and conglomerate units contain logs and fragments of petrified wood. In nearly every area these units contain medium- to large-scale planar and trough low- to medium-angle crossbeds.

The mudstone and siltstone units are grayish red to greenish gray. Most of the units are not extensive, commonly less than 50 feet long and less than 5 feet thick. The beds are fissile to very thin, and ripple laminae are common. Mica is abundant in the units in most areas.

Along the Navajo-Apache County line the Shinarump occurs in deposits that are not typical of the member in other areas. In this area it is composed of very hard siliceous fine-grained gray sandstone that might better be called orthoquartzite, or it is composed of mottled-purple and cream-colored silty gnarly material that weathers readily. Gravel and coarse-grained particles are scarce in the formation in this area.

In places the Shinarump contains radioactive material generally associated with petrified wood and carbonaceous material. The material is concentrated in channels carved in the Moenkopi Formation.

The Shinarump Member does not form a continuous mantle but is restricted to fairly well-defined broad channelways. It is generally less than 80 feet thick in the central part of Apache County. No trends in thickness are apparent in the area. The member is 10 to 41 feet thick in Hunt Valley, 25 feet thick on Cedar Mesa anticline, and 20 to 80 feet thick in the Chambers-Lupton area near U.S. Highway 66. It is missing near Lyman Reservoir and in several places near the Apache-Navajo County line.

Mesa Redondo Member of Cooley (1958b)

The Mesa Redondo Member, as described by Cooley (1958b, p. 7–15), comprises three units: a lower reddish-brown mudstone-siltstone slope-forming unit, a medial conglomeratic sandstone ledge-forming unit, and an upper mudstone-siltstone slope-forming unit. One or more of the units may be missing in a given area. The member is exposed only in the St. Johns-Hunt area, but it is probably present in the subsurface to the north. A 30-foot unit of banded purple and white sandstone, probably Mesa Redondo, crops out on the southern part of the Defiance uplift.

The lower unit consists of lenticular beds of grayish-red and grayish-red-purple mudstone commonly containing thin lenses of sandstone. The unit contains petrified logs in some places. The medial unit consists of lenticular beds of grayish-red-purple to pale-pink sandstone and conglomerate displaying small- to large-scale, low- to medium-angle crossbeds. The sandstone is composed of quartz grains that are very fine to very coarse, poorly sorted, and subangular to subrounded. The grains are clear and stained and are set in a weak to firm calcareous cement. The conglomerate consists of subrounded to well-rounded chert, quartzite, jasper, limestone, and quartz pebbles and cobbles in a fine to coarse sand matrix. Most of the pebbles are less than an inch in diameter, but a few cobbles, as much as 6 inches in diameter, are found in some places. The upper unit is similar to the lower unit.

The Mesa Redondo Member is 159 feet thick southeast of St. Johns, 98 feet thick 6 miles north of Concho, and 116 feet thick at the type area near Hunt.

Petrified Forest Member

The lower part of the Petrified Forest Member consists mainly of grayish-blue to grayish-red-purple claystone, siltstone, and mudstone and a few thin lenticular beds of sandstone and conglomerate. The claystone, siltstone, and mudstone beds are very lenticular and on freshly weathered surfaces commonly display large, sweeping crossbeds deposited at a low to medium angle. Generally, the individual lenses are different colors which reflect lithologic differences.

Many of the claystone units contain bentonite, which swells when wet. Montmorillonite is the dominant mineral in the bentonite which was formed from the decomposition of volcanic ash that fell into water (Allen, 1930, p. 287).

The sandstone and conglomerate beds are more persistent near the base of the lower part of the member and may represent the last traces of the lower red member, which has been mapped north and east of the report area. Several of the sandstone and conglomerate beds are exposed in an interval 90 feet thick about 3 miles northeast of St. Johns. The beds range in thickness from 1 to 10 feet and are separated by siltstone units. The sandstone beds are composed of pale-reddish-brown and grayish-green very fine to medium-grained quartz with considerable silt-sized particles. Micaceous material is abundant. The beds display small-scale trough and planar crossbeds, and some are ripple laminated. The conglomeratic beds are similar to the sandstone beds, but they contain angular limestone and mudstone pebbles as much as half an inch in diameter.

This 90-foot interval contains distorted rocks representing primary slumping that was the subject of an unpublished master's thesis by Green (1956). He concluded that most of the slumping resulted from oversteepening of foreset beds in a delta formed in a relatively quiet body of water.

Several light-gray sandstone lenses are scattered throughout the lower part of the Petrified Forest Member of the Chinle Formation and are well exposed in the Petrified Forest National Monument and southeastward to Hunt. One lens, a ripple-laminated very fine to fine-grained sandstone called the Newspaper Rock Sandstone of Stagner (in Daugherty, 1941) and Cooley (1959, p. 71), is a tourist attraction because it is marked by numerous prehistoric petroglyphs. Others are notable because they are composed entirely of well-sorted angular granules of white quartz and quartzite.

Logs of gas wells show that the lower part of the Petrified Forest Member of the Chinle Formation is about 400 feet thick near Pinta. It is about 300 feet thick in the Zuni River valley north of St. Johns and about 150 feet thick near Mesa Redonda.

The Sonsela Sandstone Bed of the Petrified Forest Member actually is several beds separated by siltstone units. The sandstone beds are composed of lenticular units of quartz grains that are light gray, grayish red purple, and very pale orange. The grains are subangular to subrounded, fine to coarse, and clear and frosted. Most of the beds are conglomeratic and contain subangular to well-rounded pebbles composed of quartzite, chert, jasper, angular fragments of petrified wood, and, rarely, rounded pebbles of granite and rhyolite. The pebbles average three-fourths of an inch in diameter, but a few are cobble size, as much as 6 inches in diameter.

The sandstone and conglomerate units characteristically contain small- to large-scale low- to medium-angle trough-type crossbeds. Some of the units contain small-scale planar crossbedding and ripple laminae. In the northern part of the area along the Puerco River some units contain phytosaur teeth and fragments of fossil bone, and some units contain abundant *Unio*.

The Sonsela Sandstone Bed intertongues with the underlying and overlying units of the Petrified Forest Member. The number of tongues present at one place is not always the same as it is in another. For this reason the thickness varies considerably.

The Sonsela is 150 feet thick in the Petrified Forest National Monument, 70 feet thick 15 miles north of St. Johns, and 50 feet thick at the Arizona-New Mexico State line east of St. Johns. It is not present in the Hunt area, but it crops out at Mesa Redonda and on the east side of Hay Hollow northwest of Concho. It is not present 15 miles southeast of the Petrified Forest National Monument, but the upper and lower parts of the Petrified Forest Member are separated by a zone of gray and lavender bands that occupy the same stratigraphic interval as the Sonsela Sandstone Bed.

The upper part of the Petrified Forest Member is similar lithologically to the lower part. However, the overall color of the upper part most nearly approaches a reddish brown. The individual siltstone and mudstone units in the upper part are more flat bedded and more extensive than those in the lower part.

The upper part of the Petrified Forest Member is about 1,000 feet thick in the central part of Apache County. Cooley (1957, unpub. master's thesis) measured 993 feet of the upper part of the Petrified Forest Member near the Zuni River 20 miles north of St. Johns, where most of the unit is preserved.

Owl Rock Member

The Owl Rock Member of the Chinle Formation is exposed only in the extreme northeastern part of the report area (pl. 1). The member is not present in the other parts of the report area because it has been removed by pre-Cretaceous beveling or because of nondeposition.

The Owl Rock Member consists of pale-red to light-greenish-gray cherty nodular limestone, calcareous siltstone, and, rarely, silty sandstone. The beds are flat and thin to thick. Generally, they are lenticular, but many can be traced laterally for several miles. The Owl Rock is about 200 feet thick near the Puerco River south of Lupton; it thins southward and is not present along the Zuni River.

PRE-WINGATE UNCONFORMITY

The Owl Rock Member of the Chinle Formation near the Puerco River unconformably is overlain by the Wingate Sandstone. The relief of the intervening erosion surface was slight, probably less than 10 feet. In the White Waters Draw area there are several large shrinkage cracks that extend downward from the contact into the Owl Rock Member. These cracks are about 6 inches wide at the top and 3 feet deep and are filled with sediments from the Wingate Sandstone (fig. 9).

WINGATE SANDSTONE

In most of northeastern Arizona the Wingate Sandstone of Late Triassic age is divided into two members (Harshbarger and others, 1957)—the Rock Point Member at the base, composed predominantly of fluviatile mudstone, siltstone, and sandstone; and the Lukachukai Member at the top, composed of massive eolian sandstone. The Wingate Sandstone was probably deposited throughout most of central Apache County, but the greater part was removed by pre-Late Cretaceous and pre-Bidahochi erosion. In the central part of Apache County the Wingate Sandstone is not present on the surface, but the Rock Point Member is probably present in the subsurface in the northeast corner of the area.

The Rock Point Member is exposed near the extreme northeast corner just outside of the report area in New Mexico in a small out-

FIGURE 9.—Contact of the Owl Rock Member of the Chinle Formation (Ꞧ co), and the Wingate Sandstone (Ꞧ w) in White Waters Draw near the Arizona-New Mexico State line. Note large shrinkage crack that has been filled with sediments.

crop along White Waters Draw. It consists of 250 feet of alternating thin beds of moderate-reddish-brown to moderate-reddish-orange sandstone, siltstone, and mudstone (fig. 9). The sandstone is composed of subangular to subrounded fairly well to poorly sorted fine to medium quartz grains in firm calcareous cement. Some of the beds display small- to medium-scale planar and trough crossbedding, and ripple marks are abundant locally. The member weathers to a ledge and slope topography.

PRE-LATE CRETACEOUS UNCONFORMITY

In the central part of Apache County, rocks of Triassic and Cretaceous age are separated by an unconformity representing an erosion interval in which the uppermost Triassic and all the Jurassic rocks were removed. This unconformity is well defined and easily recognized in most of the area. In most places it is marked by an abrupt change in color and lithology—from mudstone to conglomeratic sandstone—and shows evidence of moderate local relief on the erosion surface of as much as 30 feet. However, in some areas, such as on the north bank of the Zuni River near U.S. Highway 666, the unconformity is not as apparent because the basal Cretaceous beds are red like many beds in the Chinle Formation and the relief of the erosion surface was low.

Pre-Upper Cretaceous strata were tilted to the northeast and beveled by erosion so that the Upper Cretaceous rocks overlie progressively older rock from northeast to southwest. The beveling is at such a low angle that it cannot be detected except on a regional basis. The oldest Cretaceous rock in the area is the Dakota Sandstone, which overlies the Lower Cretaceous Burro Canyon Formation at the Four Corners in the extreme northeastern part of Arizona and the Upper Jurassic Morrison Formation at Lupton. In the central part of Apache County it overlies the Chinle Formation of Late Triassic age, and in the Mogollon Rim area to the south it overlies the Kaibab Limestone of Permian (Leonard) age.

CRETACEOUS ROCKS

In the central part of Apache County, Cretaceous rocks crop out along the bank of the Zuni River near the Arizona-New Mexico State line and southward in isolated exposures across the southern part of the area. They consist of sandstone, conglomerate, and carbonaceous siltstone. In ascending order, the Cretaceous rocks include the Dakota Sandstone, the Mancos Shale, and the Mesaverde Group. The nomenclature of the Cretaceous rocks in the St. Johns area was the subject of an unpublished master's thesis by T. D. Crutcher (1956). He concluded that the nomenclature used in the southern San Juan basin, New Mexico, was applicable in the St. Johns area, and this nomenclature is used in this report. However, Repenning and Page (1956, p. 263) showed that the Mancos Shale of Black Mesa and the Mancos Shale of the southern part of the San Juan basin represent only a small part of the Mancos Shale at the type section near Mancos, Colo. The same is true of the Mancos in central Apache County. Some sandstone units in the Cretaceous rocks yield water to drilled wells.

DAKOTA SANDSTONE

The oldest rock of Cretaceous age in the area is the Dakota Sandstone consisting, in ascending order, of conglomerate and sandstone, carbonaceous siltstone, and sandstone. Each of these lithologic types is characteristic of one of three units recognized in the Dakota Sandstone over broad areas in parts of northeastern Arizona (Repenning and Page, 1956, p. 259). The units are extremely variable in thickness and texture; usually, one unit thickens as another thins. In many places one or two of the units are missing.

The conglomerate at the base is from 3 to 15 feet thick and typically grades upward into sandstone. The conglomerate is formed of subangular to rounded pebbles of chert, quartzite, limestone, and angular fragments of petrified wood and siltstone in a fine to coarse sand matrix. In some places, pockets or small irregular lenses containing numerous carbonized plant fragments and chips of coal are common. The sandstone consists of quartz grains that are very pale orange to almost white, fine to medium, fairly well to poorly sorted, subrounded, and clear and stained and of black accessory minerals in firm siliceous, carbonaceous, or clay cement. It contains small to medium crossbedding of the planar and trough types deposited at a low angle. Ripple marks are common in some beds. Ironstone concretions are abundant in some places, and usually these weather out as almost perfect spheres the size of marbles. The lower unit weathers to form a ledge or vertical cliff.

The unit grades upward into the middle unit, which consists of black to dark-grayish-brown carbonaceous siltstone and interbedded lenticular beds of sandstone and low-grade coal. Selenite in isolated crystals or veinlets is common. The sandstone beds are usually thin, from 1 to 5 feet thick, fine to medium grained, and in some places contain crossbedding. The coal occurs in scattered irregular lenses from a few inches to several feet thick. The unit weathers to form a steplike slope where there are numerous sandstone beds. The middle unit is absent in some places and as much as 90 feet thick in others.

The upper unit is separated from the middle unit by an erosion surface of low relief, generally less than 5 feet. It is similar in most respects to the lower unit but contains much less conglomeratic material and more very fine to fine-grained sandstone beds interbedded with thin deposits of siltstone. These sandstone beds are thin to thick, and some contain small- to medium-scale crossbeds of the planar and trough types deposited at a low angle. Ripple marks are present locally. The unit usually contains a thin bed of conglomerate at the top, and it grades upward into the overlying Mancos Shale. It weathers more often to a vertical cliff having numerous recessions.

In the central part of Apache County, no fossils have been found in the Dakota Sandstone except poorly preserved plant remains that are not diagnostic of age. However, a collection of fossils obtained by J. G. Poole from a limy sandstone in the Cretaceous rocks on the north side of Mesa Redonda contained *Exogyra collumbella* Meek, which according to J. B. Reeside, Jr., "is widespread at the base of the Mancos Shale in Colorado and Utah, and in the top of the Dakota in Arizona" (R. F. Wilson, written commun., 1960). Studies by Reeside (1924), Williams (1951), Repenning and Page (1956), and Crutcher (1956, unpub. master's thesis) indicate that the Dakota Sandstone in northern Arizona is of Late Cretaceous age, but they recognize the possibility that it may contain some beds of Early Cretaceous age.

MANCOS SHALE

The Mancos Shale is not extensively exposed in the area. It crops out near the Arizona-New Mexico State line along the banks of the Zuni River and in the headwaters area of Carrizo Creek. Shaly sediments possibly of the Mancos are present in exposures on the flanks of Mesa Redonda southwest of Concho, but they were mapped as Upper Cretaceous rocks undifferentiated.

The Mancos Shale grades upward from moderate-orange-pink sandy siltstone near the base to brownish-black or medium-gray carboniferous siltstone and claystone in the middle to medium-gray and dark-yellowish-green sandy siltstone near the top. Thin lenticular beds of grayish-yellow to moderate-greenish-yellow sandstone appear sporadically throughout the Mancos, but they are more prevalent near the top. These beds are very similar in appearance to many in the overlying Mesaverde Group exposed to the east in New Mexico.

The entire thickness of the Mancos Shale is not exposed in the central part of Apache County, and there are no well logs that show the thickness. About 150 feet is exposed near the Arizona-New Mexico State line along the banks of an unnamed tributary 4 miles south of the Zuni River. Smith (1956, unpub. master's thesis) measured a complete section of 255 feet of Mancos Shale in an area 25 miles east of St. Johns in Catron County, N. Mex., and 383 feet in an exposure 23 miles northeast of St. Johns in Valencia County, N. Mex.

SEDIMENTARY ROCKS UNDIFFERENTIATED

The Mancos Shale wedges out between the Dakota Sandstone and the Mesaverde Group toward the southwest and is not recognizable near Pinedale (fig. 1). It becomes sandier in the same direction so that the entire Cretaceous section southwest of a line running northwest through St. Johns consists of interbedded sandstone, claystone, siltstone, and a few deposits of coal and lignite. The Upper Cretaceous formations in this area are difficult to separate, and for this reason all the Cretaceous rocks south and west of St. Johns are mapped as Upper Cretaceous sedimentary rocks undifferentiated. These rocks probably contain beds equivalent to the Mesaverde Group, Mancos Shale, and Dakota Sandstone.

Upper Cretaceous rocks undifferentiated are exposed in isolated outcrops near Floy and between U.S. Highway 666 and the New Mexico State line and north of Springerville. The most extensive outcrops are on the flanks of Antelope Valley, North Malapais, and South Malapais anticlines. The distribution of the outcrops in the southern part of the area and data from well logs suggest that these rocks are present in the subsurface under younger rocks in much of the area northeast of Springerville and in the area between Springerville and Floy.

The Upper Cretaceous rocks consist of very pale orange to grayish-orange thin-bedded to very thick bedded lenticular sandstone composed of poorly to well-sorted fine- to medium-grained quartz and arkosic material interbedded with lenticular beds of grayish-olive, dark-yellowish-brown, and dark-gray carbonaceous siltstone and mudstone. The sandstone units are usually well bonded with calcareous cement, and they weather to form cliffs or ledges. Some of these sandstone units contain so many invertebrate fossil remains that they resemble coquina.

The thickness of the Upper Cretaceous rocks undifferentiated in the area of investigation is not known. However, well 236–30(14.15 ×13.5) was drilled to a depth of 485 feet in Cretaceous rocks. At a depth between 300 and 410 feet this well penetrated a continuous unit of gray mudstone, which may be correlative with the Mancos Shale.

TERTIARY ROCKS

Tertiary rocks crop out extensively in central Apache County (pl. 1), and they include, in ascending order, the following units; the rather thick basal sequence of sedimentary rocks probably equivalent in part to the Baca Formation of Eocene(?) age in western New Mexico (Willard and Weber, 1958); the Datil Formation of Miocene(?) age, consisting of sediments derived from volcanic material; and the Bidahochi Formation of Pliocene age, consisting of sandstone, siltstone, mudstone, and claystone. However, nowhere in the area do all these formations occur at one place. The thickness of the Tertiary rocks in central Apache County ranges from 0 to more than 1,000 feet

The best water-bearing formation of the Tertiary rocks is the Bidahochi, which yields considerable water to stock wells in the area between the Puerco River and the Zuni River.

EOCENE(?) SEDIMENTARY ROCKS

The lowermost Tertiary sedimentary rocks in the central part of Apache County are exposed in the Springerville area and eastward to the Arizona-New Mexico State line. They are continuous with rocks mapped and designated by Willard and Weber (1958) as non-volcanic sediments, which they believe are, in part, correlative with the Baca Formation of western New Mexico. In this report these rocks are mapped as sedimentary rocks of Eocene(?) age.

The lower contact of these sedimentary rocks is poorly exposed, but it appears to be conformable with the underlying Upper Cretaceous rocks at the south end of the Antelope Valley anticline (pl. 1). However, the radical change in lithology from fine-grained sandstone and siltstone to conglomerate containing boulders suggests tectonic activity, and it is probable that the contact of these materials is unconformable.

The Eocene(?) sedimentary rocks consist of grayish-red-purple, pale-reddish-brown, and grayish-orange conglomerate, sandstone, and siltstone. The conglomerate consists of well-rounded pebbles, cobbles, and boulders of quartzite, jasper, and quartz and of sparse pebbles and cobbles of limestone, coarse-grained pink granite, and schistose and gneissic material imbedded in a silt and sand matrix. Some of the limestone is fossiliferous, containing shell fragments, crinoid stems, and fusilinids. The fossil types are similar to those in Paleozoic and Precambrian rocks which crop out south of the Colorado Plateaus in central Arizona. The sandstone is composed of angular to subangular fairly well to poorly sorted fine to medium quartz grains and of considerable arkosic material and fragments of claystone or mudstone. In most areas the sandstone and conglomerate are crossbedded, are weakly bonded with calcareous cement or clay, and weather readily to leave an accumulation of lag gravel. Pieces of petrified logs as much as a foot in diameter also are present in the lag material. The gravel covers a rather extensive area in the extreme southeast part of the report area, and it may be directly related to the gravel on the Mogollon Rim.

The total thickness of the sedimentary rocks is about 800 feet, as indicated from well logs and exposures near Springerville. The age of the sedimentary rocks has not been established, but their stratigraphic position suggests they are Late Cretaceous or early Tertiary. Willard and Weber (1958) suggested that these sedimentary rocks are in part correlative to the Baca Formation, which has been assigned to the Eocene(?) (Wilpolt and Wanek, 1951). The sedimentary rocks yield water to two wells in the Springerville area and probably contain water where they are present to the northeast.

DATIL FORMATION

Willard and Weber (1958) divided the Datil Formation into two units and included in the lower unit a series of deposits derived mostly from rhyolitic, latitic, or andesitic volcanic rocks. These deposits gradationally overlie the Eocene(?) sedimentary rocks. They are exposed in a small area in the flank of a lava-capped mountain bordering the north side of U.S. Highway 60 at the Arizona-New Mexico State line.

The upper unit consists of andesite and basaltic andesite with rhyolite tuff. Rocks of this unit are not present in central Apache County, but they occur to the east in New Mexico. Erosion has removed most of the Datil Formation from the area north of U.S. Highway 60, but to the south the formation has exposed thicknesses of more than 1,000 feet.

The lower unit of the Datil Formation consists of loosely to firmly consolidated material which would be classed as a sandstone. It is composed mainly of olive-gray, light-gray, and grayish-red argillaceous material and scattered lenses of pebble conglomerate, siltstone, mudstone, and volcanic ash.

The pebbles are subangular to subrounded and are composed of granite, quartz, volcanic material, and rarely, limestone. The Datil Formation forms a steep slope where it is weakly consolidated, and a cliff or ledge where it is indurated.

PRE-BIDAHOCHI EROSION SURFACES

The Bidahochi Formation comprises three members and overlies two contiguous erosion surfaces in the central part of Apache County. The three members are the lower lacustrine, middle volcanic, and upper fluviatile (Repenning and Irwin, 1954). Gregory (1917, p. 122) first used the term "Hopi Buttes peneplain" in the Navajo country. His lithologic description of the rocks seems to indicate that he placed the Hopi Buttes peneplain at the base of what is now known as the lower member of the Bidahochi Formation. Also, he stated in his description of the Hopi Buttes volcanism (Gregory, 1917, p. 89) that lava dams gave rise to lakes in which the lacustrine muds and ash, which are now considered the lower member, accumulated. His measured section of shales and sandstone associated with the lava

(Gregory, 1917, p. 82) includes strata in all three members of the Bidahochi Formation.

McCann (1938, p. 171) named the erosion surface at the base of the Bidahochi Formation on the west side of the Zuni Mountains the "Zuni surface." However, only the upper member of the Bidahochi Formation is present. Therefore, in this report, the Zuni surface is considered to be at the base of the upper member of the Bidahochi Formation and the Hopi Buttes surface, at the base of the lower member of the Bidahochi Formation (fig. 10).

In central Apache County these surfaces were cut on formations ranging from the Chinle Formation of Late Triassic age to the undifferentiated formations of Late Cretaceous age. The surfaces are very flat over large areas, but in some places the relief was as much as 200 feet. On the banks of White Waters Draw at the Arizona-New Mexico State line, the Zuni surface truncates part of the Wingate Sandstone and part of the Owl Rock Member of the Chinle Formation. Here, apparently, the upper member of the Bidahochi Formation was deposited in a rather steep-sided ancient channel whose course, in this area, coincides approximately with that of White Waters Draw.

Altitudes at the base of the upper member of the Bidahochi Formation indicate that the Zuni surface presently slopes north-northwest from 7,000 feet at the Arizona-New Mexico State line 8 miles north of U.S. Highway 60 to 5,900 feet at Sanders—a gradient of about 17 feet per mile. McCann (1938, p. 271–274) stated that the average gradient between the Zuni Plateau and Sanders is 29 feet per mile. Plate 2 shows the present configuration of the Hopi Buttes-Zuni surface in the central part of Apache County. The topography of the erosion surface and coarser basal beds of the Bidahochi Formation exert considerable control on the occurrence of ground water in the Bidahochi, for the water moves along the ancient buried channelways. The base of the lower member of the Bidahochi has an altitude ranging from about 5,500 to 6,100 feet. Beyond the basin of Bidahochi deposition, the projection of the Zuni surface probably underlies the younger volcanic rocks exposed in Mesa Redonda and the White Mountains volcanic field.

BIDAHOCHI FORMATION

The Bidahochi Formation (Reagan, 1924, 1932) is widely exposed in the area. It is present as high tablelands in most of the eastern half of the area between the Puerco River and the Zuni River, and it forms the Chalk Buttes east of St. Johns. It extends about 15 miles south of the Chalk Buttes. The westernmost exposure is at the Navajo-Apache County line southwest of the Painted Desert Lookout. The

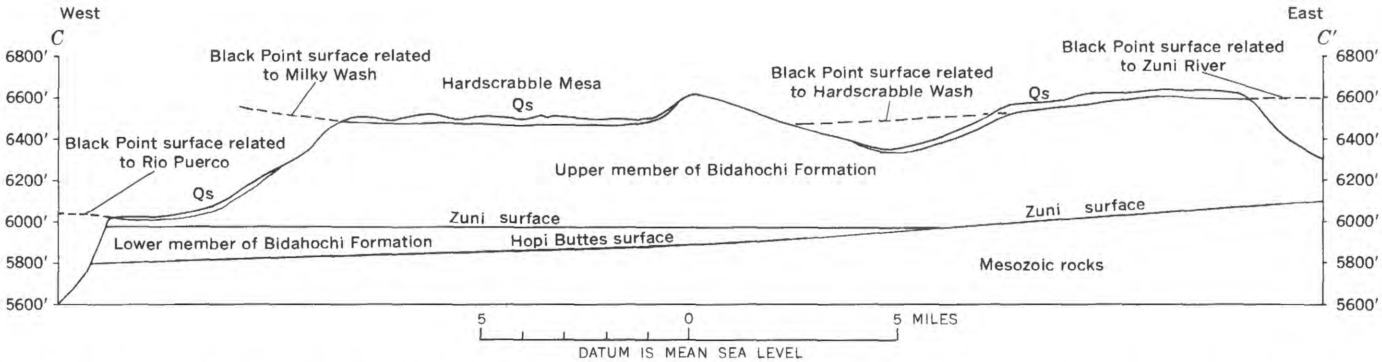

FIGURE 10.—Section along *C–C'* (see pl. 1), showing relations of erosion surfaces to the underlying rocks in the central part of Apache County, Ariz.

original thickness of the formation in central Apache County is not known because of removal of the uppermost beds by erosion.

Lower member

The lower member of the Bidahochi Formation crops out along the edges of the broad valleys of the Puerco River and Milky Wash. It is present between Sanders and a point 6 miles southwest of the Painted Desert Lookout. The lower member thins toward the south from 160 feet about 8 miles south of Navajo to a featheredge in the southeast side of Surprise Valley 25 miles south of Navajo. West of this area the member is beveled out by post-Pliocene erosion, and it is absent southwest of the Painted Desert Lookout and has not been traced in the subsurface to the east.

The lithology and color of the lower member are very similar to those of the Petrified Forest Member of the Chinle Formation because much of the material has been reworked from this formation. Were it not for the distinctive conglomerate (fig. 11) at the base of the Bidahochi, the two formations would be difficult to differentiate in this area. The conglomerate typically consists of 6 inches to 10 feet of pale-reddish-brown medium- to coarse-grained quartz sand contain-

FIGURE 11.—Lower member of the Bidahochi Formation (Tbl), overlying the Chinle Formation (Ŧc) 4 miles northeast of Navajo, Ariz. The pebbles have weathered from a bed of conglomerate at the base of the Bidahochi Formation.

ing abundant subrounded to rounded pebbles of quartzite, chert, and jasper and averaging three-fourths of an inch in diameter and of a few rounded pebbles and cobbles and, uncommonly, boulders of scoriaceous basalt. Some of the basalt cobbles have a structure suggesting they are bombs. Small-scale crossbeds deposited at low angle are conspicuous in nearly every locality. The unit is usually weakly bonded with calcareous or ferruginous cement and weathers to a weak ledge or slope.

The main mass of the lower member of the Bidahochi Formation consists of banded flat-lying beds of grayish-brown sandstone and of light-greenish-gray, pale-yellowish-brown, and dark-reddish-brown mudstone and claystone. Sandstone is the most conspicuous material and consists of quartz grains that are very fine to medium, subangular to rounded, fairly well sorted, clear and stained and of red and black accessory minerals. A few of the beds are firmly cemented and weather to a rounded ledge, but most are weakly consolidated and weather to a slope that resembles those formed by the mudstone and claystone beds. The remaining part of the member is composed of thick-bedded to very thick bedded claystone and sandy mudstone.

In the northern part of the area along the Puerco River and its tributaries, the member contains lenses of white volcanic ash and bentonite (altered volcanic ash) interbedded with the mudstone. These deposits consist of very fine grained white glass shards which in some places have weathered to clay. Where the bentonite deposits are free from silt and sand, the material is of commercial quality and, in several places, is mined.

Middle volcanic member

The middle volcanic member of the Bidahochi Formation is represented by an isolated outcrop at the Painted Desert Lookout and possibly by an isolated outcrop at Black Knoll. The lava at both places is a dense dark basalt which at the Painted Desert Lookout includes some agglomerate. The base of the lava at the Painted Desert Lookout is at an altitude of about 5,600 feet, and at Black Knoll it is at an altitude of about 5,800 feet.

The lava at the Painted Desert Lookout is a jointed basalt flow, which is underlain by mudstone beds of the lower member of the Bidahochi Formation. Black Knoll consists of an eroded volcanic neck standing 150 feet high and of an associated lava flow which forms its base. The lava flow overlies 2 feet of conglomeratic siltstone which contains basalt fragments possibly derived from the Black Knoll eruption and which may be correlative with the conglomerate at the base of the Bidahochi Formation to the east near Sanders.

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Upper member

The upper member of the Bidahochi Formation is the most widespread and is present in most of the area between the Puerco River and Carrizo Wash. It crops out in the Chalk Buttes area east of St. Johns and is present at the top of many small mesas between Black Mesa and Carrizo Wash. The upper member crops out beneath the volcanic rocks and gravels of Quaternary age on the flanks of the White Mountains volcanic field as far west as the south end of Big Hollow.

In most of the Puerco River-Hardscrabble Mesa area, the lower part of the upper member consists of yellowish-gray flat-lying thin to thick beds of silty and relatively pure travertine intercalated with lenticular beds of sandstone. However, at Sanders and Red Hill 3½ miles south of Sanders, it is oxidized and is a bright orange red. The member consists of fine- to coarse-grained sandstone interbedded with claystone, mudstone, and travertine. In some places the travertine is so silty it resembles a marl or very calcareous siltstone, and because of variation in cementation or in silt content, weathering has given the travertine a honeycombed appearance. The sandstone is light brownish gray and is composed of fine- to coarse-grained quartz and black accessory minerals. In places the sandstone is friable and weathers to form slopes or recessions under travertine ledges; in other places it is firmly bonded with calcareous cement and weathers to a hummocky surface. It characteristically contains small- to medium-scale crossbedding of the asymmetrical trough type deposited at a low to medium angle. Commonly, some crossbeds are less firmly cemented than others, and they weather to form recessions.

The upper part of the upper member of the Bidahochi Formation contains less travertine, siltstone, and claystone. It consists mainly of weakly cemented crossbedded sandstone composed of fine to medium well-rounded clear and frosted quartz grains. A few lenses of conglomerate containing quartzite, jasper, and chert pebbles as much as three-fourths of an inch in diameter are present at different horizons. The member is formed of thick horizontally bedded units containing varying amounts of silt. Vegetation grows better in the siltier units, and when viewed from a distance, the bands of vegetation on the northwest escarpment of Hardscrabble Mesa appear to be beds.

The upper member of the Bidahochi Formation in the Chalk Buttes area east of St. Johns is from 175 to 225 feet thick and probably represents only the lower part of the upper member. At Chalk Buttes it consists chiefly of sandstone but includes intercalated beds of siltstone, mudstone, and conglomerate and travertine beds as much as 35 feet thick at the base.

The upper member locally includes two sedimentary types that are not typical of the unit. One of these occupies an ancient channel and is exposed near the valley of White Waters Draw. Here, to the northeast of the draw, the lower part of the upper member consists of 80 to 100 feet of sandstone displaying large, sweeping crossbeds of the trough type deposited at a high to medium angle (fig. 12). The fact that most of the crossbeds dip to the northeast suggests prevailing southwesterly winds. The sandstone is composed of quartz grains that are white, well sorted, and medium to coarse. The grains are subrounded to rounded and clear and frosted. A few thin lenses and stringers of granule-size particles of quartz, chert, and jasper occur along bedding planes. The sandstone, as indicated by the type of crossbedding and sorting, is an eolian deposit and probably represents dunes which accumulated in the ancient channel.

The other nontypical sedimentary type is present in the Zuni River-Carrizo Wash area, where the material is coarser than it is in most areas and contains considerable granitic and rhyolitic debris. Repenning and others (1958, p. 129) suggested that the granitic material was derived from the Zuni Mountains and that the rhyolitic material was derived from the Datil Formation exposed to the southeast. Part of the granite was probably redeposited from the nonvolcanic sediments.

FIGURE 12.—Crossbedding in the eolian facies of the upper member of the Bidahochi Formation in a tributary to White Waters Draw. Scale given by man at base of cliff left of center.

The thickness of the upper member of the Bidahochi Formation is extremely variable owing to widespread late Cenozoic erosion. The thickest known section in northeastern Arizona is a few miles southeast of the escarpment in the headwater area of Gray Water Draw, where wells have penetrated more than 800 feet of the member. The member is between 50 and 150 feet thick in the bluffs enclosing the valley of the Puerco River, and it is as much as 400 feet thick north of the Zuni River near State Route 61. The member has a maximum thickness of about 200 feet in the area east of St. Johns, and it is from 20 to 100 feet thick between the headwater area of Milky Wash and Surprise Creek.

Age and relation

The age of the Bidahochi Formation has been determined from vertebrate fossils it contains. The age of the upper member has been determined as middle Pliocene by Stirton (1936, p. 229–281) and Lance (1954, p. 1276) from fossils found at White Cone on the Navajo Indian Reservation. Near Sanders, the lower member contains vertebrate fossils of late Miocene or early Pliocene age (Lance, 1954, p. 1276).

The mudstone of the lower member of the Bidahochi Formation was deposited under lacustrine conditions in part of the ancestral Little Colorado River drainage system and, therefore, has a fairly small areal distribution. The lower member becomes sandier near the margins of the lake between Hopi Buttes and Milky Wash. Intertonguing of the sandstone and mudstone indicates fluctuations in the extent of the lake. Eventually through drainage was established, and stream-laid sediments of the upper member of the Bidahochi were deposited over the previously laid lake beds and overlapped the sides of the ancient valley. The upper member is known to be at least 800 feet thick.

At Black Knoll the lava overlies the thin basal conglomerate of the lower member. However, the boulders of scoriaceous basalt found in the conglomerate have not been transported for long distances and may have been derived from the eruption at Black Knoll. On the assumption that Black Knoll furnished material to the basalt unit of the lower member, the lower member is then older than the medial volcanic member of the Bidahochi Formation in the Hopi Buttes area, and thus the age of the ancestral drainage system of the Little Colorado River would be early Pliocene or late Miocene. On this basis, the lava at Black Knoll has been mapped as basalt of Tertiary age.

QUATERNARY DEPOSITS

Quaternary deposits are widespread in the central part of Apache County and cover about 65 percent of the area. They occur as terrace deposits related to the Little Colorado River and its tributaries, deposits of gravel underlying lava of Quaternary age, travertine capping small buttes, alluvium in drainages, eolian deposits on broad, flat plains, and landslide deposits at the base of cliffs. These deposits—except for the travertine, alluvium, and deposits overlying terraces—were not mapped separately, and they are shown on the geologic map (pl. 1) as Quaternary sediments. In many places the Quaternary deposits were reworked from the underlying Bidahochi Formation; thus it is difficult to recognize the contact between the two. In some places the deposits mapped as Tertiary actually may be Quaternary. In other places the Bidahochi was tilted slightly before Quaternary deposition, and there is a well-defined contact.

TERRACE DEPOSITS

The sediments overlying the Black Point surfaces, shown on the geologic map (pl. 1), northeast of the Little Colorado River are less than 50 feet thick and are composed of light-gray to yellowish-gray silty sand and sandy gravel. Gravel is present chiefly in buried channels and near the main arteries of the old stream. For example, gravel composed of rounded to subrounded pebbles and small cobbles rims the north bluff of the valley of the Zuni River, but a short distance northward the sediments are formed chiefly of silty sand. The gravels are composed of sandstone and igneous rocks carried in from the Zuni Mountains. Crossbedded and gravelly sand, which in many places grades laterally into horizontally bedded deposits, fills large channels as much as a quarter of a mile wide cut at the base of the sediments.

Bedding in the fine-grained units is usually flat and lenticular and ranges from thin to very thick, but many of the units appear massive or structureless and resemble deposits of loess. Small- to medium-scale crossbeds of the trough type are common in the sandy deposits. Layers of caliche and old soils can be traced laterally in some of the finer grained units for more than half a mile. The coarse-grained units contain crossbeds of the trough and planar types deposited at medium and low angles and at small to large scale. This type of crossbedding is usually characteristic of flood-plain deposition.

The gravels associated with the Wupatki surfaces, shown on the geologic map (pl. 1), are in the inner valley of the Little Colorado River and its tributaries at altitudes from 10 to 100 feet above the stream beds. The materials in these deposits are similar to those in the older gravel deposits, except they are coarser and lava constitutes a greater percentage of the gravel. Cobbles and boulders as much as 14 inches in diameter are common in these deposits.

The gravels were deposited on river flood plains that were dissected into small hills and terraces in recent times. They are most plentiful in the deeper canyons, but some occur in open valleys. They are more widespread on the south side of the Little Colorado River where stream gradients were steeper and the source areas nearer.

DEPOSITS UNDERLYING LAVA

In the Concho-St. Johns area, gravel deposits ranging from 50 to 150 feet thick have been preserved on the Black Point surfaces below basaltic flows. The gravel is principally well-rounded to subangular pebble-size material averaging less than three-fourths of an inch in diameter but also includes some cobbles and a few boulders. The material is mostly lava, quartzite, and chert but includes subordinate amounts of sandstone, limestone, petrified wood, granite, and schist. The matrix and sandy beds are composed of poorly sorted fine- to coarse-grained lava and quartz. The lava particles constitute as much as 75 percent of the sand in some lenses. The deposits have been indurated to various degrees. Some stand in a vertical bank, others weather to a slope. Caliche is the most common cementing material, but some deposits are weakly cemented with iron oxide.

In some exposures the bedding is lenticular and forms a maze of overlapping crossbedded channel deposits. The crossbeds are deposited mostly at low angles and on a medium to large scale. There is a zone of red soil between the gravel deposits and the overlying lava at nearly every place.

The gravels partially filled ancient valleys that trended north to northwest. Later, lavas filled the valleys and thus caused a lateral shift of drainage to the edges of the lava flows and the deposition of gravelly sediments. In places, there are several flows separated by sediments, as in the area between St. Johns and Springerville. The lava caused temporary damming of the drainages, and gravelly sediments accumulated in stretches upstream from the dams.

TRAVERTINE DEPOSITS

Travertine deposits are present in many places and at many altitudes in the central part of Apache County. They are concentrated in specific areas and trend in three distinct directions—northwest, north-northwest, and north. These trends are mainly parallel to the structural trends, based principally on the attitude of faults and joints. However, they lie at an angle of about 20° with the St. Johns and Antelope Valley anticlines. (See pl. 1.) The travertine deposits near

Hunt follow a trend describing a broad arc and paralleling the anticline and small monocline that form Apache dome. In most places travertine forms dome-shaped deposits surrounding spring orifices. Some of these deposits overlap to form extensive exposures, such as the one just south of the intersection of the Little Colorado River and the crest of the Cedar Mesa anticline. Other deposits form the caps of buttes, such as North and South Mountains northeast of Hunt.

The travertine was deposited at various times during the Quaternary Period, and its formation is closely related to the erosional stages of the Little Colorado River. The fact that some of the spring orifices at the center of travertine deposits are very well preserved suggests that they are very young, and some warm springs along the Little Colorado River south of St. Johns are still actively depositing travertine.

The oldest travertine is deposited on the lavas and sedimentary rocks overlying the oldest Black Point surfaces at Apache dome and north of the Antelope Valley anticline. Most of the deposits east of St. Johns were formed during the planation of the youngest Black Point surfaces. Travertine deposits from active and inactive springs near the present level of the Little Colorado River indicate the erosional levels of the Wupatki surfaces.

ALLUVIAL DEPOSITS

Alluvial deposits in the Little Colorado River drainage system in the central part of Apache County range in width from a few hundred feet to about 4 miles. Drillers' logs indicate that the alluvium is from 30 to 100 feet thick along the Little Colorado and Zuni Rivers and as much as 120 feet thick in the valley of the Puerco River. The alluvium exposed in the present arroyos consists mainly of sand, silty sand, and sandy silt. Gravelly sediments are rather uncommon in exposures in the alluvium downstream from St. Johns and in the lower and middle stretches of the tributary drainages. In the headwater areas of all streams, where the valleys are constricted, the alluvium consists of gravel ranging from pebbles to large boulders. Drillers' logs of water wells indicate gravel does occur in the lower part of the alluvium and grades upward into fine material.

The valleys that now contain alluvial deposits are irregular and contain many ridges or spurs. The coarser material was deposited in the deeper parts of the valleys between the ridges or spurs. The deeper parts are the most favorable locations for water wells, but they are somewhat difficult to locate without test drilling.

EOLIAN DEPOSITS

Longitudinal sand dunes have been formed on the deposits overlying the Wupatki and Black Point surfaces in rather large areas in the central part of Apache County. The dunes associated with the Wupatki surfaces are not as extensive as those associated with the Black Point surfaces. Remnants of longitudinal dunes partly destroyed by erosion are present on the Bidahochi Formation in some areas, and their presence is indicated by long narrow ridges and by the growth of juniper. The differences in preservation of these dunes suggest several stages of dune formation throughout the Quaternary.

The dunes are oriented without exception to the northeast, and they control the position of many small drainages. This northeast alinement indicates that no change in the prevailing southwesterly winds has occurred in late Cenozoic time.

Windblown-sand deposits mantle many areas on the lee sides of flood plains and streams near any easily available source of sand. Associated with the windblown sand is blowout activity which is modifying the appearance of the longitudinal dunes and exposing the underlying Quaternary or older deposits in the bottoms of saucer-shaped depressions. Much of the windblown sand has accumulated around clumps of vegetation. In areas having little available sand, the eolian material is composed of sandy silt and silty sand.

LANDSLIDE DEPOSITS

Large-scale landslides have occurred on the sides of many mesas and oversteepened slopes that are capped by resistant basalt flows. Landslides occur in narrow belts on the mesa fronts in the Concho-St. Johns area and on the sides of the lava flow along the Zuni River at the Arizona-New Mexico State line. Many of the slump blocks show a backward rotation of a few degrees and have crumpled the underlying sedimentary rocks. The slumping is more pronounced on slopes underlain by the Chinle Formation. Most of the slumping has been caused by headward or lateral cutting and the rapid removal of the material on the steep slopes. Rainfall percolating through the overlying lavas and gravels acts as a lubricant in zones of weakness in the underlying rocks, usually the incompetent muddy units of the Chinle Formation, and aids the slipping of large masses of rock. The swelling of wet bentonite in the Chinle Formation accelerates the slump movements.

The alluvium and Quaternary sediments beneath the lavas in the southern part of the area are aquifers. All the other Quaternary deposits, although they do not contain sufficient water for development of ground-water supplies, cover broad areas and facilitate recharge. Loose mantle formed by the eolian deposits retards runoff, much of which percolates through the Quaternary deposits and into the underlying Bidahochi Formation or sandstone of Cretaceous age.

IGNEOUS ROCKS

Basaltic lava and cinders are the only exposed igneous rocks in the central part of Apache County. However, the basement rock at known depths from 2,600 to 4,500 feet is, in part, igneous rock of felsic or intermediate composition.

BASEMENT ROCK

Coarsely crystalline pink granite has been penetrated in most wells that have reached the basement. Similar granite crops out in the Navajo Indian Reservation near Hunters Point about 20 miles north of the area and is described by John Lance (1958) who stated:

> Pink orthoclase phenocrysts, some as much as two centimeters in length, are common in the coarser phases, with a finer-grained groundmass of quartz, orthoclase, and biotite. The granite is extensively jointed and badly weathered in places, particularly near the upper contact. Some of the feldspar is kaolinized and alteration products such as chlorite and hematite give a dark-green and dark-red color to some exposures.

The log of an oil-test hole recently drilled on Concho dome shows diabase at a depth from 3,650 to 3,680 feet. This is the only reported occurrence of diabase in the basement rock in the area. Lithologic descriptions of well cuttings commonly indicate that the basement rock is weathered on its upper surface and is overlain by conglomerate.

EXTRUSIVE IGNEOUS ROCK

Extensive lava flows dotted with cinder cones occur in the White Mountains volcanic field in the southern part of central Apache County. These flows are all part of the lava field at Datil centered in west-central New Mexico. The lava field contains many centers of eruption which are marked by cinder cones ranging from small knobs to hills more than 600 feet high and by small irregular vents standing barely above the present surface of the lava. In several places lava issued from the base of cinder cones in blocky flows. Several narrow projections from the main mass of lava extend northward as much as 15 miles. One of the projections extends as far north as the Little Colorado River near Hunt. The same flow may have extended as far north as South Mountain north of the Little Colorado River, as lava under the travertine here indicates that it may have flowed more than 25 miles from its source. The lava in the valley of the Zuni River flowed slightly more than 35 miles.

At least four broad periods of eruption covering a considerable period of time are represented by the lava in the central part of Apache County. The age of the lava has not been dated precisely, but the older lavas overlie the Zuni or older erosion surfaces, ranging in age from late Miocene to middle Pleistocene, or they overlie gravels deposited on the oldest Black Point surfaces of late Pliocene age. Some of the younger flows overlie gravel containing early Pleistocene fossils. The earliest lavas in the report area are well weathered, and very little flow structure is preserved. The latest lavas, probably of Recent age, are blocky angular flows that show little weathering.

The eruptive periods were classified by their relation with the erosional stages of the Little Colorado River system. Thus, lava of Tertiary age (pl. 1) overlies the Zuni-Hopi Buttes and older erosion surfaces and is at altitudes of 6,800 feet on Mesa Redonda, 7,230 feet on a hill south of Floy, and more than 7,500 feet on the summit of a prominent butte just north of U.S. Highway 60 at the Arizona-New Mexico State line. The older lava flows of Tertiary and Quaternary age (pl. 1) overlie the early Black Point surfaces. These lavas are at altitudes chiefly between 6,000 and 7,000 feet. The younger lava flows of Tertiary and Quaternary age (pl. 1) overlie the late Black Point surfaces. The Quaternary lava flows (pl. 1) include all flows younger than the preceding lava flow and are related to the Wupatki surfaces. Most of the Quaternary flows are concentrated in the area near U.S. Highway 60, and only one flow extends to the Little Colorado River in Richville Valley.

All the lavas are black massive to vesicular olivine basalt, which locally contains breccia and scoria. Small olivine phenocrysts are common nearly everywhere. In places, columnar jointing aids the downward percolation of precipitation through the lava flows.

The thickness of the lava is extremely variable. Some wells have penetrated as much as 500 feet of interbedded basalt, cinders, and fluvial sediments; others penetrated less than 50 feet before going into sedimentary rock. There are a few small areas in the lava field that the lavas did not cover. One area is at the northeast edge of Floy, where well 236–53(11.7×10.7) was drilled without penetrating any lava in a small depression completely surrounded by lava.

STRUCTURE

The central part of Apache County is entirely in the geologic division named the Mogollon slope (Kelley, 1958), which extends northward from the Mogollon Rim to the southern edge of Black Mesa basin and the Defiance uplift. The main characteristic of the Mogollon slope is a broad, gentle dip to the northeast, modified in places by small folds trending northwest.

These small folds have little effect on the occurrence and movement of ground water in the main aquifers in areas north of the Salt Lake road and State Route 61 because the water in the folded rocks in this area occurs under sufficient artesian pressure to cause it to rise to the crest of the folds. In some areas south of these roads, however, water in the folded rocks at the crest of the structures occurs under water-table conditions because the rocks have been elevated above the piezometric surface and are partially drained of water.

FOLDS

The folds in the report area are less than 6 miles long and are small compared to regional features such as the Defiance uplift. Nearly all folds trend northwest and parallel the axis of a broad trough formed between the Mogollon slope and the Defiance uplift. The anticlines are relatively well defined, but the synclines form rather indefinite structural depressions with poorly developed axes. In many places the synclinal areas are covered by Quaternary deposits, and the synclinal axes are obscured. Few of the axial traces of synclines were mapped because sufficient data to locate them were not available and because they are irregular in form. Most of the synclines are inferred to be between two anticlines.

ANTICLINES

Nearly all the anticlines in central Apache County are asymmetrical and have a steeper dip on the southwest limb. They commonly plunge more steeply to the northwest toward the Black Mesa basin. They are from 1,000 to 10,000 acres in area and have closures ranging from 75 to 175 feet.

Most of the larger anticlines were located approximately and named by Roe (1937). The Zuni River anticline 15 miles northeast of St. Johns could not be mapped completely because the rocks forming the structural feature are partly buried by younger undeformed rocks. Dips on the central part of the anticline, however, range from 4° to 10° and indicate that the trend is northwesterly. A wildcat oil well was drilled on this anticline without success. (See well 217–1T(14.3×3.4) on table 3.)

Three anticlines—Apache dome, Hidden dome, and Concho dome—are in the area near Hunt. South Mountain just northeast of Hunt is on the crest of Apache dome. This anticline plunges 6° NW. and 3° SE. The southwest limb dips about 6° and the northeast limb dips about 3°. The axis forms a wide arc and trends northwest. This structural feature was test drilled, but it failed to produce oil or gas. Hidden dome is just southeast of Apache dome on the south side of the Little Colorado River. This anticline is covered by a lava flow, and there is little indication of its presence on the surface; thus, it is not shown on plate 1. Roe (1937) stated that this anticline covers 4,000 acres and showed it trending northwest in line with the Apache dome. Concho dome is southwest of Hunt and northwest of Concho. The axis of this structural feature trends northwest in the southeast half and north in the north half and shows a subparallel alinement with Apache dome. The west limb dips as much as 4°, and the east limb dips from 1° to 2°. Contrary to the plunge of other domes this structural feature plunges more steeply to the southeast. This dome was drilled for oil and gas without success.

There are five anticlines southeast of St. Johns. Two of these—the Cedar Mesa and St. Johns anticlines—are relatively large and cover about 8,000 to 10,000 acres each. Both are typical of anticlines in this area, have steeply dipping southwest limbs, and plunge to the northwest. The Antelope Valley anticline dips as much as 18° on the southwest limb and 5° on the northeast limb. This structural feature is probably continuous in the subsurface below the Bidahochi Formation and connects with the monoclinelike southwest limb of the St. Johns anticline. The other two—the North and South Malapais anticlines—are similar, but they are small. There is no record that wildcat wells have been drilled on these structural features.

Several small unnamed anticlines and a larger one occur in the Puerco River area between Sanders and the Petrified Forest. The smaller anticlines are less than 2 miles long and are similar in most respects to others in Apache County. The larger anticline, the Pinta dome, has been drilled extensively, and many of the wells produce gas containing a large percentage of helium. The Pinta dome is between the communities of Navajo and Pinta, and it trends west-northwest. It covers an area of about 6,000 acres. The crest is rather flat, and the axial trace is approximate.

The southeastern part of an anticline in Navajo County (Johnson, 1962) extends under the lava just south of Mesa Redonda southwest of Hunt. This anticline is part of the Holbrook anticlinal trend and possibly extends under the lava into the Springerville area.

The crest of a flat, broad anticline is 2 miles northeast of Mesa Redonda and trends northwest for 3½ miles. Dips on the northeast flank are about 2° and on the southwest flank about 1°.

MONOCLINES

A monocline 4 miles east of Chambers trends north and dips between 5° and 10° W. The structural feature is buried north and south of the valley of the Puerco River, and it has not been traced beyond these limits in the subsurface. The monocline is about 3 miles long on the surface.

FAULTS

Faults are scarce in central Apache County and in the Mogollon slope. There are no large faults in the area and only a few small ones.

One of these small faults nearly parallels the Antelope Valley anticline on the southwest side. The southwest side is downthrown, and the displacement is less than 150 feet. Another fault parallels the Cedar Mesa anticline on the southwest side and is downthrown to the southwest about 75 feet. This fault has diverted the Little Colorado River for about a mile. It is part of a lineament that extends from Big Hollow southwest to Voight Mesa. Another fault occurs about 3 miles southeast of Mesa Redonda and 8 miles southwest of Concho. This fault trends almost west and may be continuous with a very small fault on the south flank of Mesa Redonda. It is downthrown about 50 feet to the south and is the only fault noted in the entire area that cuts through lava. A small fault trending northeast and downthrown to the northwest offsets the strata in the Pinta dome.

AGE OF STRUCTURES

The regional warping during the Late Cretaceous and early Tertiary Laramide orogeny produced the Black Mesa basin and tilted the Mogollon slope to the northeast. The anticlines, monoclines, and synclines probably date from this time, and most of these folds had essentially their present form by the end of the early Tertiary. The early Tertiary sedimentary rocks have been folded as have the Upper Cretaceous and older strata, but the Miocene(?) Tertiary Datil Formation shows little indication of folding.

Some late Cenozoic movement is indicated by the tilting of beds of the upper member of the Bidahochi Formation north of Apache dome and south of Sanders. In both areas the overlying Quaternary sediments were not involved in this folding. Thus, the movement probably occurred near the end of the Pliocene.

The age of the faults is not known but is probably late Cenozoic. One of these faults has displaced both Tertiary and Quaternary lava flows lying on the Black Point surfaces; thus some fault movement probably occurred in the early Pleistocene.

GROUND WATER

Ground water is present in consolidated and unconsolidated sedimentary rocks and in extrusive rocks in central Apache County. It occurs under water-table (unconfined) conditions in both sedimentary and igneous rocks and under artesian (confined) conditions in consolidated sedimentary rocks. It is obtained from rocks ranging in age from Permian to Quaternary (table 3).

TABLE 3.—*Records of selected ground-water supplies in the central part of Apache County, Ariz.*

Well number and location: See p. 4 for description of well-numbering system.
Type of supply: Dr, drilled well; OT, oil or gas test well; Sp, spring.
Aquifer: See explanation on plate 1.
Method of lift: C, centrifugal; J, jack; Je, jet; N, none; T, turbine; W, windmill.
Use: D, domestic; I, irrigation; M, municipal; N, none; S, stock.

Well no.	Location	Type of supply	Owner	Driller	Date drilled	Altitude above sea level (feet)	Depth (feet)	Diameter (inches)	Aquifer	Water level (feet)	Date measured	Method of lift	Use	Log	Chemical analysis	Remarks.
170-2	4.10×14.90	Dr	Rockwell			5,570	460		TRcps	250	7-21-55		N		Yes	
171-1T	4.00×11.40	OT	Kerr-McGee			5,780	1,520		Pc					Yes	Yes	
171-2T	4.55×12.05	OT	Kerr-McGee				1,010		Pc	790	5- 7-57				Yes	Helium well.
172-23	11.80×1.70	Dr	C. McCarrell.			5,640	100	6	Tbl	80	3-29-56	W	D, S			
172-37	2.10×14.00	Dr	Navajo Tribe.	Bud Johnson.	1960	6,105	465	12	Tbu	221	3-23-60	W	S	Yes		
173-5	6.25×7.10	Dr	Bill Roberts		1948	6,550	800		Tbu	500	4-24-57	W	S		Yes	
173-11	4.00×15.20	Dr	Navajo Tribe.	Cowley Bros.	1959	6,490	600	8⅝	Tbu	550	9-22-59	W	S	Yes		
192-1	6.35×12.60	Dr	U.S. Park Service.			5,490	1,023	8¼	TRcps, Pdc	121	1936		N		Yes	
193-12	0.25×3.40	Dr	R. Spurlock		1947	6,100	300	8	Tbu	220	4-47	W	S	Yes		
194-12	4.20×16.80	Dr	C. Platt	L. McCray	1959	5,970	630	6	TRm or Pk			W	S	Yes		
195-S1	8.80×12.60	Sp	Hinkson						Kd						Yes	Cedro Spring.
214-2	2.70×16.30	Dr	J. R. Carter			5,750			Pc	144	8-17-56	J, W	S			
214-3	3.45×7.90	Dr	H. Seymore			5,350	325	10	Pc	Flow	8-17-56		I		Yes	
214-5	2.45×8.40	Dr	H. Seymore			5,370	365	12	Pc	Flow	8-17-56	T	I			
214-9	4.80×12.10	Dr	H. Seymore			5,660	335		Pc	180	8-17-56	W	S			
214-11	0.80×8.90	Dr	D. P. Ward	H. White		5,396	400	12	Pc	Flow	8-10-56	T	I	Yes	Yes	
214-16	3.50×6.20	Dr	F. Martin	H. White		5,360	200		Pc	Flow	6-28-57		S		Yes	
214-28	2.10×4.95	Dr	M. Smith	F. Dobell		5,550	250		TRm	226	6-20-58	W				
215-1	12.20×14.00	Dr	R. Patterson.	E. White		5,620	571	12	Pk	40	8-20-56	T	I	Yes	Yes	
215-4	4.35×11.65	Dr	F. Martin	Cowley Bros.		5,495	500	5	Pc	30	9- 5-56	Je	D			
215-5	4.20×11.75	Dr	F. Martin			5,485	380	12	Pk-Pc	8.0	9- 5-56	T	I		Yes	
215-6	4.10×12.25	Dr	F. Martin	E. White		5,485	507	12	Pc	3.3	9- 5-56	T	I			
215-17	9.05×8.90	Dr	L. Johnson			5,415	400	12	Pc	20	10-14-56	T	I			
215-26	7.20×9.80	Dr	E. Hunt			5,430	330	4	Pc	15	10-14-56	C	I, S	Yes		
215-36	11.20×7.20	Dr	B. Hunt	H. White		5,410	100	5⅝	Pc	15	3- 9-55	N				
215-41	10.30×5.10	Dr	Tidewater Oil.		1956		88	4	TRm	25	6-20-56	N			Yes	Uranium test hole.

215-56	10.50×6.75	Dr	L. Paulsell	G. Cowley		5,435	280	6	Pk or Pc	18	11-21-59	W	S	Yes	
215-1T	8.20×14.70	OT	Pan American Oil.		1959	5,850	3,680							Yes	
215-2T	3.00×9.20	OT	Franco-Arizona Oil.		1939	5,672	2,595	13	Pc	235	9-6-39			Yes	Yes
215-S1	4.40×8.80	Sp	H. Platt			5,450			Pk or Pc		5-23-57		S		Yes
216-1	6.05×16.55	Dr	E. Platt			5,680	565	10	Pk	Flow	12-14-56	T	1	Yes	Yes	Flow was 20 gpm on Dec. 14, 1956.
216-10	8.10×14.15	Dr	Wilhelm			5,690	65	6	Qs	57	12-19-56	W	D		
216-14	8.55×14.60	Dr	L. Stradling	Cowley Bros.		5,735	332	6	Pk-Pc	115	12-19-56	T	D		
216-20	8.60×10.00	Dr	B. Jolly	M. White		5,640	215	6	Pk	65	6-20-46	J, W	S		Yes
216-24	14.00×8.15	Dr	E. Platt	D. Misenhiemer.	1950	5,483	252	6	Pc	105	12-19-56	W	S	Yes		Specific conductance, 2,200 micromhos.
216-60	11.00×17.10	Dr	L. Farr	Cowley Bros.	1924	5,730	190	5⅝	Pk	30	5-2-57	Je	D		Yes
216-61	2.10×3.00	Dr	7V Ranch			5,725	130	6	Qal	75	6-46	W	S		Yes
216-70	12.50×17.00	Dr	Bud Greer	Cowley Bros.	1959	5,950	400	8	Pk	256	5-4-59	T	S	Yes	Yes
216-71	9.30×16.20	Dr	L. D. S. Church.			5,890	952	10	Pk-Pc					Yes	
216-S1	6.90×16.40	Sp	L. Richey			5,680			Qal						
216-S5	2.45×16.60	Sp	St. Johns Water Co.			5,800			Tbu						Yes
217-9	4.20×15.80	Dr	Garcia Bros.			5,940			Pc	Flow	9-11-55				
217-10	9.10×16.50	Dr	Garcia Bros.	S. Walker	1949	5,960	60	4	Qt	9	9-12-55	J	S	Yes	
217-12	12.85×17.35	Dr	M. Davis	Cowley Bros.		6,125	323	4¾	Rcs	165	10-30-46	W	S		Yes
217-15	8.85×6.00	Dr	E. Hinkson	S. Walker	1946	6,090	1,300	6	Pc	275	4-18-57	J	S	Yes	
217-16	5.80×10.30	Dr	E. Hinkson	S. Walker	1945	5,950	1,022	6	Pk-Pc	48	2-10-58	W	S	Yes	Yes
217-17	8.90×3.25	Dr	E. Hinkson	S. Walker	1946	5,910	1,202	7	Pc	102	6-15-60	W	S	Yes	
217-19	9.20×9.50	Dr	E. Hinkson	White	1941	5,950	700	10	Pc	85	8-30-55	W	S		
217-20	8.60×12.90	Dr	E. Hinkson	S. Walker	1950	5,820	855	6⅝	Pc	Flow	5-60			Yes		Flow reported at 400 gpm in 1950, approximately 40 gpm in 1960.
217-1T	14.30×3.40	OT	Argo Oil Corp.			5,900	2,625		Pc	Flow				Yes	
235-20	2.40×12.20	Dr	J. Leverton	Cowley Bros.		6,700	817	6	Pc	400	6-12-57	W	S	Yes	Yes

TABLE 3.—*Records of selected ground-water supplies in the central part of Apache County, Ariz.*—Continued

Well no.	Location	Type of supply	Owner	Driller	Date drilled	Altitude above sea level (feet)	Depth (feet)	Diameter (inches)	Aquifer	Water level (feet)	Date measured	Method of lift	Use	Log	Chemical analysis	Remarks
235-24	1.00×4.50	Dr	J. Leverton			6,000	380		Pc	280	6-13-57	W	D		Yes	Headquarters Ranch.
236-2	10.10×1.70	Dr	E. Chilcott Ranch.			5,950			Pc	169	8-22-56	W	S			
236-3	9.40×4.30	Dr		E. White		6,150	302	6	Pc	234	8-22-56	W	S	Yes		
236-9	5.80×1.50	Dr	P. Bigelow			5,912	140	5	Pk(?)	90	6-24-57	J	D			
236-20	12.80×17.10	Dr	G. Dutson	L. McCray		6,790	500	6	QTb	460	6-13-57	W	D	Yes	Yes	
236-23	13.60×4.60	Dr	D. Rhoton	Cowley Bros.		6,150		5	Pc	246	6-12-57	W	S			
236-29	13.10×10.60	Dr	J. Leverton	H. White		6,220	280	12	Ku	24	6-13-57	N	I		Yes	
236-30	14.15×13.50	Dr	E. Chilcott	Cowley Bros.		6,535	485	6	Ku	282	6-13-57	W	S	Yes	Yes	
236-35	12.00×7.80	Dr	E. Chilcott			6,150	450	6	Pc	425	6-11-57	W	S	Yes	Yes	
236-38	13.30×10.60	Dr	J. Leverton	Cowley Bros.		6,025	80	5	Ku	44	6-12-57	W	D		Yes	
236-53	11.60×10.60	Dr	P. Paulsell	L. McCray		6,240	68	8	Qs	20	1- 6-60	W	S	Yes		
236-55	2.15×4.75	Dr	E. Whiting	Cowley Bros.	1950	6,180	300	5⅝	Pk-Pc	40	2-29-60	N	I	Yes		
236-56	1.60× 5.25	Dr	E. Whiting	Cowley Bros.	1958	6,210	630	16	Pk-Pc	45	2-29-60	N	I	Yes	Yes	
236-S2	9.50×16.30	Sp	A. McLluellan.			6,580			QTb		6-21-57				Yes	
236-S3	3.40× 6.40	Sp	St. Johns Water Co.						QTb						Yes	Malapais Spring.
236-S4	7.60× 5.00	Sp							QTb						Yes	Concho Spring.
237-1	10.00× 3.40	Dr	Lyman Water Co.	L. McCray	1956	5,940	720	16	Pk-Pc	29	4- 6-57	T	I	Yes	Yes	
237-10	8.40× 0.80	Dr	J. Patterson			5,920	287	6	Pk-Pc	140	12- 6-56	N				
237-34	2.30× 5.00	Dr	E. Platt			6,055	100		Pk	30	12-12-56	W	S			H_2S odor.
237-35	1.80× 1.20	Dr	M. Davis			5,963			Pk	Flow	12-12-56	W	S			

237-60	9.25× 3.50	Dr	W. Hall			5,900	120		Pk	Flow	9-18-56	T	D, S		Yes	
237-61	7.70× 9.30	Dr		E. White	1939	5,920	151	12	Pk	9.5	10- 5-39	N	I	Yes		
237-65	7.70× 9.35	Dr		E. White	1939	5,920	345		Pk	12.5	7-15-55	N	I	Yes	Yes	
237-S4	9.15×14.50	Sp	M. Hall			6,265			QTb		12-12-56				Yes	Yield, 35 gpm.
237-S9	6.30×14.00	Sp	W. Richey			6,205			QTb		12-13-56				Yes	
238-1	13.90× 6.90	Dr	L. Lockhart	Cowley Bros.		6,590	550	8	Pc	520	12-14-56	J	S	Yes		
238-20	10.75×11.00	Dr	H. LeSueur	Cowley Bros.	1955	6,860	710	6	Pk-Pc	690	7-13-56	W	S			
258-34	1.80× 8.80	Dr	A. Voigt	L. McCray	1957	7,020	360	8	Ku	179	2-29-60	T	I	Yes	Yes	
259-1T	5.25× 5.85	OT		J. Sensibaugh.	1959	7,186	2,921	16						Yes		

The greatest development of ground water in central Apache County is in the valley of the Little Colorado River in the Hunt area, where about 20 irrigation wells yield from 450 to 1,500 gpm (gallons per minute). The development of ground water began in 1945 when flowing water was obtained from a deep well tapping the Kaibab Limestone and Coconino Sandstone. Since 1945, irrigation by ground water from pumped wells has increased in the Hunt area, and in 1961 about 2,000 acres was irrigated.

Additional water for irrigation also has been developed from several deep wells in the Kaibab and Coconino in the St. Johns area. Before 1956 this area was irrigated almost exclusively by surface water of the Little Colorado River or from ground water discharging from Salado Springs. Wells in the St. Johns area yield from about 450 to 1,800 gpm.

Water for domestic and stock use outside the Hunt and St. Johns areas is obtained mostly from rocks of Tertiary or Quaternary age, which include lava, the Bidahochi Formation, terrace gravels, and alluvium. Wells in these rocks, in general, yield less than 50 gpm. However, several springs—such as Richey Springs and Concho Spring—issuing from the lava yield enough water to be used for irrigation.

The quality of the water is closely related to the stratigraphic units; the differences of quality of water from formation to formation are generally greater than they are from place to place in a formation. A notable exception is the Coconino Sandstone which, in general, contains water of fair to good quality in areas to the south of the Little Colorado River and water of poor quality to the north.

Water of quality suitable for one purpose may not be suitable for another purpose, and the standards of quality of water adhered to in one region may not be realistic in another region. For example, the people in some areas of the Navajo Indian Reservation use for domestic supplies water containing several times the concentration of soluble mineral constituents considered to be the upper limit by the U.S. Public Health Service (1946).

In this report reference is made to water that is of excellent, good, fair, and poor quality. Water of "excellent" quality, as defined here, is water which is suitable for domestic, stock, and irrigation uses and which can be used for these purposes with no adverse effect. "Good" water may have a concentration of some constituent, objectionable for one purpose or another, but not such a concentration that would render the water unusable. Water of "fair" quality might be used by stock and with some detrimental effect for irrigation. Generally, it would be undesirable for domestic use. Water of "poor" quality would be unfit for domestic use and would be marginal or unfit for stock and irrigation uses. However, water "unfit" for stock and irrigation is used at times in the arid Southwest. It is sometimes mixed with water of better quality to render it more suitable for irrigation. Stock will sometimes drink highly mineralized water that is cold but not if the same water is warm.

When reference is made to the hardness of water the following classification is used.

Hardness (ppm)	*Rating*
0–60	Soft
61–120	Moderately hard
121–180	Hard
181+	Very hard

Nearly all formations in the central part of Apache County yield water, at one place or another, to wells or springs. The yields are generally small, but some formations yield large volumes of water. The water-bearing properties of the individual aquifers are summarized below.

COCONINO SANDSTONE

WATER-BEARING CHARACTERISTICS

The Coconino Sandstone is the most productive and widespread aquifer in the central part of Apache County. It contains water under artesian pressure in most of the area, and in some places along the Little Colorado River it yields water to flowing wells. However, in most of the area east of the Little Colorado River between St. Johns and Springerville, water in the Coconino occurs under water-table conditions, and only the lower part of the sandstone contains water. Water levels in this area are as much as 520 feet below land surface.

Wells in the Coconino in the St. Johns and Hunt areas have specific capacities ranging from 6 gpm per foot of drawdown to 74 gpm per foot of drawdown. The larger yields are from areas where fracturing has greatly increased the effective permeability or where the sandstone is poorly cemented. Such conditions are common in areas south and west of the Little Colorado River.

The Coconino is not exposed in central Apache County, and no specimens were available for laboratory analysis. However, drill cuttings indicate that the Coconino Sandstone in the St. Johns and Hunt areas is similar to the Coconino exposed in other areas of the Mogollon slope. Samples obtained from exposures near Holbrook and Joseph City were analyzed in the hydrologic laboratory, and the results are tabulated in table 4. The sample taken near Holbrook was cored from an outcrop, and the one from Joseph City was taken from a chunk of Coconino brought up in a bailer from an irrigation well that was being drilled.

QUALITY OF WATER

The quality of water in the Coconino Sandstone varies with location, but, in general, the water southwest of a line through Hunt and St. Johns is suitable or marginal for irrigation and domestic uses. Northeast of this line the water is generally unfit for irrigation, domestic use, or watering stock.

TABLE 4.—*Hydrologic characteristics of the Coconino Sandstone near Holbrook and Joseph City, Ariz.*

Location	Orientation of sample	Porosity (percent)	Specific yield (percent)	Specific retention (percent)	Coefficient of permeability (gpd per sq ft—meinzer units)	Median grain size (millimeters)	Grain-size classification	Sorting
5 miles south of Holbrook.	Horizontal	22.6	21.3	1.3	4.1			
	Vertical	22.4	20.0	2.4	4.6			
Joseph City	do	27.6	26.4	1.2	42	0.212	Fine	Well.

In the Hunt-Concho area the dissolved-solids concentration of the water ranges from 130 to 700 ppm (parts per million) and in the St. Johns area, from 1,500 to 2,100 ppm. Water in the Coconino becomes increasingly poorer in quality northeast from Hunt and St. Johns. Dissolved-solids content of water from Stinking Spring at the west base of South Mountain is 2,680 ppm; of water from well 217–1T(14.3×3.4), about 4,000 ppm; and of water in gas well 171–2T(4.55×12.05) near Navajo just south of the Puerco River, about 59,300 ppm (table 5).

KAIBAB LIMESTONE

WATER-BEARING CHARACTERISTICS

In most of the area south of the Little Colorado and Zuni Rivers, the Kaibab Limestone is an aquifer, whereas to the north it is not known to contain water. The Kaibab is composed of dense hard cherty limestone that is impermeable unless fractured. Where ground water occurs, it is in interconnected solution cavities, joints, crevices, or in the sandstone beds contained in the Kaibab. This hydrologic system permits the rapid movement of ground water so that some wells producing from the limestone yield considerable quantities of water. Well 237–61(7.7×9.4) yields 830 gpm with a drawdown of 116 feet.

The openings are much more prevalent in faulted areas or in areas where crustal movement has fractured the brittle limestone. In most areas in the central part of Apache County, the fractured Kaibab Limestone and the underlying Coconino Sandstone form a single aquifer.

Several wells in the St. Johns-Concho-Hunt area produce water from sandstone beds within the Kaibab Limestone. Logs of wells drilled in the past commonly show water from the "Coconino Sandstone," but in many places the sandstone is actually a bed within the Kaibab. In most places the sandstone beds in the Kaibab are hydraulically connected with the Coconino Sandstone and thus form a single aquifer. During drilling operations, ground water was encountered usually in the upper part of the limestone, although many wells were drilled deeper in order to increase the yield.

Wells in the Kaibab Limestone have specific capacities ranging from 3 gpm per foot of drawdown to 70 gpm per foot of drawdown. The water levels range from 13 to 256 feet, and the wells are between 120 and 400 feet deep.

Two pumping tests were made in central Apache County—one on well 237–61 (7.70 × 9.30) obtaining water from the Kaibab Limestone, and one on well 237–1 (10.00 × 3.40) obtaining water from the Coconino and Kaibab.

The pumped well for the first test, 237–61 (7.70 × 9.30), is at the west edge of Lyman Reservoir about 250 yards southwest of the dam. An adjacent well, 237–65 (7.70 × 9.35), 26 feet away and 345 feet deep, was equipped with a continuous water-level recorder and used as an observation well. A complete log of the pumped well is not available, but the measured depth is 333 feet. G. E. Hazen (written commun., 1947) reported that the well bottomed in the Kaibab Limestone. The partial log shows the base of the Moenkopi Formation at 61 feet (table 6); this evidence indicates that the pumped well penetrated at least 272 feet of the Kaibab Limestone. The log also shows a sandstone bed in the Kaibab Limestone at a depth below 140 feet. Most of the water in the pumped well probably comes from this sandstone bed.

The fact that the pumped well yielded about 830 gpm for 46 hours with 116 feet of drawdown indicates a specfic capacity (discharge per foot of drawdown) of about 7 gpm per foot of drawdown. The test indicates that the aquifer has a coefficient of transmissibility [1] of about 20,000 gpd (gallons per day) per foot and a specific yield [2] of 0.03. These figures indicate that the aquifer has a low permeability. Figure 13, based on an extrapolation of data obtained during the aquifer test, shows approximate future drawdown for various times and at various distances from a well pumping 1,000 gpm. During the test, the discharge of a spring obtaining water from the Kaibab Limestone and about 1,500 feet away from the pumped well dropped from about 380 to 80 gpm.

[1] Number of gallons per day flowing under unit hydraulic gradient at the prevailing water temperature through a strip of aquifer 1 foot wide and equal in height to the penetrated thickness of the aquifer.

[2] The ratio of the volume of water that a saturated aquifer will yield by gravity to its own volume.

TABLE 5.—*Chemical analyses of ground water*

[Results in parts per million, except as indicated. Analyses by U.S. Geological Survey. Geologic source Shinarump Member of the Chinle Formation; Ꞧcps, Sonsela Sandstone Bed of the Petrified Forest upper member of the Bidahochi Formation; QTb, basalt of Tertiary and Quaternary age; Qal, alluvium]

Well and location	Geologic source	Date of collection	Temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)
170-2 (4.10×14.90)	Ꞧcps	7-21-55	--------	--------	--------	--------	--------		76
171-2T (4.55×12.05)	Pc	5- 7-57	--------	25	657	122	15,000		150
173-5 (6.25×7.10)	Tbu	4-22-59	--------	28	34	5.1	17		126
192-1 (6.35×12.60)	Ꞧcps-Pc	--------	--------	--------	56	9.0	1,380		112
195-S1 (8.80×12.60)	Kd	12-33	--------	--------	42	6.8	74		304
214-3 (3.45×7.90)	Pc	8-17-56	60	12	62	26	28		170
214-11 (0.80×8.90)	Pc	8-10-56	64	10	54	20	34		148
214-16 (3.50×6.20)	Pc	9-12-56	60	--------	--------	--------	--------		155
215-1 (12.20×14.00)	Pk	8-20-56	62	--------	--------	--------	--------		143
215-5 (4.20×11.75)	Pk-Pc	5-23-57	60	--------	--------	--------	--------		495
215-41 (10.30×5.10)	Ꞧm	8-20-56	--------	--------	--------	--------	--------		143
215-S1 (4.40×8.80)	Pk or Pc	5-23-57	64	14	246	8.2	720		554
215-2T (3.00×9.20)	Pc	10- 6-39	--------	--------	364	130	413		678
216-1 (6.05×16.55)	Pk	5-26-55	60	11	312	108	324		772
216-20 (8.60×10.00)	Pk	6-20-46	--------	--------	54	15	750		298
216-61 (2.10×3.00)	Qal	6-13-46	--------	13	13	6.3	614		592
216-70 (12.50×17.00)	Pk	5- 4-59	65	18	238	59	232		501
216-S5 (2.45×16.60)	Tbu	7- 3-46	--------	--------	--------	--------	--------		237
217-12 (12.85×17.35)	Ꞧcs	3- 1-57	58	33	173	134	953		604
217-16 (5.80×10.30)	Pk-Pc	8-30-55	69	14	151	46	114		543
235-20 (2.40×12.20)	Pc	6-12-57	62	--------	--------	--------	--------		258
235-24 (1.00×4.50)	Pc	6-12-57	65	17	27	10	15		119
236-20 (12.80×17.10)	QTb	6-13-57	64	25	14	6.7	19		97
236-29 (13.10×10.60)	Ku	8-21-58	58	14	65	18	14		260
236-30 (14.15×13.50)	Ku	6-13-57	65	--------	--------	--------	--------		278
236-35 (12.00×7.80)	Pc	6-11-57	60	21	19	8.6	13		113
236-38 (13.30×10.60)	Ku	6-12-57	60	--------	--------	--------	--------		189
236-56 (1.60×5.25)	Pk-Pc	5-23-57	60	--------	--------	--------	--------		466
236-S2 (9.50×16.30)	QTb	6-21-57	--------	22	17	7.1	12		96
236-S3 (3.40×6.40)	QTb	3-20-57	60	--------	--------	--------	--------		154
236-S4 (7.60×5.00)	QTb	6-20-46	--------	--------	--------	--------	--------		99
237-1(10.00×3.40) [1]	Ꞧcs	3-15-56	--------	10	189	62	802		532
237-1(10.00×3.40) [2]	Ꞧm	3-15-56	--------	11	167	51	339		601
237-1(10.00×3.40) [3]	Pk	3-21-56	--------	18	246	88	346		697
237-1(10.00×3.40) [4]	Pk-Pc	7- 56	64	14	294	78	362		719
237-60(9.25×3.50)	Pk	9-18-56	62	--------	--------	--------	--------		628
237-65(7.70×9.35)	Pk	7-15-55	62	16	248	60	297		636
237-S4(9.15×14.50)	QTb	7-26-46	--------	--------	--------	--------	--------		142
237-S9(6.30×14.00)	QTb	12-13-56	61	--------	--------	--------	--------		225
258-34(1.80×8.80)	Ku	3- 7-57	--------	33	46	27	52		338

[1] Sampled at 115 feet.
[2] Sampled at 160 feet.

in the central part of Apache County, Ariz.

(oldest to youngest): Pc, Coconino Sandstone; Pk, Kaibab Limestone; Ꞧm, Moenkopi Formation; Ꞧcs, Member of the Chinle Formation; Kd, Dakota Sandstone; Ku, Cretaceous rocks, undifferentiated; Tbu,

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Parts per million	Dissolved solids: Tons per acre-foot	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
0	2,020	51,000	------	------	------	------	------	------	------	------	103,000	7.5
0	1,760	23,900	------	------	------	------	2,140	2,020	94	145	59,300	7.2
0	8.6	15	0.6	8.7	179	0.24	106	2	25	.7	270	7.3
5	96	2,100	------	------	3,480	------	177	------	------	------	------	------
------	22	15	.4	.5	310	------	133	------	------	------	------	------
0	125	36	1.0	.2	374	.51	262	122	19	.8	619	7.3
0	97	47	.8	.3	336	.46	216	95	26	1.0	572	7.2
0	------	54	------	------	------	------	225	98	------	------	610	7.3
0	------	15	------	------	------	------	161	44	------	------	365	7.3
0	------	20	------	------	------	------	150	0	------	------	1,010	7.8
0	------	710	------	------	------	------	1,690	1,570	------	------	6,800	7.3
0	696	730	1.9	.9	2,690	3.66	648	194	71	12	3,920	7.4
0	766	700	------	------	3,051		------	------	------	------	------	------
0	606	465	2.3	2.4	2,210	3.01	1,220	590	37	4.0	3,300	7.1
0	819	510	3.6	1.8	2,300	3.13	196	------	------	------	3,550	------
------	395	340	5.4	3.8	1,680	2.28	58	0	------	------	2,700	------
0	486	295	2.3	.1	1,580	2.15	835	424	------	------	2,350	7.1
------	------	7	1.4	------	------	------	------	------	------	------	448	------
0	1,580	645	1.1	1.3	3,820	5.20	982	488	68	13	5,160	7.8
0	241	76	4.0	.1	913	1.24	566	120	30	2.1	1,410	6.8
0	------	8.0	------	------	------	------	210	0	------	------	458	7.5
0	28	9.5	.4	.9	167	.23	108	11	23	.6	269	7.2
0	4.9	4.0	.4	1.0	118	.16	62	0	32	.7	165	7.2
0	30	16	1.0	.3	286	.39	238	25	12	.4	492	7.6
0	------	6.0	------	------	------	------	299	71	------	------	607	7.2
0	11	4.0	.4	.4	133	.18	83	0	25	.6	202	7.2
0	------	68	.6	------	------	------	272	117	------	------	690	7.2
0	------	1,240	------	------	------	------	725	343	------	------	5,210	7.4
0	5.4	7.4	.8	.8	119	.16	72	0	26	.6	166	7.2
0	------	7.0	------	------	------	------	99	0	------	------	269	7.2
------	------	3.0	------	------	------	------	------	------	------	------	------	------
0	1,310	485	------	7.1	3,130	4.26	746	310	70	13	4,420	7.2
0	435	295	------	1.0	1,600	2.18	626	134	54	5.9	2,450	7.3
0	578	390	1.7	.4	2,010	2.73	976	405	44	4.8	3,040	7.0
0	655	400	2.1	.6	2,160	2.94	1,050	465	43	4.8	3,190	7.0
0	------	78	------	------	------	------	202	0	------	------	1,600	7.3
0	521	310	3.1	2.5	1,770	2.41	866	344	43	4.4	2,610	6.6
------	------	5.0	.4	------	------	------	------	------	------	------	255	------
0	------	16	------	------	------	------	------	------	------	------	493	7.4
0	27	17	.8	8.8	378	.51	226	0	33	1.5	562	7.7

[3] Sampled at 310 feet.
[4] Sampled at 720 feet.

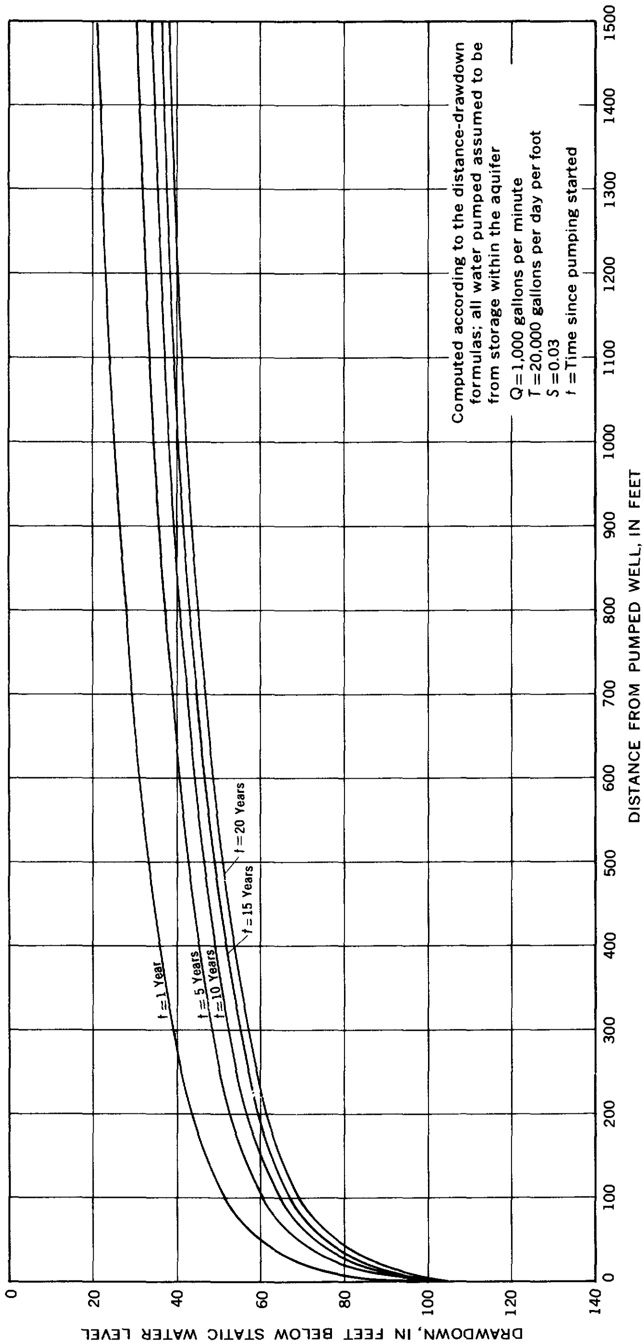


FIGURE 13.—Drawdown of water levels in the Coconino Sandstone at various times and at various distances from a well pumping 1,000 gpm.

In the second test the pumped well, 237–1(10.0×3.4), is about 5 miles southwest of St. Johns. The well obtains water from the Kaibab Limestone and the Coconino Sandstone in an area that has been fractured by faulting. The well yielded 1,800 gpm for 72 hours with a drawdown of 55.6 feet; its specific capacity was about 32 gpm per foot of drawdown. The coefficient of transmissibility here was computed to be about 24,000 gpd per ft.

No springs are known to discharge ground water directly from the Kaibab Limestone. However, several warm springs, such as Salado and Strinking Springs, derive water from the Kaibab and Coconino. These springs are actively depositing travertine, no doubt dissolved from the Kaibab Limestone.

QUALITY OF WATER

Analyses of water from well 237–1(10.0×3.4) indicate that the quality of water in the Kaibab Limestone and in the Coconino Sandstone is very similar. A sample taken when the well was 310 feet deep and still in the Kaibab Limestone shows that the water had a concentration of 2,010 ppm dissolved solids, of which 390 ppm was chloride, 578 ppm was sulfate, and 697 ppm was bicarbonate. A sample taken when the well was completed at 720 feet and obtaining water from the Kaibab and Coconino shows that the water had a concentration of 2,160 ppm dissolved solids, of which 400 ppm was chloride, 655 ppm was sulfate, and 719 ppm was bicarbonate. The other constituents were similarly present in comparable amounts in each sample (table 5). Samples taken in other areas where both formations are present indicate a similar relation in the quality of water.

MOENKOPI FORMATION

WATER-BEARING CHARACTERISTICS

The Moenkopi Formation contains ground water in the western part of Apache County near the Little Colorado River, but the yield is small, and the water is generally highly mineralized. Water within the Moenkopi Formation occurs mostly in fractures and joints because the low permeability and lenticularity of the beds restricts the movement of the water.

QUALITY OF WATER

In a few areas, where the formation has been flushed of salts, the water from the Moenkopi is tolerable to stock, but in most areas the water is unfit for any use.

Water in the Moenkopi Formation in well 237–1(10.0×3.4) 5 miles southwest of St. Johns contained a concentration of only 1,600 ppm dissolved solids, of which 295 ppm was chloride, 435 ppm was sulfate, and 601 ppm was bicarbonate. Other wells in the Moenkopi yield water containing a concentration of chloride ranging from 710 ppm in well 215–41(10.3×5.1) to 1,690 ppm in a well just outside the mapped area along the Little Colorado River.

CHINLE FORMATION

WATER-BEARING CHARACTERISTICS

Although it crops out over wide areas in Apache County, the Chinle Formation contains only a few lenticular sandstone beds, mainly in the valley of the Puerco River, that yield water to wells. These beds form the Shinarump Member at the base, the Sonsela Sandstone Bed, and a sandstone unit in the upper part of the Petrified Forest Member. All the other units in the Chinle Formation are not water bearing.

The claystone, mudstone, and siltstone units in the Chinle Formation, in combination with the siltstone units in the Moenkopi Formation, form a confining layer above the aquifers in the Coconino Sandstone and Kaibab Limestone. Drilling records show that practically no water has been obtained from the muddy units in the Chinle Formation, even in areas where these units are several hundred feet below the piezometric surface of water confined in the Coconino Sandstone and Kaibab Limestone. Thus, these units act as a nearly perfect confining layer.

Some of the claystone units contain bentonite, which is of interest hydrologically because it contains montmorillonite and other clay minerals that swell when wet. This swelling makes the drilling of deep wells in the Chinle Formation difficult because it may cause the hole to cave in or it may "freeze" the casing so it cannot be "carried" down as the hole is drilled. Each time the casing "freezes" the diameter of the hole must be reduced and another string of casing inserted. Thus, the presence of bentonitic beds may cause delays in drilling and increase the cost of the finished well.

The Shinarump Member of the Chinle Formation is utilized as an aquifer only in the valley of the Puerco River upstream from Chambers and perhaps in well 217–12(12.85×17.35) 8 miles east of St. Johns.

Recharge to the Shinarump Member of the Chinle Formation in the Puerco River area is from direct precipitation falling on the southwest-dipping slopes of the Defiance uplift. The water moves downdip toward the southwest and occurs under artesian conditions in areas where the Shinarump is not exposed. Wells completed in the Shinarump range in depth from about 100 to 600 feet, but water levels are usually between 50 and 150 feet. In most wells the yield is low, about 5 to 10 gpm. Water was found in the Shinarump Member of the Chinle Formation in well 237–1(10.00×3.40), but the yield was not determined.

The Sonsela Sandstone Bed of the Petrified Forest Member contains water in the area north of the Puerco River, but in the report area it is not utilized as an aquifer because it contains salt water. The sandstone bed is present in much of the subsurface overlain by the Bidahochi Formation, but water in the Sonsela Sandstone Bed south of the river has not been recorded, probably because wells obtaining water from the Bidahochi Formation do not penetrate very far into the underlying rocks. However, the Sonsela Sandstone Bed probably contains only salty water in the area near the Puerco River. In other areas in central Apache County the Sonsela Bed is lenticular, has a high silt content, and is locally absent—all factors which lessen its potential as an aquifer.

In the Zuni Indian Reservation in New Mexico adjoining the northeastern part of central Apache County, the Sonsela Sandstone Bed is a good aquifer. Here, the sandstone is as much as 100 feet thick, is composed of coarser materials, and is more permeable than it is to the west. Aquifer tests of this sandstone bed at Zuni Pueblo indicated specific capacities from 0.25 to 1.1 gpm per foot of drawdown and a coefficient of transmissibility of 150 gpd per ft (Cooley, M. E., Davis, G. E., and Hardt, W. F., written commun., 1956). In the Zuni River valley adjacent to the Arizona-New Mexico State line, a few flowing wells obtain water from the Sonsela Sandstone Bed.

QUALITY OF WATER

A sample of the water from the Shinarump Member taken while well 237–1(10.00×3.40) was being drilled contained 3,130 ppm dissolved solids, of which 485 ppm was chloride, 1,310 ppm was sulfate, 532 ppm was bicarbonate, and 802 ppm was sodium and potassium combined. The chemical quality of water in the Shinarump near the Puerco River in the area east of Sanders is better, as the water usually contains less than 1,000 ppm dissolved solids, of which less than 50 ppm is chloride.

The Sonsela Sandstone Bed in the Zuni River valley contains water of better chemical quality than it does near the Puerco River. In the Zuni area, water from the Sonsela Sandstone Bed contains less than 200 ppm of chloride in comparison to the water in well 170–2(4.10×14.90) that contains 51,000 ppm of chloride.

DAKOTA SANDSTONE

WATER-BEARING CHARACTERISTICS

The Dakota Sandstone usually caps mesas, and in many areas it has been drained of water. However, a few wells obtain water from the Dakota in the area just north of the Zuni River near the Arizona-New Mexico State line (fig. 14). No data are available on yields, but the wells produce sufficient water for domestic and stock uses.

QUALITY OF WATER

Water from the Dakota Sandstone is hard but otherwise is of good quality. An analysis of water from Cedro Spring 195–S1 (8.80×12.60) which issues from the Dakota Sandstone shows that it has a concentration of 310 ppm dissolved solids, of which 304 ppm is bicarbonate (table 5). The low amount of dissolved solids suggests the Dakota is recharged locally.

UPPER CRETACEOUS ROCKS UNDIFFERENTIATED

WATER-BEARING CHARACTERISTICS

Upper Cretaceous rocks, undifferentiated, yield ground water to wells in the southern part of the area near Floy, Springerville, and along the Arizona-New Mexico State line (fig. 14). Although these rocks crop out in isolated exposures, they are probably continuous beneath the lavas or the early Tertiary sedimentary rocks.

Several wells in the Floy area obtain water from sandstone of the Mesaverde Group. The yield from most wells is small. Well 236–29(13.10×10.60) is reported to produce as much as 1,000 gpm, but there is some doubt that this well receives water only from the Mesaverde. Part of the water may enter from the overlying volcanic and sedimentary rocks or possibly from fractures related to movement, as indicated by tilted strata in the area.

Drillers' logs of several wells in the Springerville area, including the town wells, report water in the "Coconino Sandstone" at depths of less than 200 feet. The depth to the Coconino Sandstone at Springerville is probably about 800 feet, and the reported sandstone unit is probably part of the Upper Cretaceous rocks that crop out in Hooper Valley 4 miles north of Springerville. Wells obtaining water from this unit yield as much as 110 gpm.

QUALITY OF WATER

Most of the wells in the Floy area produce water suitable for domestic use. Water from well 236–29(13.10×10.60), which probably is typical, has a concentration of 286 ppm dissolved solids, of which bicarbonate constitutes 260 ppm.

The water is hard but otherwise good. An analysis of water from 258–34(1.80×8.80) shows that the water has a concentration of 378 ppm dissolved solids, of which 338 ppm is bicarbonate.

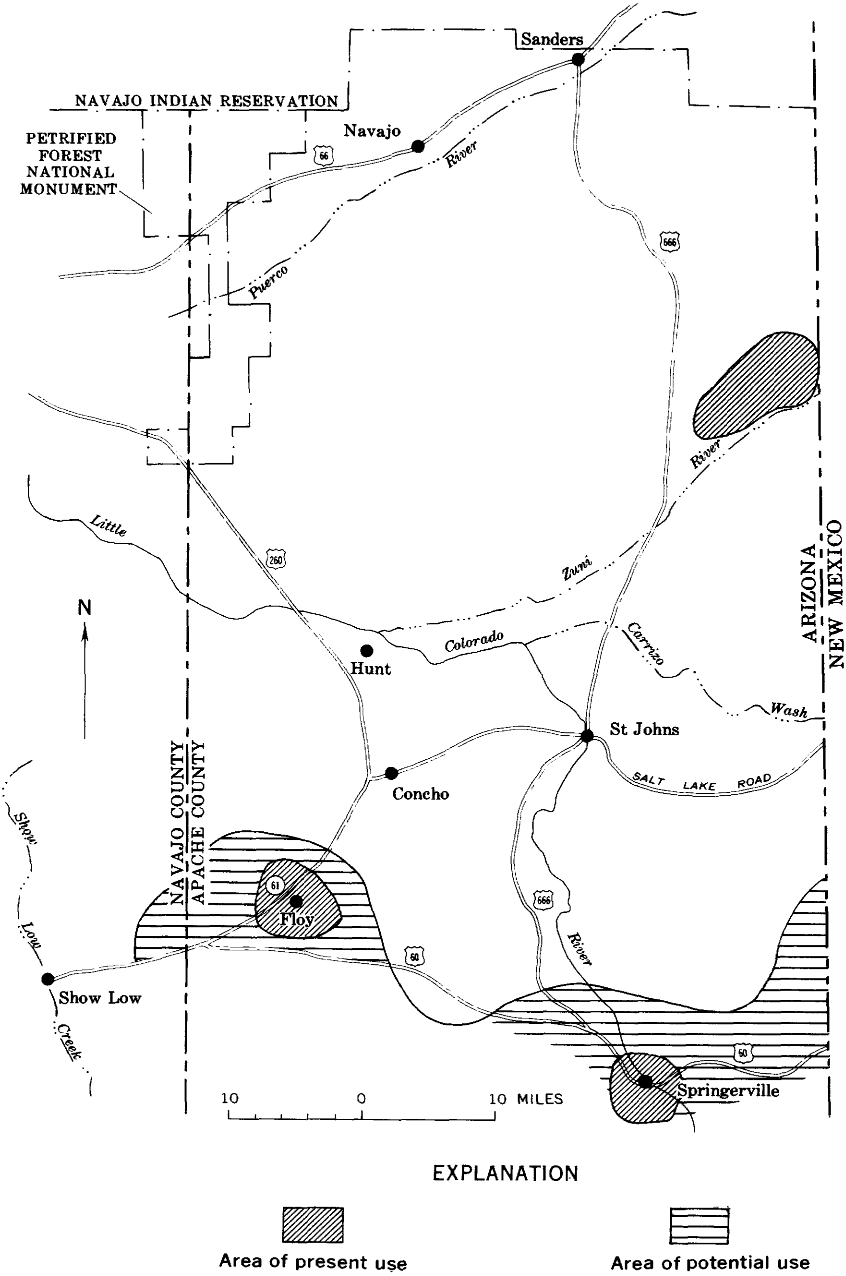


FIGURE 14.—Map of the central part of Apache County, Ariz., showing generalized areas of potential ground-water development from Cretaceous rocks.

TERTIARY SEDIMENTARY ROCKS

No wells in the central part of Apache County receive water from the Tertiary sedimentary rocks, although there are several wells immediately south of Springerville that obtain water from these rocks. In these wells the water is of good quality, but the yield is small—ranging from 10 to 25 gpm.

BIDAHOCHI FORMATION

WATER-BEARING CHARACTERISTICS

The only well known to produce water from the lower member of the Bidahochi Formation in the area of this report is well 172–23(11.8 ×1.7) north of Chambers near the Navajo Indian Reservation. This well yields 5 gpm of water, which is presently being used for domestic purposes. The water was not analyzed for quality, but quality is reported to be good.

In most places where it is present between the Zuni River and the Puerco River, the upper member of the Bidahochi Formation contains water under water-table conditions. In this area the control of occurrence and movement of the water in the Bidahochi is largely by valleys and ridges which were buried by the Bidahochi Formation and which reflect the topography of the Zuni erosion surface. In some areas the saturated thickness is not enough to cover small buried ridges on the Zuni erosion surface, and wells drilled on these ridges are dry. The alinement and position of these buried ridges cannot be determined from presently available surface or subsurface information. The contours drawn on a map of the Zuni surface (pl. 2) indicate that several large buried channels are at the base of the Bidahochi Formation. One of these channels, just south of the Puerco River, controls the direction of ground-water movement and indicates, in a general way, favorable areas for ground-water development. Wells producing from the upper member of the Bidahochi Formation yield from 10 to 50 gpm, depending upon the coarseness and thickness of the saturated material, and the depth to water is from 50 to about 500 feet.

Plate 2 shows altitudes of the water levels in part of the Bidahochi Formation, and figure 15 shows generalized areas of potential ground-water development in the Bidahochi Formation.

QUALITY OF WATER

Water from the upper member of the Bidahochi Formation is suitable for domestic use. A representative sample of the water, from well 173–5(6.25×7.10), is moderately hard and contains 179 ppm dissolved solids.

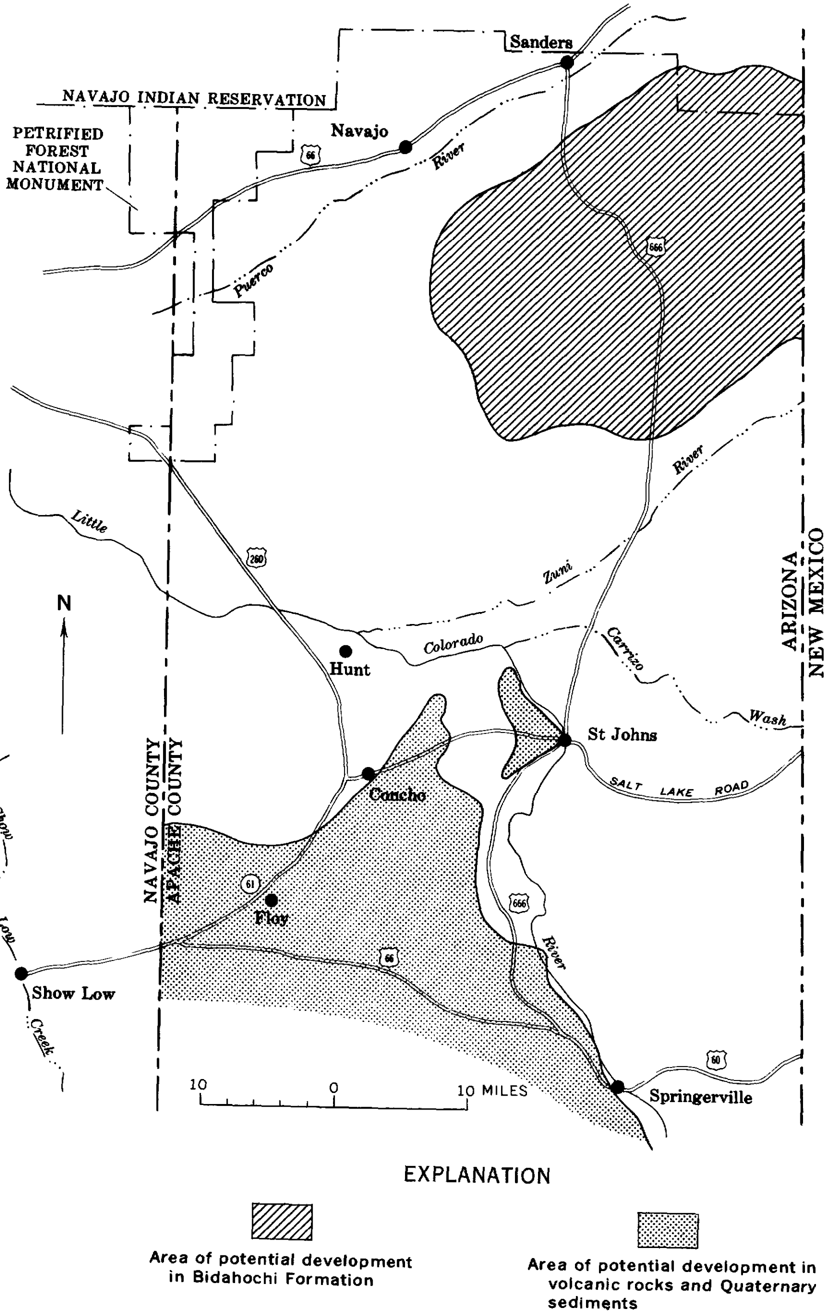


FIGURE 15.—Map of the central part of Apache County, Ariz., showing generalized areas of potential ground-water development from the Bidahochi Formation and from volcanic rocks and Quaternary sediments.

QUATERNARY SEDIMENTS

WATER-BEARING CHARACTERISTICS

Quaternary sand and gravel deposited in ancestral valleys contain water in several areas beneath the lava-capped platforms between Concho and Springerville and in extensive areas between Big Hollow and the Little Colorado River. Most wells in the gravel are less than 100 feet deep, and they yield about 10 to 20 gpm.

In much of the area south of Concho, the water in Quaternary sediments is hydraulically connected with water in the overlying lava. For this reason the areas of potential development of ground water from Quarternary sediments are included with volcanic rocks, as shown in figure 15. However, no lava overlies the Quaternary sediments in the area immediately west of St. Johns.

QUALITY OF WATER

The water in the Quaternary sediments typically has a concentration of less than 400 ppm dissolved solids. However, in the area just west of St. Johns the water is of marginal quality for domestic use. Farmers in the area report that before the irrigation ditches were built across higher parts of the Quaternary gravel, the gravel did not contain water. This fact suggests that the water now present in the gravel in this area is seepage from the ditches and irrigated fields. Also, the quality of the water in the gravel is similar to that of the water put into the ditches and used for irrigation. The water characteristically is rather highly mineralized. The dissolved-solids concentration ranges from about 1,500 to 2,000 ppm.

QUATERNARY ALLUVIUM

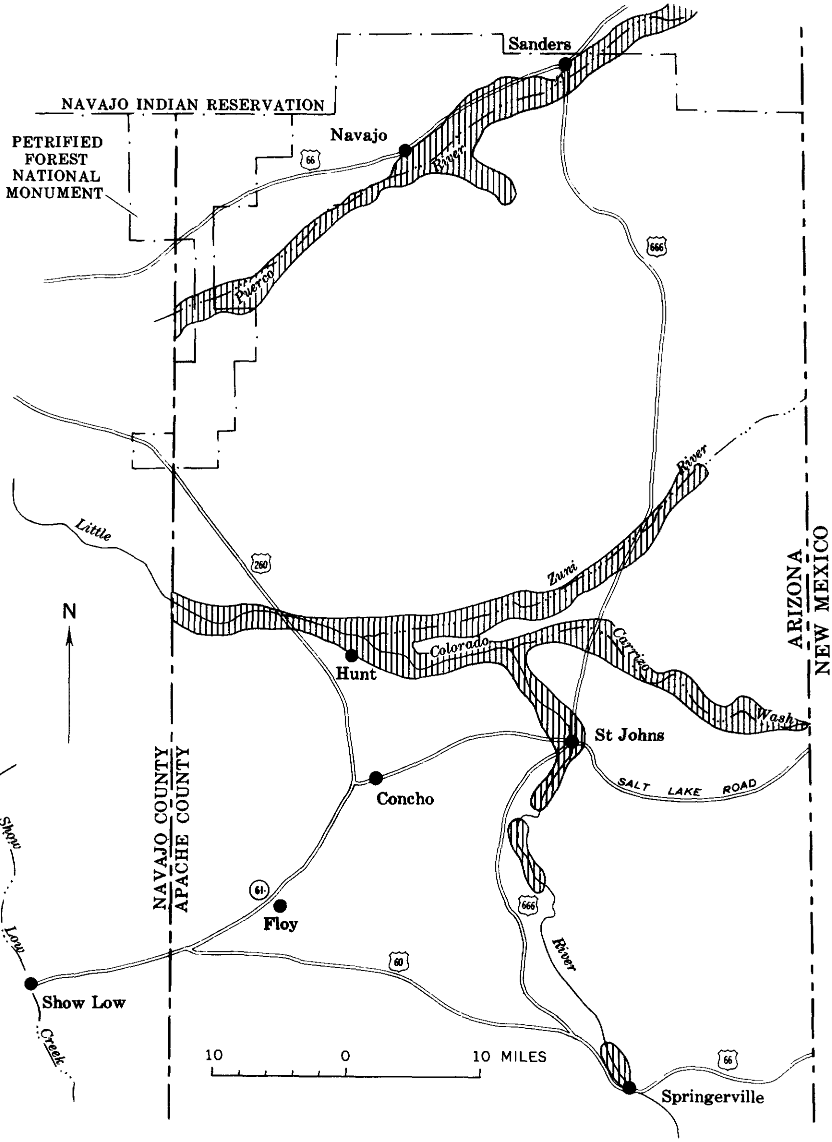
WATER-BEARING CHARACTERISTICS

Quaternary alluvium is an important source of water in central Apache County. Wells in alluvium furnish water to several ranches for domestic and stock use. Some of these wells are shallow—less than 10 feet deep—being dug in thin deposits of alluvium, and in times of drought they dry up; others are drilled to depths of more than 100 feet and are reliable sources of water.

The alluvium along nearly all the larger drainage features contains water (fig. 16), and, as a general rule, the alluvium along the tributries contains coarser material than that along the main trunk streams.

QUALITY OF WATER

The most water, which is also of best quality, generally occurs in coarse materials in the bottom of the alluvial deposits. However,



EXPLANATION

Area of potential development in alluvium

FIGURE 16.—Map of the central part of Apache County, Ariz., showing generalized areas where ground water can be developed in alluvium.

the water from well 216–61(2.10×3.00), which obtains water from near the bottom of the alluvium along the Zuni River, contains 1,680 ppm dissolved solids. Evaporation and transpiration by phreatophytes concentrates the dissolved solids in the water occurring near the top in finer grained materials, and shallow wells drilled into these sediments tend to produce water of marginal or unsuitable quality for domestic use. The water is used, however, for domestic purposes at several homes where better water is not available.

VOLCANIC ROCKS

WATER-BEARING CHARACTERISTICS

Many wells and springs in the area of investigation obtain water from volcanic rocks. The sites of springs and the occurrence of water in the lava are controlled largely by fractures, intercalated cinders, and irregularities in the surface of the underlying impermeable material. In areas where the impermeable rock stands above the water table, the chances of obtaining water in the lava are poor.

Wells in the lava range in depth from 15 to more than 500 feet, and they yield from 10 to more than 75 gpm. Springs discharge generally from 1 to 1,000 gpm.

QUALITY OF WATER

Water from the lava has dissolved-solids concentrations ranging generally from 100 to 250 ppm, but all the water is of good quality. Water from spring 236–S2(9.5×16.6) northeast of Vernon is typical of water from the basalt. This water has a concentration of 119 ppm dissolved solids, of which 96 ppm is bicarbonate. Other individual constituents are less than 25 ppm. Water from some springs is soft; from others it is moderately hard.

REGIONAL HYDROLOGY

The movement of ground water in the southern part of central Apache County is toward the north, and it is controlled largely by the regional dip. In general, the water in the Coconino Sandstone and Kaibab Limestone aquifers moves from areas of recharge in the White Mountains and along the Mogollon Rim in the south and southeast to points of natural and artificial discharge in the north (fig. 17 and pl. 3).

The Kaibab Limestone and Coconino Sandstone, as well as younger rocks, are recharged directly by rainwater and snowmelt where they crop out south of the report area. Recharge also is furnished by streams that have dissected the Mogollon Rim at altitudes above

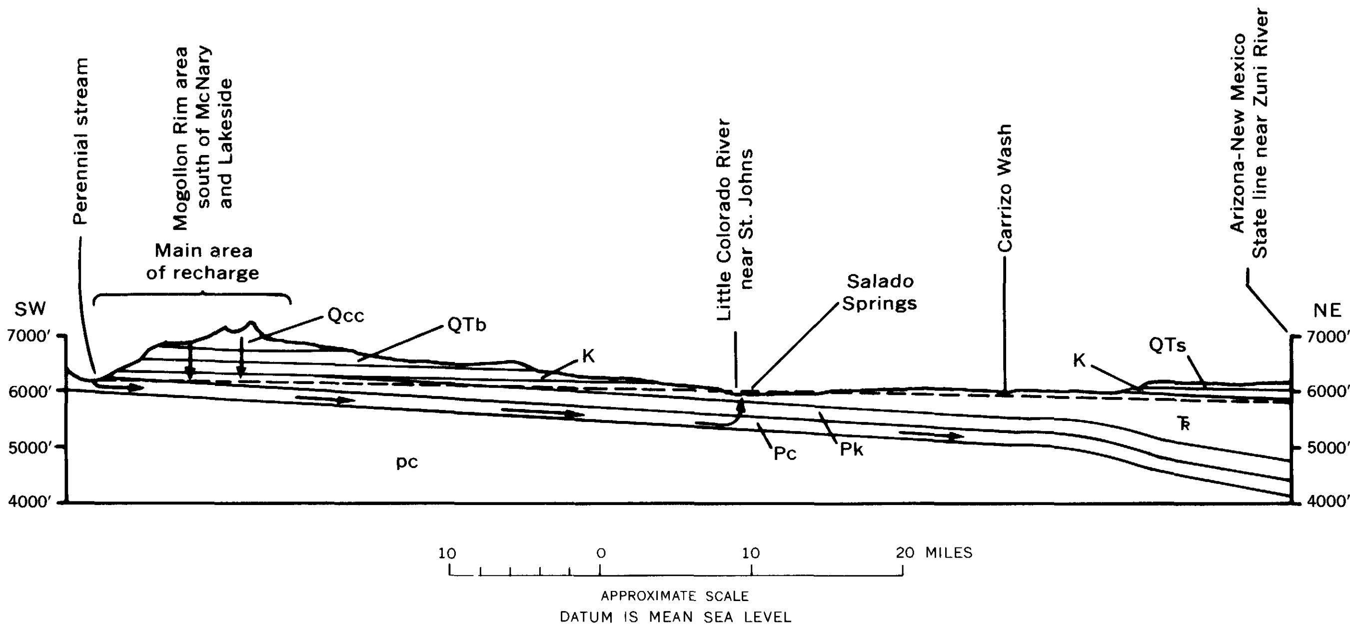


FIGURE 17.—Synoptic diagram showing relations of recharge area, direction of ground-water movement (shown by arrows), and piezometric surface of water (represented by dashed line) in the Kaibab Limestone (Pk) and Coconino Sandstone (Pc). Quaternary cinder-cone deposits (Qcc), basalt of Quaternary and Tertiary (QTb), Quaternary and Tertiary sediments (QTs), Cretaceous rocks (K), Triassic rocks (Ŧ), and rocks older than Coconino Sandstone (pc). See figure 1 for general alinement of section.

6,000 feet and cut deep canyons into these formations. Many of these streams are perennial, and they are permanent sources of recharge. Records of the U.S. Weather Bureau show that McNary, located in the recharge area, receives about 24 inches of precipitation annually, which is probably the magnitude of precipitation where the formations crop out.

South of the area of Triassic rocks, the Kaibab Limestone is overlain by lava, Quaternary and Tertiary sedimentary rocks, or by sandstone of the Cretaceous, all of which readily absorb and transmit water to the Kaibab. In most of the area between Springerville and Lakeside, the sandstone of the Cretaceous is overlain by lava or cinders which absorb most of the precipitation. This water percolates downward into and through the sandstone of the Cretaceous to recharge the Kaibab Limestone and Coconino Sandstone. The downward movement is practically stopped by relatively impermeable beds at the top of the Supai Formation, and the water moves northward downdip in response to gravity toward areas of discharge. Where Cretaceous and Triassic rocks are present, they retard or stop the downward movement of water before it reaches the Coconino and Kaibab, and the water moves laterally northward until it reaches areas where it is discharged by springs at the base of the lava. Such springs are Concho Spring, Malapais Spring in the west side of Big Hollow, "24" Ranch Springs, and Richey Springs in Richville Valley. Discharge from the individual springs ranges from 30 to more than 1,000 gpm.

Water from the Kaibab and Coconino is discharged, in part, by large springs along the Little Colorado River between Lyman Reservoir and Hunt and from flowing wells in the Little Colorado River valley between Lyman Reservoir and the Navajo County line. The combined discharge of the springs in this reach fluctuates between 4 and 10 cfs. These springs and flowing wells occur where the water in the Kaibab and Coconino is under artesian conditions, mainly at altitudes of less than 6,000 feet, and where the relatively impermeable beds in the overlying Moenkopi Formation act as confining layers. In the area southeast of St. Johns, the water occurs under water-table conditions because the upper confining beds are higher than the piezometric surface.

The water-level contours shown in plate 3 indicate that the regional movement of water in the aquifers of the Coconino and Kaibab continues toward the north beyond the discharge areas into a broad structural trough, the Tusayan downwarp of Gregory (1917, p. 112), which extends between the Little Colorado River and the southwestern limb of the Defiance uplift from the Arizona-New Mexico State line into

Black Mesa basin (fig. 18). The contours further indicate that water also enters the trough from recharge areas in the Zuni and Defiance uplifts and moves west-northwestward in the trough.

Most of the recharge from the Defiance uplift enters from the southwestern part of the uplift. Recharge from the southern tip of the uplift is prevented by a silty facies which has greatly reduced the permeability of the Coconino Sandstone (or its equivalent, the De Chelly Sandstone).

In the silty facies of the De Chelly Sandstone, according to H. W. Pierce (geologist, Arizona Bur. Mines, oral commun., 1960), the ratio of clean crossbedded sandstone units to horizontally bedded silty sandstone units decreases abruptly from the Pine Springs area, 8 miles northwest of Houck, to the area where the dry wells were drilled. The horizontally bedded silty units are not present in exposures of the Coconino Sandstone in the Holbrook-Snowflake area, and well logs in central Apache County do not indicate silty units in the Coconino. These data suggest that the silty units in the Coconino, or De Chelly, are confined to the Defiance uplift area. The approximate extent of the silty facies of the Coconino is shown in the northeast

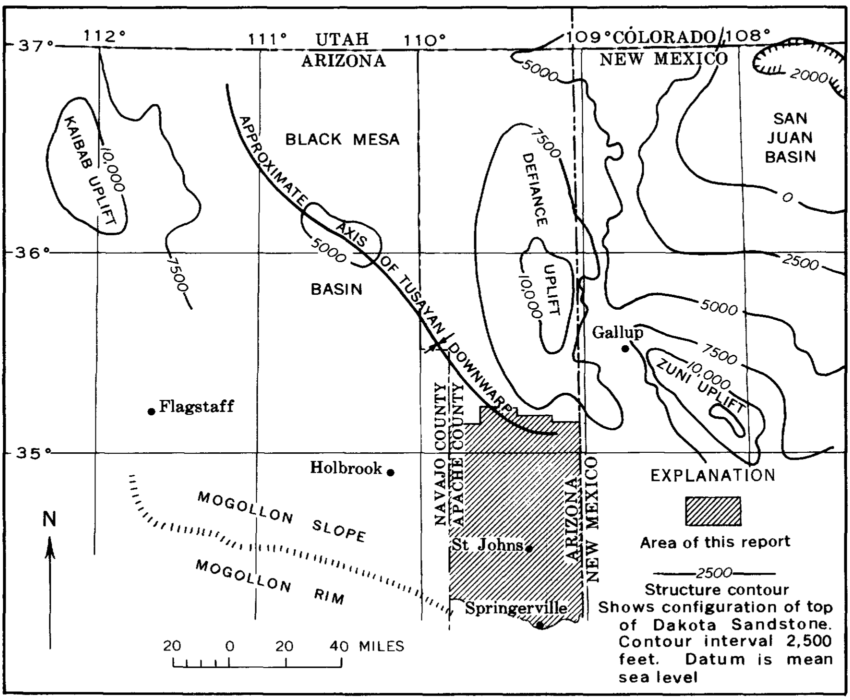


FIGURE 18.—Synoptic structure contour map of northeastern Arizona and northwestern New Mexico. Modified from Kelley (1955, p. 24).

corner of plate 3. Wells drilled in the silty facies of the De Chelly Sandstone are dry, even though the base of the silty facies is lower than the surrounding regional water levels. This fact excludes the possibility of structure being responsible for the dry wells. Pumping tests conducted on the Navajo Indian Reservation indicate that the permeability of the De Chelly Sandstone in the area of the Defiance uplift is less than that of the Coconino Sandstone to the south and southwest. The specific capacity of wells in the De Chelly Sandstone on the Defiance uplift averages about 0.2 gpm per foot of drawdown.

The water contained in the Coconino Sandstone and Kaibab Limestone is much more highly mineralized within the broad structural trough than in areas bordering or outside the trough. This highly mineralized water possibly enters these formations by upward leakage from the Supai Formation which, in this area, contains several beds of crystalline salt and other evaporites. The top of the Supai Formation in the lowest part of the trough is about 1,400 feet lower than the top of the formation in the southern part of the area of investigation (see section *B–B′*, pl. 1) ; it is about 2,000 feet lower than the lowest exposure along Black Creek in the Defiance uplift and about 3,700 feet lower than the lowest exposure in the Zuni Mountains. Therefore, water in the Supai Formation in the trough occurs under considerable artesian pressure, and upward leakage of highly mineralized water from the Supai Formation into the Coconino Sandstone in the deeper parts of the trough is likely. The upward leakage would be at a minimum at the periphery of the trough where artesian pressure in the Supai would be less and contamination of the water in the Coconino and Kaibab would be less. Also, along the periphery of the trough recharge from direct precipitation dilutes the mineralized water. The Moenkopi Formation also contains evaporite deposits, and it is possible that some mineralization of water in the Coconino and Kaibab results from solution of these salts. Probably little, if any, mineralized water from the Moenkopi enters the Kaibab Limestone and Coconino Sandstone because water in the Kaibab and Coconino in most of the area occurs under artesian conditions, which tend to prevent downward movement of water. However, the Moenkopi does contain salty water in some areas, and where water-table conditions prevail, some water from the Moenkopi might move into the Kaibab and Coconino.

A small structural trough is formed by the northeast dip of the Mogollon slope and the southwest flank of a line of anticlines extending from a point about 10 miles northeast of Springerville to North Mountain near Hunt. The lowest part of this trough coincides approximately with the course of the Little Colorado River between

Springerville and Hunt where several large springs in this reach discharge water from the Kaibab and Coconino. This discharge has relieved part of the artesian pressure in these formations and resulted in depressed water levels which are clearly reflected by the contours shown in plate 3.

Water in this small trough is rather highly mineralized, probably from upward leakage of salty water in the Supai Formation, but is used for irrigation. Water in the structural high areas on either side of the trough is under water-table or semiartesian conditions and is moderately or little mineralized because there is little, if any, upward leakage of salt water from the Supai Formation.

The occurrence and movement of ground water in other aquifers are controlled largely by the present topography or by the topography of buried erosion surfaces. In the central part of Apache County Cretaceous rock is commonly at the top of mesas, and usually, unless local recharge conditions are favorable or the mesa is extensive, the rock has been drained of water. In the southwestern part of the area near Floy, the Cretaceous rock is recharged from the overlying lava which contains water in most of the area.

The movement of water in the lava is controlled largely by the general gradient of the erosion surface—about 40 feet per mile northward—upon which the lava flowed and by irregularities on this surface.

The controls regulating the movement of water in the upper member of the Bidahochi Formation are similar to those in the lava. Recharge water moves downward through the Quaternary sediments and permeable sands in the upper member of the Bidahochi Formation until it reaches impermeable material in the underlying or in Triassic or Cretaceous formations. It then moves laterally downslope along the buried erosion surface until it emerges in springs in canyon walls or in places where the land surface intersects the water table. Several lakes—such as Red Lake, Green Lake, and Salt Seeps (pl. 1)—have formed in depressions that have intersected the water table in the Bidahochi Formation.

WATER-LEVEL FLUCTUATIONS

Annual measurements of water levels in observation wells in the Coconino Sandstone and Kaibab Limestone at St. Johns and Hunt indicate no significant change in water levels during the last several years (fig. 19). The fact that water levels decline during the heavy pumping season and recover during the winter and early spring generally indicates that recharge is at least equal to the discharge from wells and springs. In the last 15 years, however, the combined discharge of the flowing wells and springs in the Hunt area has decreased from about

2,000 gpm to less than 1,000 gpm because of heavy pumping and drought conditions which have prevailed during part of that period.

Measurements of the discharge of Concho Spring in late spring or early summer between 1942 and 1958 indicate a decline (fig. 20), which also may reflect drought conditions. The measurements were made about half a mile below the spring, and no doubt part of the differences in discharge can be attributed to differences in evapotranspiration. The average of the discharges shown for the 6 years preceding and including 1951 is 2.71 cfs, which is 0.58 cfs, or about 20 percent, more than the average for the 7 years succeeding 1951.

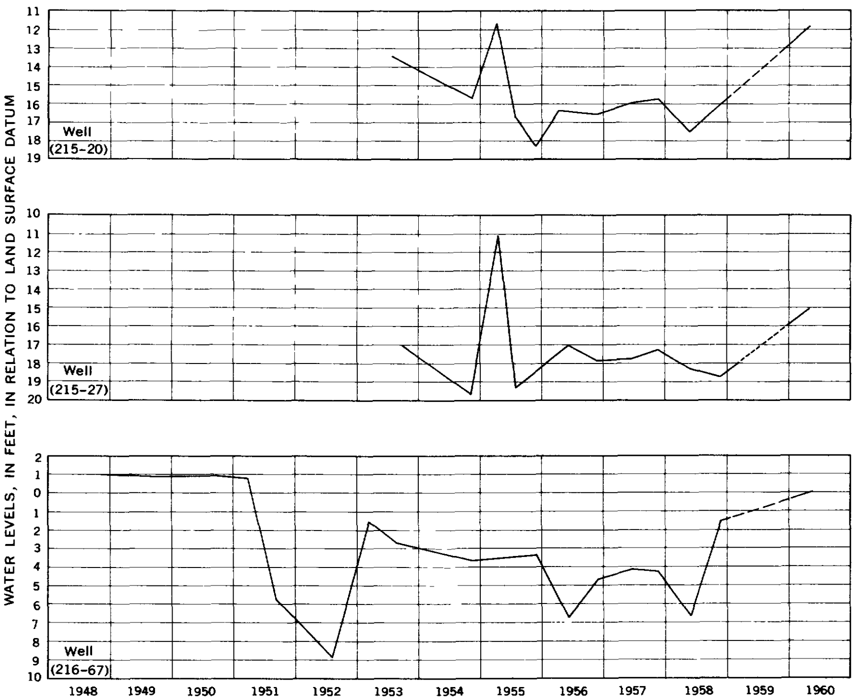


FIGURE 19.—Water levels in selected wells in the Coconino Sandstone and Kaibab Limestone in the Hunt and St. Johns areas, Apache County, Ariz.

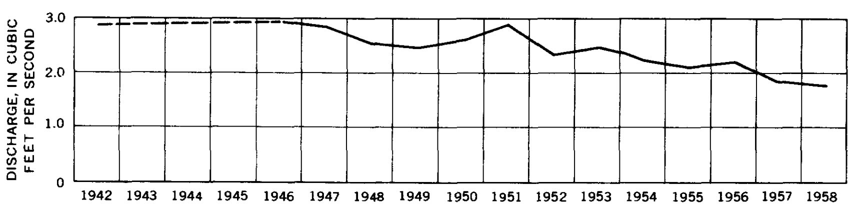


FIGURE 20.—Discharge of Concho Spring, Apache County, Ariz.

Records of water levels in other formations are not adequate to indicate trends of declines or rises. However, the fact that several springs, described by Harrell and Eckel (1939) as discharging water from Tertiary sand (Bidahochi Formation), are now dry may indicate a decline of water levels in some areas in the Bidahochi.

AREAS OF POTENTIAL GROUND-WATER DEVELOPMENT

Several factors limit the size of the areas in the central part of Apache County where water in sufficient quantity and of suitable quality for irrigation can be developed. Water in considerable quantity can be developed from the Coconino Sandstone in all the central part of Apache County except that part lying on the south tip of the Defiance uplift. However, the quality of water in the Coconino north of the Little Colorado River and Carrizo Wash is unsuitable for irrigation and in much of that area is unsuitable for stock (fig. 21) The quality of water in most of the area south of Carrizo Wash and east of Concho Creek is marginal for irrigation, unsuitable for domestic use, and suitable for stock.

In the area south of the Little Colorado River and west of Concho Creek, the Coconino contains water of suitable quality for irrigation, and the yields of wells range from about 400 to 1,500 gpm. In the topographically high areas in the southern part of the area, however, the depth to water may preclude its use for irrigation.

In summary, the area in which there is a potential of developing water from the Coconino in sufficient quantity and of suitable quality for irrigation, without excessive lift, lies south of the Little Colorado, north of the main body of lava, and west of Concho Creek (pl. 1). Water of marginal quality can be obtained from the Coconino in considerable quantities in the valley of the Little Colorado River between the south end of Richville Valley and Hunt at depths from about 200 to about 900 feet below the surface. Richville Valley is closer to recharge areas than is Hunt, and water from the Coconino in Richville Valley would probably be of somewhat better quality than that in the area between St. Johns and Hunt.

The areas where additional ground water can be developed from rocks of Cretaceous age are limited by the distribution of these rocks. In the southern part of central Apache County most of the rocks of Cretaceous age are overlain by lava which contains water; therefore, there is usually no reason to drill into the rocks of the Cretaceous. However, in several areas adjacent to, and west of, central Apache County the lava is dry, and water is obtained from the underlying rocks of Cretaceous age at depths between 200 and 1,000 feet. The areas where there is potential of developing domestic or stock water from rocks of Cretaceous age are shown in figure 16.

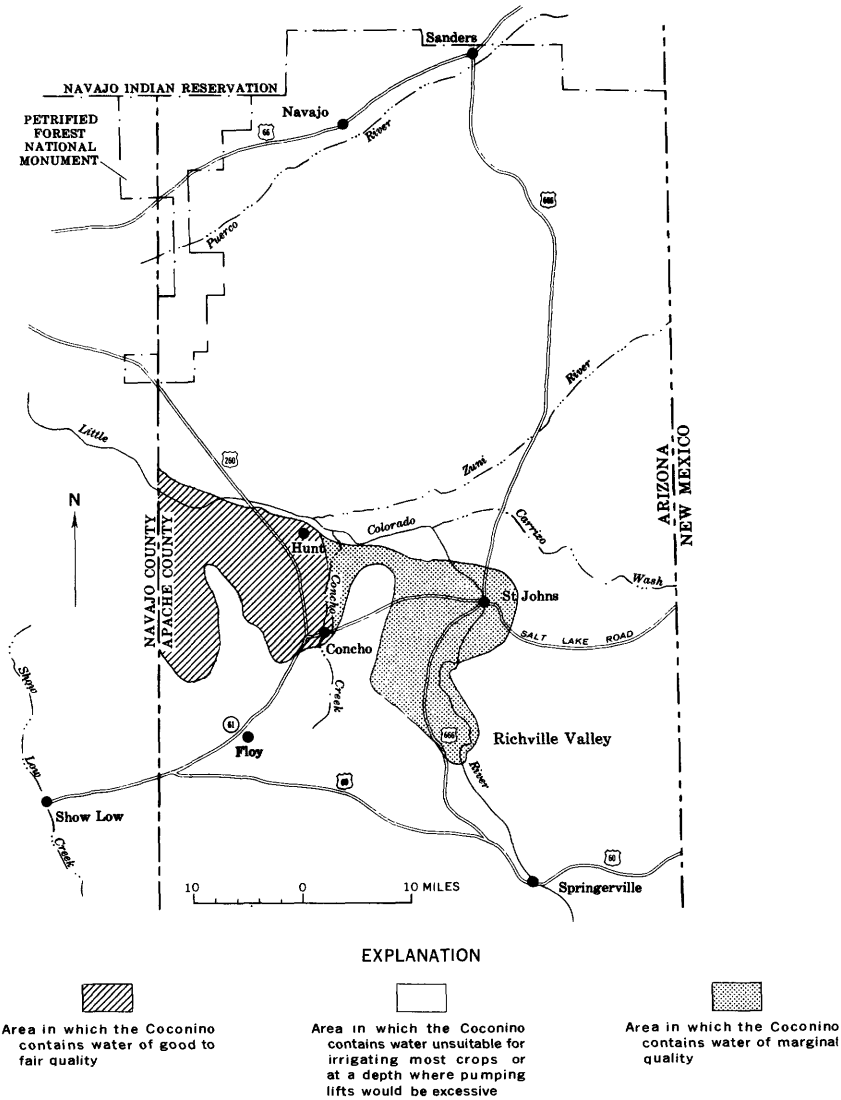


FIGURE 21.—Map of central part of Apache County, Ariz., showing areas of potential development of irrigation water from the Coconino Sandstone.

The areas where additional ground water can be developed from the Bidahochi Formation are limited by the distribution of the Bidahochi Formation and by the dissection and drainage of the formation in some areas. Additional water for stock and domestic supplies can be obtained in most of the area between the Zuni and Puerco Rivers (fig. 15) at depths from 100 to 600 feet below the surface. Potentially, some small supplies of water can be developed at depths between 100 and 300 feet from the Bidahochi in a small area adjacent to the Navajo Indian Reservation about 5 to 10 miles east-northeast of Sanders.

Some areas probably occur where considerable quantities of excellent quality water can be developed from lava and underlying Quaternary sediments in the southern part of central Apache County (fig. 15). However, the discharge of large springs—such as Concho Spring, Malapais Spring, "24" Ranch Springs, and Richey Springs—represents rejected recharge from the lava, and large withdrawals of water from the lava would almost certainly decrease the discharge from the springs.

The alluvium along the large streams in the central part of Apache County has a good potential for the development of ground water. Some wells in the alluvium along the Puerco River just outside the mapped area (pl. 1) have been pumped at rates ranging from 250 to 1,000 gpm. The areas of potential ground-water development from the alluvium are shown in figure 16. The quality of water from the alluvium differs considerably from stream to stream and from place to place along the same stream. In some areas the quality of the water may preclude its use for one purpose or another.

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
171-1T(4.00×11.40)		
[Alt: 5,780 ft]		
Chinle Formation:		
Red sandstone	60	60
Dark-lavender sandstone	25	85
Light-red sandstone	15	100
Purplish sandstone	50	150
Red shale	30	180
Light-red, purplish sandstone	80	260
Still lighter red sandstone	30	290
Medium-coarse gray sandstone	90	380
Purplish-red sandstone	100	480
Gray clay and shale	60	540
Deep, dark-purple shale and sandstone	20	560
Gray sandstone and shale	10	570
Light-purplish sandstone and shale	35	605
Darker purplish sandstone and shale	15	620
Light-gray sandstone and shale	10	630
Gray sandstone and shale	5	635
Light-purplish sandstone and shale	15	650
Gray sandstone	30	680
Mixed gray and purple sandstone	10	690
Reddish sandstone	10	700

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
171-1T(4.00×11.40)—Continued		
[Alt: 5,780 ft]		
Chinle Formation—Continued		
Dark purple, little gray layers	60	760
Light reddish brown	5	765
Dark reddish brown	5	770
Dark purple	5	775
Reddish-purple sandstone	10	785
Dark-gray sandstone	10	795
Light reddish purple	25	820
Sand and light-red shale	10	830
Dark-reddish-purple sand	11	841
Light-purple sand	4	845
Darker purple sand	30	875
Light-reddish-purple sand	5	880
Gray sandstone	5	885
Light-reddish-purple sandstone	15	900
Reddish-purple sandstone	20	920
Dark reddish purple	5	925
Very light-gray sandstone	5	930
Light reddish purple	5	935
Gray and light-reddish-purple sandstone	10	945
Moenkopi Formation:		
Light red	5	950
Light- and dark-brown sandstone, no purple	60	1,010
Purplish brown	21	1,031
White hard sandstone—helium gas	4	1,035
Coconino Sandstone:		
Yellowish powdery sand	5	1,040
Yellowish sandstone	5	1,045
Hard white sandstone	10	1,055
Light-brown sandstone	21	1,076
Yellow powdery sand	4	1,080
Soft white sandstone—more like silt	265	1,345
Reddish to tan sandstone	5	1,350
Yellow silt	25	1,375
Reddish fine-grained sand	10	1,385
Supai Formation:		
Reddish coarser grained sand	50	1,435
Brownish-red shale	15	1,450
White sand	10	1,460
Still more reddish sandstone	25	1,485
Red coarse thin sandstone	10	1,495
Finer grained sandstone and shale	5	1,500
Fine reddish sandstone	5	1,505
Coarse-grained reddish sandstone	5	1,510
Very coarse dark-gray sandstone	5	1,515
Red sandstone	5	1,520

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
172-37(2.10×14.00)		
[Alt: 6,105 ft. Water level: 221 ft. Aquifer: upper member of Bidahochi Formation]		
Alluvium:		
Sand, soft	65	65
Bidahochi Formation:		
Sandstone and clay	15	80
Sandstone	120	200
Sandstone and clay	60	260
Red and white clay	15	275
Red and white clay with sandstone ledges—water	180	455
Red shale, hard	10	465
173-11(4.00×15.20)		
[Alt: 6,490 ft. Water level: 550 ft. Aquifer: upper member of Bidahochi Formation]		
Bidahochi Formation:		
Light-gray sandstone	450	450
Red clay	5	455
Light-brown sandstone	35	490
Red clay	5	495
Light-brown sandstone, water	105	600
193-12(0.25×3.40)		
[Alt: 6,100 ft. Water level: 220 ft. Aquifer: upper member of Bidahochi Formation]		
Bidahochi Formation:		
Blow sand	220	220
Water sand	6	226
Clay	74	300
194-12(4.20×16.80)		
[Alt: 5,970 ft. Aquifer: Moenkopi Formation or possibly Kaibab Limestone]		
Quaternary sediments	8	8
Bidahochi Formation and shale of the Chinle	502	510
Conglomerate in the Shinarump	5	515
Moenkopi Formation (water at 610 ft)	115	630

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
214-11(0.80×8.90)		
[Alt: 5,396 ft. Water level: flow. Aquifer: Coconino Sandstone]		
Alluvium:		
Samples missing	30	30
Pale-red silty coarse to fine quartz sand	30	60
Light-brownish-gray coarse to fine quartz sand with limestone fragments	10	70
Light-brownish-gray silty claystone	10	80
Pale-red very coarse quartz sand	10	90
Moenkopi Formation:		
Pale-reddish-brown siltstone	40	130
Pale-reddish-brown siltstone with fine sand and limestone fragments	10	140
Pale-reddish-brown siltstone with gypsum	80	220
Pale-red fine to very fine quartz sand	10	230
Pale-red sandy siltstone	10	240
Kaibab Limestone:		
Light-gray silty limestone with fragments of sandstone	10	250
Coconino Sandstone:		
Very pale-orange fine to very fine quartz sand	150	400
215-1(12.20×14.00)		
[Alt: 5,620 ft. Water level: 40 ft. Aquifer: Kaibab Limestone and Coconino Sandstone]		
Alluvium and Quaternary sediments:		
Soil and gravel	18	18
Chinle Formation:		
Red sandstone	21	39
Yellow shale	5	44
Blue shale	6	50
Red shale	18	68
Red sandstone, water at 100 ft	55	123
Moenkopi Formation:		
Red shale	4	127
Gray sandstone	19	146
Red and blue shale	12	158
Red shale	3	161
Light-red sandstone	70	231
Red and blue shale	12	243
Light-brown sandstone	13	256
Light-gray sandstone	16	272
Blue shale	6	278
Brown sandstone	12	290
Kaibab Limestone:		
Gray limestone; water, 175 gpm	8	298
White sandstone	22	320
Dark-gray limestone	7	327
Coconino Sandstone:		
White sandstone	244	571

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
215-26(7.20×9.80)		
[Alt: 5,430 ft. Water level: 15 ft. Aquifer: Coconino Sandstone]		
Alluvium:		
Brown shale	20	20
Gravel, salt water	9	29
Chinle Formation:		
Light-blue shale	50	79
Salt-water sand	10	89
Light-blue shale	22	111
Sandstone, bitter salt water	9	120
Light-blue shale	10	130
Moenkopi Formation:		
Red-brown shale	110	240
Water sand	22	262
Red-brown shale	26	288
Red sandstone	6	294
Coconino Sandstone:		
Sandstone, main water sand	36	330
215-56(10.50×6.75)		
[Alt: 5,435 ft. Water level: 18 ft. Aquifer: Kaibab Limestone or Coconino Sandstone]		
Moenkopi Formation:		
Red shale	70	70
Shale and sandstone	130	200
Kaibab Limestone or Coconino Sandstone:		
Cream sandstone	80	280
215-1T(8.20×14.70)		
[Alt: 5,850 ft]		
Moenkopi Formation	185	185
Kaibab Limestone	18	203
Coconino Sandstone	377	580
Supai Formation (Fort Apache Limestone Member of Stoyanow (1936), 1,766 to 1,823)	2, 089	2, 669
Pennsylvanian	981	3, 650
Precambrian basement rock:		
Diabase	30	3, 680

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
215-2T(3.00×9.20)		
[Alt: 5,672 ft. Water level: 235 ft. Aquifer: Coconino Sandstone]		
Moenkopi Formation:		
Hard red standstone, shale, and gravel	160	160
Kaibab Limestone:		
Buff shaly limestone	45	205
Coconino Sandstone:		
Fine white sandstone, water	345	550
Supai Formation:		
Red standstone, dolomite gypsum, anhydrite, salt, and red clay	1, 876	2, 426
Pennsylvania(?) formation:		
Soft limestone, red and dark-gray shale, variable color	123	2, 549
Precambrian basement rock:		
Granite	46	2, 595
216-1(6.05×16.55)		
[Alt: 5,680 ft. Water level: flow. Aquifer: Kaibab Limestone]		
Chinle and Moenkopi Formations, undivided:		
Shale	200	200
Kaibab Limestone:		
Limestone	300	500
Sandstone	35	535
Limestone	30	565
216-24(14.00×8.15)		
[Alt: 5,483 ft. Water level: 105 ft. Aquifer: Coconino Sandstone]		
Alluvium and Bidahochi Formation:		
Soil	20	20
Moenkopi Formation:		
Red beds	90	110
Red beds, some lime	10	120
Red beds	10	130
Kaibab Limestone:		
Lime	100	230
Coconino Sandstone:		
Sandstone; water, 240–250	22	252

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
216-70(12.50×17.00)		
[Alt: 5,950 ft. Water level: 256 ft. Aquifer: Kaibab Limestone]		
Quaternary sediments:		
Clay and boulders	10	10
Chinle Formation:		
White sandstone	30	40
Red and blue shale	210	250
Moenkopi Formation:		
Shale with hard lime shells	30	280
Kaibab Limestone:		
Fractured lime; water bearing from 350 to 400 ft	120	400
215-71(9.30×16.20)		
[Alt: 5,890 ft. Aquifer: Kaibab Limestone and Coconino Sandstone]		
Alluvium and Quaternary sediments, undivided:		
Surface soil	3	3
Sand and gravel	77	80
Sedimentary boulders and gravel	21	101
Chinle Formation:		
Clay, red and blue	15	116
Conglomerate, chert, quartz	30	146
Moenkopi Formation:		
Nonconformative shale	121	267
Hard red sand and shale	43	310
Kaibab Limestone:		
Hard gray crystallized sand	25	335
Very hard brown lime, sand	51	386
Limestone, gray	237	623
Coconino Sandstone:		
White sandstone	82	705
Water gravel	35	740
Gray sandstone	111	851
Supai Formation:		
Hard brown sand	12	863
Red sandstone	30	893
Gypsum, white	9	902
Red shale	50	952
217-10(9.10×16.50)		
[Alt: 5,960 ft]		
Travertine (water at 9 ft)	60	60

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TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
217-15(8.85×6.00) [Alt: 6,090 ft. Water level: 275 ft. Aquifer: Coconino Sandstone]		
Bidahochi Formation:		
Sand and clay	147	147
Chinle Formation:		
Red clay	346	493
Green clay	77	570
Green shale and bentonite	170	740
Chert boulders	23	763
Blue and green shale	117	880
Red shale and hard sand	138	1,018
Limestone, white	8	1,026
Blue and green shale	24	1,050
Kaibab Limestone:		
Limestone, white	112	1,162
Red shale, sticky	8	1,170
Limestone, brown	53	1,223
Coconino Sandstone:		
Sandstone	77	1,300
217-16(5.80×10.30) [Alt: 6,540 ft. Water level: 48 ft. Aquifer: Kaibab Limestone and Coconino Sandstone]		
Bidahochi Formation:		
Fill	50	50
Sandstone	26	76
Chinle Formation:		
Red beds	162	238
Green shale	172	410
Blue muck	96	506
Chert and quartz, hard	15	521
Red shale	19	540
Hard lime	15	555
Red sand and shale	25	580
Sticky red shale	12	592
Broken sandy shale	18	610
Sticky red shale	15	625
Limestone, soft	4	629
Moenkopi Formation:		
Hard red shale	22	651
Kaibab Limestone:		
Hard lime rock	29	680
Porous limestone, water	30	710
Hard limestone	85	795
Red shale	6	801
Porous limestone	3	804
Hard gray limestone	14	818
Limestone and shale	22	840
Hard gray limestone	37	877
Gray limestone, soft	8	885
Hard red shale	7	892
Coconino Sandstone:		
Sandstone, water	130	1,022

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
217-17(8.90×3.25)		
[Alt: 5,910 ft. Water level: 102 ft. Aquifer: Coconino Sandstone]		
Alluvium:		
Fill	5	5
Clay	53	58
Sand and gravel	12	70
Chinle Formation:		
Red clay	20	90
Hard sandstone	35	125
Shale and shells	65	190
Lime, medium	22	212
Hard sand and boulders	14	226
Red-bed shells	209	435
Hard fine sand	80	515
Sticky shale	88	603
Broken lime and sand	44	647
Red and green shale	98	745
Blue clay	22	767
Hard red shale	23	790
Hard sand and streaks of shale	76	866
Red shale	24	890
Red sandstone	22	912
Hard white sand	18	930
Green shale	2	932
Moenkopi Formation:		
Red shale and shells	24	956
Kaibab Limestone and Coconino Sandstone, undivided:		
Very hard lime and chert	29	985
Porous white lime	19	1,004
Hard white lime	23	1,027
Shale	6	1,033
Gray lime	85	1,118
Red shale, traces of white sand	31	1,149
Broken sand	20	1,169
Porous sand	4	1,173
217-20(8.60×12.90)		
[Alt: 5,820 ft. Water level: flow. Aquifer: Coconino Sandstone]		
Alluvium:		
Fill	20	20
Yellow clay	50	70
Chinle Formation:		
Shale	200	270
Conglomerate, hard	10	280
Shale and sandstone	140	420
Kaibab Limestone:		
White limestone	20	440
Brown limestone	220	660
Coconino Sandstone:		
Sandstone, water	195	855

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
217-1T(14.30×3.40)		
[Alt: 5,900 ft. Water level: flow. Aquifer: Coconino Sandstone]		
Alluvium and Chinle Formation, undivided	180	180
Shinarump Member of the Chinle Formation	70	250
Kaibab Limestone	175	425
Coconino Sandstone	250	675
Supai Formation	1, 620	2, 295
Quartzite of Precamrian age	330	2, 625
236-3(9.40×4.30)		
[Alt: 6,150 ft. Water level: 234 ft. Aquifer: Coconino Sandstone]		
Moenkopi Formation:		
Red shale	28	28
Red sandstone	56	84
White sandstone	20	104
Red clay	12	116
Coconino Sandstone:		
White sandstone, water at 254 ft	116	302
236-20(12.80×17.10)		
[Alt: 6,790 ft. Water level: 460 ft. Aquifer: Quaternary and Tertiary cinders]		
Quaternary and Tertiary basaltic rocks:		
Lava	460	460
Cinders	40	500
236-30(14.15×13.50)		
[Alt: 6,535 ft. Water level: 282 ft. Aquifer: Sandstone of Upper Cretaceous]		
Upper Cretaceous rocks, undifferentiated:		
Yellow clay	50	50
Gray shale	20	70
Yellow shale	30	100
Gray shale	70	170
Yellow sand rock	30	200
Gray clay	70	270
Yellow sand rock	30	300
Gray clay	110	410
Gray shale and sand rock	75	485

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
236-35(12.00×7.80)		
[Alt: 6,150 ft. Water level: 425 ft. Aquifer: Coconino Sandstone]		
Alluvium:		
Malpais boulders and clay	10	10
Chinle and Moenkopi Formation, undivided:		
Red shale	150	160
Red sand rock	40	200
Gray shale	60	260
White sand rock	40	300
Red shale	20	320
Coconino Sandstone:		
White sandstone	130	450
236-53(11.60×10.60)		
[Alt: 6,240 ft. Water level: 20 ft. Aquifer: Quaternary sediments]		
Quaternary sediments:		
Red clay	10	10
Red clay	10	20
Sand and water	10	30
Sand and water	10	40
Quicksand and water	28	68
236-55(2.15×4.75)		
[Alt: 6,180 ft. Water level: 40 ft. Aquifer: Kaibab Limestone and Coconino Sandstone]		
Chinle Formation	50	50
Moenkopi Formation	190	240
Kaibab Limestone	10	250
Coconino Sandstone	50	300
236-56(1.60×5.25)		
[Alt: 6,210 ft. Water level: 45 ft. Aquifer: Kaibab Limestone and Coconino Sandstone]		
Surface soil:		
Clay fill	5	5
Moenkopi Formation:		
Burnt-orange clay	45	50
Brown sandstone	5	55
Brown shale	20	75
Gray sandstone	10	85
Brown sandstone	5	90
Burnt-orange shale	50	140
Gray sandstone	10	150
Brown shale	15	165

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TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
236–56 (1.60 × 5.25)—Continued		
[Alt: 6,210 ft. Water level: 45 ft. Aquifer: Kaibab Limestone and Coconino Sandstone]		
Kaibab Limestone:		
Hard gray sandstone and limestone, water	15	180
Sandstone, resembles Coconino	65	245
Limestone	235	480
Coconino Sandstone:		
Gray sand	150	630
237–1 (10.00 × 3.40)		
[Alt: 5,940 ft. Water level: 29 ft. Aquifer: Kaibab Limestone and Coconino Sandstone]		
Chinle Formation	150	150
Moenkopi Formation	95	245
Kaibab Limestone	310	555
Coconino Sandstone	165	720
237–61 (7.70 × 9.30)		
[Alt: 5,920 ft. Water level: 9.5 ft. Aquifer: Kaibab Limestone]		
Surface soil:		
Clay	8	8
Moenkopi Formation:		
Red soft sandy shale	12	20
Red very sticky soft rock	5	25
Red sand, firm, 2.8 gpm of water	3	28
Red soft sandy shale	2	30
Red sticky mud	3	33
Cavity, much water rose to 20 feet from surface	17	50
Red sandy shale	10	60
Sandy shale	1	61
Kaibab Limestone:		
Grayish-blue sandy lime, medium-hard	24	85
Brown sandy medium-hard lime	30	115
Brown very hard lime	25	140
Gray medium-hard sharp sand, with crevice	5	145
Cavity	6	151
Record missing	182	333

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
237-65(7.70×9.35)		
[Alt: 5,920 ft. Water level: 12.5 ft. Aquifer: Kaibab Limestone]		
Moenkopi Formation:		
Red clay	25	25
Sandy breaks in shale, a little water	2	27
Red hard sand	13	40
Bluish-gray hard sharp dry sand	10	50
Red sticky clay	3	53
Kaibab Limestone:		
Gray hard sandy shale, few streaks of limestone, small increase in water	17	70
Hard brown lime	76	146
Crevice, 60 gpm with 39 feet of drawdown	9	155
White hard sharp medium sand, some increase in water	45	200
Hard brown sandy lime	54	254
Hard brown lime	44	298
Crevice	2	300
Hard brown lime, in part sandy	21	321
Hard brown sand, some water increase	2	323
Very hard brown lime, in part sandy	3	326
Crevices	5	331
Hard brown lime, in part sandy; sand running into hole badly from 322 ft	14	345
238-1(13.90×6.90)		
[Alt: 6,590 ft. Water level: 520 ft. Aquifer: Coconino Sandstone]		
Chinle and Moenkopi Formations, undivided:		
Sand rock and shale	80	80
Kaibab Limestone:		
Lime rock	110	190
Coconino sandstone:		
White sandstone	360	550
258-34(1.80×8.80)		
[Alt: 7,020 ft. Water level: 179 ft. Aquifer: Sandstone of Upper Cretaceous]		
Sedimentary rocks:		
Red clay	90	90
Red rock	130	220
Upper Cretaceous rocks, undifferentiated:		
Blue clay	110	330
Hard gray sandstone	29	359
Yellowish clay	1	360

TABLE 6.—*Selected drillers' logs of wells in the central part of Apache County, Ariz.*—Continued

[Quoted verbatim; correlations by the author]

	Thickness (feet)	Depth (feet)
259-1T(5.25×5.85)		
[Alt: 7,186 ft]		
Tertiary, Cretaceous, and Triassic formations, undivided; fresh water at 270 ft	795	795
Kaibab Limestone; fresh water at 800 ft	270	1,065
Coconino Sandstone	205	1,270
Supai Formation; bad water at 1,918 to 1,927; heavy flow from 2,310 to 2,585, water rose 1,200 ft in hole; water at 2,630 rose 370 ft in hole; water at 2,735 ft	1,610	2,880
Precambrian basement rocks	41	2,921

REFERENCES CITED

PUBLISHED REPORTS

Akers, J. P., Cooley, M. E., and Repenning, C. A., 1958, Moenkopi and Chinle Formations of Black Mesa basin and adjacent areas: New Mexico Geol. Soc. Field Conf., 9th, 1958, Guidebook of the Black Mesa basin, northeastern Arizona, p. 88–94.

Akers, J. P., and Harshbarger, J. W., 1958, Ground water in Black Mesa basin and adjacent areas: New Mexico Geol. Soc. Field Conf., 9th, 1958, Guidebook of the Black Mesa basin, northeastern Arizona, p. 173–183.

Allen, J. T., 1930, Triassic bentonite of the Painted Desert: Am. Jour. Sci., 5th ser., v. 19, p. 283–288.

Barr, G. W., 1956, Arizona agriculture: Univ. Arizona, Agr. Expt. Sta. Bull. 270, 16 p.

Branson, E. B., 1927, Triassic-Jurassic "red beds" of the Rocky Mountain region: Jour. Geology, v. 35, no. 7, p. 607–630.

Branson, E. B., and Mehl, M. G., 1929, Triassic amphibians from the Rocky Mountain region: Missouri Univ. Studies, v. 4, no. 2, 87 p.

Brown, Barnum, 1933, A new genus of Stegocephalia from the Triassic of Arizona: Am. Mus. Novitates 640, 4 p.

Camp, C. L., 1930, A study of the phytosaurs with description of new material from western North America: California Univ. Mem., v. 10, 174 p.

Childs, O. E., 1948, Geomorphology of the valley of the Little Colorado River, Arizona: Geol. Soc. America Bull., v. 59, p. 353–388.

Colbert, E. H., 1950, Mesozoic vertebrate faunas and formations of northern New Mexico: Soc. Vertebrate Paleontology Guidebook, 4th Field Conf., p. 57–72.

Cooley, M. E., 1958a, Physiography of the Black Mesa basin area, Arizona: New Mexico Geol. Soc. Field Conf., 9th, 1958, Guidebook of the Black Mesa Basin, northeastern Arizona, p. 146–149.

——— 1958b, The Mesa Redondo Member of the Chinle Formation, Apache and Navajo Counties, Arizona: Plateau, v. 31, no. 1, p. 7–15.

——— 1959, Triassic stratigraphy in the State line region of west-central New Mexico and east-central Arizona: New Mexico Geol. Soc. Field Conf., 10th, 1959, Guidebook of west-central New Mexico, p. 66–73.

Darton, N. H., 1925, A résumé of Arizona geology: Arizona Bur. Mines Bull. 119, 298 p.

Daugherty, L. H., 1941, The Upper Triassic flora of Arizona, with a discussion of its geologic occurrence, by H. R. Stagner: Carnegie Inst. Washington Pub. 526, Contr. Paleontology, 108 p.

Eardley, A. J., 1951, Structural geology of North America: New York, Harper and Bros., 624 p.

Fenneman, N. M., 1931, Physiography of western United States: New York, McGraw-Hill Book Co., 534 p.

Gregory, H. E., 1917, Geology of the Navajo country: U.S. Geol. Survey Prof. Paper 93, 161 p.

——— 1950, Geology and geography of the Zion Park region, Utah and Arizona: U.S. Geol. Survey Prof. Paper 220, 200 p.

——— 1951, The geology and geography of the Paunsaugunt region, Utah: U.S. Geol. Survey Prof. Paper 226, 116 p.

Hager, Dorsey, 1922, Oil possibilities of the Holbrook area in northeast Arizona: Mining and Oil Bull., v. 8, no. 1, p. 23–26, 33–34; no. 2, p. 71–74, 81, 94; no. 3, p. 135–140.

Harrell, M. A., and Eckel, E. B., 1939, Ground-water resources of the Holbrook region, Arizona: U.S. Geol. Survey Water-Supply Paper 836–B, p. 19–105.

Harshbarger, J. W., Repenning, C. A., and Callahan, J. T., 1953, The Navajo country, Arizona-Utah-New Mexico, chap. 7 *of* U.S. Cong., House Comm. Interior and Insular Affairs, Subsurface facilities of water management and patterns of supply—type area studies, p. 105–129.

Harshbarger, J. W., Repenning, C. A., and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country: U.S. Geol. Survey Prof. Paper 291, 74 p.

Huddle, J. W., and Dobrovolny, Ernest, 1945, Late Paleozoic stratigraphy and oil and gas possibilities of central and northeastern Arizona: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart 10.

Jackson, R. L., 1951, Stratigraphic relationships of the Supai Formation of central Arizona: Plateau, v. 24, no. 2, p. 84–91.

Johnson, P. W., 1962, Water in the Coconino Sandstone for the Snowflake-Hay Hollow area, Navajo County, Arizona: U.S. Geol. Survey Water-Supply Paper 1539–S, 46 p.

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. New Mexico Pub. *in* Geology, no. 5, 120 p.

——— 1958, Tectonics of the Black Mesa basin region of northern Arizona: New Mexico Geol. Soc. Field Conf., 9th, 1958, Guidebook of the Black Mesa basin, northeastern Arizona, p. 136–145.

Lance, J. F., 1954, Age of the Bidahochi Formation, Arizona [abs.]: Geol. Soc. America Bull., v. 65, no. 2, p. 1276.

——— 1958, Precambrian rocks of northern Arizona: New Mexico Geol. Soc. Field Conf., 9th, 1958, Guidebook of the Black Mesa basin, northeastern Arizona, p. 66–70.

Longwell, C. R., 1928, Geology of the Muddy Mountains, Nevada, with a section through the Virgin Range to the Grand Wash Cliffs, Arizona: U.S. Geol. Survey Bull. 798, 152 p.

McCann, F. T., 1938, Ancient erosion surface in the Gallup-Zuni area, New Mexico: Am. Jour. Sci., 5th ser., v. 36, no. 214, p. 260–278.

McKee, E. D., 1936, Triassic pebbles in northern Arizona containing invertebrate fossils: Am. Jour. Sci., 5th ser., v. 33, no. 196, p. 260–263.

——— 1938, The environment and history of the Toroweap and Kaibab Formations of northern Arizona and southern Utah: Carnegie Inst. Washington Pub. 492, 268 p.

——— 1951, Triassic deposits of the Arizona-New Mexico border area: New Mexico Geol. Soc., Guidebook of the San Juan basin, New Mexico and Arizona, p. 85–92.

——— 1954, Stratigraphy and history of the Moenkopi Formation of Triassic age: Geol. Soc. America Mem. 61, 133 p.

Noble, L. F., 1922, A section of the Paleozoic formations of the Grand Canyon at the Bass trail: U.S. Geol. Survey Prof. Paper 131, p. 23–73.

Peabody, F. E., 1948, Reptile and amphibian trackways from the Lower Triassic Moenkopi Formation of Arizona and Utah: Calif. Univ., Dept. Geol. Sci. Bull., v. 27, p. 295–467.

Poborski, S. J., 1954, Virgin Formation (Triassic) of the St. George, Utah, area: Geol. Soc. America Bull., v. 65, no. 10, p. 971–1006.

Reagan, A. B., 1924, Stratigraphy of the Hopi Buttes volcanic field, Arizona: Pan-Am. Geologist, v. 41, p. 355–366.

——— 1932, The Tertiary-Pleistocene of the Navajo country in Arizona, with a description of some of its included fossils: Kansas Acad. Sci. Trans., v. 35, p. 253–259.

Reeside, J. B., Jr., 1924, Upper Cretaceous and Tertiary formations of the western part of the San Juan basin of Colorado and New Mexico: U.S. Geol. Survey Prof. Paper 134, p. 1–70.

Repenning, C. A., and Irwin, J. H., 1954, Bidahochi Formation of Arizona and New Mexico: Am. Assoc. Petroleum Geologists Bull. v. 38, p. 1821–1826.

Repenning, C. A., Lance, J. F., and Irwin, J. H., 1958, Tertiary stratigraphy of the Navajo country: New Mexico Geol. Soc. Field Conf., 9th, 1958, Guidebook of the Black Mesa basin, northeastern Arizona, p. 123–129.

Repenning, C. A., and Page, H. G., 1956, Late Cretaceous stratigraphy of Black Mesa, Navajo and Hopi Indian Reservations, Arizona: Am. Assoc. Petroleum Geologists Bull., v. 40. no. 2, p. 255–294.

Roe, H., 1937, Geological structures mapped in Apache County, Arizona: Oil and Gas Jour., v. 36, no. 10, p. 29–30.

Shimer, H. W., 1919, Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., v. 30, no. 4, p. 471–497.

Stewart, J. H., 1957, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 3, p. 441–463.

Stirton, R. A., 1936, A new beaver from the Pliocene of Arizona with notes on the species of Dipoides: Jour. Mammology, v. 17, p. 279–281.

Sumner, Lowell, 1945, Life zones [map], *in* A survey of the recreational resources of the Colorado River basin: U.S. Dept. Interior, Natl. Park Service, 1950, 241 p.

U.S. Bureau of Reclamation, 1955, Report on sediment deposition above Zion Dam, Little Colorado River basin, Arizona: U.S. Bur. Reclamation rept., p. 19–20.

U.S. Geological Survey, 1959, Surface water supply of the United States, 1957, part 9, Colorado River basin: U.S. Geol. Survey Water-Supply Paper 1513, 358 p.

Von Huene, Friedrich, 1926, Notes on the age of the continental Triassic bed in North America, with remarks on some fossil vertebrates: U.S. Nat. Museum Proc., v. 69, art. 18.

Welles, S. P., 1947, Vertebrates from the upper Moenkopi Formation of northern Arizona: Calif. Univ., Dept. Geol. Sci. Bull., v. 27, no. 7, p. 241–294.
Willard, M. E., and Weber, R. H., 1958, Reconnaissance geologic map of the Canon Largo thirty-minute quadrangle: New Mexico State Bur. Mines and Mineral Resources Geol. Map 6.
Williams, G. A., 1951, Coal deposits and Cretaceous stratigraphy of the western part of Black Mesa, Arizona [abs.]: Geol. Soc. America Bull., v. 62, no. 12, pt. 2, p. 1514–1515.
Wilpolt, R. H., and Wanek, A. A., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U.S. Geol. Survey Oil and Gas Inv. Map 121.
Winters, S. S., 1951, Permian stratigraphy in eastern Arizona: Plateau, v. 24, no. 1, p. 10–16.

UNPUBLISHED THESES

Cooley, M. E., 1957, Geology of the Chinle Formation in the upper Little Colorado River drainage area, Arizona and New Mexico: Arizona Univ., Tucson, Ariz,
Crutcher, T. D., 1956, Nomenclature of Cretaceous rocks, St. Johns vicinity, Apache County, Arizona, and Catron County, New Mexico: Texas Univ., Austin, Tex.
Green, T. D., 1956, Disturbed Chinle beds near St. Johns, Apache County, Arizona: Texas Univ., Austin, Tex.
Hughes, P. W., 1950, The stratigraphy of the Supai Formation in the Chino Valley area, Yavapai County, Arizona: Arizona Univ., Tucson, Ariz.
Maar, R. J., 1956, Geology of Lynch Ranches, Catron and Valencia Counties, New Mexico: Texas Univ., Austin, Tex.
O'Brian, B. R., 1956, Geology of the Cienega Amarillo area, Catron County, New Mexico, and Apache County, Arizona: Texas Univ., Austin, Tex.
Rehkemper, H. L., 1956, Petrology of the Springerville area, Apache County, Arizona: Texas Univ., Austin, Tex.
Robertson, R. S., 1956, Chinle stratigraphy of the St. Johns vicinity, Apache County, Arizona: Texas Univ., Austin, Tex.
Rutledge, R. F., 1956, Cenozoic history of the Springerville area, Apache County, Arizona: Texas Univ., Austin, Tex.
Sirrine, G. K., 1958, Geology of the Springerville-St. Johns area, Apache County, Arizona: Texas Univ., Austin, Tex.
Smith, H. L., 1956, Cretaceous stratigraphy of Carrizo drainage basin, Apache County, Arizona, and Catron and Valencia Counties, New Mexico: Texas Univ., Austin, Tex.
Underwood, J. R., 1956, Geology of Carrizo valley, southern Apache County, Arizona: Texas Univ., Austin, Tex.
Woodyard, K. E., 1956, Clays of the St. Johns vicinity, Arizona and New Mexico: Texas Univ., Austin, Tex.

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Akers, Jay P., 1921–

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Akers, Jay P., 1921– Geology and ground water in the central part of Apache County, Arizona. 1964. (Card 2)

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