;round Water in the Wupatki nd Sunset Crater National ⁄Ionuments, Coconino County \rizona

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YDROLOGY OF THE PUBLIC DOMAIN

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GROUND WATER IN THE WUPATKI AND SUNSET CRATER NATIONAL MONUMENTS, COCONINO COUNTY, ARIZONA

By Oliver J. Cosner

ABSTRACT

The Wupatki and Sunset Crater National Monuments are 15 and 30 miles, respectively, northeast of Flagstaff on the San Francisco Plateau. They are in the eastern part of the San Francisco volcanic field and on the southwest flank of the Black Mesa basin. The Supai formation, Coconino sandstone, Kaibab limestone, Moenkopi formation, and Chinle formation are overlain in parts of the area by volcanic rocks and alluvium. The regional water table occurs chiefly in the Coconino sandstone at altitudes of about 5,000 feet at Sunset Crater, about 4,075 feet near Wupatki Ruin, and about 4,100 feet near Citadel Ruin. The general movement of the ground water is northeastward. Small supplies of perched water occur in the Moenkopi formation and in the alluvium, and perched water may be present locally in the volcanic rocks. The results of the field investigation indicated that adequate ground-water supplies were available from the Coconino sandstone to meet the needs of the National Monuments, and a well was drilled at the Wupatki Monument headquarters in 1958 to a total depth of 904 feet. It produced 50 gpm (gallons per minute) of water with 45 feet of drawdown from a static water level of 780 feet below land surface.

INTRODUCTION

PURPOSE, SCOPE, AND METHODS OF INVESTIGATION

A ground-water investigation of the Wupatki and Sunset Crater National Monuments was made by the Geological Survey during the fall of 1954, at the request of the National Park Service. The purpose of the investigation was to determine sites favorable for the development of ground water to supply the proposed expansion of National Park Service installations at both monuments. This work was done under the supervision of L. C. Halpenny, then district engineer of the Geological Survey, Ground Water Branch, and was financed by the National Park Service. This report presents the results of the study and of the drilling done on the basis of the administrative report prepared for the National Park Service in 1955.

The investigation was of a reconnaissance nature, and the geologic mapping was done on aerial photographs. The accompanying geologic map (pl. 20) is a compilation of this work and previously published data. An inventory of wells and springs was made, including measurements of water levels, discharge, and collection of water samples for chemical analysis.

LOCATION AND EXTENT OF AREA

The area studied is northeast of Flagstaff, Ariz. (fig. 43). It includes both National Monuments and encompasses about 420

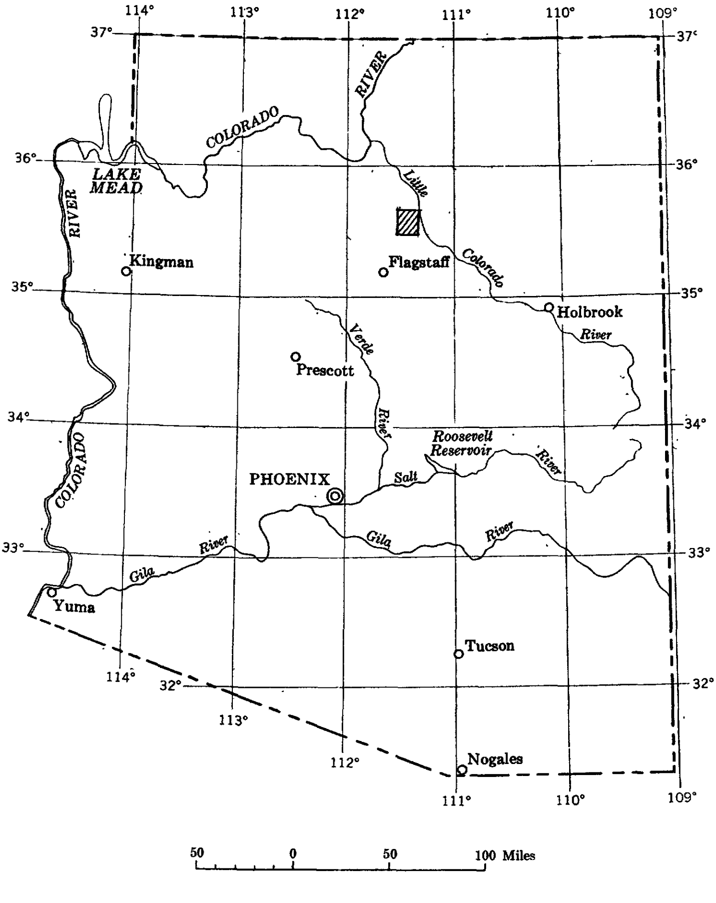

FIGURE 43.—Map of Arizona showing the Wupatki-Sunset Crater area.

square miles. The Wupatki National Monument, in the northern part, is about 30 miles northeast of Flagstaff and includes about 70 square miles. The Sunset Crater National Monument, in the southern part, is about 15 miles northeast of Flagstaff and includes about 8 square miles.

PREVIOUS INVESTIGATIONS

Previous geologic investigations including the areas of the Wupatki and Sunset Crater National Monuments were made by Robinson (1913), Colton (1937), and Childs (1948). A ground-water investigation covering part of the area was made by Feth (1953).

ACKNOWLEDGMENTS

The cooperation and help received from the National Park Service in supplying data from their files, aiding in the collection of field data, and discussing various phases of the work were of great benefit. This assistance, as well as that given by H. S. Colton, Director of the Museum of Northern Arizona at Flagstaff, and the cooperation of ranchers and other individuals, is gratefully acknowledged.

WELL-NUMBERING SYSTEM

The well numbers used by the Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants (fig. 44). These quadrants are designated counterclockwise by the capital letters A, B, C, and D. All land north and east of the point of origin is in A quadrant, that north and west in B quadrant, that south and west in C quadrant, and that south and east in D quadrant. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract (fig. 44), the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within a 10-acre tract, three lowercase letters are shown in the well number. In the example shown, well number (A–4–5)19caa designates the well as being in the NE¼NE¼SW¼ sec. 19, T. 4 N., R. 5 E. Where there is more than one well within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes.

PHYSIOGRAPHY

LANDFORMS

The Wupatki-Sunset Crater area is in the eastern part of the San Francisco volcanic field, northeast of San Francisco Mountain, the

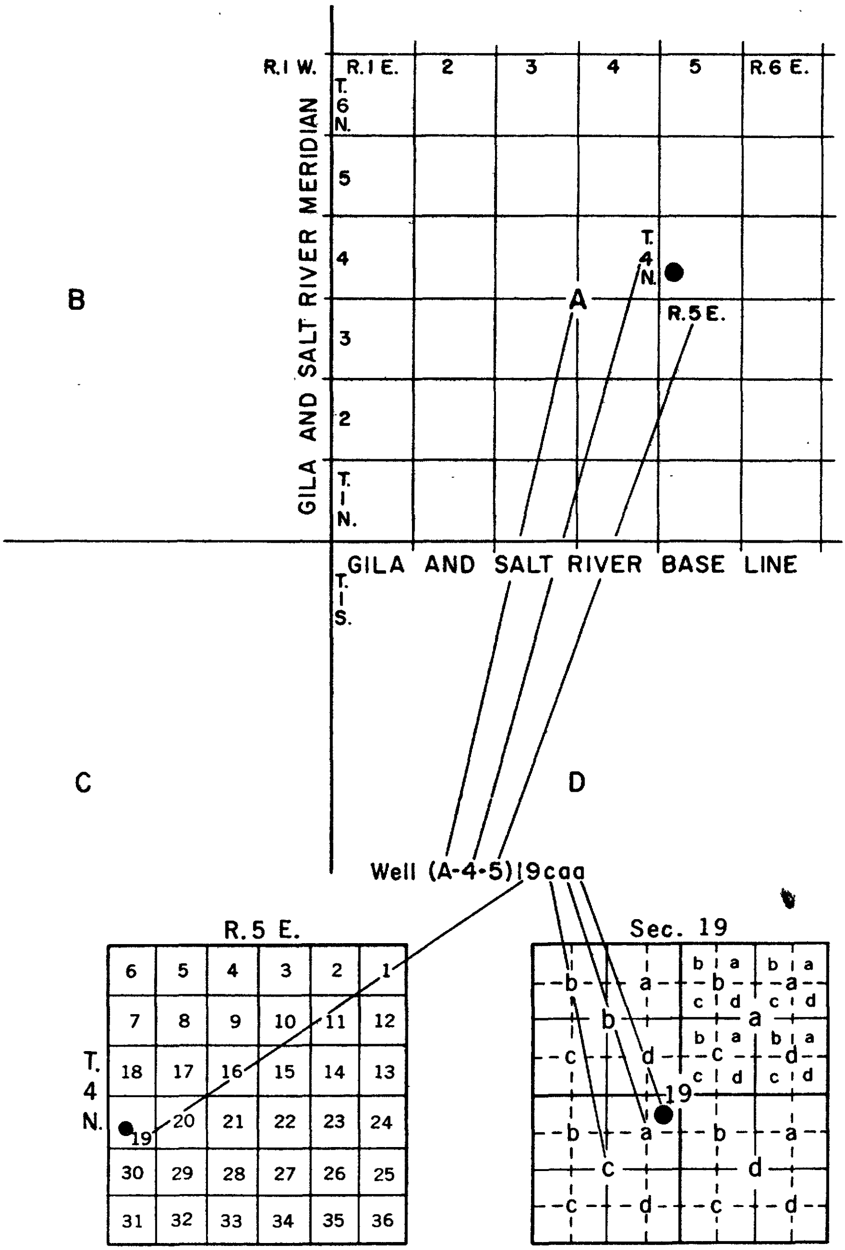

FIGURE 44.—Well-numbering system in Arizona.

highest point in Arizona. The area is on the southwest flank of the Black Mesa basin and the regional dip of the rocks averages between 1° and 3° NE. Physiographically, it is partly in the valley of the Little Colorado River and partly on the San Francisco Plateau. The slope of the plateau is to the northeast, and locally it is accentuated by the Black Point segment of the East Kaibab monocline. In the vicinity of the Wupatki National Monument, the Black Point segment of the East Kaibab monocline separates the lower tableland from Antelope Prairie, the northeastern part of the San Francisco Plateau. The surface of the lower tableland is carved from the Moenkopi formation near the Little Colorado River. Antelope Prairie is a stripped surface eroded on the Kaibab limestone. Many of the low mesas near Wupatki Ruin are capped by thin basalt flows.

The southern part of the area, near the Sunset Crater National Monument, is in a rugged and irregular terrain that flanks the east slopes of San Francisco Mountain and includes groups of dissected extinct volcanoes consisting of numerous cinder cones and associated flows. Deposition of alluvial material in the basins between many of the extinct volcanoes has formed parks. West of O'Leary Peak, along U.S. Highway 89, glacial outwash from San Francisco Mountain forms small, rounded valleys and ridges, which contrast with the surrounding volcanic terrane.

The altitudes range from about 7,000 feet in the Sunset Crater area to about 5,000 feet in the Wupatki area. The highest point within the mapped area (pl. 20) is O'Leary Peak, which has an altitude of 8,925 feet. The lowest altitude is about 4,200 feet, at the Little Colorado River where it leaves the mapped area.

DRAINAGE

The area is drained by the Little Colorado River and its tributaries; the largest in the area being Deadman Wash. All the streams in the area are intermittent. Channels as deep as 150 feet have been eroded where the streams have breached the East Kaibab monocline in the Wupatki area. In some places the channels are choked by windblown cinders and small alluvial fans, indicating that they may have been dry for several years. Several small basins, of interior drainage due to damming by volcanic rocks, have developed near Sunset Crater. These include parts of Bonito, Black Bill, and Doney Parks.

CLIMATE

Climatological data for the Wupatki-Sunset Crater area were obtained from official records of the U.S. Weather Bureau and from records of the National Park Service. Precipitation ranges from more than 25 inches per year in the Sunset Crater area to less than 10 inches per year in the Wupatki area. For the most part, the precipitation occurs as torrential summer rainfall and winter snowfall. At Wupatki, the mean annual temperature is about 57°F. A mean annual temperature of about 45°F is estimated for the Sunset Crater area, on the basis of Weather Bureau data for Flagstaff, which is at a slightly lower altitude. The difference in climate at Sunset Crater and Wupatki National Monuments is due primarily to the difference in altitude.

GEOLOGY AND ITS RELATION TO GROUND WATER

The rocks of the Wupatki-Sunset Crater area are composed of Permian and Triassic formations, overlain in part by a series of younger volcanic rocks and alluvial deposits principally of Quaternary age. The oldest formation exposed is the Coconino sandstone; however, some of the deeper wells penetrate the underlying Supai formation at depths of more than 1,000 feet below the land surface. No formations older than the Supai are discussed in this report.

The Kaibab limestone of Permian age and the Moenkopi formation of Triassic age crop out in most of the Wupatki National Monument, and there are also small outcrops of the Coconino sandstone, the Toroweap formation, and Quaternary volcanic rocks and alluvial materials. The strata dip gently to the northeast, but this regional dip is interrupted by a transverse fold known as the Black Point segment of the East Kaibab monocline. In the northern part of the area the monoclinal flexure has a southerly strike, but within a few miles it changes to a southwesterly strike. Here the monocline steepens and grades into a fault that can be traced to the edge of Doney Crater. This fault has a displacement of more than 150 feet. Small northeast- and northwest-trending faults and grabens displace the Kaibab limestone on Antelope Prairie (Babenroth and Strahler, 1945, pl. 2), but they are not shown on the geologic map (pl. 20).

In the vicinity of the Sunset Crater National Monument, the volcanic rocks and associated alluvium completely cover the underlying sedimentary rocks and mask the structural pattern. However, structural relations can be observed along the north and east fringes of the volcanic field, where the underlying rocks are exposed. The diagrammatic cross section *B–B′* on plate 20 is based on the projection of these relations. The alinement of the volcanoes suggests the presence of zones of structural weakness in the rocks underlying the volcanic field, but in the absence of specific field evidence the nature and location of such zones are not indicated on the cross section.

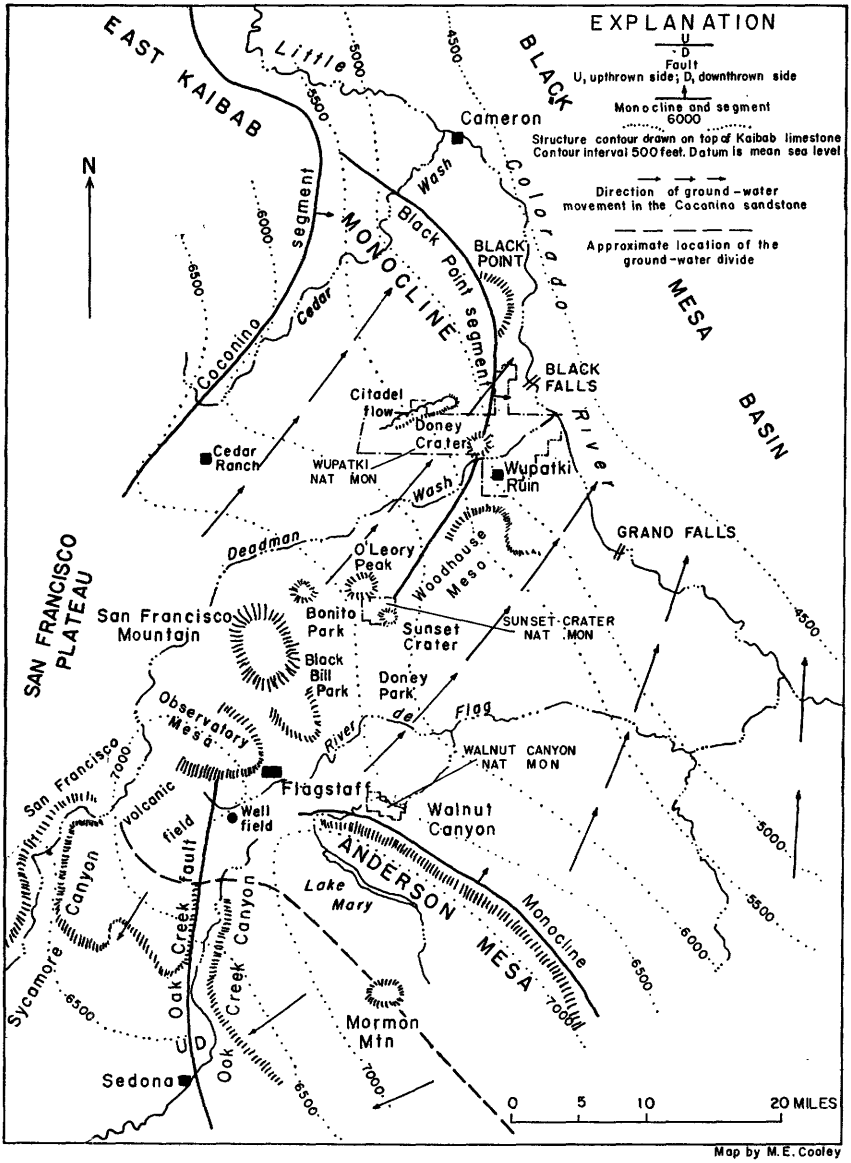

FIGURE 45.—Map of north-central Arizona, Wupatki-Sunset Crater area, showing major structural features, structure contours, and direction of ground-water movement.

The generalized structure contours shown on figure 45 indicate a broad, shallow trough, plunging to the northeast from Flagstaff to Wupatki Ruin on the east side of the Black Point segment.

SEDIMENTARY ROCKS

PENNSYLVANIAN AND PERMIAN ROCKS

SUPAI FORMATION

The Supai formation consists mostly of brownish-red fine-grained sandstone and siltstone and some thin beds of limestone. It is about 750 feet thick on the east slope of Elden Mountain (Brady, 1934, p. 10), about 10 miles south of the Sunset Crater National Monument. A study of well cuttings revealed that the upper 480 feet of the formation is a very fine grained to fine-grained, fairly well sorted to well-sorted friable sandstone. In Oak Creek Canyon, about 25 miles south of Flagstaff, the upper part of the Supai formation contains large-scale crossbeds and is a transitional zone between the more typical flat-bedded units and the overlying highly crossbedded Coconino sandstone. The Supai formation yields water to well (A–22–10)-3ad in the southeastern part of the area (table 1). The formation also yields water to a well at the Navajo Ordnance Depot, 12 miles west of Flagstaff.

PERMIAN ROCKS

COCONINO SANDSTONE

The Coconino sandstone is a very pale-orange to grayish-orange, very fine to fine-grained friable sandstone composed of well-rounded quartz grains; it is crossbedded on a large scale. The degree of cementation varies, but most of the sandstone is firmly bonded. The thickness of the formation ranges from about 600 feet in the Elden Mountain area (Brady, 1934, p. 10) to a possible 1,035 feet near the north boundary of the Wupatki National Monument, as reported in the driller's log of well (A–26–9)33dd (table 2). Due to the difficulty in identifying the formations from well cuttings, this excessive thickness may include part of the upper sandy zone of the Supai formation. In this report the Coconino sandstone and the overlying Toroweap formation are undifferentiated, and have been mapped as a single unit (pl. 20). The Coconino sandstone is the main aquifer in the area, and at least five deep wells obtain water from it.

KAIBAB LIMESTONE

The Kaibab limestone is a thick-bedded, jointed, very pale orange cherty and sandy limestone that crops out extensively in the Wupatki area. It overlies the Coconino sandstone, or the Toroweap formation where present, and ranges in thickness from about 300 feet near Elden Mountain (Brady, 1934, p. 10) to about 365 feet north of Wupatki National Monument, as reported in the driller's log of well (A–26–9)33dd (table 2). In this area the Kaibab limestone is not an aquifer, as it is above the water table. Where it is exposed the Kaibab limestone, because of its jointed nature, absorbs water and is an important recharge medium.

TABLE 1.—*Records of selected wells and springs in Wupatki–Sunset Crater area, Coconino County, Ariz.*

[C, cylinder; G, gasoline; D, domestic; S, stock; N, not used.]

Location No. (fig. 44)	Depth of well (feet)	Diameter (inches)	Water level: Depth below land-surface datum (feet) [1]	Water level: Date of measurement	Land-surface elevation (feet above msl)	Type of lift	Use of water	Log on file	Analysis on file	Water-bearing strata	Remarks
Wells											
(A-22-7)13ca	49.2	48	3.6	11-1-50		None			×		
32cc	80	6	[2] 70				D			Sand	
(A-22-8)26cc	50	3	38.9	10-15-54		C, G	D			Gravel, clay	
32dc	107	4	[2] Dry								
33b	410	4	[2] Dry					×			
(A-22-9)30cb	95		[2] Dry					×			
(A-22-10)3ad	2,400	12	1,137	10-21-54	5,710	None		×		Supai formation	
(A-22-11)19cc	1,060	6	[2] 1,000			C, G	D, S		×	Coconino sandstone	Discharge 10 gpm, measured 10-20-54.
(A-23-8)20aa	60	36						×		Alluvium	
(A-23-10)1bb	800+	8	740.5	10-19-54	4,950	C, G	D, S		×		Discharge 6 gpm, measured 10-19-54.
13dc	900+	8	858.6	do	5,200	C, G	S		×	Coconino sandstone	
(A-24-8)29ab	300	8			6,365	None		×			
29ca	285	8	[2] Dry			None		×			
(A-25-10)30bca	904	10	780.7	10-27-58	4,855	G	D	×	×	Coconino sandstone	Headquarters well.
(A-26-8)36bb	1,662	8	[2] 1,500			None		×			
(A-26-9)33dd	1,410	8	1,342.7	10-22-54	5,392	C, G	S	×		Coconino sandstone	Discharge 15 gpm, reported.
(A-26-10)31ca	1,009	8		do	5,085	C, G	S		×	do	Discharge 12–15 gpm, reported.
35ac	193	8¼	35.2	7-13-54	4,342	None	N	×			Bailed 12 gpm, reported.
Springs											
(A-24-10)7ad				10-15-54	4,965		S		×	Moenkopi formation	Coyote Spring, flow 6 gph, 10-15-54.
(A-25-10)30bb				10-22-54	4,890		D		×	do	Wupatki Spring, flow 7 gph, 10-22-54.
32ba				do	4,860		D, S		×	do	Heiser Spring, flow 50 gph, 10-22-54.

[1] Depths corrected to land-surface datum from measuring point.
[2] Water level reported.

TABLE 2.—*Logs of selected wells in the Wupatki-Sunset Crater area, Coconino County, Ariz.*

[Drillers' logs, except (A-22-10)3ad, geologist's log, and (A-23-8)20aa, owner's log]

	Thickness (feet)	Depth (feet)
(A-22-8)33b:		
Dirt, loose rock, a little clay	29	29
Rock (big boulder)	5	34
Dirt and loose rock	84	118
Red sandstone	23	141
Dirt and loose rock	56	197
"Soft tuffa or lava"	20	217
Coarse gravel	10	227
"Soft tuffa or lava"	66	293
Limestone	117	410
Total depth		410
(A-22-9)30cb:		
Cinder soil	5	5
Cinders, black	75	80
Hard black shell	15	95
Total depth		95
(A-22-10)3ad:		
Cinders	45	45
Kaibab limestone	240	285
Coconino sandstone	730	1,015
Supai formation	480	1,495
(No record)	905	2,400
Total depth		2,400
(A-23-8)20aa:		
Cinders	3	3
Coarse sand and gravel	57	60
Total depth		60
(A-24-8)29ab:		
Cinders and alluvium	65	65
Basalt with interbedded cinders	195	260
Sand and gravel	5	265
Pumice	35	300
(Drilling as of May 31, 1960)		300
(A-24-8)29ca:		
Cinders and alluvium	30	30
Basalt with interbedded cinders	255	285
Total depth		285
(A-26-8)36bb:		
Sandstone and limestone (Kaibab limestone)	150	150
Varicolored sandstone (Coconino sandstone)	950	1,100
Brown sandstone (Supai formation)	10	1,110
Sandstone, some water (Supai formation)	430	1,540
Coarse brown sand, more water (Supai formation)	122	1,662
Total depth		1,662
(A 26-9)33dd:		
"Malapai" (probably basalt)	85	85
Kaibab limestone	365	450
Coconino sandstone	960	1,410
Total depth		1,410
(A-26-10)35ac:		
Sandy soil	5	5
Red clay	10	15
Brown sandy shale	15	30
Red beds	133	163
Coarse gravely sand	7	170
Hard sand	23	193
Total depth		193

TRIASSIC ROCKS

MOENKOPI FORMATION

The Moenkopi formation was deposited unconformably on Kaibab limestone. It is generally reddish brown and consists of flat, very thin to thick layers of siltstone, mudstone, and sandstone; lenticular beds and thin stringers of gypsum are common in the middle part of the formation. The particles within the individual beds are for the most part composed of fine, poorly sorted quartz sand and are cemented with varied amounts of calcareous, or more rarely ferruginous and gypsiferous, material. Where it crops out in the eastern part of the area, the Moenkopi formation ranges in thickness from a few feet to more than 300 feet; in the western part of the area the formation is less than 100 feet thick. This range in thickness is due chiefly to postdepositional prelava erosion.

The Moenkopi formation does not transmit water readily in the Wupatki-Sunset Crater area because of its small average grain size, poor sorting, and alternation of nearly impermeable siltstone, mudstone, and sandstone beds. In addition, south of the Little Colorado River it is above the regional water table. In some areas, as at Heiser and Wupatki Springs, impermeable beds within the formation have prevented the downward percolation of water, and a perched water table exists. All the springs in the area yield less than 1 gpm; all issue from joints and bedding planes in the sandstone units.

CHINLE FORMATION

The Chinle formation overlies the Moenkopi formation and crops out along the northeast side of the Little Colorado River (pl. 20). Its lower part consists of brownish- to pinkish-gray poorly sorted sandstone and conglomerate, bonded with varied amounts of siliceous cement. The lower part formerly was a separate formation, the Shinarump conglomerate, but it is now considered the Shinarump member of the Chinle formation. The upper part of the Chinle formation is composed of variegated mudstone, siltstone, and sandstone assigned to the Petrified Forest member. The Chinle formation does not occur southwest of the Little Colorado River.

QUATERNARY DEPOSITS

GLACIAL OUTWASH

In the southwest corner of the area, glacial outwash from San Francisco Mountain locally overlies the volcanic rocks of the second general period of eruption and underlies and intertongues with the basalt flows of stage III (Robinson, 1913, p. 38; Childs, 1948, p. 362–364). (See *B–B′*, pl. 20.) The best exposures of glacial outwash are west of Bonito Park in the Sunset Crater area. The outwash consists of unconsolidated sediments ranging in size from boulders to clay particles and in thickness from a few feet to more than 100 feet. Lenses and beds of coarse sand and gravel are present, but their extent and permeability are unknown. The coarse beds probably contain small amounts of perched water where they are underlain by impermeable material. A shallow well in glacial outwash gravel west of U.S. Highway 89 furnishes water for a highway maintenance camp.

CONGLOMERATE

One small area of volcanic conglomerate crops out northwest of Merriam Crater in the southeast corner of the area. This conglomerate is between basalt flows of stages I and III. It is well cemented by calcareous material and composed of poorly sorted rhyolitic to basaltic volcanic fragments which range in size from silt to cobbles. The character of the conglomerate and its altitude above the water table make it a doubtful source of ground water.

ALLUVIAL FANS AND STREAM-CHANNEL DEPOSITS

The valley floor of Deadman Wash in the western part of the area is underlain by alluvium, which in some places is at least 65 feet thick, as shown in the driller's log of well (A–24–8)29ab (table 2).

The other washes in the area contain small amounts of alluvium, and in many places small tributaries have built alluvial fans into the channels of the larger washes. There is also a considerable amount, possibly more than 75 feet, of alluvium along the Little Colorado River where it passes through the area. It is not known to contain usable amounts of ground water, although, between Black Falls and Cameron, the drilling of test holes for uranium prospecting has tapped water in the alluvium. All the alluvial deposits range in age from late Pleistocene to Recent.

ALLUVIAL FILL IN SMALL BASINS

Bonito Park in the Sunset Crater National Monument is a basin partly filled with alluvium whose total thickness is not known, although about 300 feet of fill is present south of Sunset Crater in Doney Park. Well (A–23–8)20aa, dug in sand and gravel of the alluvium, yielded some water at 30 feet. When the well was deepened to 60 feet the water drained away and was lost to the well. Therefore, it is known that there are perched-water zones in the alluvium, but it is believed they contain only minor quantities of ground water.

Several basins in the vicinity of Citadel Ruin, formed by the collapse of underground solution channels, have been filled with alluvium and cinders. The fill in these basins may be as thick as 100 feet, and small amounts of perched water may be obtained where the permeable deposits are underlain by impermeable beds.

EXTRUSIVE IGNEOUS ROCKS

The extrusive igneous rocks in the Wupatki–Sunset Crater area are divided according to the work of Robinson (1913, p. 38) and Childs (1948, p. 362–364), into three main groups: stages I and II basaltic flows and cinders of the first, or oldest, period of eruption; intermediate to acidic flows with associated pumice and tuff of the second period of eruption; and stages III and IV basaltic flows and cinders of the third, or youngest, period of eruption. Stages I and II basalts range in age from late Pliocene to middle Pleistocene, and stages III and IV range in age from late Pleistocene to Recent. The silicic flows range from early to middle Pleistocene but some were deposited contemporaneously with the stage III basalts.

BASALT FLOWS OF STAGES I AND II

The basalts of stages I and II were extruded on erosion surfaces cut on the Kaibab limestone and Moenkopi formation. They are exposed principally along the edges of the volcanic field, where they extend beyond the mantle of the younger flows. Stages I and II basalt flows are similar in composition, and their combined thickness is reported by Robinson (1913, p. 38) to range from 25 feet to 200 feet. The basalts are highly fractured and faulted, with displacements of less than 75 feet; if and where they extend below the water table they are likely to be good aquifers.

ROCKS OF SECOND PERIOD OF ERUPTION

The silicic volcanic rocks—composed mainly of andesite, dacite, and rhyolite—of the second period of eruption are exposed on the flanks of O'Leary Peak and west of U.S. Highway 89 on the slope of San Francisco Mountain. The rocks are not as highly fractured as the underlying basalts and possibly would not yield substantial amounts of ground water to wells. They may form an impermeable barrier to the downward movement of ground water where covered by alluvial sediments.

BASALT FLOWS OF STAGES III AND IV

Basalt flows of stages III and IV are widely exposed in the southern part of the area and as far north as the Doney Crater. They are distinguished from flows of stages I and II by their rough, unweathered, fresh surfaces. Although these basalts are highly fractured, their position above the water table precludes their consideration as a source of ground water.

CINDER CONES AND CINDERS

Numerous cinder cones, some of which rise about 1,000 feet above the surrounding land surface, occur in the southern part of the mapped area. Deposits of cinders occur also at Doney Crater, near Wupatki Ruin. There are cinders corresponding in age to all four stages of the basalt flows, but the cinders are not differentiated on the basis of age in this report. In the Sunset Crater area the flows of stages III and IV are covered nearly everywhere with layers of basaltic cinders, which range in thickness from a few inches to several tens of feet. Thin weathered zones and some deposition of calcium carbonate occur locally at the top of some of the cinder beds. Many small exposures of basalt flows, which have not been mapped separately, occur within the area covered by cinders. The cinders are highly permeable and conducive to ground-water recharge, but their general altitude above the water table makes them a doubtful source of ground water in this area.

GROUND-WATER HYDROLOGY

The main source of ground water in the area is from that part of the precipitation which percolates down through the permeable rocks into the zone of saturation in the Coconino sandstone and the upper sandy part of the Supai formation. Perched zones of saturation occur where the downward percolation is retarded by impermeable material. Most of the ground water in the Coconino sandstone in this area is probably from precipitation received in the region south and southwest beyond the mapped area (pl. 20). Recharge to the alluvial deposits is aided by intermittent streams carrying small quantities of runoff from San Francisco Mountain.

Ground-water movement in the Coconino sandstone, as indicated by the water-table gradient, is to the northeast (fig. 45). The altitude of the water table in the Sunset Crater area is estimated to be about 5,000 feet, based on the projection of the slope of the water table as determined from wells (A–22–10)3ad, (A–23–10)1bb, and (A–23–10)13dc (table 1). Data from deep wells in the vicinity of the Wupatki National Monument indicate that the water table is at an altitude of about 4,075 feet near Wupatki Ruin and about 4,100 feet near Citadel Ruin.

Only a few wells have been drilled in the volcanic rocks; therefore, the amount of water these rocks contain is not known. However, they are not likely to yield large quantities of ground water because they are above the regional water table. Small supplies of perched water occur in the Moenkopi formation and Quaternary alluvium, and some may be present in the volcanic rocks. A few springs discharge from the base of basalt flows west and south of the area.

The southwestern part of the area is most favorable for recharge of water to the underground reservoir in the Coconino sandstone, owing to the presence of highly permeable volcanic rocks and the large amount of annual precipitation. In the northern part of the area, the total amount of recharge through the exposed surfaces of the Kaibab limestone and volcanic rocks is limited because of the low annual precipitation. Some recharge may occur from the Little Colorado River to permeable beds in the Moenkopi formation and possibly through them to older formations. The recharge areas that contribute to perched ground-water bodies, such as those at Wupatki and Heiser Springs, are probably small and do not extend far from the areas of discharge.

Perched ground water from aquifers in the Moenkopi formation and volcanic rocks in the Wupatki-Sunset Crater area is discharged from springs and seeps, which occur at a few locations in the Wupatki area and along the Little Colorado River. Data from Wupatki and Heiser Springs indicate that the total spring discharge is not directly related to total precipitation (table 3). However, there is a correlation between the winter snowfall and the flow of the springs, as shown in plate 21. Summer rainfall seems not to affect spring discharge. The combined yield from Wupatki and Heiser Springs ranges from less than 1 to about 3 gpm.

TABLE 3.—*Comparison of spring discharge and precipitation, Wupatki–Sunset Crater area, Coconino County, Ariz.*

[Assumed recharge area: Heiser Spring, 8½ acres; Wupatki Spring, 3½ acres]

Year ending Sept. 30—	Precipitation at Wupatki (inches)	Estimated total volume of precipitation on recharge area (acre-feet)		Discharge (acre-feet)		Ratio of spring discharge to total precipitation on recharge area (percent)	
		Heiser Spring	Wupatki Spring	Heiser Spring	Wupatki Spring	Heiser Spring	Wupatki Spring
1949	9.46	6.8	2.8				
1950	7.34	5.3	2.2	4.3	0.7	0.81	0.32
1951	4.59	3.3	1.4	2.6	.5	.79	.36
1952	9.85	7.1	3.0	1.7	.5	.24	.17
1953	6.24	4.5	1.9	2.5	.5	.56	.26
1954	8.40	6.1	2.5	2.0	.3	.33	.12

Ground water in the Coconino sandstone is pumped from a few deep wells that are used for stock and domestic purposes. Some of these wells yield as much as 15 gpm, but larger yields probably could be obtained by a deeper penetration of the saturated zone of the aquifer and by installing pumps of larger capacity. About 20 miles southwest of the Sunset Crater National Monument, a well in the Flagstaff well field that penetrated about 375 feet of saturated Coconino sandstone produces about 450 gpm.

The results of the field investigation indicated that adequate ground water was available in the Coconino sandstone for the needs of the headquarters area of the Wupatki National Monument. It was estimated that a well drilled to a depth of 800 to 900 feet would have a water level of 700 to 800 feet. Well (A–25–10)30bca was drilled for the Wupatki National Monument in the fall of 1958 on the basis of this information. Mr. Russell L. Mahan, superintendent, supplied the following information. The well was drilled to a total depth of 904 feet, through 10 feet of overburden, 95 feet of Moenkopi formation, 220 feet of Kaibab limestone, and 579 feet of Coconino sandstone. Water was tapped in the Coconino at a depth of 801 feet and rose 21 feet, reaching a static water level at 780 feet below land surface. The well was pumped for 24 hours at 50 gpm with a drawdown of 45 feet. The water level is reported to have returned to the static level 17 minutes after the pump was shut off. The chemical quality of the water is reported to be fair (table 4).

QUALITY OF WATER

The ground water within the Wupatki–Sunset Crater area contains moderate to large amounts of dissolved solids (table 4). The dis-

TABLE 4.—*Chemical analyses of water from selected wells and springs, Wupatki–Sunset Crater area, Coconino County, Ariz.*

[Analyses expressed in parts per million. Analyses by U.S. Geological Survey, except (A-26-10) 35 ac by U.S. Bureau of Indian Affairs]

Location No. (fig. 44)	Date of collection	Temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum of determined constituents)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25°C)
Wells															
(A-22-7)13ca	11-1-50	------	44	16	8.2	7.8	86	13	4	0.2	0.7	136	74	19	169
(A-22-11)19cc	10-20-54	60	11	45	25	22	138	116	19	.4	.8	307	216	18	513
(A-23-10)1bb	10-19-54	66	8.5	57	47	159	205	213	205	.8	.3	792	336	51	1,330
13dc	10-19-54	66	12	93	59	370	172	270	605	.6	3.2	1,500	474	63	2,590
(A-25-10)30bca	10-27-58	------	10	69	62	218	224	200	360	.8	1.3	1,030	427	53	1,850
(A-26-10)31ca	10-26-54	------	9.4	67	62	257	240	198	408	.8	1.7	1,120	422	57	2,010
35ac	------	------	------	315	68	1,020	342	1,630	------	------	------	------	------	------	------
Springs															
(A-24-10)7ad, (Coyote)	10-14-54	68	------	50	23	74	205	176	18	------	5.5	448	220	42	705
(A-25-10)30bb (Wupatki)	10-21-54	63	35	49	30	269	410	375	65	3.2	4.2	1,030	246	70	1,520
32ba (Heiser)	10-21-54	64	20	79	25	90	201	293	12	1.8	6.8	627	300	40	900

solved-solids content of the water from 3 sampled springs ranges from 448 to 1,030 ppm (parts per million); in the water from 7 sampled wells, the range is from about 136 to more than 1,500 ppm. Drinking water should contain less than 500 ppm of dissolved solids, but as much as 1,000 ppm is permissible for use on interstate carriers, according to U.S. Public Health Service standards (1946). Water containing more than the suggested limits of dissolved mineral matter has been used by many persons for long periods without ill effects.

The fluoride content of the water in Wupatki and Heiser Springs is greater than the 1.5 ppm maximum recommended by the U.S. Public Health Service, and the water is undesirable for drinking water for children because it is likely to cause mottling of teeth. The fluoride content of water from wells in the area is less than the recommended maximum.

Chemical analysis of a sample of water taken from well (A–25–10)30bca at Wupatki headquarters during a bailing test showed a total of 1,030 ppm of dissolved solids and a hardness of 427 ppm. The fluoride content is only 0.8 ppm, which is not objectionable in supplies for domestic consumption.

SUMMARY AND CONCLUSIONS

1. The main aquifer in the Wupatki-Sunset Crater area is the Coconino sandstone, and water can be obtained from this aquifer throughout the area. Ground water is obtained locally from perched water zones in the Moenkopi formation and Quaternary alluvium; perched water may be present locally in the volcanic rocks.

2. The new well at the Wupatki headquarters (drilled in 1958) yielded 50 gpm during a 24-hour test, and other wells penetrating the Coconino sandstone in the area have yields of as much as 15 gpm. South of Flagstaff, beyond the Wupatki–Sunset Crater area, yields from the Coconino sandstone are as high as 450 gpm. The water-bearing characteristics of the Coconino sandstone in the area appear to be similar to those where the formation is more productive. It is possible that larger yields can be obtained from wells penetrating a greater thickness of the saturated aquifer and equipped with larger pumps.

3. The yields of wells tapping the alluvium and of springs issuing from the Moenkopi formation are small.

4. The chemical quality of water from wells is considered poor to satisfactory for domestic use, according to the U.S. Public Health Service standards for drinking water. Fluoride is present in the waters from Wupatki and Heiser Springs in amounts sufficient to make them undesirable as drinking water for children.

5. In the Sunset Crater National Monument area, a test well at site (A–23–8)16dca (pl. 20) would explore the possibilities of both shallow (perched) water below the volcanic rocks and deep ground-water supplies from the Coconino sandstone. Such a well possibly would have to be 2,500 feet deep, because the depth to the regional water table may be as much as 2,000 feet. An alternate site for the drilling of a test well is shown at site (A–23–8)33ddd. The depth to the regional water table probably is somewhat less at this location, but there is less chance of obtaining a shallow supply.

6. At Wupatki Ruin, small supplies of perched water from shallow depths may be developed along the base of the escarpment of Woodhouse Mesa between Heiser and Wupatki Springs.

7. In the Citadel Ruin area in the Wupatki National Monument, a well drilled to a depth of about 1,600 feet would be the most likely source of ground water.

8. The possibilities of shallow perched water in the alluvium in the vicinity of Citadel Ruin could be explored by means of test holes drilled in the basin between Citadel Ruin and Arrowhead Sink. The average thickness of the alluvium is about 50 feet and it is not likely to exceed 100 feet.

9. Information needed to properly appraise the ground-water resources of an area can be obtained only when test holes and wells are drilled. This information includes drill cuttings taken at intervals of 10 feet or less; measurements of water levels, especially during periods of no drilling; and samples of water for chemical analysis from each water-bearing zone penetrated.

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