Spring Flow from Pre-Pennsylvanian Rocks in the Southwestern Part of the Navajo Indian Reservation, Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 521-F

Prepared in cooperation with the Bureau of Indian Affairs and the Navajo Tribe

SPRING FLOW FROM PRE-PENNSYLVANIAN ROCKS IN THE SOUTHWESTERN PART OF THE NAVAJO INDIAN RESERVATION, ARIZONA

Blue Spring issuing from the Redwall Limestone along the left bank of the Little Colorado River. The amount of flow is between 90 and 95 ft^3/s. Photograph by J. A. Baumgartner.

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By M. E. COOLEY

HYDROGEOLOGY OF THE NAVAJO AND HOPI INDIAN RESERVATIONS, ARIZONA, NEW MEXICO, AND UTAH

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Multiply English units	By	To obtain metric units
cubic feet per second (ft^3/s)	0.02832	cubic metres per second (m^3/s)
feet (ft)	.3048	metres (m)
square miles (mi^2)	2.590	square kilometres (km^2)
gallons per minute (gal/min)	.06309	litres per second (l/s)
miles (mi)	1.609	kilometres (km)

SPRING FLOW FROM PRE-PENNSYLVANIAN ROCKS IN THE SOUTHWESTERN PART OF THE NAVAJO INDIAN RESERVATION, ARIZONA

By M. E. Cooley

ABSTRACT

About 220 cubic feet per second of spring flow issues from the pre-Pennsylvanian rocks in the canyon of the Little Colorado River; the flow is mainly from the Redwall and Muav Limestones, which combine hydraulically to form a multiple-aquifer system. Blue Spring—the largest spring in the Colorado Plateaus physiographic province—discharges about 90 ft^3/s from the left bank of the Little Colorado River. Blue Spring and other nearby springs maintain the perennial flow of the Little Colorado. Vaseys Paradise Spring is the only large spring in Marble Canyon; several estimates of the spring flow were made between 1923 and 1967 and range from 0.1 to 10 ft^3/s. The flows from Blue Spring and the other springs in the canyon of the Little Colorado River represent most of the discharge from Paleozoic rocks in the Black Mesa hydrologic basin. Spring occurrence is controlled mainly by the many normal faults that converge in the area; the faults have caused extensive fracturing in the rocks.

The chemical quality of the water from the springs that issue from the Redwall and Muav Limestones is related directly to the unit from which the water issues and to the distance that the water has traveled in the subsurface. Water from Vaseys Paradise Spring contains 163 parts per million of dissolved solids; the spring receives its recharge from the Kaibab Plateau, which is only a short distance from Vaseys Paradise. In contrast, spring flow discharged into the canyon of the Little Colorado River has moved long distances in the subsurface and contains from 2,320 to 3,970 parts per million dissolved solids. Blue Spring has precipitated large amounts of travertine in irregular ledges and dams downstream in the channel of the Little Colorado River. The water from a few small springs that issue from the Tapeats Sandstone and Bright Angel Shale is highly mineralized. Salt deposits precipitated by springs near the base of the Tapeats Sandstone have been used for centuries by the Hopi Indians.

In the southwestern part of the Navajo country the potential for the development of ground water from the pre-Pennsylvanian rocks is limited to the Redwall and Muav Limestones multiple-aquifer system. At the present time, the use of Blue Spring and the other nearby springs for water supplies is not feasible because of (1) the poor chemical quality of the water and (2) the amount of lift from the channel of the Little Colorado River to the canyon rim.

INTRODUCTION

The springs that discharge into the deep canyons of the Little Colorado and Colorado Rivers in the southwestern part of the Navajo Indian Reservation issue from pre-Pennsylvanian rocks—mainly the Redwall Limestone, of Mississippian age, and the Muav Limestone, of Cambrian age. These springs have not been developed for water supplies, partly because of their inaccessibility and partly because the water is of poor chemical quality; most of the water contains more than 2,000 ppm (parts per million) of dissolved solids. The largest amount of spring discharge is in the canyon of the Little Colorado River, where Blue Spring and other springs flow at a combined rate of about 220 ft^3/s; the springs issue more than 2,000 feet below the canyon rims, and their flow maintains the perennial reach of the Little Colorado River. In contrast, only a small amount of spring flow discharges in Marble Canyon and the eastern part of the Grand Canyon.

LOCATION AND LAND NET SYSTEM

The Navajo and Hopi Indian Reservations have an area of about 25,000 mi^2 in the south-central part of the Colorado Plateaus physiographic province (fig. 1). The area of outcrop of the pre-Pennsylvanian Paleozoic rocks from which the springs discharge is in the southwestern part of the Navajo Indian Reservation in Coconino County, Ariz.

In this report the term "Navajo country" (Gregory, 1917, p. 11) is used broadly to include the Navajo and Hopi Indian Reservations and the rest of the area mainly between the Colorado, San Juan, and Little Colorado Rivers. The reservations are divided by the Bureau of Indian Affairs into 18 administrative districts. Districts 1–5 and 7–18 are in the Navajo Indian Reservation, and district 6 is the Hopi Indian Reservation (fig. 1).

PURPOSE AND SCOPE OF INVESTIGATION

From 1946 to 1950, the U.S. Geological Survey, at the

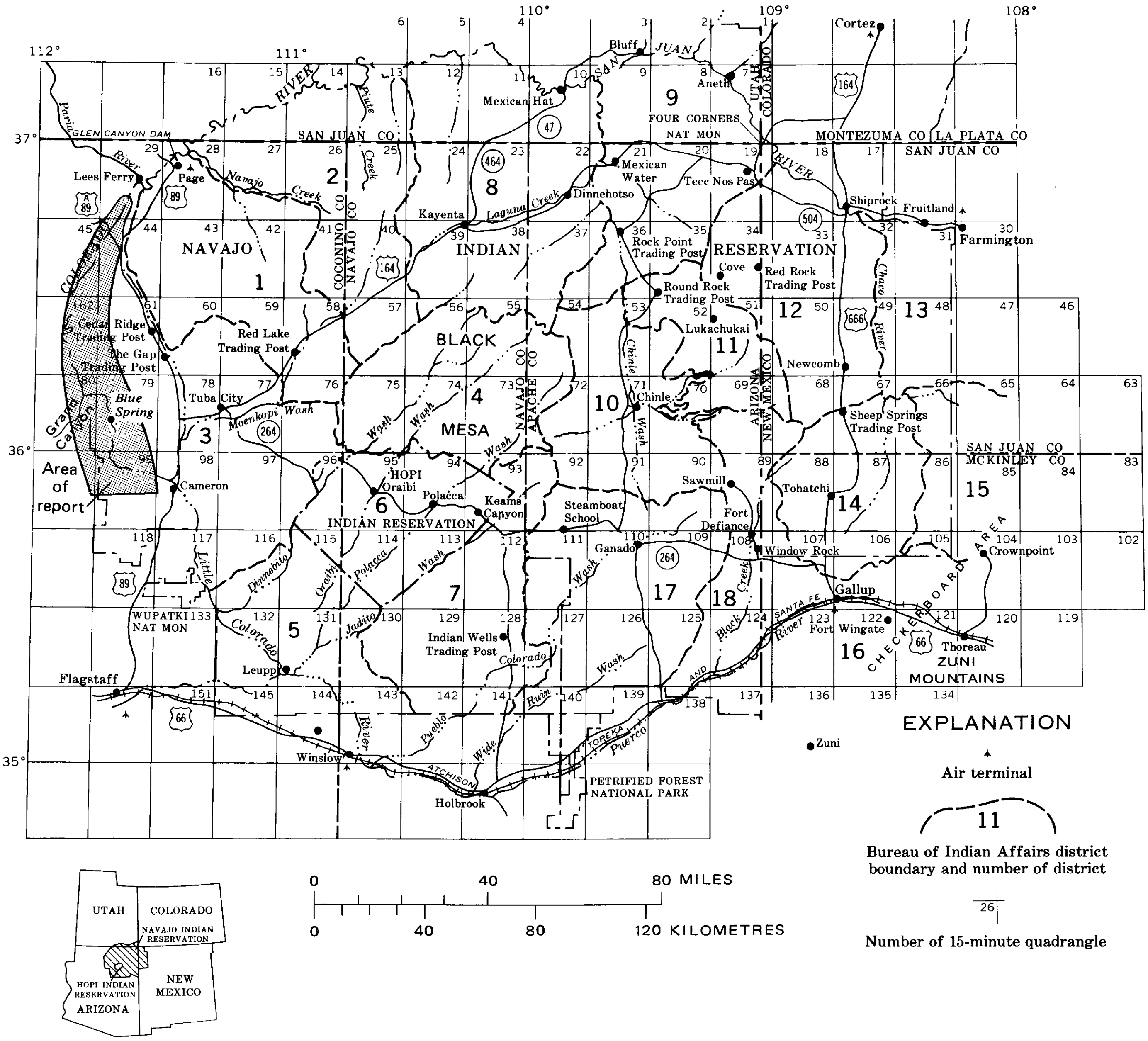

FIGURE 1.—Location map of the Navajo and Hopi Indian Reservations showing the Bureau of Indian Affairs' administrative districts.

request of the Bureau of Indian Affairs, made a series of hydrologic investigations to help alleviate water shortages in several places in the reservations. In 1950, the Geological Survey, in cooperation with the Bureau of Indian Affairs, began a comprehensive regional investigation of the geology and ground-water resources of the reservations. A well-development program supported by the Bureau of Indian Affairs and the Navajo Tribe was carried on concurrently with the regional investigation and is being continued by the Navajo Tribe. The principal objectives of these investigations were: (1) to determine the feasibility of developing ground-water supplies for stock, institutional, and industrial uses in particular areas and at several hundred well sites scattered throughout the reservations and in adjoining areas owned by the Navajo Tribe; (2) to inventory the wells and springs; and (3) to appraise the potential for future water development.

ORGANIZATION OF THE REPORT

This report is the sixth chapter of a series which describes the geology and hydrology of the Navajo and Hopi reservations. The springs that issue from the pre-Pennsylvanian rocks in Marble and Grand Canyons and in the canyon of the Little Colorado River are described in this report; the lithologic and stratigraphic descriptions of the pre-Pennsylvanian rocks are given in Irwin, Stevens, and Cooley (1971) and are not included in this report. The basic geohydrologic data—records of wells and springs inventoried through 1961 (Davis and others, 1963; McGavock and others, 1966); selected chemical analyses (Kister and Hatchett, 1963); selected drillers' logs, lithologic logs, and stratigraphic sections (Cooley and others, 1964); and maps showing locations of wells, springs, and stratigraphic sections (Cooley and others, 1966)—are published separately as Arizona State Land Department Water Resources Reports. In addition, other spring data that were collected in Marble Canyon and the canyon of the Little Colorado River but which are not included in the reports mentioned above are given in table 1.

The geologic maps and the discussion of the hydrologic and geologic framework of the reservations are included in Cooley, Harshbarger, Akers, and Hardt (1969). The locations of the springs that discharge water from the pre-Pennsylvanian rocks in Marble Canyon and in the canyon of the Little Colorado River are shown on plates 1 and 2.

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PREVIOUS INVESTIGATIONS

Major John Wesley Powell was the first scientific investigator to descend the Colorado River and to describe the rocks and spring flow in its canyons (Powell, 1875). Considerable effort has been expended by other investigators in describing the rock outcrops in the Grand Canyon and nearby areas (Gilbert, 1874, 1875; Walcott, 1880; Dutton, 1885; Darton, 1910; Noble, 1914; and Gregory, 1917). LaRue (1925), however, was the first investigator to describe some of the important hydrologic characteristics of Marble and Grand Canyons. Since World War II, several hydrologic investigations have been made in the Grand Canyon and Navajo country. In the early 1950's studies of spring flow in the canyon of the Little Colorado River were made by J. A. Baumgartner and other personnel of the U.S. Geological Survey; the results of these studies are included in a report on the large springs in the Grand Canyon area (Johnson and Sanderson, 1968) and in this report. Metzger (1961) described the ground-water conditions along the south rim of the Grand Canyon. Cooley (1963) discussed aspects of the regional movement and natural discharge of ground water in the Arizona part of the Colorado Plateaus, and McGavock (1968) compiled records of water wells for an area south of the Colorado and Little Colorado Rivers in Coconino County.

WATER-BEARING CHARACTERISTICS OF THE PRE-PENNSYLVANIAN ROCKS

In the southwestern part of the Navajo Indian Reservation the pre-Pennsylvanian Paleozoic rocks are of Cambrian, Devonian, and Mississippian age. The rocks crop out only in Marble and Grand Canyons and the canyon of the Little Colorado River, overlie the nearly impermeable Grand Canyon Supergroup (Elston and Scott, 1975) of Precambrian age, and underlie the Pennsylvanian and Permian strata that outline the upper parts of the canyons. The pre-Pennsylvanian rocks consist of the Tapeats Sandstone (Noble, 1914, p. 61–65), Bright Angel Shale, and the Muav Limestone, all in the Tonto Group (Gilbert, 1874, p. 109) of Cambrian age, the Temple Butte Limestone (Walcott, 1880; 1883) of Devonian age, and the Redwall Limestone (Gilbert, 1875, p. 161) of Mississippian age. Near the confluence of the Colorado and Little Colorado Rivers, the nearly impermeable younger Precambrian strata of the Grand Canyon Supergroup (Elston and Scott, 1975; Powell, 1875, p. 70) unconformably underlie the rocks of the Tonto Group. These strata in turn overlie the Vishnu Schist (Walcott, 1894) and the granitic rocks of older Precambrian age, which are exposed downstream from the area shown on plate 2.

TAPEATS SANDSTONE

A small amount of ground water is discharged from the basal Tapeats Sandstone of the Tonto Group. The sandstone caps a prominent bench composed mainly of Precambrian rocks near the mouth of the Little Colorado River in eastern Grand Canyon. The sandstone is 300 feet thick adjacent to the Colorado River between Desert View and the mouth of the Little Colorado River (McKee, 1945, p. 142). In the upland areas near Marble and Grand Canyons, the Tapeats is overlain by more than 3,000 feet of younger rocks.

Direct recharge to the unit in the Navajo country, therefore, is restricted to the outcrops in the canyons of the Colorado River.

The Tapeats Sandstone is well cemented, principally by silica, and in many places is a quartzitic sandstone or a quartzitic conglomerate. The silica cement is the cause of the low permeability of the unit. The unit is brittle and contains many joints. Ground-water movement is mainly through crevices formed along the joints and bedding planes rather than through the pores of the silica-cemented sandstone. In the eastern Grand Canyon a few small springs and seeps issue along the bedding planes in the sandstone and along the contact between the Tapeats and the underlying Precambrian rocks (Metzger, 1961, p. 115, 124).

Along the Colorado River, principally between the mouth of the Little Colorado River and Palisades Creek (pl. 2), the basal part of the Tapeats Sandstone is covered with a white band of alkali. For centuries the Hopi Indians have used part of this alkali deposit as a source of salt. In niches some of the salt has been precipitated as slender well-formed stalactites. The deposits outline a broad "seep" area mainly along the east side (left bank) of the Colorado River. In 1967, when this area was inspected briefly by the author from a helicopter and a boat, a few damp areas were observed, which indicates that ground water is presently issuing from the Tapeats Sandstone in this area.

The Tapeats Sandstone is present in the subsurface in the southwestern part of the Navajo Indian Reservation, but the water from spring GC–24 may be the only water discharging from the unit (table 1). The water from spring GC–24 is derived from the Tapeats or from the underlying Precambrian basement rocks, but its point of discharge is in the Bright Angel Shale. This unusual spring has built a domal mound of impure travertine several feet high. The mound has an opening at the top, and when visited by Don Talayesu in 1912, he observed that the orifice was "filled to the brim with yellow water—quiet, then boiled" (Titiev, 1937, p. 244). Eiseman (1959, p. 27), who visited the spring in May 1958, stated:

> * * *This structure [built by and now containing the spring] is a rounded travertine dome, approximately 30 yards in diameter, roughly round at the base, about 20 feet high, and with a flat top about 15 feet in diameter. The stream side [south side] of this dome is somewhat higher than the north side. A pool of yellow water about 10 feet in diameter occupies most of the top of the dome. Gas bubbles ascend constantly through the water. The depth of the pool was not ascertained, but it must be fairly deep, since the pool was opaque and a sample of the water taken in a cup appeared almost colorless. A travertine-encrusted log lies wedged in the pool. The pool spills over the east side of the dome down a chute, colored bright yellow by the mineral deposit, to the river below.* * *

The discharge of the spring has been estimated by inspection of a photograph by Eiseman (1959, p. 28) and is not more than 3 or 4 gal/min. The spring was visited by J. B. Gillespie and H. M. Babcock in January 1966 and by E. L. Gillespie and M. E. Cooley in March 1967. At the time of these visits, the yellow water in the orifice was muddy in appearance and was churning and surging about 3 or 4 feet below the rim.

Only one other spring in the southern Colorado Plateaus area is similar to spring GC–24—a spring in the western part of the Grand Canyon along the left bank of the Colorado River a few miles upstream from the mouth of Diamond Creek. (See fig. 3.) The spring, which has built a travertine dome similar to that of spring GC–24, issues from fractured granitic rocks near the Hurricane fault only a few tens of feet below the base of the Tapeats Sandstone.

BRIGHT ANGEL SHALE

The middle unit of the Tonto Group—the Bright Angel Shale—erodes into a continuous steep slope between the cliff-forming Tapeats Sandstone below and the Muav and Redwall Limestones above. The Bright Angel Shale is about 300 feet thick where it is exposed in the bottoms of the canyons near the mouth of the Little Colorado River. The formation consists of four broad lithologic zones, which are, in ascending order, soft, green, micaceous, sandy shale and thin, partly crossbedded sandstone; brown limestone; soft, greenish, micaceous, sandy shale; and alternating layers of shale and purplish-brown sandstone.

Only a small amount of water is discharged from the Bright Angel Shale. The water from spring GC–24, which was discussed above, probably is from the Tapeats Sandstone or basement rocks and not from the Bright Angel Shale. In the Navajo Indian Reservation the only water known to discharge from the unit is from spring GC–48, which is near the mouth of Marble Canyon. Metzger (1961, p. 116) reported several small springs issuing from this unit in the Grand Canyon. In general, the Bright Angel Shale restricts rapid movement of ground water and forms a confining layer below the multiple-aquifer system formed by the Muav and Redwall Limestones.

MUAV LIMESTONE

The uppermost unit of the Tonto Group—the Muav Limestone—is about 400 feet thick near Desert View (McKee, 1945, p. 141). The formation erodes into a series of small blocky cliffs or steep slopes below the palisadelike escarpment of the Redwall Limestone; in many exposures the Muav in combination with the Redwall Limestone, and locally with the intervening Temple Butte Limestone, forms sheer walls. The limestone units of the Muav become more impure and

TABLE 1.—*Spring flow from pre-Pennsylvanian rocks in Marble Canyon and the canyon of the Little Colorado River*

[E, estimated]

Spring No. or name (see pls. 1 and 2)	Quadrangle name and No.	Discharge: Gallons per minute	Discharge: Cubic feet per second	Date estimated	Altitude above mean sea level (feet)	Altitude above canyon bottom or stream (feet)	Strati-graphic unit (aquifer)	Source	Physio-graphic position	Remarks
Marble Canyon										
GC-29	Nankoweap, 62	<5	<0.01	8-31-67	2,920	50	Redwall Limestone	Bedding planes-joints	Side of canyon	Located by M. E. Cooley; good taste; leakage through limestone from Vaseys Paradise Spring.
Vaseys Paradise Spring	do	135-2,400	0.3-5.5E	1950-60	3,070	200	do	Prominent joint	do	Johnson and Sanderson, 1968, table 1; 40-50 gal/min estimated Aug. 31, 1967, by R. H. Roeske and M. E. Cooley; considerable vegetation including brush, poison ivy, watercress, etc.; used by river parties.
GC-30	do	<1E	<0.002E	8-31-67	3,000	150	do	Bedding plane-joint	do	Located by M. E. Cooley and R. H. Roeske from rubber raft; small seep.
31	do	<1E	<0.002E	8-31-67	2,865	5	do	do	do	Do.
32	do	<1E	<0.002E	8-31-67	2,865	5	do	do	do	Do.
33	do	<1E	<0.002E	8-31-67	2,845	5	do	----	do	Located by M. E. Cooley and R. H. Roeske from rubber raft; several small seeps at base of Redwall Limestone and near top of Muav Limestone.
34	do	<1E	<0.002E	8-31-67	2,910±	75	Redwall and Muav Limestones	Bedding plane-joint	Alcove	Do.
35	do	<1E	<0.002E	8-31-67	2,910±	75	do	do	do	Do.
36	do	<1E	<0.002E	8-31-67	3,075±	250±	do	do	do	Do.
37	do	----	<0.002E	8-31-67	3,100±	275±	do	do	do	Located by M. E. Cooley and R. H. Roeske from rubber raft; in side of canyon having Royal Arch.
38	do	Seep	----	8-31-67	3,100±	275±	Muav Limestone	----	----	Located by M. E. Cooley and R. H. Roeske from rubber raft.
39	do	do	----	8-31-67	3,000±	175±	Muav(?) Limestone	Bedding plane-joint	Side of canyon	Do.
40	do	do	----	8-31-67	3,125±	300±	do	----	do	Located by M. E. Cooley and R. H. Roeske from rubber raft; dry, Aug. 31, 1967.
41	do	<5E	<0.01E	8-31-67	3,200±	190±	do	Bedding plane-joint	Alcove	Located by M. E. Cooley and R. H. Roeske from rubber raft; flows to river.
42	do	<1E	<0.002E	8-31-67	3,200±	190±	do	do	do	Located by M. E. Cooley and R. H. Roeske from rubber raft; other seeps in nearby alcoves.
43	do	Seep	----	8-31-67	3,100±	280±	do	----	do	Located by M. E. Cooley and R. H. Roeske from rubber raft.
44	do	<5E	<0.01E	8-31-67	3,100±	280±	do	----	do	Located by M. E. Cooley and R. H. Roeske from rubber raft; flows almost to river.
45	do	Seep	----	8-31-67	3,200±	400±	do	do	Side of canyon	Located by M. E. Cooley and R. H. Roeske from rubber raft; several seeps in area.
46	do	do	----	8-31-67	3,200±	400±	Muav Limestone	----	do	Located by M. E. Cooley and R. H. Roeske from rubber raft.
47	do	do	----	9-1-67	3,000	230	do	Bedding planes-joints	Alcove	Located by M. E. Cooley and R. H. Roeske from rubber raft; several small seeps.
48	do	<5	<0.01E	9-1-67	2,850	110	Bright Angel Shale	Joints	Side of canyon	Johnson and Sanderson, 1968.
49	Vishnu Temple, 80	Seep	----	9-1-67	3,050	325	Muav Limestone	Bedding planes-joints	Alcove	Located by M. E. Cooley and R. H. Roeske from rubber raft.
53	Nankoweap, 62	<1	<0.002	8-31-67	2,900	60	do	do	do	Do.
Canyon of the Little Colorado River										
GC-1	Blue Spring, 79	200-300E	0.44-0.66	3-15-67	3,200	0	Redwall Limestone	Fractures along fault	Bottom of canyon	Located from helicopter by M. E. Cooley and E. L. Gillespie.
2	do	10-100E	0.02-0.22	3-15-67	3,195	0	Alluvium	----	do	Located from helicopter by M. E. Cooley and E. L. Gillespie; water derived originally from Redwall Limestone; sample taken for chemical analysis; probably includes water from springs GC-2, 3, 4, and 5.
3	do	10-100E	0.02-0.22	3-15-67	3,195	0	do	----	do	Do.
4	do	10-100E	0.02-0.22	3-15-67	3,190	0	do	----	do	Do.
5	do	10-100E	0.02-0.22	3-15-67	3,190	0	do	----	do	Do.
6	do	Seep	----	3-15-67	3,185	0	Redwall Limestone and alluvium	Fractures	do	Located from helicopter by M. E. Cooley and E. L. Gillespie.
7	do	do	----	3-15-67	3,230	50	Redwall Limestone	----	Side of canyon	Do.
8	do	----	----	3-15-67	3,180	0	do	----	Bottom of canyon	Do.
Blue Spring	do	41,850-44,550	93-99	----	3,165	0	do	Solution channel along fault	do	Previously measured by J. A. Baumgartner, June 14, 1950, and J. B. Gillespie, May 17, 1966.
GC-9	do	<100	<0.22	3-15-67	3,165	0	do	Fractures along fault	do	Located from helicopter by M. E. Cooley and E. L. Gillespie.

TABLE 1.—*Spring flow from pre-Pennsylvanian rocks in Marble Canyons and the canyon of the Little Colorado River*—Continued

Spring No. or name (see pls. 1 and 2)	Quadrangle name and No.	Discharge: Gallons per minute	Discharge: Cubic feet per second	Date estimated	Altitude above mean sea level (feet)	Altitude above canyon bottom or stream (feet)	Strati-graphic unit (aquifer)	Source	Physio-graphic position	Remarks
Canyon of the Little Colorado River—Continued										
10	Blue Spring, 79	15,750E	35E	1966	3,160	0	Redwall Limestone	Solution channel along fractures	Bottom of canyon	Located from helicopter by J. B. Gillespie and H. M. Babcock; sample of water under pressure taken from spring by J. B. Gillespie by diving below surface of the river.
11	do	11,250E	25E	1966	3,160	0	do	do	do	Do.
12	do			3-15-67	3,135	<10	do	Fractures	do	Located from helicopter by M. E. Cooley and E. L. Gillespie; 1,000 gal/min estimated in area of spring; flow 200 gal/min estimated June 20, 1951(?).
13	do			3-15-67	3,130	0	Travertine	Bedding planes	do	Located from helicopter by M. E. Cooley and E. L. Gillespie; water derived originally from Redwall Limestone.
14	do	100E	0.22E	3-15-67	3,100	150±	Redwall Limestone	Fractures	Side of canyon	Located by J. A. Baumgartner, 1950; flow at river is about 100 gal/min estimated.
15	do				2,925	<10	Alluvium		Bottom of canyon	Located by J. A. Baumgartner, 1950; water derived originally from Redwall Limestone.
16	do				2,925	<10	do		do	Located by J. A. Baumgartner, 1950; water derived originally from Redwall Limestone; seep area.
17	do	50E	0.11E	3-15-67	3,400	200±	Redwall Limestone		Side of canyon	Located by J. A. Baumgartner, 1950; in Salt Trail Canyon.
18	do				2,910	<10	Muav Limestone and alluvium		Bottom of canyon	Located by J. A. Baumgartner, 1950; seep-spring area; some willows.
19	do				2,950	75	Muav Limestone		Side of canyon	Located by J. A. Baumgartner, 1950; at base of Muav Limestone.
20	do				2,950	75	do		do	Do.
21	do				2,950	75	do		do	Do.
22	do				2,950	80	do		do	Do.
23	do				2,975	100	do		do	Do.
24	do				2,860	<10	Travertine		Bottom of canyon	Located from helicopter by M. E. Cooley and E. L. Gillespie; domelike mound of travertine; described originally by Don Talayesu (in Titiev, 1937, p. 244); water derived originally from Tapeats Sandstone and (or) granitic basement rocks.
25	do				2,870	50	Muav Limestone	Bedding planes-joints	Side of canyon	Located by J. A. Baumgartner, 1950.
26	do				2,870	50	do	do	do	Do.
27	do				2,870	50	do	do	do	Do.
28	do	Seep		3-15-67	2,870	50	do	do	do	Located from helicopter by M. E. Cooley and E. L. Gillespie; mainly an alkali band.

the number and thickness of clastic beds increase progressively eastward through the Grand Canyon (McKee, 1945, p. 103–104) and into the Navajo Indian Reservation. Near the mouth of the Little Colorado River, the Muav Limestone consists of a lower shale and sandstone interval, a middle limestone interval, and an upper shale and sandstone interval that is capped by a thin limestone bed.

The spring discharge from the Muav and Redwall Limestones maintains the perennial flow of the Little Colorado River downstream from Blue Spring and of several other streams tributary to the Colorado River in Grand Canyon (Johnson and Sanderson, 1968). (See section entitled "Redwall Limestone.") Ground water moves readily through the Muav where solution channels have developed along fractures and bedding planes. A few large springs (Johnson and Sanderson, 1968) and many small springs issue from the Muav Limestone in the eastern Grand Canyon, but only a few small springs and seeps are known to discharge water from the unit in Marble Canyon. In addition to the small amount of visible spring flow in Marble Canyon, an unknown but probably small quantity of water discharges from the Muav into the alluvium below the channel of the Colorado River. A combined flow of from 10 to 20 ft^3/s is discharged to the Little Colorado River downstream from the mouth of Salt Trail Canyon by at least 10 springs that issue from the Muav Limestone (pl. 2).

TEMPLE BUTTE LIMESTONE

The Temple Butte Limestone, of Devonian age, is exposed in discontinuous outcrops in Marble Canyon and in the lower reach of the canyon of the Little Colorado River. Springs are not known to discharge water from the scattered limestone exposures in the southwestern Navajo country or in the eastern Grand Canyon.

REDWALL LIMESTONE

The nearly impassable perpendicular bench of the Redwall Limestone, of Mississippian age, is displayed spectacularly in the lower parts of the canyons in the southwestern part of the Navajo Indian Reservation. The Redwall is the main contributor of spring flow in the area; in the Navajo country the Redwall Limestone, Muav Limestone, and Temple Butte Limestone, where present, constitute a multiple-aquifer system, herein termed the "Redwall and Muav Limestones multiple-aquifer system." Most of the spring flow from the Redwall is discharged into the canyon of the Little Colorado River, and it maintains the large perennial base flow in the lowermost 13 miles of the river. The brilliant blue water in this reach of the river is a striking contrast with the barren brownish-red canyon walls and surrounding semiarid uplands.

The light-gray Redwall Limestone is stained brownish red in most exposures by the wash from the red siltstone in the overlying Supai Formation, of Pennsylvanian and Permian age. The Redwall is a very fine to medium-grained crystalline carbonate. According to McKee (1960), several types of limestone and dolomite are present in the Redwall; most of the dolomite is in the lower part of the formation. Large zones in the limestone are characterized by alternating thin chert and thick calcareous layers. Eliminating the chert, the limestone contains less than 1 percent insoluble residue—very fine grained quartz sand, clay, and particles of iron oxide.

When viewed at a distance, the Redwall Limestone appears to be solid and massive, but, on close inspection, it is seen to contain numerous channels, cavities, and caves developed by solution of the limestone along bedding planes, faults, and joints. In several places near the north rim of the Grand Canyon, large solution channels, many of which have several branches, provide conduits for the transmission of ground water in the Redwall and Muav Limestones (P. W. Huntoon and G. L. Beck, oral commun., 1968). Some of the solution channels have been explored by spelunkers for distances of more than 3,000 feet (J. H. Hassemer, oral commun., 1968). Several small springs issue from the solution channels along fractures and bedding planes near the level of the Colorado River in Marble Canyon. In the canyon of the Little Colorado River, Blue Spring and the other large springs discharge a combined flow of about 220 ft^3/s from openings developed along fractures in the Redwall and Muav Limestones (pl. 2; table 1). In the Grand Canyon area, large springs that issue from the Redwall and Muav Limestones, including the springs in western Grand Canyon that issue from the limestone beds at the base of the Supai Formation, discharge a combined flow of about 190 ft^3/s.

Vaseys Paradise Spring is the only large spring in Marble Canyon (pl. 1); several spring-flow estimates ranging from 0.1 to 10 ft^3/s were made between 1923 and 1967 (table 2). From 1950 to 1967, most of the water from Vaseys Paradise Spring issued from a sharply defined notch in a smooth cliff face carved from the Redwall Limestone (fig. 2); however, a photograph taken in 1923 (LaRue, 1925, pl. 26) shows the estimated flow of 10 ft^3/s issuing from three openings. Powell's (1895, p. 238) picturesque description of this spring as "fountains bursting from the rock high overhead* * *" indicates that there was considerable flow and that the spring flow in 1869 was more similar in appearance to that in 1923 than to that in 1950–67. The differences in the flow of this spring are caused mainly by the seasonal variations in the amounts of precipitation and recharge. Spelunkers exploring the cavern of Vaseys Paradise Spring noted an increase in flow only 12 hours after a rainstorm occurred above the Kaibab Plateau (P. W.

TABLE 2.—*Estimated discharge of Vaseys Paradise Spring, 1923–67*

Estimated discharge (ft^3/s)	Date estimated	Party
10	8– 8–23	LaRue.
5.5	5–17–50	Baumgartner.
.3	6– 6–53	Baumgartner.
.15	6–14–60	Sanderson and Johnson.
4.0	6–20–65	Bell and Myrick.
.1	8–30–67	Roeske and Cooley.

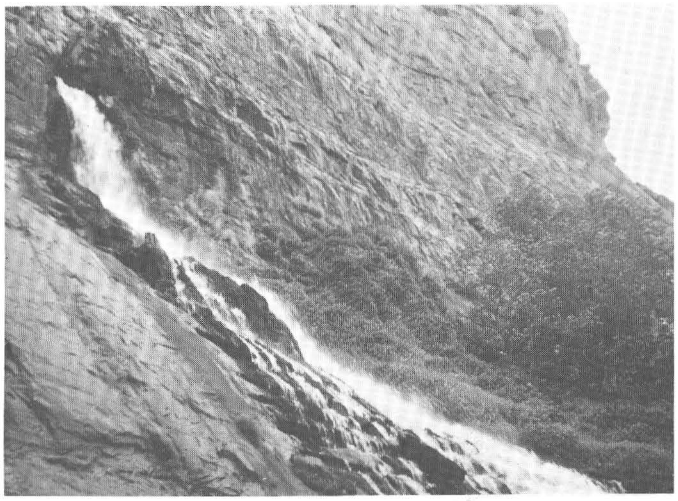

FIGURE 2.—Vaseys Paradise Spring in 1950, when the spring was flowing at an estimated rate of 5.5 ft^3/s. The spring issues from the Redwall Limestone on the right bank of the Colorado River. Photograph by J. A. Baumgartner.

Huntoon, oral commun., 1969); the water traveled about 10 miles. The cavern of the spring has been explored for 2½ miles west of the Colorado River.

SPRING FLOW IN THE CANYON OF THE LITTLE COLORADO RIVER

Blue Spring and the other springs that discharge from the Redwall Limestone in the canyon of the Little Colorado River are found along both banks of the river mainly in the reach 10–13 miles above the confluence with the Colorado River (pl. 2). When viewed from the canyon rim or from the air, the water in the reach from Blue Spring to the confluence of the Colorado River is a brilliant blue—about the color of a dilute solution of copper sulfate (frontispiece). Visitors to the canyon are struck by the water's unusual blueness. It has been speculated that the intense blue color is due to chemical composition, growth of algae, or even to the depth of the water in the channel, especially where it forms pools behind dams of travertine.

DISTRIBUTION OF THE SPRING FLOW

The flows of Blue Spring and the other springs in the canyon of the Little Colorado River are steady. Although most of the spring flow is from the Redwall Limestone, some is from the Muav Limestone. Near the mouth of the Little Colorado River at mile 3.1 (pl. 2), the combined flow of the springs, which were measured at different times between 1950 and 1967, ranged from 217 to 232 ft^3/s (Johnson and Sanderson, 1968, table 1); the average is 223 ft^3/s. The error in the measurements is within about 7 percent. Much of the spring-flow data were obtained by J. A. Baumgartner during several trips into the canyon of the Little Colorado River in 1950–53. Blue Spring issues from a solution channel in the Redwall Limestone (frontispiece) and contributes about 90 ft^3/s or nearly half the perennial flow to the Little Colorado River. About 60 ft^3/s is contributed to the river from springs GC–10 and GC–11, which are less than 0.3 mile downstream from Blue Spring. The flow from the two springs enters the channel below river level (J. B. Gillespie and H. M. Babcock, oral commun., 1967). Streamflow (base flow) measurements indicate an increase of 40 to 45 ft^3/s between the springs and mile 10, which is about halfway between Blue Spring and Big Canyon, and an increase of only about 20 ft^3/s between mile 10 and a small tributary near mile 3.1 (pl. 1). The amount of spring flow contributed to the Little Colorado River between the tributary and the mouth of the river is insignificant.

STRUCTURAL CONTROL

Large and small normal faults and associated joints have fractured the rocks extensively in the middle reach of the canyon of the Little Colorado River, and in places near Blue Spring the rocks are a jumbled mass; the faults probably control the occurrence of Blue Spring and the other large springs in the area. In general, the faults are concentrated in a rather broad zone that borders the canyon between Big Canyon and Red Butte; they tend to converge in the area near Blue Spring (pls. 1 and 2). Blue Spring, spring GC–10, and spring GC–11 issue from highly fractured strata near the intersection of the Blue Spring fault and an east-northeast-trending fault (pl. 2). Near the Little Colorado River, the faults trend mainly north. These faults are joined by northeast-trending faults near Big Canyon, by northwest-trending faults in the Lee Canyon area, and by an east-northeast-trending fault near Blue Spring. The longest fault, which extends more than 30 miles, crosses the Little Colorado River at the mouth of Big Canyon. The north-trending Blue Spring fault is subparallel to the trend of the canyon and crosses the channel of the river at six places. This fault may largely control the distribution of the perennial spring flow in the canyon; spring flow begins a short distance from the point where the fault crosses the river about a mile south-southeast of Blue Spring (pl. 2).

ORIGIN OF THE SPRING FLOW

In the canyon of the Little Colorado River most of the spring flow from the Redwall and Muav Limestones multiple-aquifer system is derived from the Coconino Sandstone, of Permian age, which is the principal unit of the C multiple-aquifer system in the southwestern part of the Navajo Indian Reservation (Cooley, 1963, fig. 7 and p. 35; Cooley and others, 1969). The C multiple-aquifer system is the main aquifer system in the Black Mesa hydrologic basin—an area of about 28,000 mi^2 in northeastern Arizona and northwestern New Mexico (fig. 3). In the canyon of the Little Colorado River the base of the Coconino Sandstone is between 800 and 1,200 feet above the top of the Redwall Limestone; the stratigraphic interval between the Redwall and Coconino is occupied by red beds of the Supai Formation and Hermit Shale. The absence of springs along the basal contact of the Coconino, which is exposed above river level downstream from the scenic lookout 8 miles from Cameron, indicates that the Coconino is drained in most of the area adjacent to the canyon of the Little Colorado River. West of Cameron and south, southeast, and east of Blue Spring, water moves downward in fractures through the Coconino, Hermit, and Supai Formations and into the Redwall and Muav Limestones multiple-aquifer system. Ground water in the limestones then moves laterally along solution channels, which probably are controlled by fractures. Most of the ground-water movement toward the Blue Spring area probably takes place in a highly fractured zone along and near the East Kaibab monocline, particularly near the Coconino Plateau (pl. 1). This conclusion is supported by water-level data for the Coconino Sandstone and underlying Supai Formation south and southwest of Cameron (McGavock, 1968, fig. 4; J. T. Callahan, M. E. Cooley, W. F. Hardt, and G. E. Davis, written commun., 1968).

A small part of the water that issues from Blue Spring and the other large springs has traveled considerable distances in the Redwall Limestone. Some of this water is from direct recharge to the Redwall and Muav outcrops outside the reservations, particularly in the Grand Canyon south and east of the Colorado River.

To obtain more information on the origin of spring flow into the Little Colorado River, the channel was inspected by E. L. Gillespie and the author by helicopter on March 15, 1967. The reach inspected contains many faults, and starts upstream from where the perennial flow begins near Blue Spring and extends to slightly beyond the scenic lookout 8 miles downstream from Cameron. In this reach the channel of the river is bordered by strata (the Supai Formation of Pennsylvanian and Permian age and the Hermit Shale and Coconino Sandstone of Permian age) that overlie the Redwall Limestone. Closely spaced pools of blue water similar in color to that discharging from Blue Spring were observed to a point about 2 miles upstream from Waterhole Canyon. For the next 1½ miles the channel was dry, but from there many pools of blue water were distributed upstream to Red Butte. Although the number of pools was not counted, pools were noted in 40 different localities. Upstream from Red Butte, the blue pools were less numerous; none were present upstream from the scenic lookout (pl. 1). In addition, pools of relatively clear water were present in the channel of the Little Colorado River upstream from about Red Butte. The clear pools were found for about 2½ miles upstream from the scenic lookout; at this point the helicopter reconnaissance trip was terminated. The relatively clear pools of water probably are part of the underflow in the channel and are derived from runoff that originates upstream. The pools of blue water may be ground water discharged into the river channel from fractures in the Supai Formation, Hermit Shale, and Coconino Sandstone or may be caused by the gray colloidal clay that lines some of the pools inspected by E. S. Buell of the U.S. Geological Survey (oral commun., 1968). The clay probably is derived from the bluish-gray unit of the Petrified Forest Member of the Chinle Formation (Triassic), which is exposed in areas along the Little Colorado River and some of its tributaries. If the blue color is caused by the clay, the implication is that the source of the water is underflow, the same source as the clear pools. The main data to support the hypothesis of ground-water inflow into the channel of the Little Colorado River are the chemical analyses of water sampled at mile 20.9. The quality of this water is different from that of the underflow in the river's channel but similar to that of spring GC–12, which discharges into the river downstream from Blue Spring. (See table 3.)

CHEMICAL QUALITY OF THE SPRING FLOW

Chemical analyses of the spring flow from the pre-Pennsylvanian rocks indicate that the dissolved-solids concentration ranges from 163 to 24,300 ppm (table 3). Chloride is the main contaminant except in water that has a small amount of dissolved material. Chemical analyses of water samples taken near the mouth of the Little Colorado River indicate that the combined flow from Blue Spring and the other springs in the canyon of the Little Colorado River contains between 2,500 and 2,600 ppm of dissolved solids. Most of the available chemical data are for water from the Redwall Limestone, and only a few analyses are available for water from the other stratigraphic units (table 3).

Little is known about the overall distribution of dissolved solids in water in the Tapeats Sandstone. In the canyon of the Little Colorado River the water from spring GC–24 contains 24,300 ppm dissolved solids, 11,000 ppm of which is chloride and 2,470 ppm of which is bicarbonate (table 3). Chemical analyses of water from two springs along the south rim of the Grand Canyon indicate a dissolved-solids concentration of 540 and 667 ppm, 23 and 190 ppm of chloride, 271 and 98 ppm of sulfate, and 0.2 ppm of fluoride for both (Metzger, 1961, table 1). In many places small salt-crystal deposits are associated with seeps and small springs or with potholes carved in the Tapeats Sandstone. Analyses of the salt crystals (Sturdevant, 1926, p. 4) show them to be nearly pure sodium chloride; similar deposits have been mined for centuries by the Hopi Indians near the mouth of the Little Colorado River. Salt samples collected by Eiseman (1959, p. 30) at the main Hopi "mine" were combined, and the mixture was analyzed by the St. Louis Testing Laboratories in August 1958. The analysis shows the following:

	Percent
Moisture and water of hydration	2.37
Sodium chloride (NaCl)	64.20
Sodium sulfate (Na_2SO_4)	18.04
Iron oxide (Fe_2O_3)	1.43
Calcium oxide (CaO)	.70
Silica (SiO_2)	8.66
Acid insoluble	.98
Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	3.14

TABLE 3.—*Selected chemical analyses of spring flow in Marble Canyon, canyon of the Little Colorado River, and eastern Grand Canyon*

[Analysis by U.S. Geological Survey. Results in parts per million except as indicated. Dissolved solids: Dissolved-solids values represent sum of determined constituents in solution]

Sampling point	Date of collection	Temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	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	Remarks
Tapeats Sandstone																							
Monument Spring ----	10-16-57	69	10	80	47		99	289	0	98	190	0.2	1.0	----	667	0.91	393	156	----	----	1,190	----	Metzger (1961, table 1).
Bright Angel Shale																							
GC-48 ------	6-15-60	----	----	111	85	1,800	0	317	0	558	2,320	----	----	----	5,000	6.80	627	367	85	31	7,900	----	
24 ------	1-29-66	74	----	646	291	8,190		2,470	0	2,950	11,000	1.5	----	----	24,300	----	2,810	787	----	----	33,800	6.5	Although spring is in outcrop of Bright Angel Shale, water probably is from Tapeats Sandstone and (or) rocks of Precambrian age; dissolved-solids concentration does not include silica.
Muav Limestone																							
Indian Garden Springs (all springs) ----	4-9-58	53	12.0	54	35		11	308	0	28	14	0.2	0.2	----	305	0.41	278	26	----	----	543	----	Metzger (1961, table 1).
Redwall Limestone																							
Vaseys Paradise Spring ----	6-20-65	----	----	40	15	1.4	0.8	195	0	4	1.5	0.2	0.4	----	163	0.22	162	2	2	0.1	308	7.4	
Blue Spring --	6-14-50	69	19	264	79	513	23	964	--	147	815	.2	3.2	0.1	2,340	3.18	984	194	----	----	3,940	6.5	
Blue Spring --	5-17-66	69	17	252	76	535		951	0	140	835	.3	----	----	2,320	----	940	161	----	----	3,960	6.8	
GC-10 ------	1966	----	17	214	73	623		936	0	135	910	.1	----	----	2,430	----	835	----	----	----	------	7.0	
11 ------	1966	----	16	238	67	785		840	0	175	1,210	.2	----	----	2,900	----	870	182	----	----	------	6.9	
12 ------	6-20-51	71	13	215	76	1,200		634	0	243	1,910	.2	1.0	----	3,970	5.40	849	330	76	----	6,840	----	Two springs at this locality, but sample probably from this spring.

Unidentified spring flow in channel of Little Colorado River

[Sampling point given in miles upstream from mouth of Little Colorado River]

20.9, right bank	Summer, 1963	----	14	163	74		1,100		492	0	238	1,740	0.3	0.2	----	3,570	4.86	710	307	77	18	6,130	7.4	Collected by Harvey Butchart.
14.7, right bank	do	----	14	215	71		1,070		674	0	226	1,680	.5	.9	----	3,610	4.91	830	278	74	16	6,140	7.0	Flow probably from spring GC -1; collected by Harvey Butchart.
14.3, right bank	do	----	7.4	209	73		1,110		655	0	230	1,740	.5	.1	----	3,690	5.02	820	283	75	17	6,290	7.1	Flow probably from springs GC -2, 3, 4, and 5; collected by Harvey Butchart.
13.1	10 -21 -50	----	16	221	80	1,000		32	698	--	233	1,580	.4	1.9	----	3,510	----	880	308	----	----	6,000	----	Flow of 5 ft³/s estimated from springs GC -1, 2, 3, 4, and 5; sample taken in channel of Little Colorado River 0.1 mi upstream from Blue Spring.
12.7, right bank	6 -14 -50	69	16	246	79	779		22	840	--	191	1,220	.4	2.0	0.1	2,970	4.04	938	250	----	----	5,020	6.5	Probably spring GC -11; flow of 40 ft³/s estimated.
10.5	6 -14 -50	----	17	252	77	724		27	874	--	221	1,110	.4	2.2	----	2,860	3.89	945	229	----	----	4,730	----	Flow of 196 ft³/s from Blue Spring and springs GC -1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13; sample taken in channel of Little Colorado River.
10.0	6 -21 -51	----	15	167	75		707		622	0	165	1,120	.2	1.1	----	2,560	3.48	725	216	68	----	4,500	----	Sample taken in channel of Little Colorado River.
6.7	5 -15 -53	----	15	104	73		712		428	0	169	1,120	.2	1.3	----	2,400	3.26	560	209	73	----	4,270	----	Calcium carbonate precipitate present.
3.1	1 -29 -66	----	----	124	59		610		457	0	145	960	.4	----	----	------	----	554	180	----	----	3,720	----	Total flow 248 ft³/s from all springs and some intermittent flow of Little Colorado River; sample taken in channel of Little Colorado River.
3.1	3 -15 -67	----	18	114	72		776		478	0	175	1,200	.3	----	----	2,590	----	580	189	----	----	------	7.4	Total flow 223 ft³/s from all springs; sample taken in channel of Little Colorado River.
2.5	5 -15 -53	----	15	96	73		768		404	0	176	1,200	.2	1.6	----	2,530	3.44	540	208	76	----	4,460	----	Calcium carbonate precipitate present; sample taken in channel of Little Colorado River.

Intermittent flow of Little Colorado River

15	1 -29 -66	----	----	54	12		166		145	0	91	235	0.2	----	----	----	184	65	----	----	----	1,220	7.7	Flow 52.2 ft³/s.

Apparently, the water in the Tapeats Sandstone has a wide range in dissolved solids and in individual constituents. The water having a low dissolved-solids concentration may have been recharged recently on or near the area of outcrop in the canyons, and the water precipitating the salt may have moved several miles through the Tapeats Sandstone. Metzger (1961, p. 133) postulated that "the quality of water from these seeps is not as poor as would be suggested by the presence of the salt stalactites and stalagmites, for some of the concentration of this mineral content leading to salt deposition doubtless is due to evaporation of the small quantities of water seeping from the rocks." Most of the salt in the water, however, may have been derived from the overlying Bright Angel Shale. The water of spring GC–48 probably is from the Tapeats Sandstone and contains 2,320 ppm of chloride (table 3).

Chemical analyses of water from several springs that issue from the Muav Limestone and (or) the Redwall Limestone in eastern Grand Canyon indicate that the water is suitable for domestic purposes (Metzger, 1961, table 1; Johnson and Sanderson, 1968, table 2). The dissolved-solids concentration of water from most of these springs is less than 1,000 ppm and in a few places is less than 350 ppm. In Marble Canyon the spring flow from the Muav appears to be similar in chemical quality to that of Vaseys Paradise Spring.

The chemical quality of the water in the Redwall Limestone is related directly to its source and to the distance the water has traveled in the subsurface. The water in Vaseys Paradise Spring, which has long been used by river parties descending the Colorado River, contains only 163 ppm of dissolved minerals (table 3). The spring receives its recharge from the Kaibab Plateau a few miles to the west, and the water has traveled less than 15 miles through the Redwall Limestone. The water from this spring probably is indicative of the chemical quality of the water from all the springs on the west side (right bank) of the Colorado River in Marble Canyon.

In contrast, the water from Blue Spring and from the other springs in the canyon of the Little Colorado River that discharge from the Redwall contains 2,320 to 3,970 ppm of dissolved solids. Most of this water has moved long distances in the subsurface and is derived from the Coconino Sandstone and other units of the C multiple-aquifer system (fig. 3). The amount of sodium and potassium generally is about 1½ to 3 times the amount of calcium and magnesium (table 3). Chloride is the dominant ion in most samples analyzed; in others bicarbonate is dominant. Although differences occur in the amounts of chemical constituents, the relative amounts of the ions are similar. A sample of the intermittent flow of the Little Colorado River at mile 15, which is upstream from the springs, was taken on the same date as a sample of the spring flow and stream discharge at mile 3.1. The chemical analyses show that river water upstream from the springs contains less dissolved solids and more sulfate than the spring flow (table 3).

Blue Spring and spring GC–10 contain the smallest amounts of dissolved solids—2,320 and 2,430 ppm, respectively (table 3)—of any samples that have been analyzed to date (1967) from the canyon of the Little Colorado River. In contrast, spring GC–11, which is a short distance downstream from GC–10, has a dissolved-solids concentration of 2,900 ppm. Springs GC–1 through 5 (mile 14.3–14.7) and GC–12 contain the largest amounts of dissolved solids—from about 3,500 to 4,000 ppm. The amount of fluoride in water of springs along the Little Colorado River ranges from 0.1 to 0.5 ppm; the amount of sulfate ranges from 135 to 243 ppm. A major constituent in the spring flow is bicarbonate, which ranges from 634 to 964 ppm. Part of the bicarbonate is precipitated as travertine (J. D. Hem, written commun., 1951) in the channel of the Little Colorado River, however, and the bicarbonate in the spring-fed flow at miles 2.5 and 3.1 ranges from 400 to 500 ppm (table 3).

Most of the spring flow in the canyon of the Little Colorado River is water that has moved some distance in the Coconino Sandstone, and, therefore, the differences in the chemical quality of the water in this unit probably account for some of the differences in the quality of water of Blue Spring and the other springs. In part of the area between Leupp and the Hopi Buttes, water in the Coconino contains more than 10,000 ppm of dissolved solids; however, in the Coconino Plateau, San Francisco Plateau, and Mogollon Slope areas much of the water contains less than 500 ppm (fig. 3). The differences in the amount of dissolved solids in the water issuing from Blue Spring and the other springs may be the result of mixing of the highly mineralized water moving west-northwestward across the area north of the Little Colorado River with the relatively pure water from the plateaus southwest of the Little Colorado River (fig. 3). The mixed water moves downward from the Coconino Sandstone through the highly fractured rocks in the area between U.S. Highway 89 and Blue Spring, collects in solution channels in the Redwall and Muav Limestones multiple-aquifer system, and discharges at and near Blue Spring. The solution channels terminate at Blue Spring and at the other springs and may extend in different directions from their points of emergence, thus intercepting water of varying chemical quality. If the

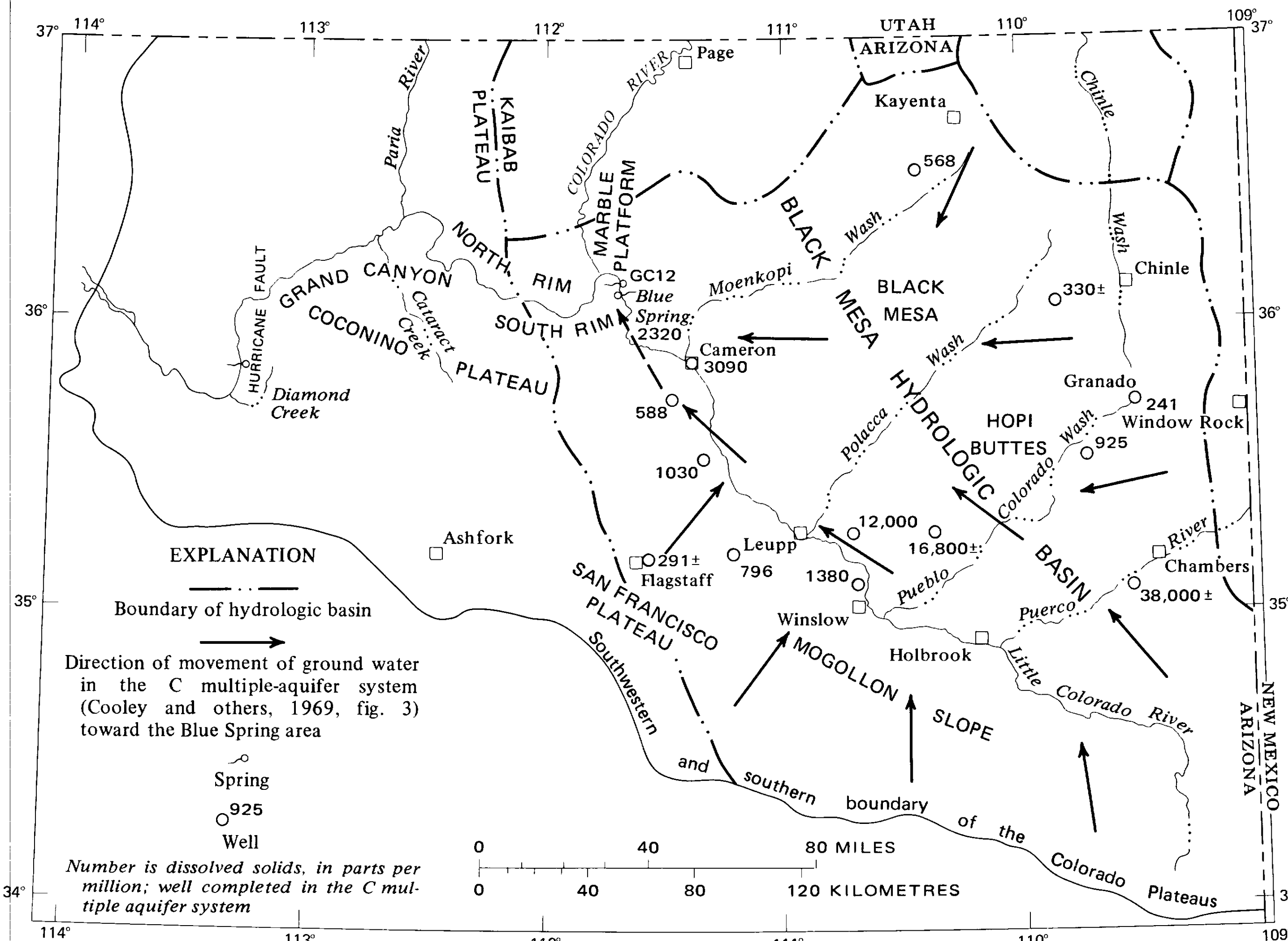

FIGURE 3.—Black Mesa hydrologic basin and other features that influence the ground water in the sedimentary rocks.

chemical quality of the water that issues from the Redwall Limestone in the Blue Spring area is indicative of the quality of water in the Muav Limestone, then the ground water in the Muav in the part of the Navajo Indian Reservation near the Little Colorado River may contain more than 2,000 ppm of dissolved solids.

Chloride is the dominant chemical constituent in the water from the springs. Analyses indicate that the chloride concentration is 835 ppm at Blue Spring, about 1,700 ppm in the small springs a short distance upstream from Blue Spring, and 1,910 ppm at spring GC–12. A progressive decrease in the chloride concentration of the springs occurs from east to west; Blue Spring, the westernmost spring, has the smallest amount of chloride, and springs GC–1, 2, 3, 4, 5, and 12, the easternmost springs, have the highest amounts of chloride. The amount of discharge from most of the springs east of the north-trending Blue Spring fault (pl. 2) is much less than that from the springs west of the fault; therefore, the fault probably exerts a strong local control on the movement of ground water, an interpretation that is also supported by the differences in the amounts of chloride and dissolved solids.

PRECIPITATION OF TRAVERTINE

Between Blue Spring and Big Canyon, at least several tens of feet of travertine has been deposited in the channel of the Little Colorado River by precipitation from spring flow (pl. 2). Pools of water are enclosed by resistant travertine ledges or are ponded by travertine dams across the canyon floor. The ledges form small waterfalls and rapids and at present retard downcutting by the Little Colorado River. In other places, travertine deposits and talus cemented by travertine, which formed during Pleistocene and Holocene time, extend to about 500 feet above the river level in the canyon of the Little Colorado River and in Marble Canyon (pl. 2).

Most of the travertine deposits are between mile 10 and the mouth of Big Canyon (pl. 2). About nine-tenths of the spring flow occurs between miles 10 and 13, and about three-fourths occurs upstream from mile 12.5; however, the bulk of the travertine is being deposited between miles 7.5 and 10. In describing the precipitation of the carbonate that forms the travertine, Hem (written commun., 1951) stated:

* * *From Blue Spring to mile 12.5 the water is clear with little evidence of deposition. The springs in this area all discharge water containing considerable amounts of dissolved carbon dioxide. This CO_2 is gradually lost as the river flows downstream, causing deposition of carbonates at mile 10 and below. The decrease in bicarbonate from 914 ppm at Blue Spring [analysis not given in table 3 of this report] to 622 ppm at mile 10 probably is indicative of deposition of carbonates. Part of the decrease, however, may be the result of inflow of water lower in bicarbonate than that from Blue Spring.* * *

It is unfortunate that the determination of pH, which influences the precipitation of calcium carbonate, is missing from some of the key analyses (table 3), but the differences between a pH of 6.5 to 6.8 at Blue Spring and 7.4 to 7.5 at mile 3.1 support the conclusion that the decrease in bicarbonate is the result of precipitation of the travertine. Some travertine is present at mile 10.5 (pl. 2), but the amount is small when compared to that in the two areas downstream from mile 10. Except when the channel has been flushed recently by floods, encrustations of travertine are present in places on rocks upstream from Blue Spring and downstream from spring GC–1.

DEVELOPMENT OF WATER SUPPLIES

At the present time, the use of Blue Spring and the other nearby springs for water supplies is not feasible because of (1) the poor chemical quality of the water—more than 2,000 ppm of dissolved solids—and (2) the amount of lift that would be required—about 2,000 feet from the channel of the Little Colorado River to the canyon rim. Away from the canyons, little is known about the potential for the development of water supplies from ground water in the deeply buried pre-Pennsylvanian rocks in the southwestern part of the Navajo country.

Ground water in the Redwall and Muav Limestones multiple-aquifer system probably is under artesian pressure in much of the southwestern part of the reservation. On Marble Platform, the multiple-aquifer system is overlain by about 1,500 feet of younger Paleozoic rocks; eastward from Marble Platform, the limestones are overlain by an additional several thousand feet of Mesozoic rocks. Most of the water in the Redwall and the Muav probably fills the solution channels that are distributed throughout the limestones. Although no water wells have been drilled into the limestones in the Navajo Indian Reservation, some water has been reported in a few oil-test wells that penetrate the Redwall in the Black Mesa hydrologic basin. Development of ground-water supplies by drilling wells in the Redwall and Muav Limestones is not feasible at the present time because the limestones are deeply buried and because the water in the limestones probably contains more than 2,000 ppm of dissolved solids.

Similarly, water wells have not been drilled in the Tapeats Sandstone east of the canyons, since there is more than 3,000 feet of overlying strata. In general the unit is tightly cemented and will yield insufficient water for the development of wells. Wells that penetrate crevices along fractures may obtain enough ground water to warrant development, but the water is probably too highly mineralized to be usable for most purposes. Development of a water supply from the discontinuous but generally permeable Temple Butte Limestone is not feasible because of the proximity of the water-bearing Redwall Limestone above and the Muav Limestone below. The Bright Angel Shale acts as an aquiclude and is not considered a suitable source of water because it contains so few water-yielding beds.

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