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RELATIONSHIP OF TECTONIC STRUCTURE
TO AQUIFER MECHANICS
IN THE WESTERN GRAND CANYON DISTRICT
ARIZONA

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April 1977

COMPLETION REPORT, Project B-31-WYO
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To
Office of Water Research and Technology
U.S. Department of the Interior

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ABSTRACT

The Rampart Cave Member of the Muav Limestone is the major aquifer in the western Grand Canyon district based on spring locations in the walls of the Grand Canyon. Permeabilities of the Paleozoic rocks are locally enhanced by faulting. Caves are not associated with springs in the area.

Most of the waters discharging from the carbonate rocks in the district are of the calcium-magnesium-bicarbonate type; total dissolved solids range between 272 and 810 mg/l, temperatures range between 69° and 80°F, and discharges range up to about 7 ft³/sec. Minimum recharge rates in the district are on the order of 0.1 in/yr. Total spring and seep discharge in the area is approximately 20 ft³/sec.

Prospects for developing large ground water supplies in the district are dim because: (1) the total recharge is small, (2) permeabilities are small, and (3) there are no extensive permeable zones under the plateaus in which large quantities of water are in storage. Selected fault zones that supply water to large springs offer the most promising areas for drilling. The drill sites should be located on the downthrown block along the fault and the hole should penetrate to the bottom of the Rampart Cave Member. Minimum drilling depths along promising faults in the area are 1,900 ft. Prospects for ground water development from the Paleozoic rocks on the Shivwits plateau are virtually non-existent because the rocks in the region appear to be essentially dry, even along permeable fault zones.

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OBJECTIVE

This report will define the geologic occurrence of ground water supplies in the western Grand Canyon district and use those criteria to locate potentially productive drilling sites.

STATEMENT OF THE PROBLEM

The western Grand Canyon is extremely arid. No perennial water supplies exist in the area except for the Colorado River and selected springs in the depths of the Grand Canyon. Users who need water on the adjacent plateaus have historically resorted to temporary surface impoundments and water hauling from outside the area. The surface water impoundments characteristically consist of earth dams on ephemeral channels. The water caught by these structures is flood runoff from infrequent heavy storms and has the disadvantages of being unreliable and of poor quality due primarily to large suspended sediment loads. The risk of washed-out dams is great and this, combined with large initial construction costs, has hindered utilization of this type of water supply.

Ground water has been examined as a potential supply by users including individual ranchers, Bureau of Land Management, Bureau of Indian Affairs, Hualapai Indian Tribe, National Park Service, and Forest Service. Their interest culminated in a ground water study by Twenter (1962) in which he selected potential sites for drilling on the Indian Reservation south of the Colorado River. Twenter

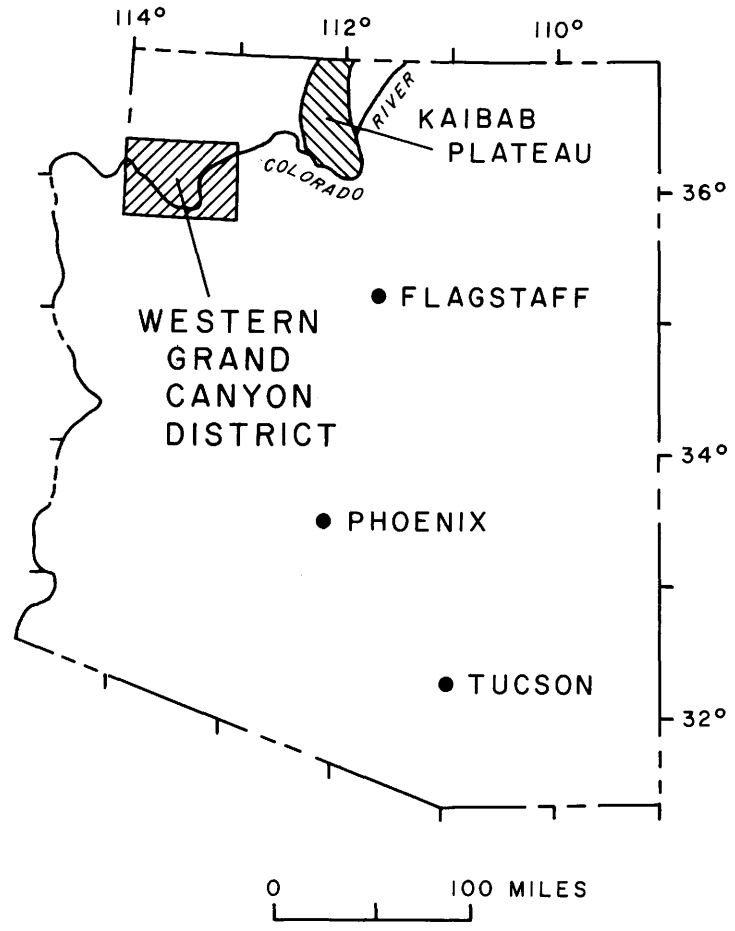


Figure 1. Location of the western Grand Canyon district in Arizona.

recognized that the area was underlain by rocks having small permeabilities and drilling was a high-risk investment. Based on his site selections, the Bureau of Land Management, Bureau of Indian Affairs, and Hualapai Tribe invested in a small number of water wells. Some of these were drilled to depths of 770 ft and all produced negligible quantities or were dry. As will be shown, this lack of success is not entirely due to poor site selection; rather in at least two cases the wells did not penetrate the target aquifers delineated by Twenter.

Because ground water does not occur in uniformly abundant supplies, the prospects for developing ground water in the region are poor. The chances for success can be substantially improved by identifying the regional and local circulation patterns. The circulation system is dominantly controlled by permeability zonation in the gently dipping sedimentary rocks that comprise the plateaus and secondary zones of permeability that are associated with faults.

LOCATION AND GEOGRAPHY

The western Grand Canyon district is located in northwestern Arizona (Figure 1). The study area encompasses approximately 3,000 mi² and includes large tracts of land within the Grand Canyon.

The physiographic setting of the region is that of elevated plateaus that have been dissected by deep canyons. The Colorado River is at an elevation of 1,700 ft in the eastern part of the area and descends to 1,120 ft at Lake Meade in the west. The adjacent plateaus generally lie between 6,000 and 7,000 ft. The land can be characterized as extremely rugged.

Access to the region is poor. The Hualapai plateau (Figure 2, inside back cover) is accessible from a dirt road and a subsidiary net of poor jeep and foot trails, the Aubrey cliffs area is reached via a paved road and secondary dirt roads of poor quality, and the entire area north of the Colorado River is reached only by very poor dirt roads and jeep trails. No roads or trails directly link the areas north and south of the river. Travel in the Grand Canyon is primarily by raft on the Colorado River, boat on Lake Mead, or helicopter. Foot trails in the canyons are scarce and poor.

The primary land use is cattle grazing. Hualapai tribal herds and private herds operated under lease on public lands comprise the bulk of the local economy. A small amount of timber is harvested on the Shivwits plateau and small mines are operated at selected mineral deposits throughout the area. Most of the land use activity is seasonal so there are virtually no permanent residents in the area. Most users prefer to commute from adjacent settlements or establish temporary line camps as needs arise. Because access is poor, tourism in the area is negligible although the canyon scenery is equal to that found in the eastern Grand Canyon.

CLIMATE AND VEGETATION

The climate of the region is arid and largely a function of elevation. Figure 3 shows that annual precipitation in the bottom of the Grand Canyon is less than 8 in/yr, and slightly over 16 in/yr on the high parts of the adjacent Shivwits plateau and Aubrey cliffs area (U.S. Weather Bureau Water Forecasting Unit, undated). The region experiences the four seasons and precipitation occurs

EXPLANATION

- 82 SPRINGS AND SEEPS, NUMBERS CORRESPOND TO TABLE 1
- W6 WELLS, NUMBERS CORRESPOND TO TABLE 3
- f 4 FAVORABLE GROUND WATER TEST DRILLING AREAS, NUMBERS CORRESPOND TO TABLE 4

0 6 MILES
SCALE

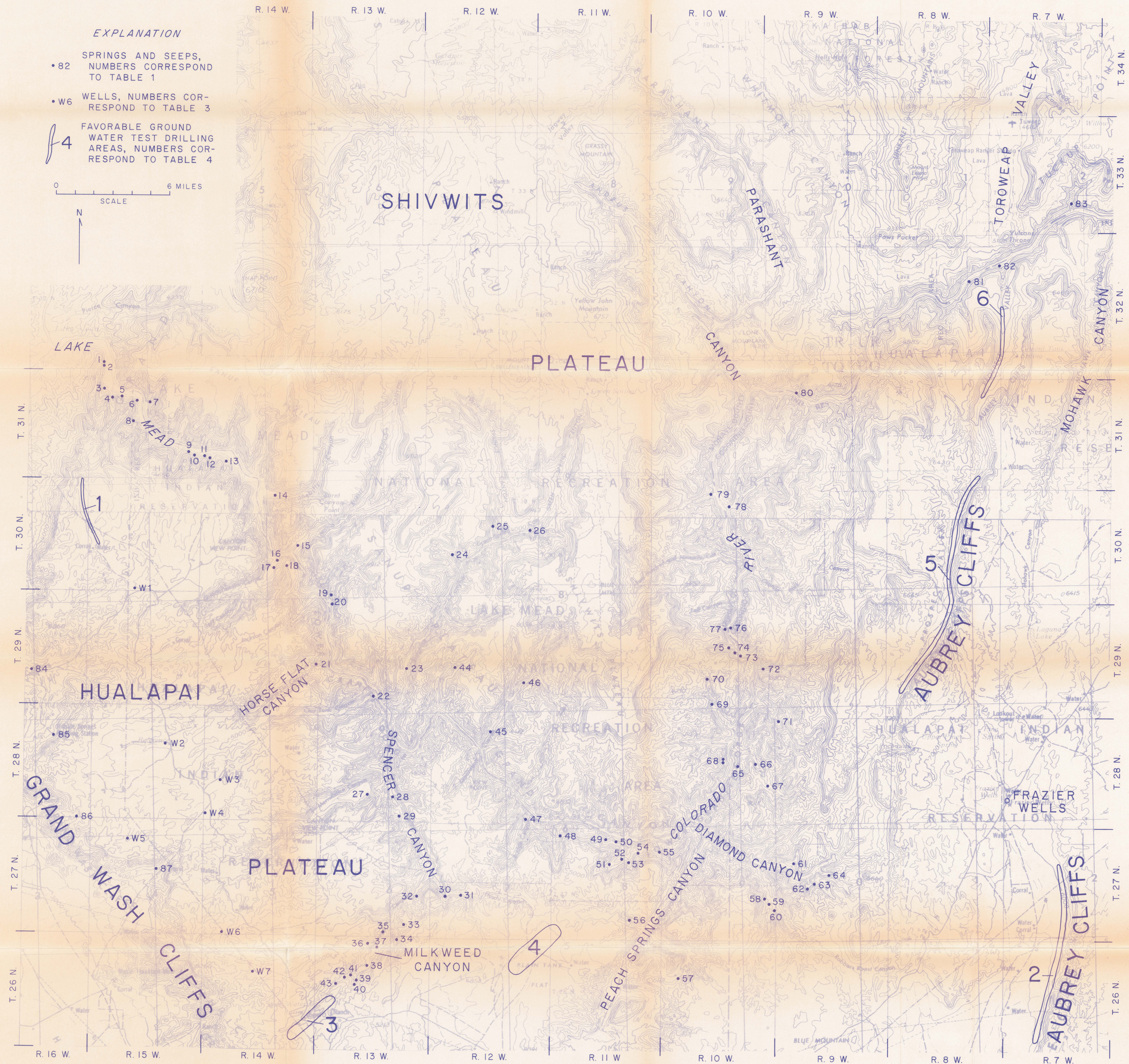


Figure 2. Locations of springs, seeps, wells, and favorable drilling sites, western Grand Canyon district, Arizona.

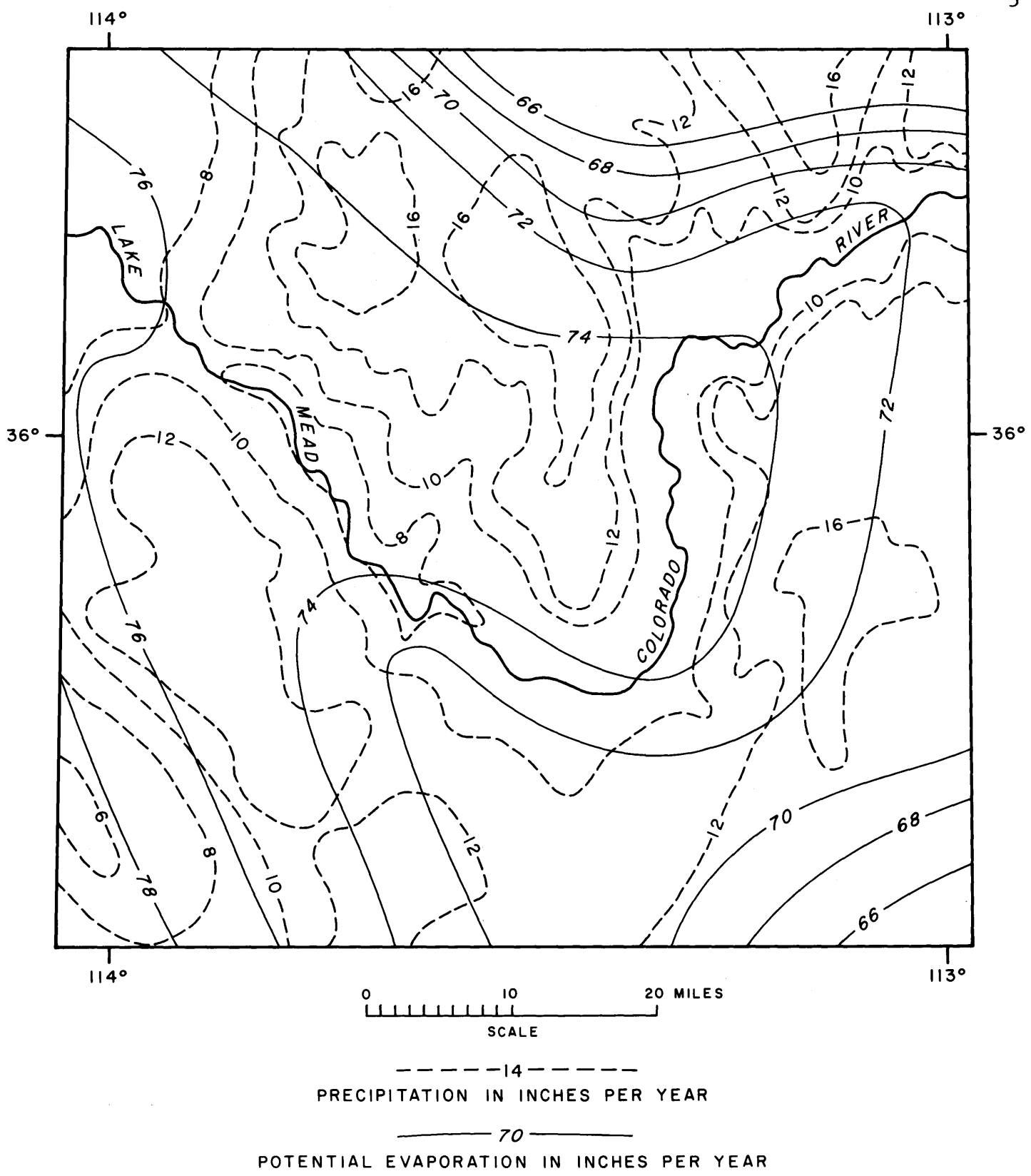


Figure 3. Average rates of precipitation and potential evaporation in the western Grand Canyon district, Arizona.

bimodally as winter cyclonic storms and summer convective showers (Green and Sellers, 1964). Summer rains are generally intense and localized; flash flooding is fairly common. Winter storms are of longer duration, may include light snow, and produce little runoff.

Figure 3 summarizes the evaporation potential for the region (Meyers and Nordenson, 1962) which is everywhere many times greater than the annual average precipitation. Summer convective showers are followed by large evapotranspiration rates as a result of the intense solar heat.

The vegetation in the region is sparse. The slopes in the Grand Canyon contain hearty but distantly spaced desert flora attesting to the extreme aridity at those depths. The plateaus are covered by sparse grasses and desert shrubs at elevations below 5,000 ft. Juniper trees and associated plants dominate the landscape above 5,000 ft. These grade into stunted pines above 6,000 ft. Throughout the area springs and seeps transform the desert environs into jungles dominated by cottonwood or other trees and lush undergrowth. Such places are readily identifiable on aerial photography due to the vegetal anomaly.

GEOLOGY

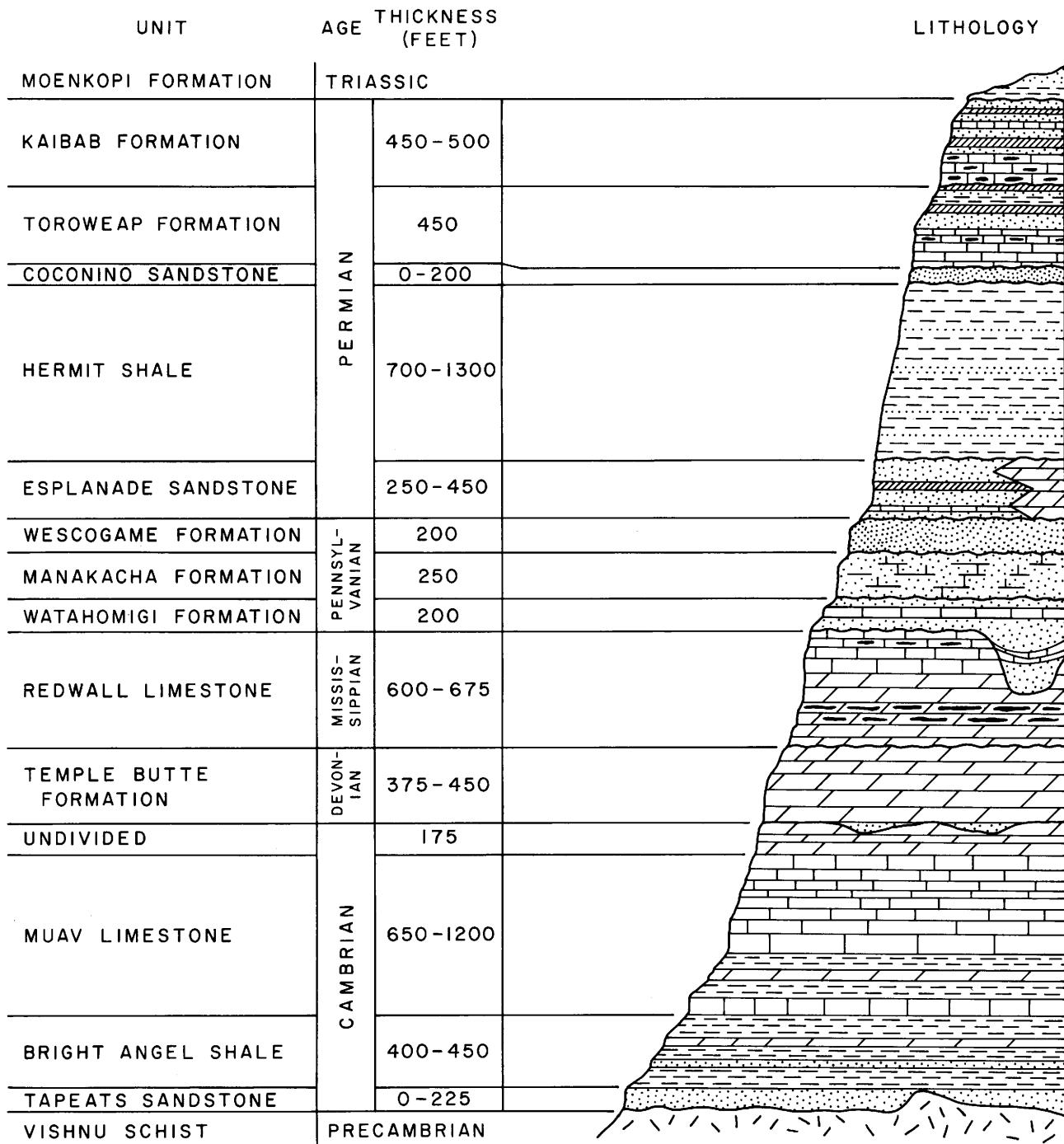
The Paleozoic rocks that comprise most of the walls of the western Grand Canyon are the focus of this study. The Paleozoic section ranges in thickness from 4,000 ft in the eastern part of the study area to over 5,000 ft in the west. Throughout the region these rocks are characterized by very gentle dips. They are capped

by a thin veneer of volcanic rocks on the Shivwits plateau, and scattered deposits of volcanic and Tertiary sedimentary rocks on the Hualapai plateau. For the most part the rocks are exceptionally well exposed. The structural fabric of the region is dominated by generally north-trending normal faults and monoclines. Maximum displacements across these structures are less than 3,000 ft, with most displacements substantially less than 500 ft.

The Paleozoic section is summarized on Figure 4. For descriptive purposes these rocks can be divided into two groups: (1) an upper group of mixed clastic and marine sediments inclusive of the Kaibab Formation and Supai Group, and (2) a lower group of dominantly carbonate rocks. The plateaus north of the Grand Canyon and east of the Hurricane fault are largely underlain by upper group rocks. The Hualapai plateau is developed on the lower group. The inner gorge of the Grand Canyon in the western part of the study area has eroded through the entire sequence of Paleozoic rocks and exposes a Precambrian basement comprised of metasedimentary rocks. The Precambrian rocks are essentially impermeable and dry, and consequently have no importance to this study.

Cambrian Rocks

The Cambrian rocks, especially the Bright Angel Shale and Muav Limestone, are the most important rocks in terms of ground water. This results because the Bright Angel Shale acts as a laterally pervasive aquitard, thus perching water in the overlying Muav Limestone. Unfortunately the stratigraphic relationships are not simple. Nobel (1914, 1922) named the three Cambrian units in the eastern Grand Canyon, but McKee and Resser (1945) worked out



EXPLANATION

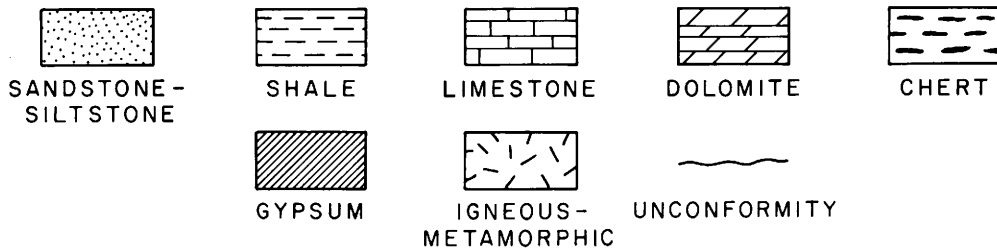


Figure 4. Paleozoic rocks in the western Grand Canyon district, Arizona. The Muav Limestone-Bright Angel Shale contact on this diagram is arbitrarily chosen at the base of the Rampart Cave Member of the Muav Limestone (see Figure 5).

in detail the intricate stratigraphic relationships in the Cambrian system and extended the nomenclature westward in the area under consideration. As Figure 5 shows, McKee and Resser used a complicated system of nomenclature to describe the relationships they observed. The principal lithologies were given the formation labels Tapeats, Bright Angel, and Muav, respectively, for the basal sandstone, overlying shales, and upper carbonates. Because these rocks transgress time toward the east, the formational names apply to rocks that become progressively younger toward the east.

Although the Bright Angel Shale interfingers eastward with the Tapeats Sandstone, individual tongues are not laterally extensive or thick. Consequently the Tapeats Sandstone offers little problem in the field; it rests unconformably on the underlying Precambrian rocks and is expressed topographically as a red-brown cliff at the base of the Paleozoic sedimentary pile.

The overlying Bright Angel Shale and Muav Limestone present quite another complexity. McKee and Resser (1945, Fig. 1) defined selected members within the Muav Limestone and Bright Angel Shale that were time stratigraphic units (see Figure 5). Characteristically a member thins and grades eastward from a limestone to a transitional red-brown dolomite and finally into a shale. McKee and Resser designated the limestone facies as the Muav Limestone, the transitional red-brown dolomites as tongues of the Muav Limestone, and the shale facies as Bright Angel Shale. The field problem associated with this nomenclature arises because the limestone and dolomite facies of some members extend many tens of miles eastward into the Bright Angel Shale. The result is a stacked sedimentary

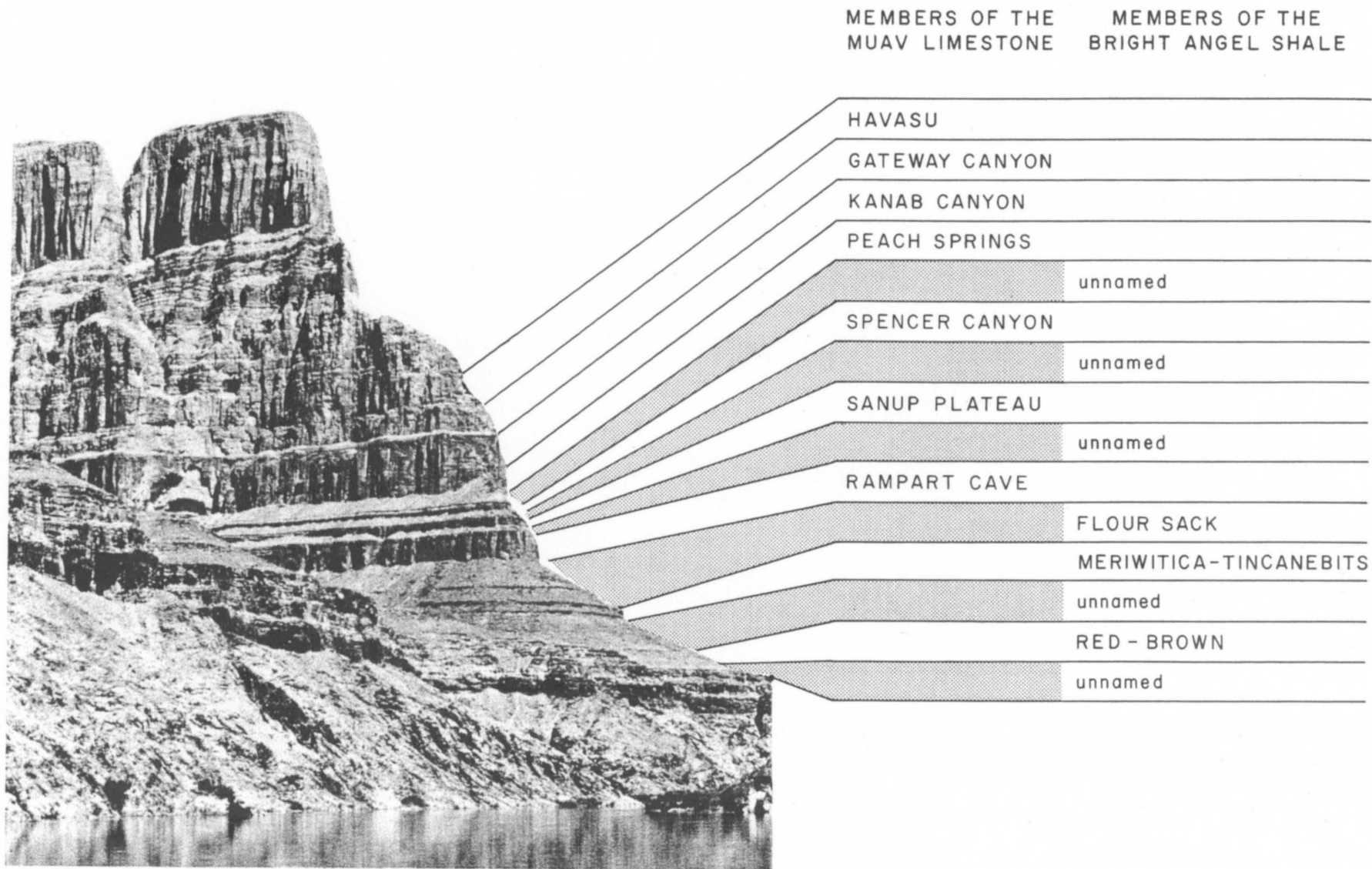


Figure 5. Cambrian stratigraphy in the western Grand Canyon district, Arizona. Shaded units are shale members. Nomenclature and spelling of Meriwitica from McKee and Resser (1945).

sequence that alternates vertically between the Bright Angel Shale and Muav Limestone when McKee's formational nomenclature is applied (Figure 5).

From a ground water perspective, the Tapeats Sandstone is usually well indurated and has small permeabilities. Locally the Tapeats Sandstone is an orthoquartzite with nothing but fracture permeability. More importantly, the entire unit is hydraulically sealed from overlying carbonates by thick sequences of Bright Angel Shale. Although selected seeps and springs are associated with the Tapeats Sandstone in the study area, they usually have discharges on the order of gallons per minute to gallons per day. Larger springs in the Tapeats Sandstone are generally associated with faults or folds that have rendered the unit more permeable and which have also allowed a small degree of hydraulic interconnection through the Bright Angel Shale with the overlying carbonates.

The Bright Angel Shale can be characterized as a regional aquitard, whereas the Muav Limestone has sufficient permeability that numerous small springs discharge from its lowermost members. Huntoon (1974a, p. 581) pointed out that the Bright Angel Shale usually acts as a barrier to circulation in faulted areas because the shales are pulverized into an impermeable gouge that effectively seals the fractures. In the western Grand Canyon, parts of the Bright Angel Shale are known to possess at least small permeabilities. Evidence for this is the fact that most of the small quantities of ground water that discharge into the western Grand Canyon issue from small springs in the Rampart Cave Member (Figure 5). The Rampart Cave Member is the basal limestone in the Paleozoic section throughout the western Grand Canyon district but it is separated from thick

overlying sequences of carbonate rocks by intervening tongues of Bright Angel Shale that occur respectively below the Peach Springs, Spencer Canyon, and Sanup Plateau members of the Muav Limestone (Figure 5). Some of these shale tongues are as much as 100 ft thick.

Large permeabilities in the Muav Limestone are related to faults and to a lesser degree to fracturing along folds. Several large springs associated with the Muav Limestone lie on or in close proximity to fault zones. Small permeabilities exist in the unit in tectonically undeformed regions as demonstrated by many small springs and seeps that discharge along the canyon walls. Most of these smaller springs occur in the Rampart Cave Member. Joints and partings along bedding planes account for much of this circulation, but intercrystalline permeability may exist within parts of the Rampart Cave Member. Seep zones that wet large surface areas of outcrops illustrate that flow through the rocks is distributed rather than channeled along specific fractures. Karstification has not occurred to any significant degree in the Muav Limestone in the western Grand Canyon. A few dry caves are known and some cavities have been encountered in drill holes on the Hualapai plateau; however, caves are noticeably absent in the vicinity of springs in the canyons.

Devonian and Mississippian Rocks

Overlying the Muav Limestone are thick, laterally extensive sequences of Devonian and Mississippian strata named, respectively, the Temple Butte Limestone and Redwall Limestone (Figure 4). These carbonates combined with the upper members of the Muav Limestone

to form towering stepped cliffs as high as 2,000 ft throughout the western Grand Canyon. The stratigraphy of these units is detailed in Gilbert (1875), Darton (1910), Noble (1922), Beus (1973), McKee and Gutschick (1969), and McKee (1969). Thin- to thick-bedded finely crystalline dolomites dominate the composition of the Temple Butte Formation; and thin- to thick-bedded dolomite, limestone, and chert comprise the Redwall Limestone. Unconformities between and within the units separate individual members. The upper surface of the Redwall Limestone has developed on it a Pennsylvanian paleokarst and system of paleochannels that were eroded as much as two thirds (400 ft) of the way through the unit (Billingsley, 1976).

The hydrologic properties of these thick carbonates are virtually identical to those of the Muav Limestone. Faults and fractures associated with folds render the units permeable in both the horizontal and vertical directions. The permeabilities in unfaulted areas are dependent upon joints and partings along bedding planes. Little intercrystalline permeability exists. Springs are rare in these units, indicating that they are essentially dry or that water moves vertically through them to underlying members of the Muav Limestone.

The lack of springs or seeps from the paleokarst on the top of the Redwall Limestone demonstrates that it is hydraulically inactive. This situation is best explained by the filling of the ancient solution channels with cemented breccias and fine-grained and clay-size sediments which have extremely small permeabilities. Aside from locally reexcavated paleokarst features, caves are virtually missing from the extensive outcrops of the Mississippian and Devonian rocks in the western Grand Canyon.

Pennsylvanian and Permian Rocks

Overlying the lower group of carbonates is a sequence of Pennsylvanian and Permian dominantly clastic rocks that thicken from 2,600 ft in the eastern part of the study area to over 3,300 ft in the west. These rocks underlie the Shivwits plateau and Aubrey cliffs areas. Stratigraphic units defined from this sequence include, in ascending order, the Watahomigi Formation, Manakacha Formation, Wescogame Formation, Esplanade Sandstone (McKee, 1975), Hermit Shale (Noble, 1922), Coconino Sandstone (McKee, 1933), Toroweap Formation and Kaibab Formation (McKee, 1938).

Shales within the Pennsylvanian and Permian rocks generally act as aquitards, resulting in seeps and small springs that discharge from these units. The Coconino Sandstone is a locally productive aquifer east of the study area (McGavock, 1968); however, it is not known to contain large amounts of ground water in the western Grand Canyon district aside from small, local production immediately west of the Aubrey cliffs. This situation results because the rocks are well drained and recharge is extremely small. Both the Toroweap and Kaibab formations contain gypsum which will be shown to influence ground water quality at springs that drain areas underlain by these units.

In a style much like the older carbonates, the Pennsylvanian and Permian rocks depend on secondary fracturing for enhancement of otherwise very small regional permeabilities. Fracture zones form vertical channels that allow for downward movement of ground water in areas underlain by these rocks. Evidence supporting the dependence of fracture permeability in the vertical flow of ground

water is found in the Hermit, Esplanade, Wescogame, Manakacha, and Watahomigi formations where the red beds adjacent to selected fractures are bleached white and voids are partially or totally filled with crystals of calcite precipitated from circulating water (Huntoon, 1974a).

Mesozoic and Cenozoic Rocks

The Moenkopi Formation has been recognized under parts of the Shivwits plateau and area east of the Aubrey cliffs (Koons, 1964; Lucchitta, 1975), and is the basal Triassic unit in the region. It is comprised primarily of mudstones, siltstones, and shales. The unit can yield small quantities of water to wells but acts regionally as an aquitard (U.S. Geological Survey, undated).

Basaltic volcanism has been extensive over large areas of the plateaus north of the Colorado River in the project area. The Shivwits plateau is capped with basalt flows and the area near Toroweap Valley (Figure 2) is covered by basalt flows and cinder cones (Hamblin, 1974; Lucchitta, 1975). Similar rocks and locally occurring andesitic volcanics are found on the Hualapai plateau in association with locally thick coarse clastic deposits (Koons, 1945 and 1948; Blissenback, 1952; Gray, 1959; Young, 1966). These younger rocks fill many valleys in the area and otherwise bury a topographic surface that was developing on the Mesozoic and Permian rocks prior to the eruptions.

In the region south of the Colorado River the Tertiary volcanic rocks are laterally discontinuous and interbedded clastic rocks have substantially greater permeabilities than the Paleozoic rocks that underlie them. The areally extensive basaltic flows preserved

on the surface of the Shivwits plateau appear to be permeable on the basis of close joint spacings; however, during the course of this study I observed extensive sheets of standing water over the southern part of the plateau following a rapid spring snowmelt. The water was definitely not infiltrating; rather it was discharging in small quantities through surface channels and mostly evaporating. It appears that the lava flows are effective aquitards. In contrast, the cinder cone areas near Toroweap valley are highly permeable and water rarely flows on the surface.

Structural Geology

One of the keys to successful ground water prospecting in the plateau country is a detailed delineation of the tectonic structures that deform the rocks, a fact recognized by Metzger (1961), Twenter (1962), Cooley and others (1969), and Huntoon (1974a) in areas contiguous to the western Grand Canyon district. The basis for this statement is the fact that secondary fracturing enhances the permeabilities of the rocks, as well as providing a mappable target for drilling.

Figure 6 (inside back cover) summarizes the structural geology of the western Grand Canyon district. The regional dip is gentle toward the northeast, and north-trending faults and folds dominate the tectonic fabric. The major structures, from west to east, are the Grand Wash fault zone, Meriwhitica monocline and fault, Dellenbaugh fault, Hurricane fault zone, and Toroweap-Aubrey fault zone. The terranes that lie between the Grand Wash, Meriwhitica, and Hurricane zones are largely undeformed.

The Grand Wash fault bounds the western Grand Canyon district and results in displacement of the Paleozoic section over 5,000 ft down on the west where it is buried by Cenozoic rocks. Although the Grand Wash fault is not of particular interest to this project, the subsidiary Rampart fault, which extends 15 miles from the northwest into the Hualapai plateau, serves as a hydraulic drain in the area. Displacement along the Rampart fault reaches a maximum of 600 ft, east side down.

The sinuous Meriwhitica monocline and fault, respectively north and south of the Colorado River, trend through otherwise undisturbed rocks. Stratigraphic offset across the monocline is as great as 1,000 ft, east side down, whereas the displacement across the fault north of the river is approximately 200 ft, west down. The subsidiary north-trending Horse Flat monocline results in less than 250 ft of displacement east down, but it and related small faults shatter the Mississippian and older carbonate rocks locally.

The Dellenbaugh fault trends into the district from the north and underlies the most recent volcanic rocks in the Shivwits field. Displacements along the fault are approximately 600 ft, west side down, and the trace terminates near the head of Surprise canyon.

The Hurricane, Toroweap, and Aubrey faults and hundreds of associated high-angle normal faults create a major structural zone coincident with the northward trend of the Colorado River which has been treated by Davis (1903), Dutton (1882), Gardner (1941), Hamblin (1970), Huntington and Goldthwait (1903), Koons (1945, 1964), Lucchitta (1975), Young (1970), and Huntoon (in press). The western

blocks are displaced down along the Hurricane, Toroweap, and Aubrey faults, maximum displacements along the respective faults being 2,800, 900, and 400 ft in the area. The numerous closely spaced subsidiary faults, especially those between the Hurricane fault and Shivwits plateau, complicate the region. Because displacements along individual faults tend to attenuate upward in the Paleozoic section (Huntoon, 1974b), the subsidiary faults are particularly well exposed and appear to be more numerous in the canyons than on the surfaces of adjacent plateaus. Springs are associated with specific faults in this complex zone, attesting to the hydraulic importance of their permeability.

SPRINGS

Springs in the Grand Canyon and along the Grand Wash cliffs offer solid evidence that most of the ground water in the region is concentrated in the Muav Limestone. The yields from the springs illustrates the aridity of the area and provide evidence for the very small total supply of ground water available.

The project area includes over 3,000 mi², an area which is but a fraction of the total land surface that can potentially yield ground water to springs in the western Grand Canyon and Grand Wash cliffs. Yet the total observed ground water discharge from the Mississippian and older rocks in the area is on the order of 20 ft³/sec.

Table 1 and Figure 2 list and show the locations of 87 springs and seeps that were located in Mississippian or older rocks in the Grand Canyon and along the Grand Wash cliffs during the course

of this study. A few of these springs were examined by Twenter (1962), Johnson and Sanderson (1968), and U.S. Geological Survey (undated). Many of the seeps yield no water to the surface; rather they can be identified from abnormally dense clusters of vegetation. The largest single spring (82 on Table 1) yields on the order of $7 \text{ ft}^3/\text{sec}$ from a fault zone in the Muav Limestone. All but two of the remaining springs discharge considerably less than $1 \text{ ft}^3/\text{sec}$. No springs were discovered that discharged more than a very few gallons per minute from the Pennsylvanian or younger Paleozoic rocks in the region. Consequently no attempt was made to locate or gage them.

The springs and seeps in Table 1 fall into two general categories: stratigraphic and structural drains, and rises in alluvium associated with bedrock highs under stream channels. In all cases, however, the ultimate source of water is the lower Paleozoic section. Springs that rise from the alluvial floors of canyons represent accumulated spring and seep discharge in the channel that has circulated downstream as underflow.

Rises from Alluvium

Springs 15, 19, 21, 22, 23, 28, 45, 47, and 66 on Table 1 rise from the alluvium on the canyon floors. In all cases the springs occur where the stream channel enters the resistant Tapeats Sandstone or Precambrian Vishnu Schist, locations that are characterized by abruptly increased channel slopes in the downstream direction and a corresponding thinning of the alluvial cover.

Five rises (springs 15, 19, 21, 22, and 47) occur in canyons that contain no upstream springs or seeps. Their waters are derived

Table 1. Springs and seeps associated with the pre-Pennsylvanian rocks in the western Grand Canyon district, Arizona

Number ^a	Name ^b	Direction from Colorado River ^c	Elevation ^d	Stratigraphic Position ^e	Structural Control	Discharge ^f (gal/min)	Date observed ^g
1		S	1600	base Gm_{rc}		2E	Jan. 8, 1972
2		S	1600	base Gm_{rc}		seep	June 5, 1976
3		S	1400	Qa1 (Gm_{rc})	fault	seep	
4	Columbine	S	1450	Gm_{rc}	fault nearby	153	June 5, 1976
5	Weeping	S	1400	base Gm_{rc}		10E	June 5, 1976
6		S	1400	base Gm_{rc}		seep	June 5, 1976
7		N	1320	base Gm_{rc}		3E	
8		S	1480	Gm_{rc}		seep	October 1971
9		S	1450	base Gm_{rc}		seep	
10		S	1400	Qa1 (Gm_{rc})		seep	
11		S	1500	base Gm_{rc}		seep	
12		S	1600	base Gm_{rc}		seep	
13		S	1600	base Gm_{rc}		seep	
14		N	1460	6ba (Gm_{rc} ?)		seep	
15		N	1350	Qa1	fault nearby	seep	
16	Quartermaster	S	1300	Qt (base Gm_{rc})		660	June 5, 1976
17		S	1600	Qt (base Gm_{rc})		15E	Nov. 23, 1969
18		S	2000	base Gm_{rc}		seep	Nov. 23, 1969
19		N	1240	6t		seep	Mar. 22, 1973
20		N	1240	6t		3E	Mar. 22, 1973
21		S	1540	Qa1		25E	Mar. 21, 1973
22		S	1380	Qa1		20E	
23	Surprise	N	1510	Qa1		202	June 5, 1976
24		N	2880	base Mr_{mf}	syncline	3E	Oct. 31, 1976
25		N	2880	Mr_{mf}	fault	5E	Oct. 17, 1973
26	Cottonwood	N	3160	Mr_{mf}		30E	Oct. 17, 1973
27	Meriwhitica	S	2650	Qt (Gm_{rc})		92	June 7, 1976
28	Spencer	S	1830	Qa1		296	June 6, 1976
29		S	2320	Qt (Gm_{rc})		15E	June 7, 1976
30		S	2960	base Gm_{rc}		seep	June 7, 1976
31		S	2800	Qt (base Gm_{rc})	near fault	5E	June 7, 1976
32		S	2920	6t	fault	seep	June 7, 1976
33		S	3560	top 6t		seep	Apr. 15, 1977
34		S	3550	base 6t	monocline	seep	Apr. 15, 1977
35		S	3550	6t		seep	Apr. 15, 1977
36		S	3920	Tbd		seep	June 7, 1976
37		S	3700	top 6t		3E	Feb. 5, 1974
38		S	3740	Tmm		10E	Feb. 5, 1974
39		S	3950	Tmm		3E	Feb. 6, 1974
40		S	4360	Gm_{rc}	landslide	seep	June 7, 1976
41		S	4080	Tw		5E	June 7, 1976
42		S	4250	Tbd		seep	June 7, 1976
43		S	4420	Tbd		10E	June 7, 1976
44		N	2320	Gm_{kc}		seep	
45		N	1440	Qa1		15E	Jan. 10, 1974
46		N	2280	Gm_{sp}	fault	2E	Jan. 10, 1974
47		S	1460	Qa1		5E	Mar. 6, 1971
48		S	2240	top 6t		10E	Mar. 6, 1971
49		S	2040	base 6t		20E	Sept. 9, 1968
50		S	2040	base 6t		seep	
51		S	2700	base Gm_{rc}		seep	Mar. 18, 1973
52	Travertine	S	2160	Qt (Gm_{rc})		225E	Mar. 18, 1973
53		S	2480	Qa1 (6ba)		seep	

Number ^a	Name ^b	Direction from Colorado River ^c	Elevation ^d	Stratigraphic Position ^e	Structural Control	Discharge ^f (gal/min)	Date Observed ^g
54		S	2600	base 6m _{rc}		seep	
55		S	2600	base 6m _{rc}		seep	
56		S	3200	base 6m _{rc}		seep	
57	Metuck	S	4100	base 6m _{ps}		seep	
58		S	3640	base 6m _{rc}		seep	June 7, 1976
59		S	3420	Qal (base 6m _{rc})		seep	June 7, 1976
60		S	3440	6ba		seep	June 7, 1976
61		S	3400	base 6m _{rc}		seep	June 7, 1976
62	Diamond	S	3630	base 6m _{ps}		100E	June 7, 1976
63	"Diamond East"	S	3640	base 6m _{ps}	fault	72	June 7, 1976
64	"Big Diamond"	S	3650	base 6m _{ps}	fault	450E	June 7, 1976
65		S	1720	p6v	fault	seep	Dec. 14, 1975
66		S	2440	Qal		2E	Dec. 13, 1975
67		S	3400	base 6m _{rc}	fault	2E	Dec. 13, 1975
68		N	1960	top 6ba		seep	
69		N	2080	Qal (base 6m _{rc})		seep	
70	Shanley	N	2950	Dtb		seep	
71		S	3320	base 6m _{rc}		seep	
72	"Three Springs"	S	1720	base 6m _{rc}	fault	30E	Nov. 10, 1975
73		N	1880	base 6m _{rc}		seep	Nov. 9, 1975
74		N	1900	base 6m _{rc}		seep	Nov. 9, 1975
75		N	1900	base 6m _{rc}		seep	Nov. 9, 1975
76	Pumpkin	S	1440	6t		2E	June 2, 1976
77		N	1840	base 6m _{rc}	fault	seep	
78	"205 Mile"	S	1500	Qal	fault nearby	15E	June 1, 1976
79	"Spring Canyon"	N	1600	base 6m _{rc}	fault	153	June 1, 1976
80		N	1550	6m _{rc}		10E	Nov. 6, 1975
81		S	1640	6m _{kc}		10E	Apr. 25, 1971
82	Warm	S	1680	6m _{kc}	fault	>3000E	May 31, 1976
83		N	1840	6m _{rc}		seep	July 1974
84		S	4120	Tmc		seep	
85	Hillside	S	5280	6ba		seep	
86	Hells Canyon	S	5350	6m		seep	
87	Clay	S	4550	Qal (6m)		seep	

a. Number corresponds to location on Figure 2.

b. Name corresponds to usage on U.S. Geological Survey 7.5 minute topographic maps; quotes indicate informal name.

c. N - north; S - south.

d. Estimated from U.S. Geological Survey 7.5 minute topographic maps.

e. Symbols:

p6v	Vishnu Schist	Dtb	Temple Butte Formation
6t	Tapeats Sandstone	Mr _{mf}	Redwall Limestone, Mooney Falls Member
6ba	Bright Angel Shale	Tmm	Music Mountain Conglomerate
6m	Muav Limestone	Tw	Westwater Formation
6m _{rc}	Muav Limestone, Rampart Cave Member	Tbd	Buck and Doe Formation
6m _{sp}	Muav Limestone, Sanup Plateau Member	Tmc	Muddy Creek Formation
6m _{ps}	Muav Limestone, Peach Springs Member	Qt	Travertine
6m _{kc}	Muav Limestone, Kanab Canyon Member	Qal	Alluvium

() indicates stratigraphic source of water for springs discharging from younger rocks, if known.

f. E - estimated; seep - wet area or dense cluster of vegetation that indicates presence of water; most seeps are assumed to discharge less than 5 gal/min based on field observations.

g. If no date is specified, seep was observed on aerial photographs.

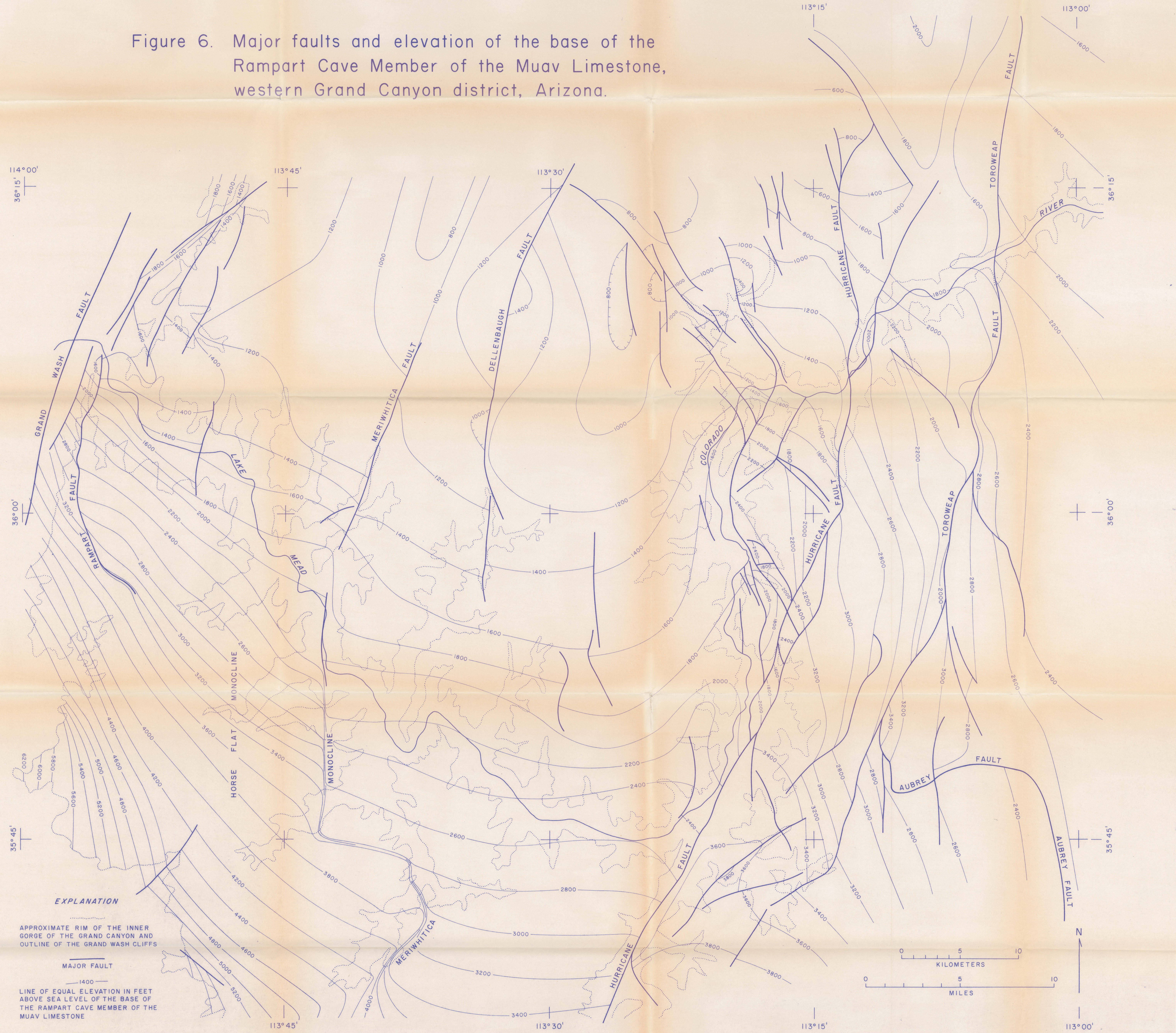
from the Paleozoic section from buried sources under the alluvium on the canyon floors. Other rises, including springs 23, 28, 45, and 66, yield more water than the total observed inflows of upstream springs and seeps in their respective canyons. For example Surprise spring (23), Spencer spring (28), and Diamond creek were gaged in June, 1977, and found to discharge 0.45, 0.66, and 2.81 ft^3/sec as compared to known upstream inflows of 0.1, 0.4, and 1.4 ft^3/sec respectively. Despite large evapotranspiration rates associated with thick vegetation on the floors of their canyons, the known inflows represented only 20 to 60 percent of the downstream discharges. It is apparent that buried sources occur in these canyons also.

Drains

Aside from the rises treated in the previous section, the springs and seeps listed in Table 1 serve as drains for the Paleozoic and younger rocks. The springs on the north side of the Hualapai plateau discharge from down-dip exposures of permeable rocks. In contrast the springs on the south side of the Shivwits and Hualapai plateaus discharge from the up-dip exposures, as do a few of the springs in the area south of the Colorado River and east of Peach Springs canyon. These relationships can be observed by comparing Figures 2 and 6.

Structurally Controlled Drains. Six large springs in the area discharge directly from fault zones or from subsidiary fractures in the immediate vicinity of faults, specifically springs 4, 26, 63, 64, 79, and 82 of Table 1. Columbine spring (4), which

Figure 6. Major faults and elevation of the base of the Rampart Cave Member of the Muav Limestone, western Grand Canyon district, Arizona.



discharges from fractures associated with the Rampart fault in the Rampart Cave Member of the Muav Limestone, is the only fault-controlled spring that drains from the Hualapai plateau.

A small north-trending graben supplies water to Spring Canyon spring (79) which discharges from the Rampart Cave Member on the eastern side of the Shivwits plateau. On the west side of the Shivwits plateau Cottonwood spring (26) drains from a small, north-trending fault zone. The water flows from bedding planes near the top of the Redwall Limestone just west of the fault. The high stratigraphic setting of the spring reflects a favorable hydraulic outlet for the water, which leaves the Paleozoic section at the head of the first deep canyon in the vicinity.

Faults in the Aubrey cliffs area control the locations of Diamond East spring (63), Big Diamond spring (64), and Warm springs (82) which discharge from the Peach Springs Member of the Muav Limestone, the lowest limestone exposed at the respective sites. Warm springs is the largest spring in the district and discharges from the Toroweap fault. It cannot be gaged because the water flows from distributed outlets in travertine directly into the Colorado River. Previous workers (Johnson and Sanderson, 1968) and this study have estimated the discharge at less than $10 \text{ ft}^3/\text{sec}$; however, it is unknown if additional water may discharge subaerially into the river. The source of this water is drainage from the Toroweap-Aubrey fault zone south of the spring. No water is known to discharge from the Toroweap fault north of the Colorado River.

Although Diamond East and Big Diamond springs are located on the same fault, their relationship to the fault appears to be

fortuitous. I believe that the source of water for these springs is the plateau to the south and east, an area that lies structurally up-gradient from the springs. Evidence for this conclusion is presented below.

Several minor springs discharge from faults or fractures associated with folds as indicated on Table 1. Their small yields simply indicate that the collection area for the springs is small.

A close relationship between folds and springs has not been established in the district. The Meriwhitica and Horse Flat monoclines are the principal folds in the area. No springs are known where the Horse Flat monocline is exposed in the Muav Limestone or older rocks in Horse Flat canyon. Springs 32 through 43 lie just west of the Meriwhitica monocline in Spencer canyon, but they are on the upthrown block and no genetic relationship exists between their locations and the monocline. Rather these springs represent favorable stratigraphic outlets in the deep canyon. Meriwhitica spring (27) and spring 29 are located within three miles of the monocline on the downthrown block but no specific relationship between their locations and the monocline can be established. It is possible but speculative that fracturing associated with the fold accounts for their yields.

Stratigraphically Controlled Drains. Most of the small springs and seeps in the district discharge from the Rampart Cave Member of the Muav Limestone which establishes the Rampart Cave Member as the principal aquifer in the region. Smaller numbers of springs discharge from the underlying Bright Angel Shale and Tapeats Sandstone. Because the permeabilities are dependent solely on joints,

partings along bedding planes, and possible intercrystalline or intergranular porosity, yields are generally small.

Quartermaster spring (16), Meriwhitica spring (27), and Travertine spring (52) are the largest springs in the district that have no known structural control. In each case the water is derived from the Rampart Cave Member although the water in Quartermaster and Travertine springs discharges from the base of massive travertine deposits respectively 700 and 500 ft below the Rampart Cave Member. The large travertine desoposits associated with these springs demonstrates their long geologic presence and suggests that the springs result from solutional enhancement of permeabilities in the Rampart Cave Member. No caves, however, are associated with any of these springs.

A group of springs (36, 41, 42, 43, and possibly 38) located in the head of Milkweed canyon discharge directly from interbedded conglomerates and volcanic rocks of Tertiary age. These young rocks fill parts of Milkweed canyon and are very permeable. The discharge from these springs represents water that has largely recharged directly into the Tertiary fills and circulated north-eastward to down-gradient outlets in Milkweed canyon.

WATER QUALITY

Eleven springs in the district were sampled for water quality. The laboratory analyses are presented in Table 2 and the waters are classified using the trilinear diagram (Piper, 1944) on Figure 7. The sampled springs were selected to include a diversity of geographic sources for the water, a number of different stratigraphic

Table 2. Chemical quality of water from selected springs in the western Grand Canyon, Arizona^a

Number ^b	Name	Date of Collection	Discharge ^c (ft ³ /sec)	Temp. (°F)	Ca	Mg	Na	K	CO ₃	HCO ₃	SO ₄	Cl	NO ₃
4	Columbine	June 5, 1976	0.34	78	48	37	18	2.3	0.0	290	16	28	18
16	Quartermaster	June 5, 1976	1.47	75	66	47	17	2.3	0.0	410	11	22	11
23	Surprise	June 5, 1976	0.45	69	120	41	19	4.4	0.0	370	150	32	0.0
27	Meriwhitica	June 7, 1976	0.21	75	61	35	15	1.9	0.0	340	9.1	19	15
28	Spencer	June 6, 1976	0.66	72	58	55	22	2.8	0.0	420	21	30	8.3
63	Diamond East	June 7, 1976	0.16	72	44	25	15	1.6	0.0	230	8.2	22	15
64	Big Diamond	June 7, 1976	1E	74	45	25	15	2.1	0.0	230	9.1	24	15
76	Pumpkin	June 2, 1976	0.005E	86	220	71	3200	120	0.0	2200	330	4100	0.0
78	205 Mile	June 1, 1976	0.033E	71	110	37	99	4.0	0.0	250	280	120	0.9
79	Spring Canyon	June 1, 1976	0.34	80.5	85	39	15	2.8	0.0	230	190	17	2.9
82	Warm	May 31, 1976	>7E	78	120	60	83	7.2	0.0	700	27	87	2.5

Number ^b	Name	F	B	SiO ₂	Total Dissolved Solids	Hardness (CaCO ₃)	Total CO ₃	Total Alkalinity	pH ^d	Conductance	Sodium (%)
4	Columbine	0.2	0.09	14	334	270	140	240	8.0	566	12
16	Quartermaster	0.2	0.09	14	406	360	200	340	7.8	702	9
23	Surprise	0.4	0.06	21	594	450	180	310	7.7	882	8
27	Meriwhitica	0.2	0.07	17	356	300	160	280	7.9	590	10
28	Spencer	0.3	0.10	21	420	370	210	350	7.9	767	11
63	Diamond East	0.2	0.07	18	272	210	110	190	8.3	450	13
64	Big Diamond	0.2	0.06	18	272	220	110	190	8.3	453	13
76	Pumpkin	3.8	16	140	8940	840	1100	1800	7.3	12800	88
78	205 Mile	0.4	0.21	13	810	420	120	210	7.7	1270	34
79	Spring Canyon	0.4	0.06	17	498	370	110	190	8.0	725	8
82	Warm	0.2	0.82	17	742	530	340	580	7.5	1280	25

a. All analyses are in milligrams per liter; analyses performed by Wyoming Department of Agriculture, Division of Laboratories, Laramie, Wyoming.

b. Numbers correspond to Figure 2 and Table 1.

c. E - estimated.

d. pH determined in the laboratory.

and structural settings of springs, and most of the major springs in the area. Other water quality samples have been collected from sources in the area by Twenter (1962) and Johnson and Sanderson (1968). Figure 7 illustrates that most of the springs discharge calcium-magnesium-biocarbonate waters. The remaining are enriched in chloride and/or sodium.

With the exception of Pumpkin spring (76), which yields brackish water, the springs in the district discharge fresh water. Pumpkin spring was selected for analysis only because it obviously represents an extreme in terms of poor quality in the region. The source of the water is a fault-controlled spring that discharges about 2 gallons per minute from the Tapeats Sandstone, a unit known for salty water elsewhere in the Grand Canyon. An odorless gas, probably carbon dioxide, also discharges from the spring. This type of water is rare in the area and occurs only in seeps that discharge from the Tapeats Sandstone. The temperature of the water probably represents heating associated with geothermal gradient.

Samples from springs 23, 28, and 78 represent rises in alluvium and include two of the chloride- or sodium-rich samples. These waters have moved downstream in alluvium as much as several miles from their original sources in the Paleozoic rocks and have been chemically altered. The quality of the water is primarily changed by concentration of dissolved solids through evapotranspiration, precipitation of calcium carbonate, and a suspected dissolution of sodium chloride from the beds of the canyons. Deposition of calcium carbonate is demonstrated by the abundance of travertine deposits along the streams, and also semiquantitatively by a comparison of data obtained in this study for springs

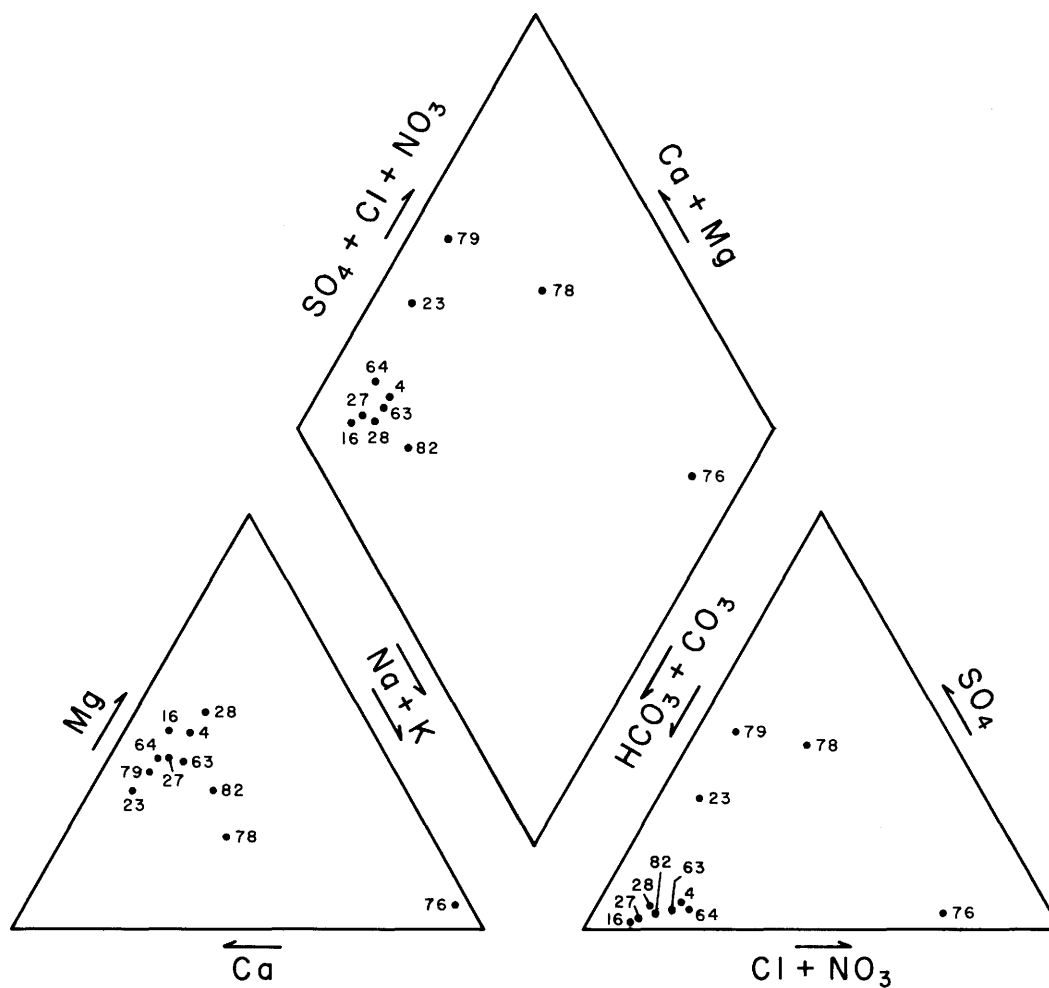


Figure 7. Trilinear diagram showing the chemical characteristics of the waters from springs in the western Grand Canyon district, Arizona. Coordinate axes are the percentages of the equivalents per million of the major ions. Numbers correspond to Tables 1 and 2.

63 and 64, and two samples for the same springs collected by Twenter (1962). Springs 63 and 64 discharge from the same fault (see Figure 6) and the samples in Table 2 were collected at the respective springs. As expected, the analyses are virtually identical. Twenter's samples (1962, Table 1, numbers 11 and 12) for these springs were collected respectively at spring 63 and one mile below spring 64. His downstream sample had lost 22 percent of the original calcium and 13 percent of the bicarbonate. No change in chloride or sulfate was recorded.

Dissolution of salt from the beds of streams for springs 23, 28, and 78 is suggested by slightly larger than normal sodium and chloride concentration in their samples as compared to most of the other data. This interpretation is not conclusive because the increases in salt concentrations in the samples are small.

The total concentration of sulfate is used here as an indicator of the geographic source for the spring waters. Aside from Pumpkin spring, the greatest concentrations of sulfate occur in springs 23, 78, and 79. Springs 23 and 79 drain adjacent parts of the Shivwits plateau that are capped by the Toroweap and Kaibab formations, both of which contain abundant gypsum. Likewise springs 78 and 82, which drain respectively part of the Hurricane fault zone and Toroweap fault zone east of the Colorado River, appear to be gaining sulfate from Toroweap and Kaibab formations on adjacent plateaus. Springs 4, 16, 27, 28, 63, and 64 are low in sulfate, which I attribute to the absence of the Toroweap and Kaibab formations in their source areas.

Table 3. Known wells drilled into Devonian or older rocks in the western Grand Canyon district, Arizona

Number ^a	U.S.G.S. Location Number	Drilling Completion Date	Reported Depth (ft)	Elevation of Land Surface (ft)	Lowest Stratigraphic Unit Penetrated	Reported Water Level (ft below surface)	Date Measured	Reported Discharge (gal/min)	Land Owner	Remarks
W1	B-30-15-33	6/71	719	5040	Upper third of Muav Limestone	dry	6/71	---	Hualapai Indian Tribe	Location in section 33 not certain; penetrated upper third of Muav Limestone.
W2	B-28-15-10ddc	74	275	5100	Temple Butte Formation (?)	220	74	1/2	Hualapai Indian Tribe	Well may only have penetrated Quaternary and Tertiary rocks; no log available. Source of water unknown.
W3	B-28-14-20cb	unknown	800	4950	Shale between Peach Springs and Rampart Cave members of Muav Limestone	dry	9/67	---	Hualapai Indian Tribe	Well did not penetrate the Rampart Cave Member of the Muav Limestone.
W4	B-28-14-31cb	9/67	720	5040	Shale between Peach Springs and Rampart Cave members of Muav Limestone	420	9/67	1/4E	Hualapai Indian Tribe	Produced water from Muav Limestone at a depth of 450 ft. Driller reported Bright Angel Shale at 690 ft; however this was one of the thick shale tongues that lies between the Peach Springs and Rampart Cave members of the Muav Limestone. Well did not penetrate the Rampart Cave Member of the Muav Limestone.
W5	B-27-15-4cc	10/68	634	5475	Flour Sack Member of Bright Angel Shale	575	10/69	negligible	Bureau of Land Management	Dampness at depths of 125-130 ft, 387-388 ft; seep in shale at 597-599 ft. Bright Angel Shale encountered at 597 ft.
W6	B-27-14-31da	10/68	772	5320	Flour Sack Member of Bright Angel Shale	381	10/69	negligible	Bureau of Land Management	Open cavity between 86 and 102 ft; seep in shale at depth of 453 ft; seep at 737 ft. Bright Angel Shale encountered at 737 ft.
W7	B-26-14-9dc	11/68	480	5350	Muav Limestone	unknown		2-3E	Bureau of Land Management	Dampness in clay beds at depth of 50-65 ft and 192-193 ft; 3 gal/min above clay at 340 ft; noticeable water from clay at 415 ft.

a. Number corresponds to Figure 2.

WELLS

Deep wells are rare in the district; only seven are known to have been drilled into the Temple Butte Formation or older rocks (U.S. Geological Survey, undated; U.S. Bureau of Indian Affairs, undated). As shown on Figure 2 and Table 3, all of these wells have been located on the Hualapai plateau. Although they have produced valuable information, they have yielded little water. A few shallow wells have been drilled into Quaternary, Tertiary, and Permian rocks in the district but do not fall in the scope of this report (U.S. Geological Survey, undated; U.S. Bureau of Indian Affairs, undated).

Most of the drilling in the area has resulted from recommendations made by Twenter (1962, pp. A35-A37). Twenter identified the Rampart Cave Member of the Muav Limestone as the major aquifer in the area and selected a small number of potentially productive drilling sites on the Hualapai plateau (Twenter, 1962, plate 1). His bases for site selection were (1) the Rampart Cave Member is the source for several springs in the adjacent Grand Canyon, (2) sites were centrally located in large areas of potential recharge, and (3) anticipated drilling depths were economically feasible. The subsequent lack of success with drilling can be attributed to two factors: (1) the permeabilities associated with the Muav Limestone were less than Twenter had expected based on his observation of spring discharges in the Grand Canyon and (2) some of the wells were not drilled into the Rampart Cave Member and thus missed their target.

Wells W5, W6, and W7 (Table 3 and Figure 2) were drilled under contract with the Bureau of Land Management through or close to the bottom of the Rampart Cave Member of the Muav Limestone. W5 and W6 produced negligible quantities of water and W7 produced 2 to 3 gal/min from above a clay or shale layer within the Muav Limestone. Water level data from W5 and W6 demonstrate that the small quantity of water encountered is under artesian conditions.

Wells W1, W2, W3, and W4 were drilled for the Hualapai Tribe but were not successful. W2 and W4 produced respectively 1/2 and 1/4 gal/min. A careful analysis of the well logs indicates that the holes were not drilled into the Rampart Cave Member. Tongues of Bright Angel Shale that lie between the Peach Springs and Rampart Cave members of the Muav Formation (See Figure 5) were encountered and apparently mistaken to be the Bright Angel Shale beneath the Rampart Cave Member. From the logs, I suspect that drilling in W3 and W4 was stopped in the Bright Angel tongue between the Peach Springs and Spencer Canyon members. W1 was drilled only into the upper third of the Muav Limestone and W2, which appears to have been a test in the Tertiary sediments, may not have reached the Temple Butte Formation. No log of W2 was available for examination.

An examination of existing logs for the wells in Table 3 yields the following generalizations: (1) water, when found, exists above or in shale beds, (2) water, where encountered, occurs under artesian conditions, and (3) water was scarce, presumably due both to lack of water in the rocks and small permeabilities.

Twenter (1962, p. A26) acknowledges the importance of secondary fracturing to permeability; however, none of his recommended drilling

sites included structurally deformed areas. Possibly the structurally deformed areas were excluded because of unfavorable drilling depths or rough topography.

RECHARGE

It is possible to compute the approximate minimum rate of ground water recharge to the Paleozoic rocks underlying the Hualapai plateau because the plateau is elevated and the ground water discharge from it can be accurately estimated. This favorable condition results because the Grand Wash cliffs and the Grand Canyon expose virtually all of the permeable Paleozoic rocks around the edges of the plateau. Consequently the ground water system within the Paleozoic rocks under the plateau is essentially closed.

Because no significant quantity of water leaves the plateau in the subsurface, the discharge of all springs and seeps were summed to obtain a minimum value for the mean recharge. In cases where the sum of the visible discharges in a given canyon was less than the actual flow measured at the mouth of the canyon, buried springs and seeps were assumed to exist and the larger discharge was used in the computation. This situation exists, for example, in Spencer canyon. The average discharge from a seep was assumed to be 5 gal/min, an amount thought to be liberal based on field observations.

Total spring and seep discharge from the Hualapai plateau was approximately $3.85 \text{ ft}^3/\text{sec}$ during the period of this study. Distributed over the 600 mi^2 surface area of the plateau, this quantity yields a recharge rate of slightly less than 0.1 in/yr.

This value assumes that (1) the discharge data used are representative of long-term conditions, (2) springs and seeps account for all of the water leaving the plateau, and (3) insignificant amounts of water are lost directly from the slopes of the plateau as unmeasured evapotranspiration.

Obviously the 0.1 in/yr rate of recharge is a minimum. True recharge could be as much as ten times greater if there is significant loss of water through evapotranspiration directly off the slopes along the edge of the plateau. This low rate of recharge is, however, consistent with the large disparity that exists between potential evaporation and actual rainfall in the area (Figure 3).

Ground water recharge rates for the Shivwits plateau north of the Colorado River are less than those on the Hualapai plateau because spring and seep discharge from this area is less, as indicated in Table 1 and Figure 2. It is my opinion that recharge rates in the Aubrey cliffs area are greater than those on the Hualapai plateau based on total spring discharge from the area. However, the total area contributing to the springs is not known so this conclusion is speculative.

REGIONAL GROUND WATER FLOW

Because springs represent low points on the potentiometric surface, it is apparent from Figure 2 that hydraulic gradients are directed toward the Grand Canyon in the district. Ground water flow in the Hualapai plateau is strongly influenced by the regional dip of the rocks because the plateau is well drained. The potentiometric

surface associated with the Rampart Cave Member of the Muav Limestone can be assumed to conform closely to the structural gradients on Figure 6. The scattered locations of springs in the Grand Canyon demonstrate that ground water flow under the plateau is planimetrically distributed through the rocks. Columbine spring (4) represents water that has been concentrated in the Rampart fault zones and is the only fault on the Hualapai plateau that functions as a collector structure.

The elevations of springs on the southern side of the Shivwits plateau indicate that regional hydraulic gradients are toward the canyon opposite to the dip of the rocks. This conclusion is further supported by the fact that no spring systems lie to the north of the Grand Canyon that are topographically low enough to drain the Mississippian or older rocks.

The total yield of springs along the Shivwits plateau indicates that there is little recharge in the area. Aside from Spring Canyon spring (79) there is little concentration of water in faults under the plateau. The lack of springs along the Meriwhitica, Dellenbaugh, Hurricane, and Toroweap faults in deep canyons north of the Colorado River illustrates that these structures do not deliver significant quantities of water southward to the Grand Canyon. Although they could serve as drains for vast areas of the plateau to the north, they appear to be essentially dry.

The Parashant area (Figure 2) presents a particularly unusual situation. The entire basin containing Parashant canyon is traversed by northwest-trending tensional faults that should significantly enhance permeabilities along the axis of the structural

trend. Major faults in the system intercept the Dellenbaugh fault, thus bounding a large part of the Shivwits plateau on the west and north by potentially permeable faults zones (Figure 6). Hydraulic gradients in these faults should be toward Parashant canyon, yet no spring systems discharge from the Mississippian or older rocks in the area. It is possible that springs discharge directly into the alluvial fills in Parashant and tributary canyons and the water drains as underflow to the Colorado River. However these canyons are dry and noticeably lack phreatophytes on their floors.

The Aubrey cliffs area is characterized by northeasterly dips and major north-trending faults. Springs in the area are characteristically associated with faults. Three springs (72) and 205 Mile spring (78) discharge from the Hurricane fault zone and drain buttes between the Colorado River and the eastern margin of the Hurricane fault zone. Discharges from these springs are correspondingly small.

The Toroweap fault conducts large quantities of water to Warm springs from an area that could extend 25 mi or more southward from the springs. The trace of the fault and its several major branches combine with favorable structural gradients in the Muav Limestone to serve as collector structures (Figure 6). The regional dip of the rocks indicates that most of the water entering the faults from the Paleozoic section originates in the structural block between the Hurricane fault zone and the Toroweap fault zone. Smaller amounts of water may originate on the structural block to the east of the Toroweap fault but flow would have to be up-dip. Because the block to the east is well drained

by Mohawk canyon, appreciable flow toward the Toroweap fault is minimized. I doubt that the collection area for Warm springs extends significantly beyond the junction of the Toroweap and Aubrey faults north of Frazier Wells (Figure 2). No potentiometric data is available to support this conclusion but the structural elevation of the Paleozoic rocks declines southward from the fault junction toward the Chino drainage basin, so southerly hydraulic gradients can be expected in the Frazier Wells area.

Diamond East (63) and Big Diamond (64) springs represent a paradox. Both of these springs discharge from the same fault and their waters have identical quality (Table 2). I have made the case for fault control of springs wherever possible using the argument that the water will follow these zones of enhanced secondary permeability if favorable gradients exist. It is my opinion, however, that these two springs are fortuitously located along a major fault in the Toroweap-Aubrey fault zone and that in fact they do not derive appreciable water from the fault zone. Rather, the water originates to the south on the adjacent plateau and is simply intercepted by the fault before reaching the head of Diamond canyon. Four important lines of evidence support this conclusion.

The structural gradients in the fault south of the spring system are steeply oriented toward the south; thus water entering this part of the fault could be expected to move toward Warm springs. A comparison of the water quality (Table 2) between Warm springs and the springs in Diamond canyon indicates that the waters are significantly different. Not only are their total dissolved solids

different by a factor of three, but individual ionic components occur in differing ratios. The large boron and sodium chloride concentrations in Warm springs water can be attributed to contact of the water with the marine Bright Angel Shale as it circulates along the fault zone. The substantially smaller percentages of these constituents in Diamond East and Big Diamond waters suggests that they do not encounter the Bright Angel Shale, as would occur along a fault; rather they circulate through the Mauv Limestone above the shales. A structural gradient exists in the area to the south of the Diamond Springs from plateaus large enough to account for the observed discharges. Furthermore, these plateaus are capped by lower Permian rocks, the gypseous Kaibab and Toroweap formations having been stripped from the area. In contrast, the drainage area supplying Warm springs contains abundant gypsum. A comparison of water qualities illustrates that, as expected, the sulfate concentration in Warm springs is significantly greater than that in the Diamond springs. By contrast, the chemical character of the water in the Diamond springs is similar to that of water draining the Hualapai plateau, an area that is geologically similar to the environment found south of Diamond canyon.

Based on the foregoing, it is my opinion that the water discharging from the fault at the head of Diamond canyon in fact originates from solution-enhanced permeable zones in the Muav Limestone that are similar to the circulation systems responsible for Quartermaster (16), Meriwhitica (27), and Travertine (52) springs along the north side of the Hualapai plateau. The fact

that these waters encounter the Diamond Springs fault, which lies oblique to the flow path, is sheer coincidence.

COMPARISON OF GROUND WATER SYSTEMS, WESTERN GRAND CANYON DISTRICT AND KAIBAB PLATEAU

Huntoon (1974a) has documented the ground water circulation system that drains the Kaibab plateau north of the Grand Canyon. The Kaibab plateau occupies approximately 950 mi^2 and lies at an elevation between 6,400 and 9,300 ft. Water drains from the plateau through a system of large springs in the Grand and Marble canyons.

Discharge

The total ground water discharge from the 950 mi^2 Kaibab plateau is approximately $100 \text{ ft}^3/\text{sec}$ with large seasonal variations. Combined flood discharges can approach or exceed $200 \text{ ft}^3/\text{sec}$. Most of the water leaving the plateau discharges through 20 large springs, the majority with discharges between 0.5 and $50 \text{ ft}^3/\text{sec}$. Numerous smaller springs and seeps discharge in the area.

This compares to a cumulative discharge of $4 \text{ ft}^3/\text{sec}$ from the 600 mi^2 Hualapai plateau. Warm springs, which is the largest spring in the western Grand Canyon district, yields less than $10 \text{ ft}^3/\text{sec}$, and the remaining "large" springs yield amounts that are usually less than $1 \text{ ft}^3/\text{sec}$. We have no data on seasonal variations of flows but point measurements that have been collected indicate that discharges are variable (Johnson and Sanderson, 1968; Twenter, 1962).

Water Quality

Data from Johnson and Sanderson (1968) reproduced in Huntton (1974a, Table 3) illustrate that water from the Kaibab plateau is of the calcium-magnesium-bicarbonate type and contains less than 180 mg/1 total dissolved solids (Figure 8). Most of the water in the western Grand Canyon district is of the same type but usually contains more than 300 mg/1 dissolved solids. Warm springs contain in excess of 800 mg/1 dissolved solids. Temperatures of water discharging from the Kaibab plateau average 50°F compared to 74°F for springs in the western Grand Canyon district.

Geologic Setting of Springs

The large springs in the eastern Grand Canyon are usually associated with faults or subsidiary fractures, and most discharge from the Peach Springs Member of the Muav Limestone. The large springs not associated with the Peach Springs Member discharge from higher carbonates primarily because the Peach Springs Member is not exposed. Several of the large springs in the western Grand Canyon district have no known association with faults, notably springs 16, 26, 27, and 52. The location of springs 63 and 64 along a fault appears to be coincidental, as explained previously. The stratigraphic position of most of the large springs in the western Grand Canyon district is the Rampart Cave Member of the Muav Limestone, a unit stratigraphically lower than the Peach Springs Member (Figure 5). Caves are associated with several of the large springs that drain the Kaibab plateau whereas no caves have been discovered that are associated with any of the springs in the western Grand Canyon district.

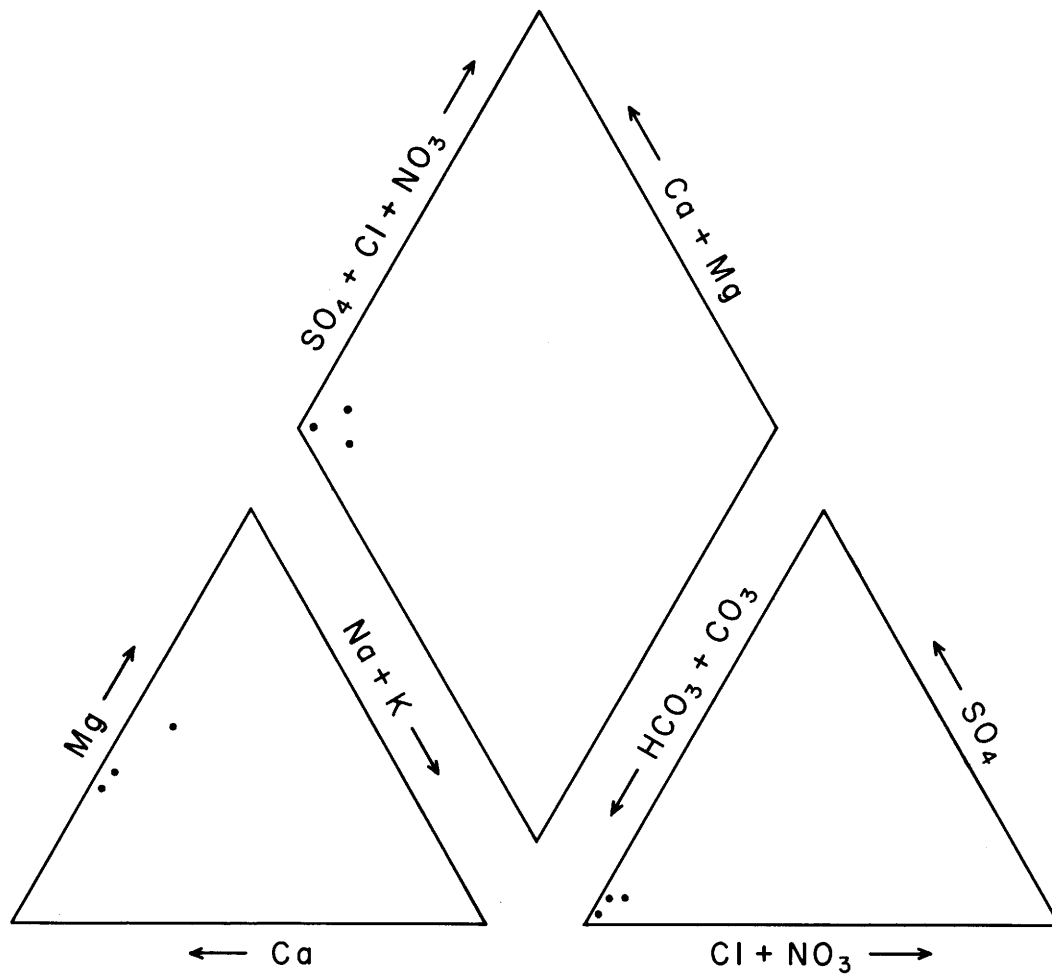


Figure 8. Trilinear diagram of representative water samples from springs that drain the Kaibab plateau, eastern Grand Canyon, Arizona. Coordinate axes are the percentages of the equivalents per million of the major ions. Data from Huntoon (1974a, Table 3).

Explanation of Differences

The larger discharges and cooler temperatures of springs draining the Kaibab plateau as compared to springs in the western Grand Canyon district can easily be explained by the higher average elevation of the Kaibab plateau. Rainfall on the Kaibab plateau ranges from 16 over 30 in/yr as compared to rainfall of 1 to 16 in/yr over the plateaus in the western Grand Canyon district. Because the western plateaus are lower, mean average temperatures are warmer and hence the ground water recharging and circulating in the area is warmer.

I interpret the poorer chemical quality of ground water in the western Grand Canyon district to be the result of longer residence time for the water in the aquifer as compared to the Kaibab ground water system. This results largely because the water in the western Grand Canyon is circulating through less permeable rocks than the waters draining through the open fault systems in the Kaibab plateau. A second and potentially influential factor is dilution of water in the Kaibab system which results directly from the larger quantities of water available.

The primary water-bearing unit in the western Grand Canyon is the Rampart Cave Member of the Muav Formation as compared to the Peach Springs Member in the Kaibab system. In both cases ground water circulates to depths as low in the Paleozoic section as possible. Water does not discharge from the Kaibab system in the Rampart Cave Member because the unit is very thin and separated from overlying carbonates by a laterally continuous, thick sequence of Bright Angel Shale. This is a consequence of an

almost complete pinch out of both the Spencer Canyon and Sanup Plateau tongues of the Muav Limestone west of the Kaibab plateau and a replacement of these lithologies by Bright Angel Shale (Figure 5). Caves associated with many of the springs in the eastern Grand Canyon probably developed because larger volumes of water have circulated through the permeable zones.

GROUND WATER PROSPECTING

The following procedure can enhance the chances for success in prospecting for water in the western Grand Canyon district and similar terrains. (1) Identify the water-bearing stratigraphic units on the basis of spring locations and productive zones in existing wells. (2) Identify and map the locations of faults or other fracture zones that can increase the permeabilities of rocks. (3) Prepare a structural contour map for the base of the producing stratigraphic unit and use this map (a) as approximation for the hydraulic gradients in areas that are well drained or (b) as an indicator of zones in which water is trapped stratigraphically. (4) Once promising areas are identified, use a map showing the locations of producing wells or springs to determine if significant water is circulating through areas or zones of interest. (5) Given the choice, drilling should be undertaken along structures that have improved, through secondary fracturing, the original porosity and permeability of the rocks. Drilling sites along faults should be located on the downthrown block and situated sufficiently close to the fault that the hole will intersect the fault plane or subsidiary fractures at the depth of the

principal water-bearing unit. Drilling depths can be computed by subtracting the structural elevation of the base of the anticipated producing unit from the surface elevation of the site.

The foregoing criteria were used to locate six potentially productive drilling areas, which are shown on Figure 2 and listed in Table 4. All but one of these are deep drilling ventures that will involve high drilling costs. In my opinion, these areas are the best in the district. Other areas are so speculative at this time that their consideration is unwarranted until additional test hole data can be accumulated.

The Paleozoic rocks underlying the Shivwits plateau offer no good ground water exploration potential because: (1) known spring discharges from the plateau are negligible, (2) known faults yield little or no water, and (3) drilling depths to the Rampart Cave Member of the Muav Limestone exceed 4,000 feet. The southwestern part of the Hualapai plateau offers equally dismal prospects for ground water development. Although drilling depths to the Rampart Cave Member are shallower, the rocks contain little water as proven by the lack of springs along the Grand Wash cliffs and negligible yields from existing wells W5, W6, and W7.

RECOMMENDATIONS

Before attempting to develop ground water from areas 1, 3, and 4 (Figure 2) on the Hualapai plateau, it would be wise to deepen existing well W4 an additional 200 feet to reach the potentially productive Rampart Cave Member of the Muav Limestone. Although the prospects for obtaining even moderate stock watering supplies from

Table 4. Promising areas for deep ground water test drilling, western Grand Canyon district, Arizona

Area ^a	Location	Target	Drilling Depth (ft)	Expected Yield (gal/min)	Risk	Justification
1	Dowthrown side along Rampart fault	Base of Rampart Cave Member of Muav Limestone	1900-2500	10-100	Fair	Water from Columbine spring (4) circulates along the Rampart fault.
2	Dowthrown side along Aubrey fault	Peach Springs and Rampart Cave members of Muav Limestone.	3300-3800	50-500	Fair	Water is predicted to circulate along the Aubrey fault to the south in this area.
3	Tertiary volcanic fill in Milkweed canyon	Base of Tertiary rocks	400-1000	5-100	Good	Water appears to exist in Tertiary rocks based on seeps and springs in these rocks in Milkweed canyon.
4	Plains area	Base of Rampart Cave Member of Muav Limestone	1500-1800	1-10	Poor	Structural gradient is small, which may allow for accumulation of water in a saturated lens at the base of the carbonate section. Water exists in small quantities as indicated by Travertine (52) and nearby springs.
5	Dowthrown side along Toroweap fault	Peach Springs and Rampart Cave members of Muav Limestone	3400-4000	50-500	Good	Water from Warm springs (82) circulates along the Toroweap fault.
6	Dowthrown side along Toroweap fault	Peach Springs and Rampart Cave members of Muav Limestone	2400-3000	50-500	Good	Water from Warm springs (82) circulates along the Toroweap fault.

a. Numbers correspond to Figure 1.

this hole are less than favorable, the small cost associated with deepening the already 720 ft well makes the project viable. If usable quantities of water are obtained from W4, wells W3 and W2 could be deepened to the Rampart Cave Member with equal chances for success. The deepened W4 would serve as an excellent indicator for success in area 4 because the geologic environment is similar.

I would recommend test drilling in area 1 before attempting to drill in 2, 5, or 6. The primary reason for this cautionary suggestion is that area 1 offers the shallowest depths to the Rampart Cave Member. Experience gained in area 1 would be valuable for locating drilling sites in areas 2, 5, and 6, should they ever prove to be economically feasible.

Site 3 offers good potential. If a well were successful, it would justify further examination of the ground water resources in the Tertiary rocks in the area.

I would recommend against drilling into the Paleozoic rocks anywhere on the Shivwits plateau because the entire hydrologic and geologic environment of the area is adverse to success.

Under no circumstances should drilling be commenced without proper siting and technical advice from a trained professional ground water hydrologist familiar with the rocks and structures in the area. Use of such a professional will eliminate the risks of missing target aquifers or structures as has occurred in the past in at least wells W3 and W4. The professional should be required to compile a complete drilling and sample log of the new wells which can serve as an invaluable source of data for evaluating future drilling sites.

CONCLUSIONS

Most of the ground water in the western Grand Canyon district occurs in the Rampart Cave Member of the Muav Limestone which is the basal carbonate in the Paleozoic section. Although half of the large springs in the district are associated with faults and drain definable parts of the adjacent plateau, the other large springs demonstrate that faulting is not required for their development. Seeps and small springs occur throughout the district and illustrate that flow through the rocks is planimetrically distributed. Water yielded by the small seeps and springs moves primarily along joints and partings along bedding planes.

Minimum computed recharge rates in the district are on the order of 0.1 in/yr. Total discharge from springs in the district is on the order of 20 ft³/sec. Most of this water discharges into the Grand Canyon from plateaus on the south side. Prospects for developing large ground water supplies in the district are severely limited because: (1) very little water circulates through the rocks, (2) permeabilities are small, and (3) there are no extensive permeable zones under the plateaus in which large quantities of water are in storage.

The most favorable locations for finding water appear to be south of the Colorado River. Drilling sites that offer the best chances for success lie on the downthrown block along selected faults that are known to transmit water to large springs in the Grand Canyon. Drilling depths at such sites will exceed 1,900 ft and potential yields are not likely to exceed the 500 gal/min

range. No good prospective drilling sites in the Paleozoic rocks on the Shivwits plateau are known.

Water quality in the district is generally good. Most springs yield calcium-magnesium-bicarbonate water with total dissolved solids in the 250 to 500 mg/l range at temperatures between 69° and 80°F. Warm springs is the largest in the district, discharges approximately 7 ft³/sec from the Toroweap fault zone at 86°F, and has a total dissolved solids concentration of 742 mg/l.

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