ISOTOPIC AND CHEMICAL CHARACTERIZATION OF GROUND WATERS IN THE VICINITY OF FLAGSTAFF, ARIZONA

by

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STATEMENT BY AUTHOR

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ABSTRACT

The sustained yield of a well field adjacent to Lower Lake Mary reservoir, south of Flagstaff, Arizona, has been calculated in two separate studies, and the results differ significantly. One reason for the difference is the lack of understanding of the effect that the reservoir has on recharge to the well field. Samples were taken from various surface waters, springs, and production wells in the area surrounding Flagstaff to chemically characterize the waters and to examine the potential recharge source(s) to the Lake Mary well field. Results indicate that nearly all ground waters in the area are calcium-magnesium-bicarbonate in composition, but they differ significantly in total hardness. Isotopic values of the samples indicate that only one well within the Lake Mary well field is definitely receiving significant recharge from the reservoir.

SECTION 1

INTRODUCTION

The City of Flagstaff and the surrounding area utilize a number of sources for their water supply. The city manages three well fields and a reservoir system to meet its needs. The well fields are termed Lake Mary, Woody Mountain and the Inner Basin. Two reservoirs are in series and are named Upper Lake Mary and Lower Lake Mary. This current system provides an adequate supply at the present time; even during peak summer months. However, in order to meet the water supply needs required by future population growth, the City of Flagstaff will probably need to develop new well fields or utilize the present sources to their fullest potential.

Previous Work

To optimize the conjunctive use of the water resources, the City of Flagstaff conducted studies of the individual well fields (Harshbarger, 1973, 1974,1976 and 1977). As part of these studies, the data gathered were used to calculate an optimum sustained yield for each well field.

A sustained yield of approximately 15 million gallons per day (mgd) was predicted for the Lake Mary well field, assuming new wells could be installed in proper locations (Harshbarger, 1977). Harshbarger states that the sustained yield is "approximately equal to the recharge in the Lake Mary area." The estimate of sustained yield was based on an assumption that ground water recharge was originating from two primary areas: (1) an area which contains a significant ground water mound to the southwest of the Lake Mary well field; and (2) seepage from the Lake Mary reservoirs which infiltrates through fractures within a graben underlying the reservoirs (estimated by Harshbarger [1976] at 3,940 acre-feet per year). Two new wells were to be placed within the fracture zone to capture more of the seepage.

In a later study conducted for the City of Flagstaff, a sustained yield of 1.0 to 1.5 mgd was calculated for the Lake Mary well field (Duren, 1983). One reason for this much lower estimate was the assumption that seepage from Lake Mary did not recharge the aquifer penetrated by the present well field, but instead infiltrated to a second regional aquifer below. Wells in the fracture zone to capture the seepage were not a part of Duren's assumptions. However, only an additional yield of 3.5 mgd from seepage could be added to Duren's estimate, if he assumed that wells within the graben could capture all of the seepage. These conflicting yield estimates may make it difficult for the city to properly manage future production of the well field.

Statement of Objective

This study was conducted with two objectives in mind, namely: the characterization of water quality, and the investigation of recharge to the Lake Mary well field. Due to the small volume of surface runoff in comparison to the quantity of rainfall in the Flagstaff region (Harshbarger, 1976), ground water plays a major role as a water supply. Private and public wells are scattered throughout a large area, supplying water from various locations of the regional aquifer. The first objective is to chemically characterize these supplies in order to compare the waters from different sources, as well as from different locations of the regional aquifer.

A second objective is to examine the origin of recharge to the Lake Mary well field. The naturally occurring isotopes deuterium, tritium and oxygen-18 are used to compare potential ground-water recharge sources to water pumped from the well field.

Background of Investigation

The field work and sample analyses for this study were performed in the fall of 1983 and winter of 1984. Other studies after this period are not incorporated into this report. Funding for the isotope analytical work was provided by the Water Department of the City of Flagstaff. No other grant or contract funds were used to support the remaining work. Thus, samples could only be taken from existing sources, and the number of samples had to be limited.

SECTION 2

SITE DESCRIPTION

Location

The study area is shown in Figures 1 and 2. This area encompasses the San Francisco Mountains, the southern portion of the San Francisco Plateau, and Oak Creek Canyon, including the City of Sedona. Although the area is large (more than 500 squares miles), the number of wells available to sample was small. The depth to water in the regional aquifer in the areas south and east of Flagstaff ranges from approximately 300 feet to over 1,300 feet. This results in high drilling and pumping costs, making small domestic wells expensive. Housing developments on the outskirts of Flagstaff are supplied water from community wells.

For this study, samples were collected from the three well fields which supply Flagstaff. Wells which supply the City of Sedona were also sampled, as were wells which supply five community developments on the outskirts of Flagstaff. Samples from several springs and surface

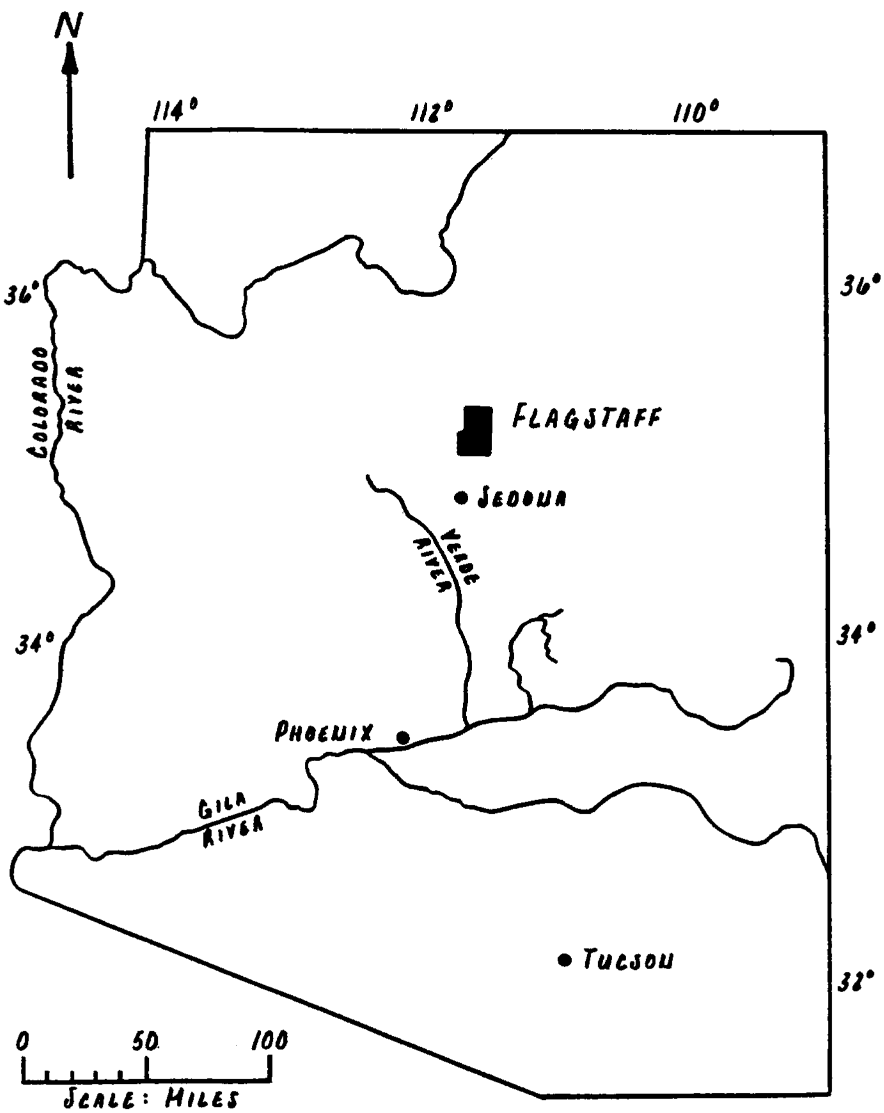

Figure 1. Location of Study Area in Arizona.

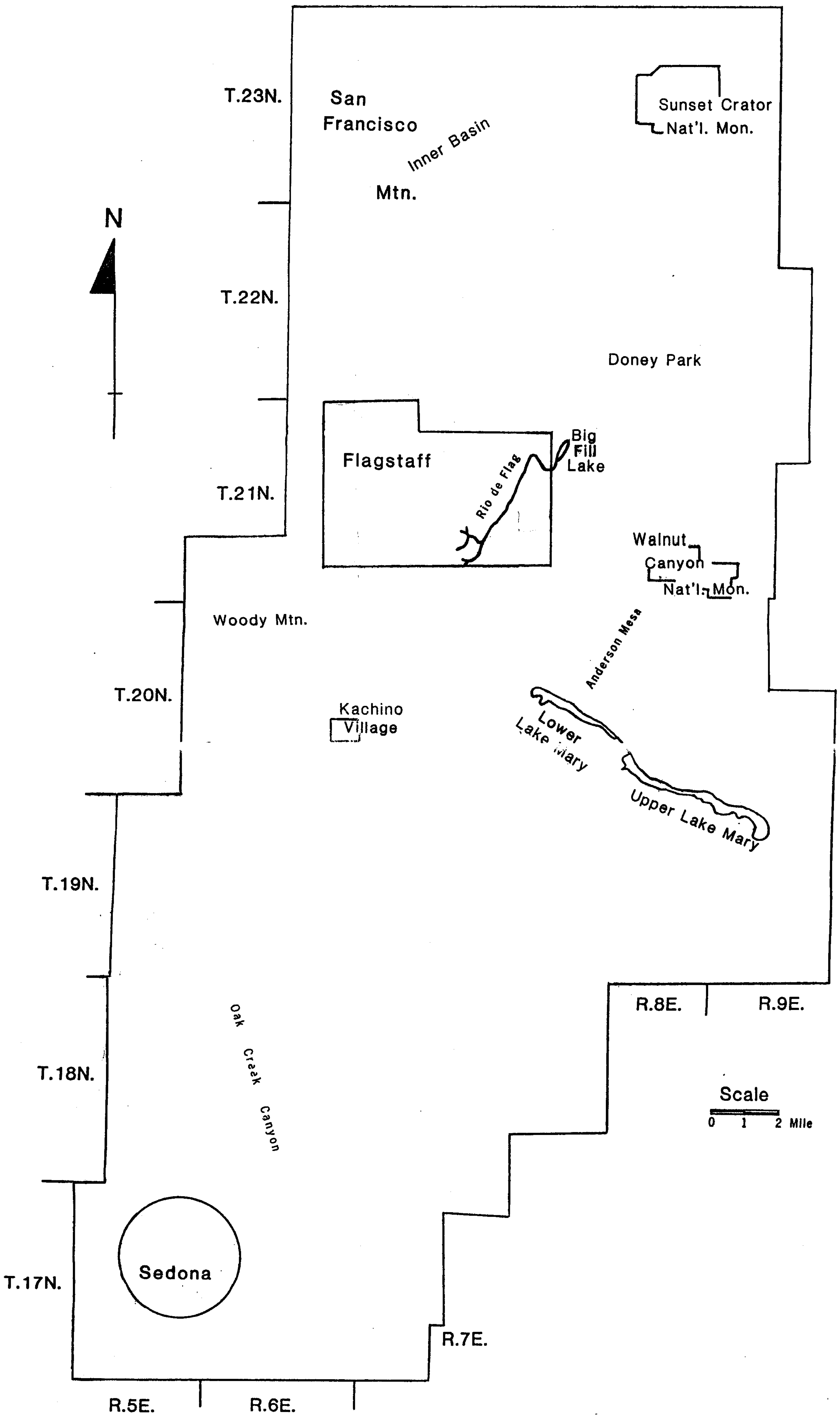

Figure 2. Regional Map of the Study Area

water bodies, principally in the vicinity of the Lower and Upper Lake Mary, were obtained to characterize potential recharge and discharge waters. Exact sample locations and descriptions will be provided in Section Three.

Climate, Land Use And Surface Drainage

Flagstaff has a cool, temperate climate, with higher than average rainfalls in comparison to the lower elevation regions of Arizona. The average annual precipitation recorded at Pulliam Airport outside Flagstaff was 19.50 inches for the period 1941 through 1976 (Harshbarger, 1977). The annual average precipitation for the Inner Basin of the San Francisco Mountains was 36.4 inches for the period 1957 through 1973 (Harshbarger, 1974).

The Coconino National Forest nearly surrounds the City of Flagstaff. Much of the land is heavily forested with numerous small canyons throughout the southern plateau region.

Small ephemeral streams and lakes are common throughout the region. The streams flow normally only during snowmelt. Some of these systems drain into the two man-made lakes, Lower and Upper Lake Mary (see Figure 2). Upper Lake Mary provides approximately fifty percent of the water used by Flagstaff (Duren, 1983). The earthen dam that created the lake was built in 1941. The capacity of the lake was doubled in 1951 when the height of the dam was raised. When the lake is at full capacity, the depth near the dam is approximately 40 feet and the average depth throughout the lake is 17.9 feet (Blee, 1984). Spillage from Upper Lake Mary drains into Lower Lake Mary. The average depth of Lower Lake Mary is less than 10 feet (Scott, 1984), and the lower lake is not part of the water supply system of Flagstaff.

Oak Creek is a perennial stream which is spring-fed. It flows from north to south through Oak Creek Canyon and Sedona. The head of the canyon is approximately eleven miles southwest of Lower Lake Mary.

Rio de Flag is a large, normally dry river bed that runs through the City of Flagstaff. The sewage treatment plant for Flagstaff is adjacent to the river. Discharge of secondary treatment effluent from the plant flows down the Rio de Flag to the northeast until it reaches Big Fill Lake on the eastern edge of the city. Big Fill Lake loses water through evaporation and seepage.

Geology

The potential significance of the sample locations is related to an understanding of the geologic and hydrologic characteristics of the study area.

The stratigraphic sequence underlying Flagstaff and much of the surrounding area is composed of volcanic flow rocks at the surface, underlain by a few thousand feet of sedimentary rocks of Triassic to Devonion age. The sedimentary rocks lie nonconformably atop Precambrian Metamorphic rocks.

Prior to volcanism, the sedimentary rocks were warped upward to form the Mormon Mountain anticline (Akers, 1962). The anticline is a broad, gentle arch which trends southeast from an area approximately five miles south of Flagstaff. On the northeast side of the arch lies a set of faults associated with the Anderson Mesa fault, which trends northwest and north. The Oak Creek fault, which trends north, lies to the west of the anticline. Two of the three well fields used by the City of Flagstaff for water supply are in portions of these two fault systems. Surface deposits are shown in Figure 3.

Plateau South of Flagstaff

A series of basalt lava flows and pyroclastic rocks, which are part of the San Francisco Volcanic Field (Manera, 1975), overlie a large portion of the Flagstaff area. The pyroclastic rocks are composed of ash, cinders and bombs, and, together with the lava flows, range in age from Pliocene to Holocene (Harshbarger, 1976).

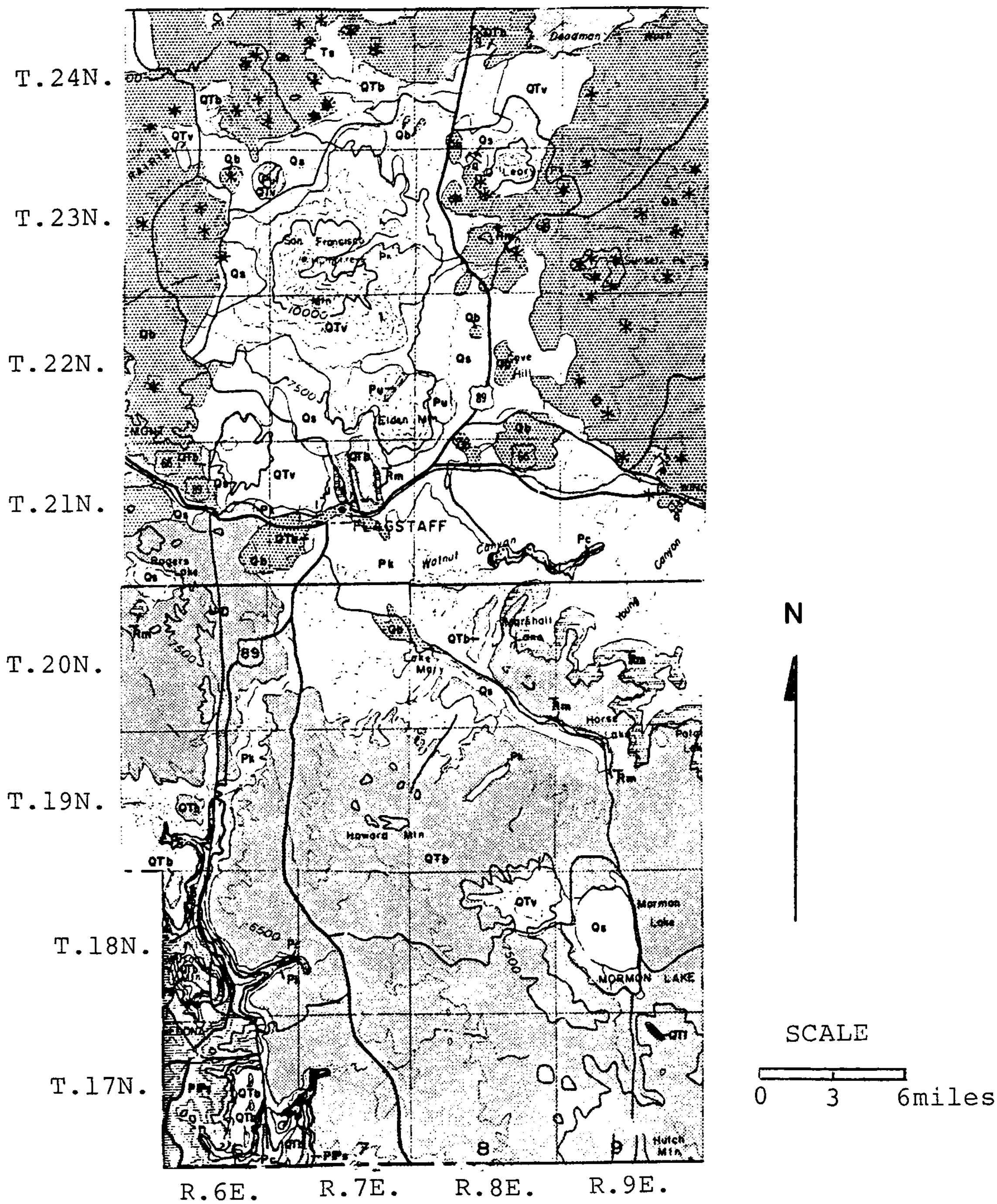

Figure 3. Geologic Map and Stratigraphic Column
(from Moore, 1960).

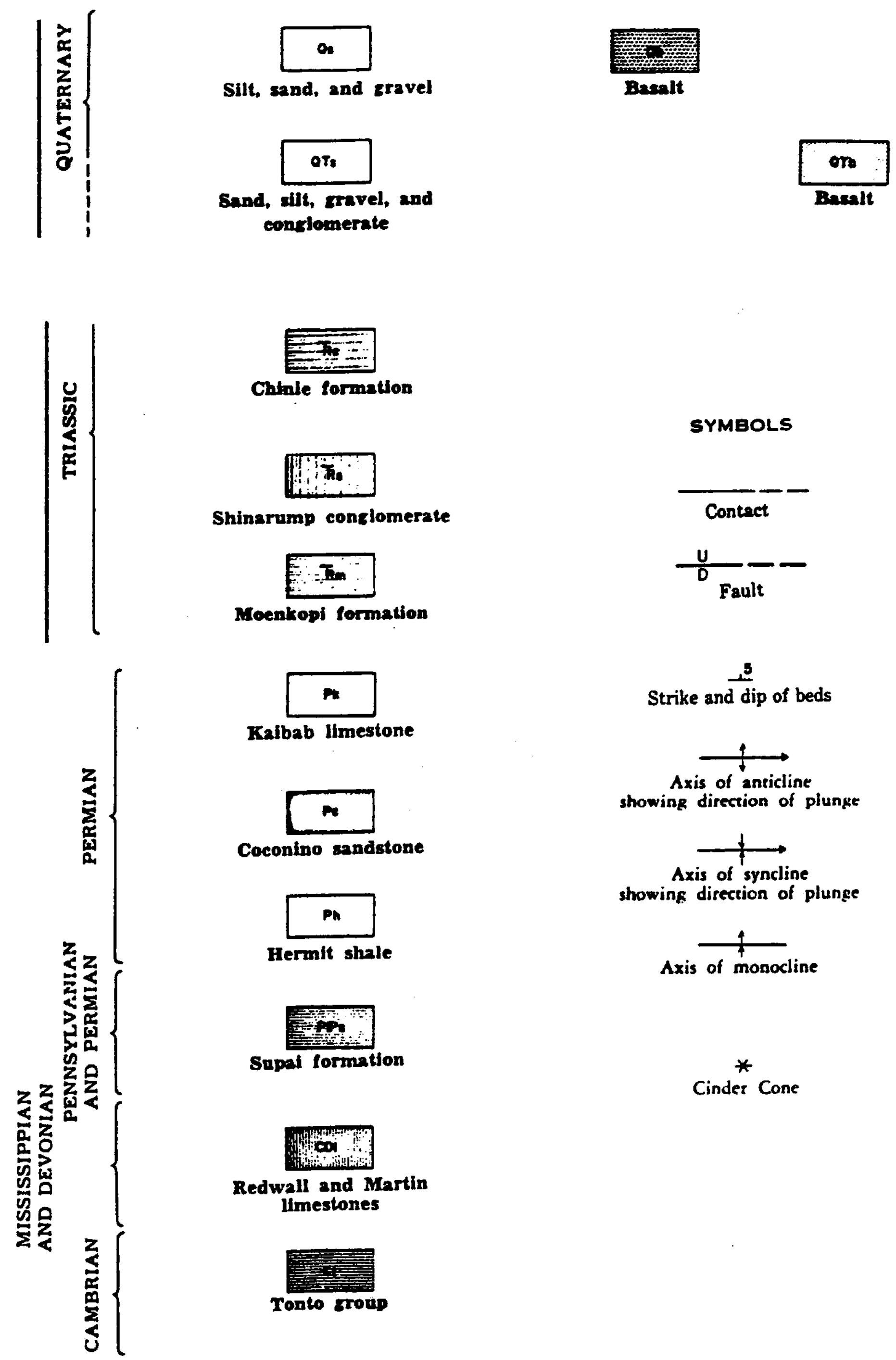

Figure 3. cont.

The volcanic rocks crop out in the Woody Mountain well field area, and in the areas north, south and east of the Lake Mary well field. Two wells in the latter field penetrate more than 100 feet of volcanic rock. Thin layers of pyroclastic rocks are near the cinder cones in the area.

The volcanic rocks lie unconformably over the sedimentary rocks, the uppermost of which is the Moenkopi Formation of Triassic age. This formation consists of medium to thin-bedded, fine-grained, red sandstone and mudstone (Harshbarger, 1976). This formation is easily eroded and is not continuous throughout the area.

The uppermost formation which is continuous throughout the area is the Kaibab Limestone of Permian age. The Kaibab crops out to the north and west of Lower Lake Mary, and is penetrated by wells of both major well fields. Lake Mary well #1 penetrates 354 feet of the Kaibab, which is the most of any well in the field. Regionally, the thickness of the formation varies from approximately 200 to 400 feet.

The Kaibab Limestone is composed of yellowish-gray, silty-to-sandy dolomitic limestone (Harshbarger, 1976). Lower members of the limestone are composed of thick-bedded limestone with some sandstone.

The Coconino Sandstone underlies the Kaibab Limestone and is continuous throughout the region. The Coconino is also of Permian age. The depth to this formation ranges from approximately 200 to 475 feet in the Lake Mary well field, and the thickness ranges from 645 feet to 750 feet based upon data from those Lake Mary wells which completely penetrate the formation.

The Coconino Sandstone is composed of fine-grained, cross-bedded sandstone which is well-sorted. Analysis of the sandstone indicates that it is 95% quartz with silica cement, and minor amounts of carbonate cement (Harshbarger, 1976).

Harshbarger (1976) reported that the grain-size data from well cores, along with geophysical logs, identify two distinct zones. The upper zone has coarser grains and greater porosity than the lower zone. In addition, the upper zone has a greater abundance of fractures. Each zone is approximately 300 feet thick.

Next in the sequence is the Supai Formation of early Permian to late Pennsylvanian age. The contact between the Coconino and the Supai is transitional and ranges in thickness from approximately 50 to 250 feet thick. The thickness of the formation is approximately 1,800 feet in the Lake Mary area based on well logs (Harshbarger, 1976). Harshbarger states that, according to grain-size analyses and well cutting descriptions, "little noticeable difference exists between the transition zone of the Supai and the lower part of the overlying Coconino."

The rest of the Supai is composed of three members. The upper unit, which is approximately 700 feet thick, is composed of fine-grained to silty sandstone in massive beds. Approximately 275 feet thick, the middle member is composed of finer-grained sediments, including dolomitic-conglomerate, mudstone, limestone, siltstone and sandstone. The lower member is composed of sandstone, shaly mudstone, limestone and dolomite beds (Harshbarger, 1976).

Water supply wells in the Flagstaff area do not extend past the transition zone of the Supai, so geologic logs of formations below the Supai are not abundant. The geologic and geophysical logs of one oil and gas test hole in particular were used to confirm the presence of the remaining formations in the Flagstaff area (Harshbarger, 1977). This hole is the Wichita Industries Test Hole located southwest of Lake Mary.

Underlying the Supai is the Redwall Limestone which is of Mississippian age. The Redwall is approximately 200 feet thick in the Flagstaff area and lies approximately 2,800 to 3,000 feet below the land surface. The Redwall is composed of thick to thin beds of crystaline limestone.

Harshbarger (1977) discusses three members, the lower of which contains both limestone and dolomite.

Underlying the Redwall is the Martin Group. This Devonian strata is composed of fine-grained dolomite and limestone and is approximately 300 to 400 feet thick (Harshbarger, 1976).

Metamorphic rocks of Precambrian age underlie the Martin Group.

Alluvial deposits of Quaternary age are located in various areas, lying atop volcanic rocks or Kaibab limestone. These deposits are poorly consolidated or unconsolidated and are a result of stream deposition. Alluvial deposits underlie the beds of the many ephemeral streams and shallow lakes, including Upper and Lower Lake Mary. Harshbarger (1976) estimated the maximum thickness of alluvium in the Lake Mary graben to be approximately 60 feet using geophysical data.

Sunset Crator Area

The Sunset Crator National Monument lies to the northeast of Flagstaff. The litholgic units of this area are similar to those south of Flagstaff, except that the Tertiary and Quaternary volcanic deposits are much thicker. These deposits are nearly 700 feet thick, according to well logs (Christensen, 1982). The volcanic units are composed of silicic tuff, basalt, basaltic pyroclastics and andesite. Within the volcanic deposits is an interflow zone called the Senagria Formation. This unit is approximately 280 feet thick and composed of sediments originating from the volcanic rock.

Inner Basin

North of Flagstaff is a group of peaks forming the San Francisco Mountain. The highest peak, 12,633 feet, is almost 6,000 feet above the city. The peaks nearly surround an area termed the Interior Valley. Within this area is the Inner Basin, which contains a number of shallow wells used by the city for water supply. The elevation of the Inner Basin ranges from 8,500 to 10,500 feet above sea level.

The San Francisco Mountain is composed of andesite volcanics and is thought to be the center of late Cenozoic volcanism (Harshbarger, 1974). The volcanic rocks overlie the sedimentary formations described previously. From the Inner Basin, the depth to the sedimentary rocks may be as much as 3,500 feet.

The location of the Inner Basin in relation to the surrounding peaks is seen in Figure 4. The locations of the City of Flagstaff wells are also identified. Figure 5 contains a geologic cross section of the Inner Basin as derived from logs of three Inner Basin wells.

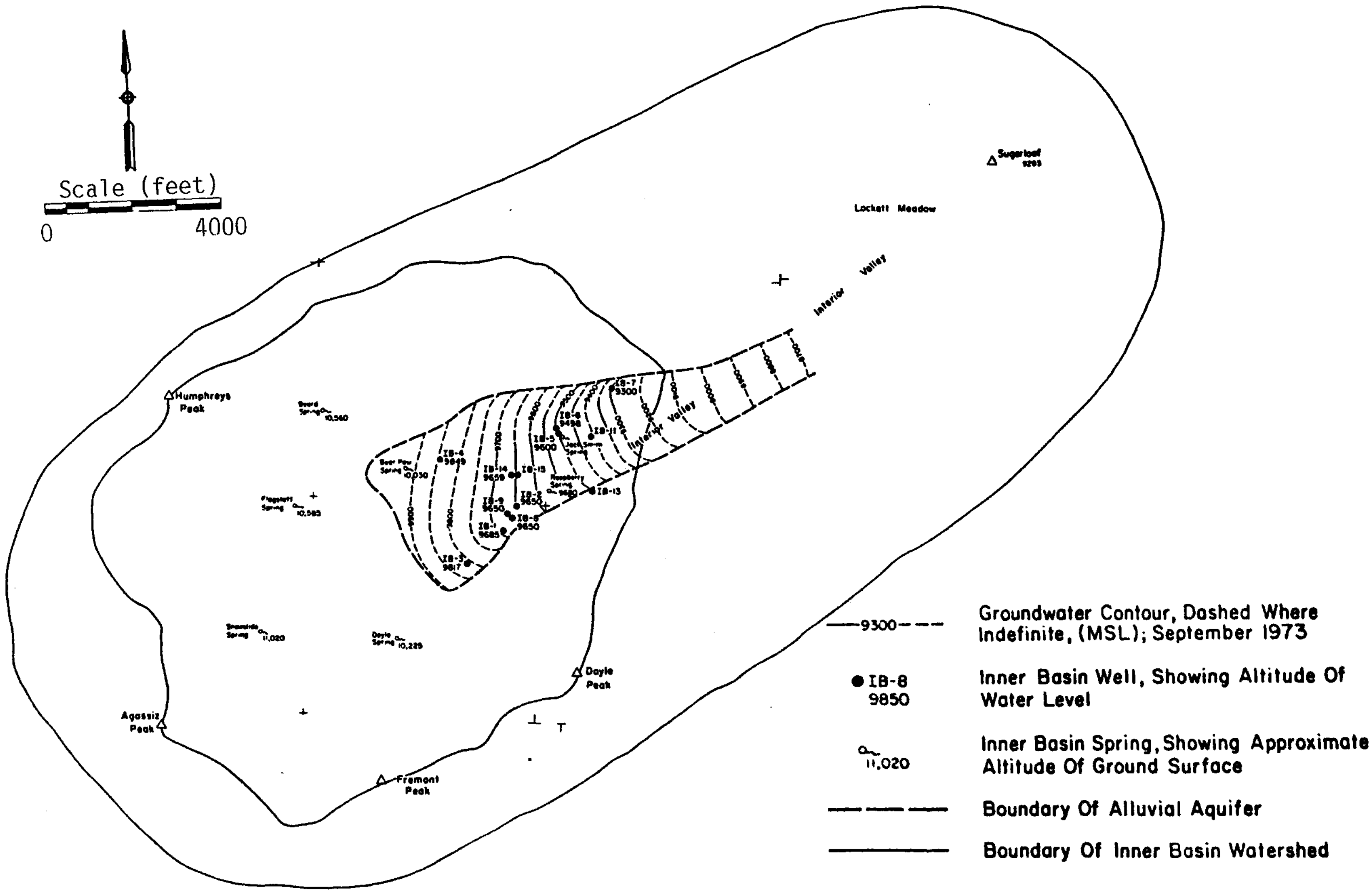

Figure 4. Alluvial Aquifer of the Inner Basin, Including Groundwater Elevations (from Harshbarger, 1974).

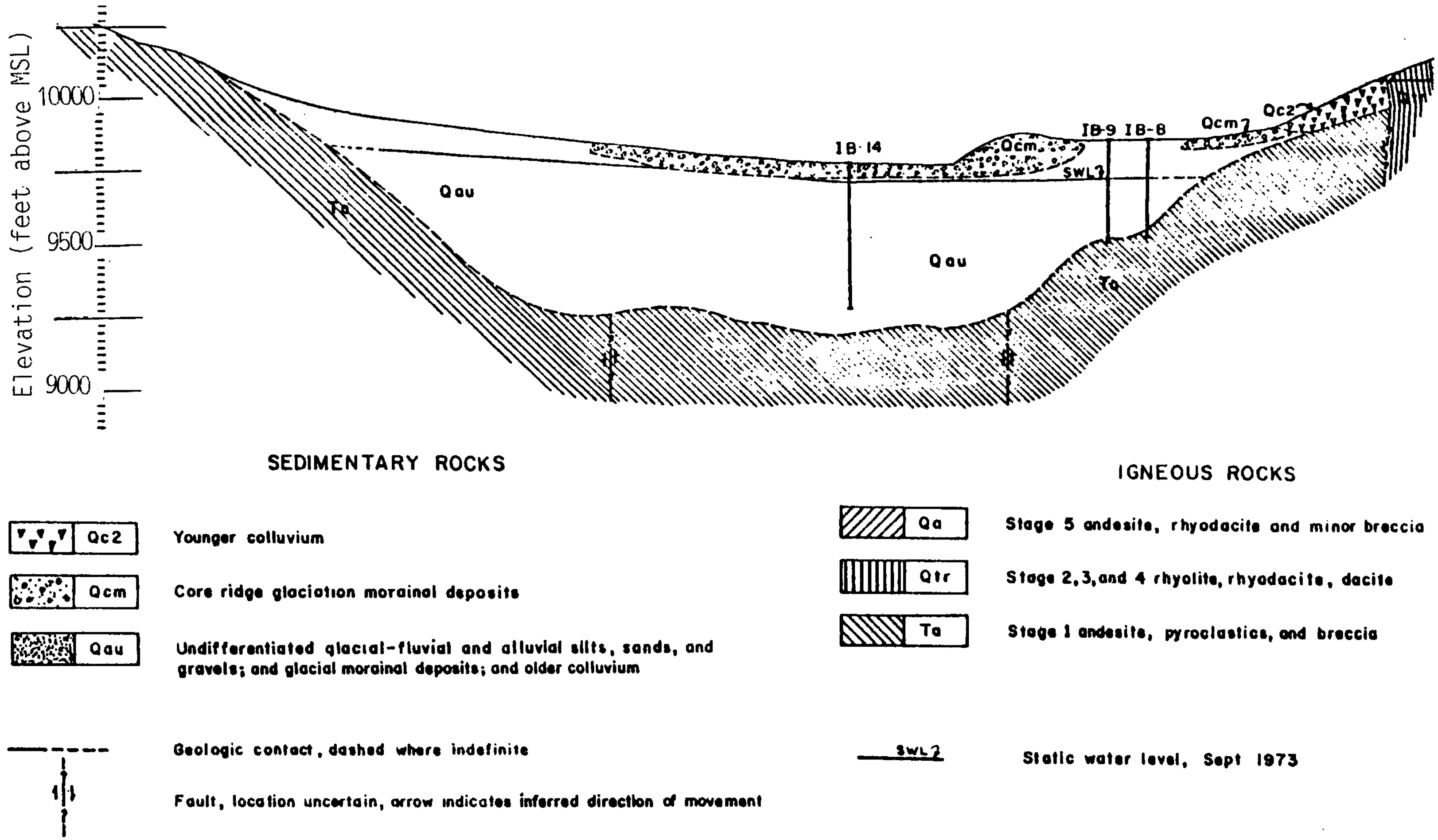

Figure 5. Geologic Cross Section of the Inner Basin, North - South Through Well Nos. 8,9, and 14 (from Harshbarger,1974).

Colluvial deposits lie along the slopes of the mountain and are projected to lie below the alluvial floor of the Inner Basin (Harshbarger, 1974). These deposits are made up of tallus and other such debris that are a result of weathering and gravity forces on the volcanic rocks above. The colluvium is poorly sorted, ranging in size from clay to boulders. The younger colluvial deposits are loose, and the older colluvial deposits are poorly cemented.

The Inner Basin aquifer is primarily composed of unconsolidated alluvial and glacial deposits which overlie the older colluvial deposits and volcanic rocks.

Glacier retreat left deposits of glacial tills within the basin. The poorly sorted tills are composed of particles ranging in size from volcanic ash and silt to boulders. The larger particles are composed of the volcanic rock, including andesite and rhyolite.

Alluvial deposits are found throughout the Inner Basin. These deposits are a result of both glacial outwash and erosion of the glacial till. The maximum thickness of the glacial and alluvial deposits is greater than 500 feet. The alluvium thins out at lower elevations in the Interior Valley.

Fractures

In the plateau area south and east of Flagstaff, groundwater flow is governed by the secondary permeability of the aquifer. The sandstone and limestone rocks which comprise the aquifer are well cemented and have a low primary porosity.

The most important fault system, in regards to this study, is the Anderson Mesa fault. This high angle fault trends northwest and is downthrown on the west side (Akers, 1962). The maximum topographic displacement is approximately 400 feet and the stratigraphic displacement is projected to be as high as 700 feet (Harshbarger, 1977). Figure 6 is a surface geologic map of the Lower Lake Mary area. It contains the location of the fault system and the Lake Mary well field. Figure 7 is a geologic cross-section which cuts through Lake Mary well no. 4.

Running nearly parallel to the Anderson Mesa fault is the Lake Mary fault. The latter is a high-angle fault and is downthrown on the east side (Harshbarger, 1977). The stratigraphic displacement ranges from less than 200 to over 600 feet.

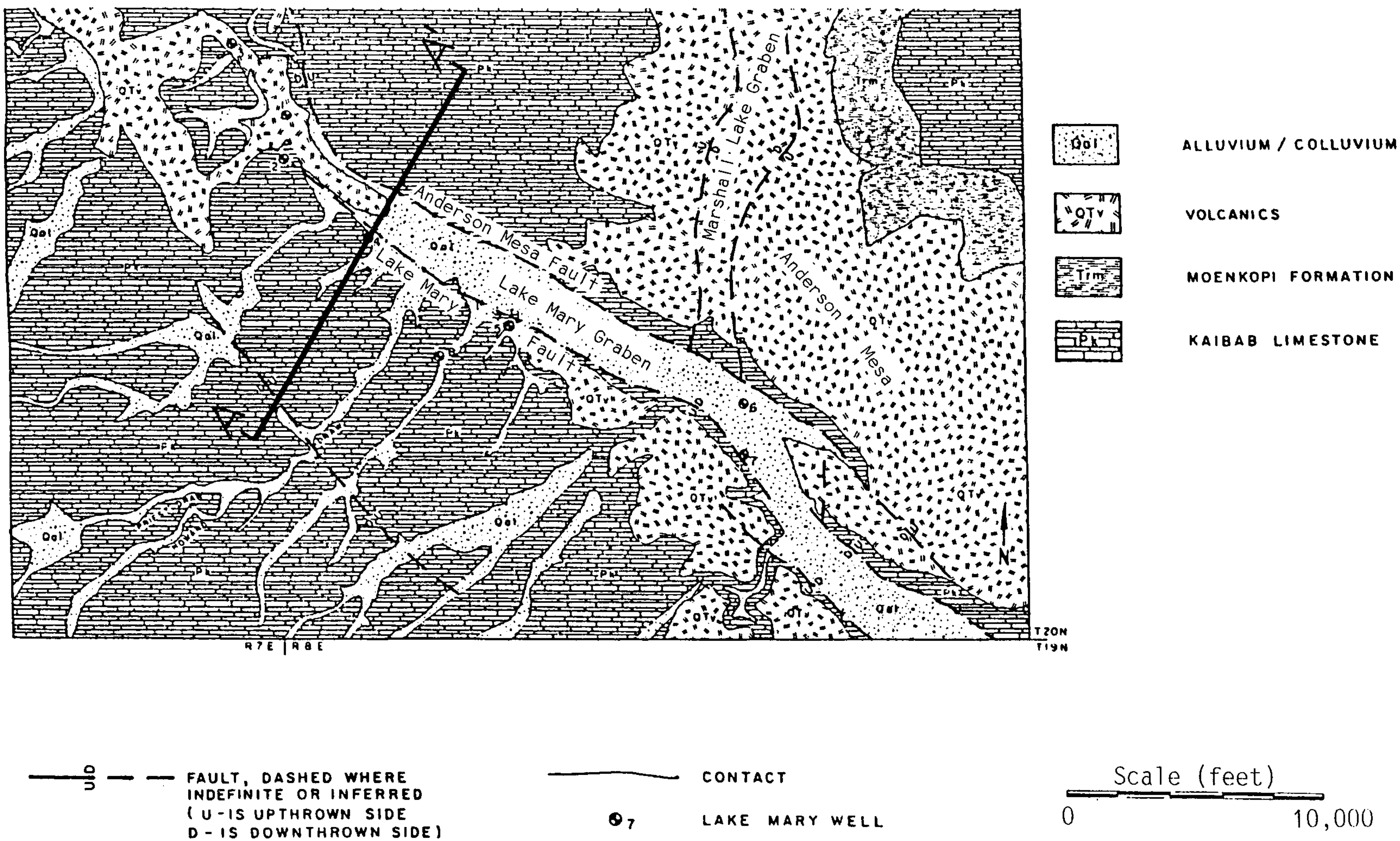

Figure 6. Geologic Map of Lake Mary Well Field (from Duren, 1983).

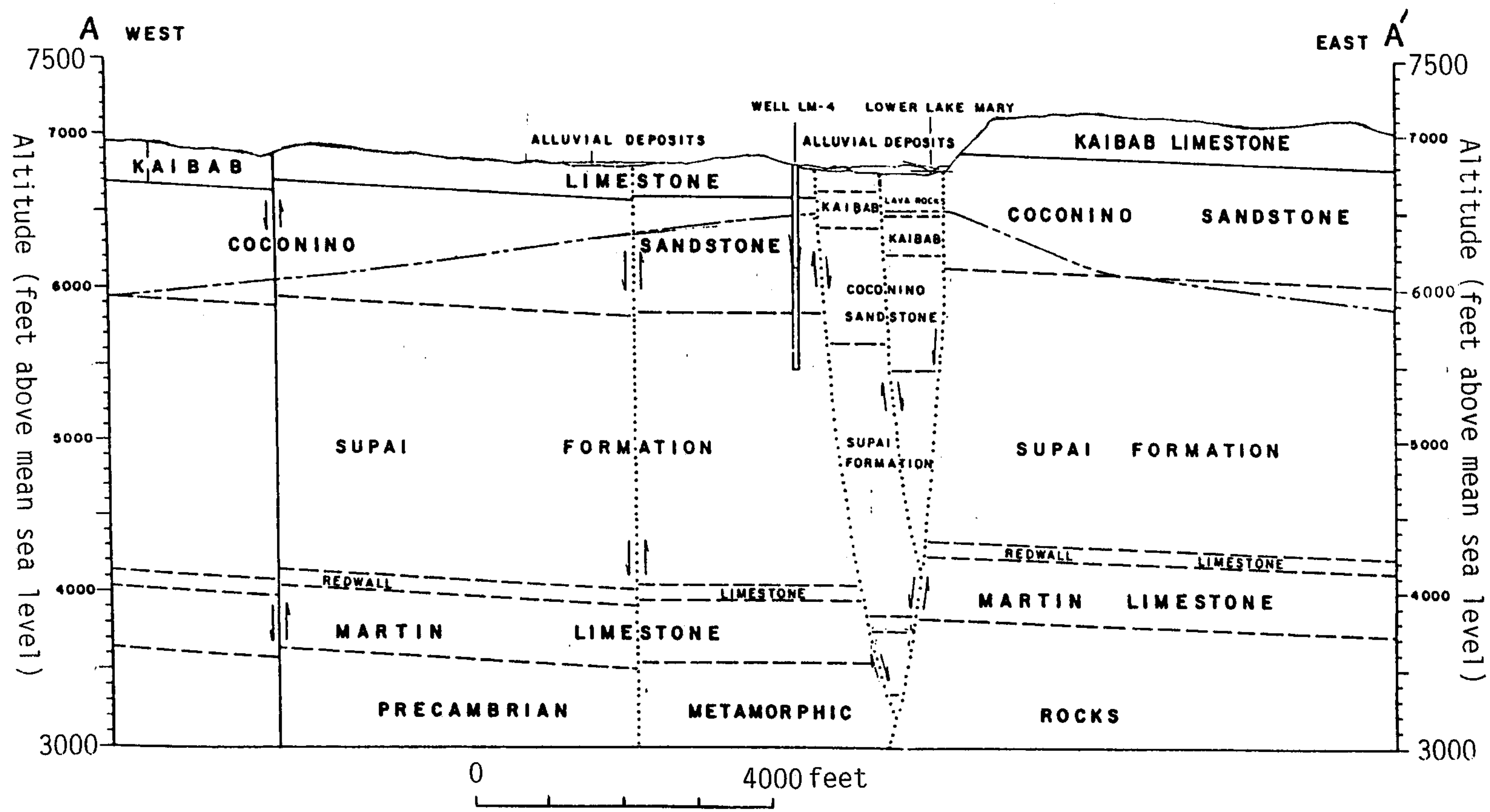

Figure 7. Geologic Cross-Section of Lake Mary Graben.
A-A' of Figure 6 (from Harshbarger, 1976).

These two faults surround the Lake Mary graben which underlies the Upper and Lower Lake Mary reservoirs. The graben is subdivided into smaller graben blocks by smaller parallel faults (Figure 7).

Two north trending faults run transverse to the Lake Mary graben and form the boundaries of the Marshall Lake graben. Geophysical data indicate that where the two grabens intersect, the fracturing is most intense (Harshbarger, 1977). Within the Lake Mary graben, joints and minor faults within the consolidated sedimentary rocks are probably more prevalent than at a distance from the graben.

Observations from well logs and outcrops indicate that some units of the Paleozoic rocks are sufficiently fractured to transmit ground water. Harshbarger (1977) used geophysical logs to observe fractures in the Kaibab Limestone, Coconino Sandstone, and the transition zone of the Supai. The fractures appear to end in the finer sediments of the three members of the Supai. Fracturing again is apparent in the lower portion of the Supai, the Redwall Limestone and the Martin Group.

In the Kaibab Limestone, the fractures have been widened due to dissolution of the soluble limestone by water. In the area of the Lake Mary fault, this solutioning is quite apparent from the surface. A few hundred yards to the south of Lake Mary well #4, large solution cavities were dammed off from the Lower Lake Mary to keep large quantities of surface water from draining to the subsurface. A recent earthen dam was placed there in approximately 1980. The photograph in Figure 8 shows an open solution cavity near the dam.

The Harshbarger investigations indicate that solution cavities have developed in the Redwall and Martin units as well. The fracturing associated with the Lake Mary graben is also thought to extend to the Redwall and Martin units, perhaps creating a hydraulic link with the ground water above.

In the Woody Mountain area, the Oak Creek fault is the largest, extending from Sedona to an area west of Flagstaff. The Woody Mountain and Dunnam faults transverse the Oak Creek fault. As in the Lake Mary graben, the fracturing in the Woody Mountain area is extreme, which does facilitate ground-water flow to the well field. Figure 9 contains a surface geologic map of the area, including faults and well locations.

Hydrogeology

Lake Mary Well Field

The Coconino Sandstone and the transition zone in the upper Supai Formation contain the primary aquifer (referred to as Coconino below) in the plateau region just

Figure 8. Photograph of Solution Opening (Location: SW1/4,NE1/4,NE1/4 of Sec. 19, T.20N., R.8E.; Taken from the Dike South of Lake Mary Well #4, Looking Southwest).

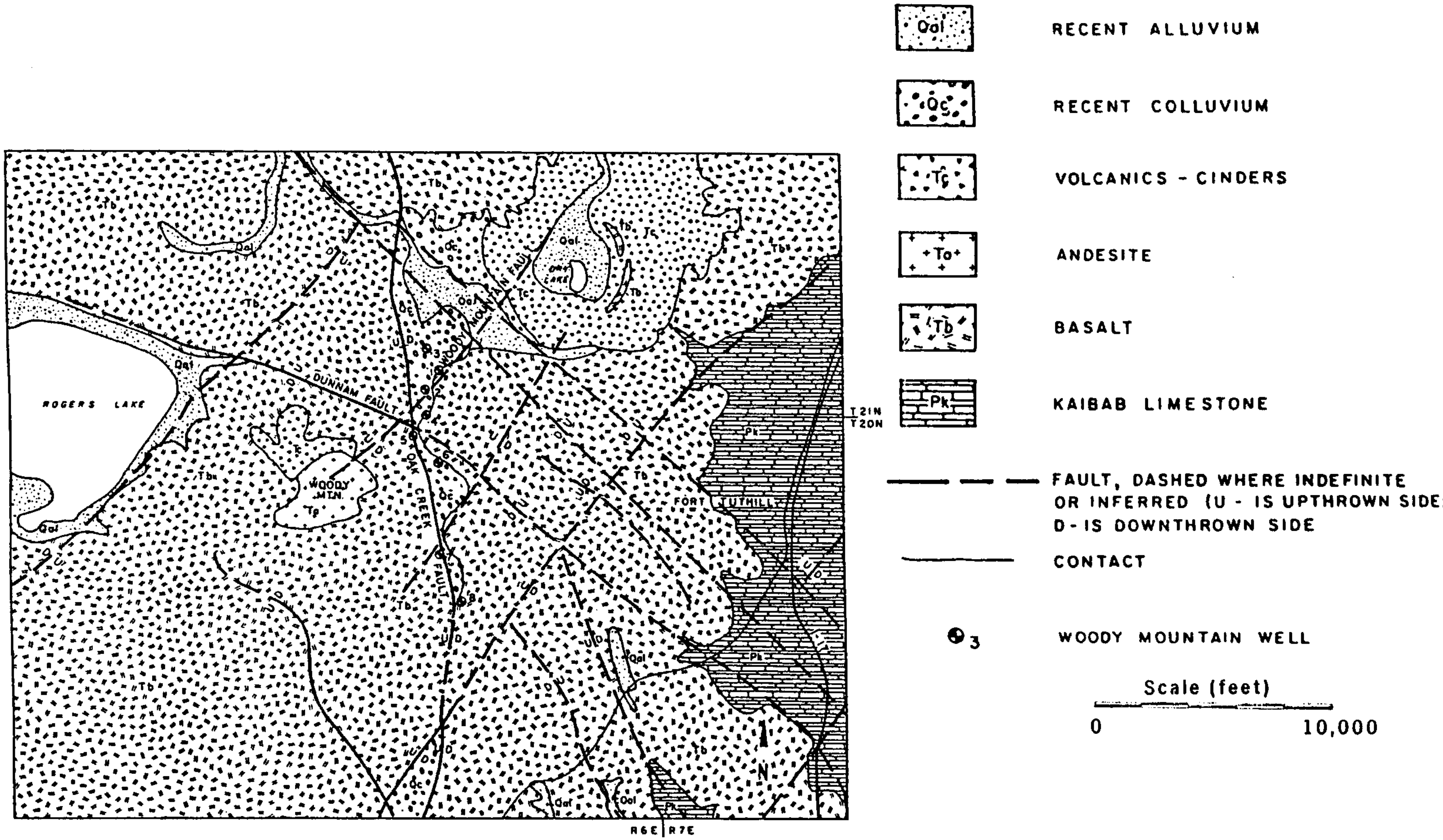

Figure 9. Geologic Map of Woody Mountain Well Field (from Duren, 1983).

south of Flagstaff. The Lake Mary and Woody Mountain well fields draw from this aquifer as do smaller community wells in the area.

Figure 10 contains a map of static ground water elevations based on data collected in Table A.1. of Appendix A. A major recharge area (as apparent by a ground-water mound) is near Hoxworth Springs, south of the Lake Mary well field. This would indicate that the watersheds of Newman Canyon, Elk Meadows and others are contributing substantial recharge to the aquifer.

The average annual precipitation recorded at Pulliam Airport was 19.50 inches, as mentioned previously. The average surface run-off into Upper Lake Mary is 2.7 inches per square mile of watershed (Harshbarger, 1976). Although the majority of the precipitation is lost through evapo-transpiration, a percentage infiltrates through the alluvial deposits, fractured Kaibab, and/or volcanic rocks in the area.

Both of the conflicting estimates of sustained yield to the Lake Mary well field, discussed in the Introduction, assume that the mounded area to the southwest of the well field is the primary recharge source. However, the location of that mound is based largely on the data from one well: the Wichita Industries test hole. Personal observation has revealed that water is cascading into this

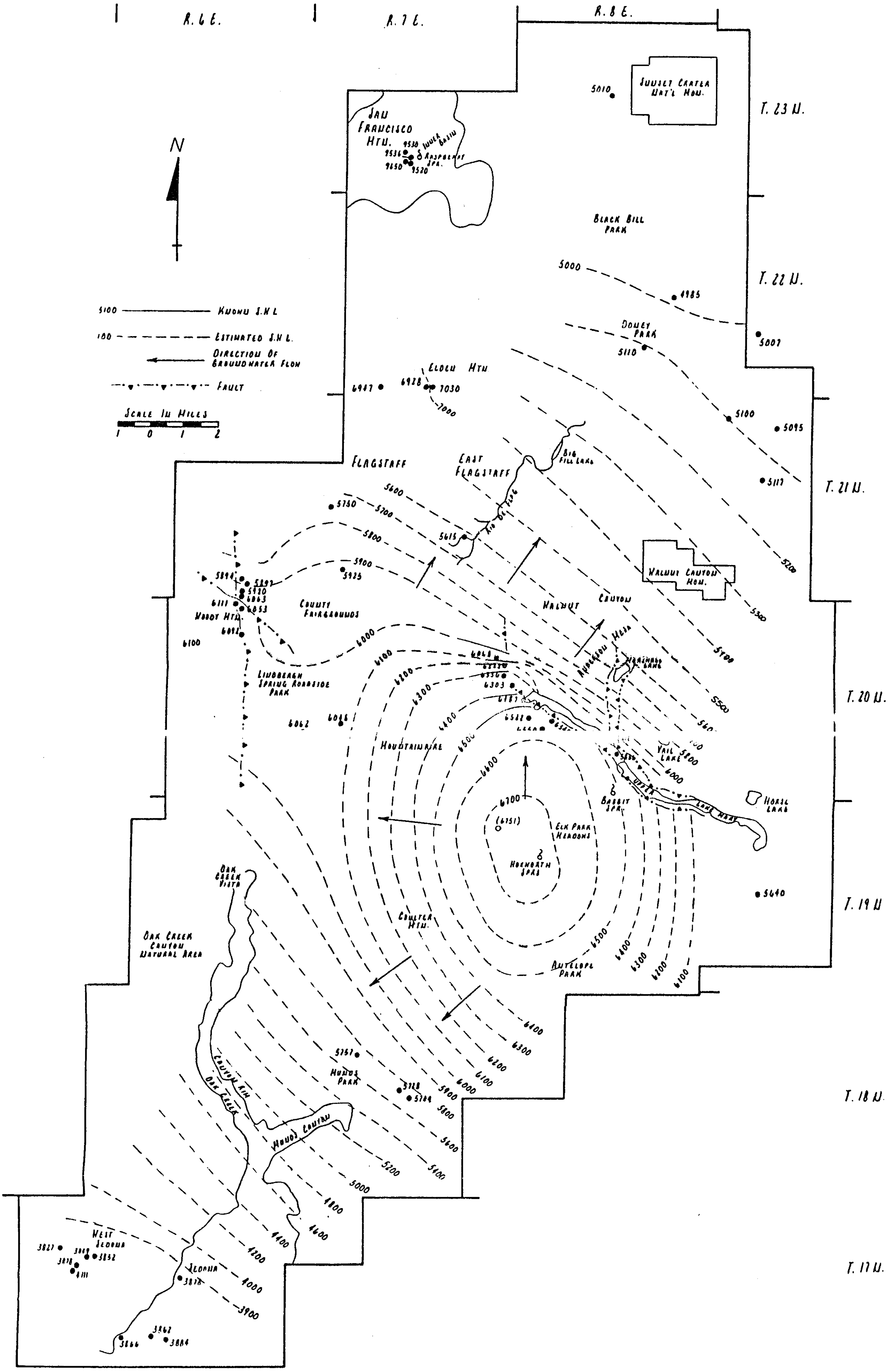

Figure 10. Map of Groundwater Elevations in Region.

hole, probably from a perched water source. An electric tape water level indicator was used to take the measurements used in the previous studies (Water Department, 1983). It may be possible that cascading water falling onto the probe at the end of the electric tape created a false reading. A false reading would occur if the cascading water triggered a signal from the probe before it actually was lowered to the water table. The water table would actually be lower than recorded, if that occurred.

The second important recharge discussion is the effect of the Lake Mary graben upon recharge. A study by Blee (1984) revealed that a large amount of water was lost from the Upper Lake Mary reservoir by seepage and evaporation. From the period 1950-1971, Blee calculated that 28% of the inflow into Upper Lake Mary was lost due to evaporation and 42% was loss to seepage from the lake. The conflicting studies by Duren and Harshbarger differ as to whether this seepage and seepage from Lower Lake Mary is available as recharge to the Lake Mary well field.

Water levels within the graben are lower than in the Coconino aquifer to the west (Hargis and Montgomery, 1980). The gradient within the graben is to the southeast from the dam of Lower Lake Mary to the intersection of the Marshall Lake and Anderson Mesa grabens. At that location, the writers of the Hargis and Montgomery report speculate that the ground water in the Coconino aquifer within the graben drains most readily to the Redwall-Martin formations below.

The Duren report and Harshbarger report differ as to the ability of the present well field to draw the recharge water from within the graben. A pump test run at Lake Mary well no. 4 by Harshbarger and Associates (1976) indicates that a recharge boundary (the graben) is intercepted by the cone of depression and that the faults act to transmit the water. Duren (1983) concludes that the faults act as a barrier to ground water flow, thus eliminating the opportunity for seepage from Lower and Upper Lake Mary to reach the Lake Mary wells.

Beyond The Lake Mary Well Field Vicinity

A second aquifer system underlies the Coconino. The lower portion of the Supai, the Redwall Limestone, and the Martin Group form this aquifer (termed the Redwall). According to Harshbarger, the Redwall aquifer is under artesian pressure. The middle portion of the Supai is an aquatard. The water level in the Redwall is thought to be below that of the Coconino aquifer, thus creating a downward vertical gradient. Very little data exists on this subject due to the depth of the Redwall aquifer.

Beyond the vicinity of the Lake Mary well field area, the water level is below the Coconino formation (Harshbarger, 1977). It is thought that the ground water in the Coconino slowly drains into the Supai and Redwall Limestone and then moves horizontally to discharge points. This movement is to the southwest to springs along Oak Creek and the Verde River; and to the northeast to springs which discharge from solution openings in the Redwall Limestone along the Little Colorado River (Harshbarger, 1976). Wells in the Sedona area which draw water from the Redwall Limestone may possibly receive recharge originating from the Lake Mary graben and/or the Elk Park Meadows area.

Localized zones of perched water exist on the plateau. Near the Lake Mary graben, water infiltrates into the alluvium and fractured volcanic rocks and perches upon unfractured rocks or alluvial deposits of low permeability. Both Hoxworth and Babbit Springs result from this type of situation. These springs are located to the south of Lower Lake Mary.

Woody Mountain Well Field

The Coconino aquifer is the source of water supply to the Woody Mountain well field. The area is highly fractured (see Figure 9) and it is possible that recharge through these fractures is significant. Likely recharge sources are the ephemeral streams in the area and also Rogers Lake. Ground-water levels on the west side of the Oak Creek fault are not much higher than on the east side; thus the fault may not act as a barrier to flow (Duren, 1983).

Inner Basin Well Field

In the Inner Basin, the primary aquifer is the permeable outwash, alluvial and colluvial deposits. The young colluvial deposits at the sides of the Inner Basin receive run-off from the peaks above and transmit the water to the aquifer (Harshbarger, 1974). The water then flows down along the Inner Basin (see Figure 4). The saturated thickness of the alluvium is very small in the middle of the Interior Valley. The Harshbarger study suggested that the water infiltrates into the fractured volcanics below the colluvium.

Surface run-off from the Interior Valley is not frequent, thus infiltration into the alluvium takes place rapidly. In those places where the alluvial deposits are underlain by poorly sorted glacial tills, perched water zones form and springs emerge, such as Raspberry Spring. The springs are intermittent and flow is slight in the late summer (Harshbarger, 1974).

SECTION 3

SAMPLE LOCATIONS AND ANALYSES

Sample locations were chosen in order to accomplish both of the study objectives. However, the small number of operable wells in the area limited the number of samples which could be taken.

In order to identify the recharge source(s) for the Lake Mary well fields, the values for the major ions and the natural isotopes, deuterium and oxygen-18, from potential recharge sources will be compared with values from well discharges.

The location of the samples gathered for this study are shown in Figure 11. Table 1 contains the descriptions of the surface water and spring samples, and Table 2 contains the descriptions of the wells which were sampled. The columns of greatest interest on Table 2 are the perforation intervals of the well casing and the adjacent formations from which the ground water is drawn. The samples were taken over a period from September 1983 through January 1984. Sample collection was dependent upon knowledge of the site, permission for site entry, and time available.

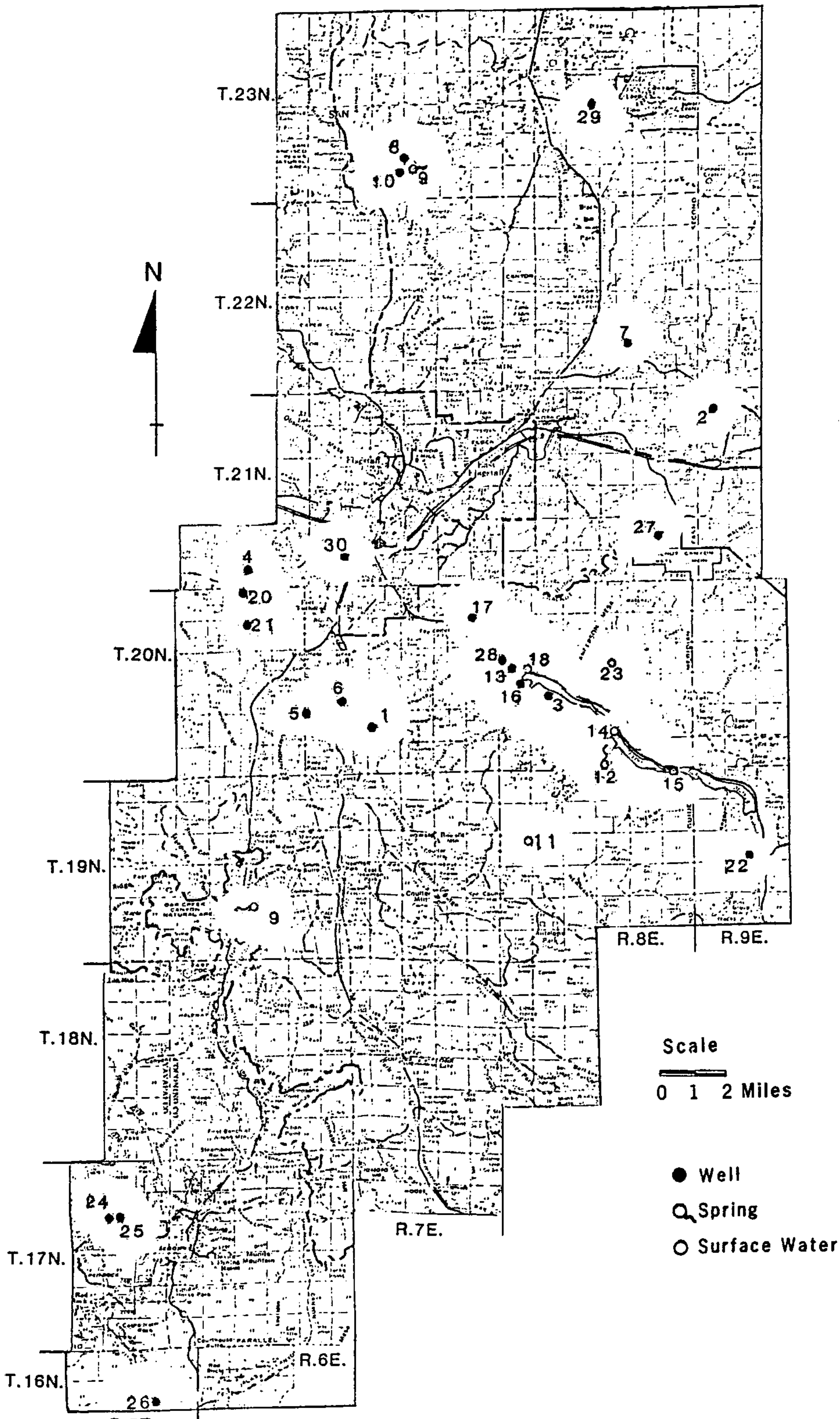

Figure 11. Sample Locations in Study Area. (Coconino National Forest Map).

TABLE 1. SURFACE WATER AND SPRING SAMPLE SITE DESCRIPTIONS

Sample	Local ID	Site Descriptions
9	(A-23-7)27ccc	Raspberry Spring, Inner Basin. Discharge of 4 GPM.
11	(A-19-8)18a	Shallow Creek (sample at 1 ft. depth). Just upstream from Hoxworth Spring.
12	(A-20-8)34cdb	Babbit Spring. Discharge of 10-15 GPM
14	(A-20-8)27dc	Upper Lake Mary, at depth of approximately 20 ft. Taken at inlet structure near spillway. Depth of Lake Mary approximately 33.2 ft.
15	(A-19-8)1ba	Upper Lake Mary, at depth of 3 ft. Taken off beach area.
18	(A-20-8)18dd	Lower Lake Mary, at depth of 2.5 ft. Taken across lake from well #4.
19	(A-19-6)27ebcc	Fracture opening in Supai formation (?), along Oak Creek Canyon. Discharge unknown.
23	(A-20-8)15ca	Marshall Lake, taken at 1 ft. depth. Marsh conditions.

TABLE 2. WELL CONSTRUCTION AND STATIC WATER LEVEL DATA

Sample	Site Description	Local ID	Well Depth (Ft.)	Casing Depth (Ft.)	Casing Diameter (In.)	Perf. Interval (Ft.)	Elev.* at Well Head(Ft.)	Formations Penetrated or at Perforation	SWL Elev.* (Ft.)
1	Mtnaire Village	(A-20-7)28bcc	800(?)	30	10.0 (Hole)	Open Hole Beyond 30'	6785	[a]Kaibab (145-405) Coconino (405-800)	6095(?)(7/83) 5994(?)(3/78)
2	Doney Park Mtn View Ranchos #2	(A-21-9)6ca	1675	1675	8	1275-1675(?)	6430	[b]Supai	5100 (1975)
3	Lake Mary #5	(A-20-8)20dbc	1279	0-279 267-1279	24 20	650-1279	6817	[c]Kaibab (0-260) Coconino (260-1010) Supai (1010-1279)	6540.4 (11/82) 6536 (10/76) 6542 (3/75)
4	Woody Mtn #3	(A-21-6)35bcc	1820	1820	14	1144-1820	7130	[b]Coconino Supai	5894 (11/82) 5905 (10/76) 5917 (11/58)
5	Kachino #1	(A-20-7)30bbb	1075	0-726 704-1065	12 10	626-726 965-1065	6675	[a]Kaibab (20-250) Coconino (250-1065) Supai (1065-1075)	6062 (7/80) 6045.2 (4/78) 6052 (8/65)
6	Kachino #3	(A-20-7)20cca	1210	0-968 968-1210	12 10	637-1210 (856-861 closed)	6715	[a]Kaibab (0-250) Toroweap (250-410) Coconino (410-1005) Supai (1005-1210)	6048 (12/79) 6050.2 (4/78) 6052 (12/74)
7	Doney Pk Koch #5	(A-22-8)27daa	1772	0-1651 1651-1772	8 7	1397-?	6620	[b]Supai	5110 (9/80) 5110 (1971)
8	Inner Basin #11	(A-23-7)27cbd	485	485	12	160-485	9482	[d]Glacial Outwash (0-470) Volcanics (470-485)	Artesian Flow

TABLE 2. (continued)

Sample	Site Description	Local ID	Well Depth (Ft.)	Casing Depth (Ft.)	Casing Diameter (In.)	Perf. Interval (Ft.)	Elev.* at Well Head(Ft.)	Formations Penetrated or at Perforation	SWL Elev.* (Ft.)
10	Inner Basin #9	(A-23-7)33aab2	352	0-196 186-352	20 16	196-342	9793	[d]Glacial Outwash (0-340) Volcanics (340-352)	9650 (10/76) 9649.8 (9/73)
13	Whitley	(A-20-8)18cac	675	675	6	555-675	6830	[c]Lava (4-102) Kaibab (102-382) Coconino-Supai (382-675)	6302.5 (4/78) 6306
16	Lake Mary Well #4	(A-20-8)19aba	1345	0-260 260-1300	28 20	800-1280	6809	[c]Kaibab (20-222) Coconino (222-962) Supai (962-1345)	6487 (11/82) 6480.5 (3/75) 6474.1 (2/73)
17	Heckethorn Well	(A-20-7)12bba	1074	20	12	Open Hole Beyond 20'	6839	[e]Kaibab (10-180) Coconino (180-960) Supai (960-1074)	5939 (6/65)
20	Woody Mtn #5	(A-20-6)2bbc	1583	1583	12	1150-1583	7187	[b]Coconino Supai	6097 (11/82) 6087 (10/76) 6085 (9/66)
21	Woody Mtn #7	(A-20-6)11bba	1720	1720	14	1122-1720	[f]7175	Coconino-Supai	6092 (11/82)
22	Pine Grove Campground	(A-19-9)17dcd	1700	1700	6	1400-1700	[f]6960	Volcanics (0-160) Kaibab (160-530) Coconino (530-1190) Supai (1190-1700)	5640 (12/67) 5651 (8/67)

TABLE 2. (continued)

Sample	Site Description	Local ID	Well Depth (Ft.)	Casing Depth (Ft.)	Casing Diameter (In.)	Perf. Interval (Ft.)	Elev.* at Well Head (Ft.)	Formations Penetrated or at Perforation	SWL Elev.* (Ft.)
24	Sedona-SW Ctr #8	(A-17-5)11ccb	800	0-600 501-717 706-791	16 14 10	600-791	[f]4380	[g]Redwall	3849 (7/83) 3844 (9/75) 3849 (8/75)
25	Sedona-Harmony Hills Well	(A-17-5)11cdb	720	684	6	?	[f]4415	[g]Supai-Redwall	3852 (7/83) 3847 (4/75) 3840 (1962)
26	Sedona-Valley Vista	(A-16-5)14ddd	582	578	6	498-578	[f]4095	[g]Supai	3727 (7/83) 3712.5 (8/74)
27	Walnut Canyon Nat'l Mon.	(A-21-8)26dab	2007	0-13 13-2007	10 8	1493-2007	6710	[e]Kaibab (0-280) Coconino (280-920) Supai (920-?)	5174 (8/70)
28	Lake Mary #2	(A-20-8)18bcc	1091	0-11 11-420 420-1091	38 26 20	569-1081	6837	[a]Kaibab (10-260) Coconino (260-1010) Supai (1010-1091)	6336 (11/82) 6363 (3/75) 6405 (4/65) 6385 (1964)
29	Sunset Crator Nat'l Mon.	(A-23-8)21aab3	2210	720	12 12 Hole	Open Hole Beyond 720'	6920	[h]Volcanics (0-680) Kaibab (680-985) Coconino (985-1710) Schnebly Hill (1710-2210)	4960 (1960) ?
30	Mtn Dell Jack's Hauling	(A-21-7)32bbc2	1350	100	8	Open Hole Beyond 100'	6900	[e]Coconino Supai	5925 (5/75)

[a]Fousel (1983),Manera (1975)
[b]McGavock (1968)
[c]Harshbarger (1977)
[d]Harshbarger (1974)
[e]Driller's log
[f]Elevation estimated from topographic map
[g]Levings & Mann (1980)
[h]Christensen (1982)
*Elevation in feet above mean sea level
(?) Questionable or unknown datum

Sample Locations

Using the knowledge of the site geology, potential recharge sources of the Lake Mary well field were chosen and sampled.

Sample 11, as described in Table 1, was from a small ephemeral stream near Hoxworth Spring in the area of the groundwater mound southwest of the well field. Hoxworth Spring was not flowing significantly at the time. Sample 12 was taken from Babbit Spring which discharges from alluvial deposits overlying the Kaibab (as discussed in Section 2). Samples 14 and 15 were taken from Upper Lake Mary at different locations and depths. Sample 18 was taken from Lower Lake Mary.

Marshall Lake was also sampled (23). It is on Anderson Mesa, within the fractured Marshall Lake graben. This lake is probably not a recharge source for the Lake Mary well field, but it may be for the Coconino-Supai aquifer to the northeast.

For the best results of an isotopic study, a complete spatial and seasonal sample record of potential recharge sources, including precipitation, is required. However, limits on the scope of this project, including time and funding, did not permit such a complete effort.

The samples are assumed to represent the average values of potential recharge (as discussed in Section 5) with the full realization that this assumption is only a rough approximation of the real system.

Samples were taken to identify potential discharge locations of the recharge water discussed previously. Three of the wells in the Lake Mary well field were operable and a sample was taken from each (sample nos. 3, 16 and 28 described in Table 2). Sample nos. 13 and 17 are from nearby wells which supply small housing communities.

If the Lake Mary graben acts as a drain to the Redwall aquifer, samples taken downgradient in that aquifer may yield results similar to the Lake Mary well field area.

The static water levels shown in Figure 10 represent levels in wells penetrating the Coconino near Lower and Upper Lake Mary, and as far southwest as Munds Park. The water levels near Sedona represent the static head within the Redwall. As discussed earlier, it has been assumed in earlier reports that the Coconino aquifer eventually drains into the Redwall aquifer. It is also possible that the Redwall aquifer receives recharge through the Lake Mary graben. If this is the case, the ground-water flow pattern derived from Figure 10 may not represent that within the Redwall itself. However, the main source of recharge for the Redwall aquifer in the Sedona area, may still likely come from the plateau area to the northeast, including Lower and Upper Lake Mary.

Sample nos. 24, 25 and 26 were taken from wells which supply water to the City of Sedona, and which penetrate the Supai-Redwall aquifer.

Sample no. 19 was taken from a spring along the Oak Creek. It appeared as if the spring was flowing from the fractured Supai Formation, and the sample was taken with thoughts that the water may be representative of recharge from the plateau above. Further field investigation revealed a colluvial deposit just above the spring with boulder size rocks. It is possible that recharge through the colluvial deposits supplies the spring. Discussion with a nearby resident revealed that the spring flows year around, including the dry late-summer, indicating that the source may be the Supai formation.

The ground-water flow pattern reveals a northeast component of flow from Lower and Upper Lake Mary. Sample nos. 2 and 27 were taken from wells which are directly downgradient. Sample no. 7 may be too far to the west to receive the recharge from the Lake Mary graben. All three wells draw water from the Supai Formation. The Coconino Sandstone is dry at these locations.

Sample no. 22 was taken from a well servicing a Forest Service campground to the south of the head of Upper Lake Mary. This well also draws from the Supai Formation.

Sample nos. 1, 5, 6 and 30 are from wells which supply three small housing communities south of Flagstaff.

The Woody Mountain well field had three wells operating at the time. They are represented by sample nos. 4, 20 and 21.

Wells servicing Bonita Park and the Sunset Crater National Monument have historically obtained water with a greater hardness than wells near Flagstaff. A sample (no. 29) was obtained in order to compare with the wells to the south.

Ground waters of the Inner Basin are represented by sample nos. 8, 9 and 10.

Sample Analyses

Temperature and pH were measured in the field at the time of sampling. An attempt to measure alkalinity in the field was made, but poor analytical technique produced erroneous results. The method to resolve this is discussed in Appendix B. Field measurements were not made for sample 22. This sample was collected by a Forest Service employee due to the short time that the well was operable and accessible.

Samples were collected and analyzed for the major cations and anions. These consisted of calcium, magnesium, sodium, potassium, iron, chloride, sulfate and nitrate. Silica content was also measured.

Twenty-six of the samples were measured for the stable isotopes deuterium and oxygen-18. Tritium was measured in five of these samples in order to examine the travel time of recharge water to selected wells (sample nos. 3, 6, 16, 27 and 28). Due to a limit on funding, not all of the samples could be analyzed for the isotopes.

SECTION 4

CHEMICAL CHARACTERIZATION AND COMPARISONS

The thirty samples were analyzed for the major ions, nitrate, silica and iron in the laboratory. Field measurements were also taken for pH, specific conductance, temperature and alkalinity. By noting similarities amongst the values in the tables, the ground waters can be classified by their major cations and anions.

The results of the pH, specific conductance and temperature analyses are located in Table 3. The remaining results are located in Table 4.

Two techniques were used to determine whether the results were representative of actual values. First, an ion balance of cation and anion values was calculated. As mentioned previously and in Appendix B, procedural difficulties in the analyses of alkalinity required that the alkalinity values be calculated (estimated) using the available data. Thus, determining the ion balance in order to detect analytical error was, unfortunately, not as useful.

TABLE 3. FIELD MEASUREMENTS

Sample	Site Description	Date	Temperature °C	pH	Spec. Cond. at 25°C (umhos/cm)
1	Mountainaire Village	09/21/83	11.3	7.73	340
2	Doney Park, Ranchos #2	09/22/83	17.7	7.44	463
3	Lake Mary #5	09/22/83	11.1	7.31	543
4	Woody Mountain #3	09/22/83	12.8	7.92	213
5	Kachino Village #1	09/23/83	11.1	7.60	344
6	Kachino Village #3	09/23/83	11.1	7.56	355
7	Doney Park, Koch Field #5	09/24/83	15.0	7.33	458
8	Inner Basin #11	09/24/83	4.4	7.10	103
9	Raspberry Spring	09/24/83	5.0	6.62	83
10	Inner Basin #9	09/24/83	3.9	7.18	75
11	Upstream/Hoxworth Spring	09/26/83	13.3	7.29	396
12	Babbit Spring	09/26/83	8.9	7.08	490
13	Whitley Trailer Park	09/26/83	12.2	7.76	289
14	Upper Lake Mary 20' depth	09/27/83	17.2	7.34	94
15	Upper Lake Mary 3.5' depth	09/27/83	20.0	7.62	90

TABLE 3. (contined)

Sample	Site Description	Date	Temperature °C	pH	Spec. Cond. at 25°C (umhos/cm)
16	Lake Mary #4	09/27/83	11.1	7.65	258
17	Heckethorn Well	09/27/83	11.7	7.28	484
18	Lower Lake Mary 2.5' depth	09/28/83	18.3	8.11	120
19	Spring in Oak Creek Canyon	11/01/83	11.7	7.85	260
20	Woody Mountain #5	10/13/83	11.9	8.17	202
21	Woody Mountain #7	10/13/83	12.9	8.06	193
22	Pine Grove Campground	10/14/83	-	-	-
23	Marshall Lake	11/03/83	5.0	8.17	154
24	SW Center #8, Sedona	11/03/83	18.3	7.14	692
25	Harmony Hills, Sedona	11/03/83	18.9	7.07	696
26	Valley Vista, Sedona	11/29/83	16.7	7.86	265
27	Walnut Canyon Nat'l Mon.	11/30/83	8.9	7.50	382
28	Lake Mary #2	01/16/84	10.5	7.35	541
29	Sunset Crator Nat'l Mon.	01/16/84	15.0	6.20	936
30	Mountain Dell Well	01/16/84	10.0	7.31	400

TABLE 4 CHEMICAL DATA

(All Values in mg/l)

Sample	Site Description	Date	Na	K	Ca	Mg	Total Hard. as $CaCO_3$	Alkalinity* as $CaCO_3$	Cl	SO_4	NO_3	Total Fe	SiO_2
1	Mountainaire	09/21/83	3.6	0.5	39.6	23.5	195.8	168	3.7	0.5	1.6	0.8	14.6
2	Doney Park, Ranchos #2	09/22/83	13.6	1.3	46.7	27.5	229.8	190	27.0	13.0	1.3	--	12.2
3	Lake Mary #5	09/22/83	4.2	0.5	55.8	48.8	340.3	327	2.7	3.0	1.5	--	8.6
4	Woody Mtn. #3	09/22/83	4.4	0.9	20.8	10.8	96.5	105	2.5	2.5	0.9	--	18.3
5	Kachino #1	09/23/83	4.2	0.7	43.4	22.0	199.0	226	2.6	2.0	1.1	--	11.6
6	Kachino #3	09/23/83	4.7	0.6	47.6	16.6	187.2	193	2.7	2.5	2.2	--	15.8
7	Doney Park, Koch #5	09/23/83	4.4	1.6	51.8	33.2	266.0	247	6.3	2.0	7.1	--	21.6
8	Inner Basin #11	09/24/83	3.1	2.4	4.8	2.2	21.0	30.2 (27.4)	0.8	1.5	0.9	--	45.7
9	Raspberry Springs	09/24/83	3.1	1.9	3.2	1.5	14.0	19.8 (17.8)	1.2	2.5	1.3	--	37.2
10	Inner Basin #9	09/24/83	3.1	1.9	4.4	2.1	19.5	23.0 (25.0)	1.0	1.5	0.9	--	37.7
11	Upstream/Hoxworth Spr.	09/26/83	3.9	0.9	36.4	26.4	199.5	207	3.1	1.5	1.3	--	14.6
12	Babbit Springs	09/26/83	5.8	0.5	61.9	31.7	285.0	279	4.9	1.8	1.3	0.4	21.2
13	Whitley Trailer Park	09/26/83	4.2	0.3	37.2	11.4	140.0	165	2.8	4.0	1.1	--	7.4
14	Upper Lake Mary/20'	09/27/83	1.9	1.3	7.0	4.0	34.0	36.3	1.9	4.0	1.3	1.8	10.8
15	Upper Lake Mary/3.5'	09/27/83	2.2	1.1	6.8	5.1	38.0	34.9	1.4	3.0	1.3	2.2	10.6

TABLE 4 (continued)

Sample	Site Description	Date	Na	K	Ca	Mg	Total Hard. as $CaCO_3$	Alkalinity* as $CaCO_3$	Cl	SO_4	NO_3	Total Fe	SiO_2
16	Lake Mary #4	09/27/83	2.5	0.3	29.6	16.6	142.5	142	1.2	1.0	0.9	--	8.7
17	Heckethorn	09/27/83	5.0	0.6	61.5	36.2	303.0	292	3.5	1.0	1.3	--	12.0
18	Lower Lake Mary/2.5'	09/28/83	1.9	1.5	11.0	4.7	46.9	49.4 (49.9)	1.6	1.0	1.1	0.7	8.0
19	Spr. in Oak Creek Canyon	11/01/83	3.3	0.7	30.0	17.2	146.0	141	2.1	1.0	1.1	--	14.6
20	Woody Mountain #5	10/13/83	5.3	1.3	22.4	12.3	106.8	110.5	2.2	2.0	1.1	--	29.3
21	Woody Mountain #7	10/13/83	4.7	1.0	18.8	13.6	103.0	109.3	1.8	2.0	0.4	--	17.1
22	Pine Grove Campground	10/14/83	7.5	1.0	51.3	26.6	237.5	(245)	5.0	2.0	0.9	--	15.9
23	Marshall Lake	11/03/83	6.7	5.8	8.0	7.9	52.6	73	3.9	0.5	0.9	0.5	18.4
24	SW Center #8	11/03/83	11.9	1.3	75.8	32.2	322.0	300	19.5	5.8	3.5	--	17.4
25	Harmony Hills	11/03/83	11.4	1.2	74.4	30.6	312.0	306	16.5	5.5	3.5	--	16.8
26	Valley Vista	11/29/83	7.2	1.1	24.1	11.4	107.0	117	4.9	1.0	1.3	--	22.5
27	Walnut Canyon	11/30/83	5.6	0.7	42.7	25.1	210.0	195	6.9	1.5	7.5	--	10.0
28	Lake Mary #2	01/16/84	5.6	0.6	62.8	46.9	350.0	346	2.9	1.0	1.1	--	10.0
29	Sunset Center	01/16/84	15.6	2.0	130.1	32.8	460.0	450	14.0	2.0	8.0	--	41.0
30	Mountain Dell	01/16/84	4.2	1.3	56.9	26.7	252.0	250	3.1	2.5	5.3	--	14.1

*Values in parentheses used to bring ion balance to zero.

However, the calculations were still made in order to verify that the analytical work was reasonably accurate. The equation below was used to calculate the ion balance.

$$\frac{\sum \text{anions} - \sum \text{cations}}{\sum \text{anions} + \text{cations}} \times 100 = \%\ \text{difference.}$$

With ion values in meq/1, a value of 5% or less is considered within analytical error. It should be noted that samples 1, 5, 13 and 15 are above that limit, however, the estimated alkalinity values will remain the same (see Table 5).

Next, the results from this study were compared with historical data for these sites. Water quality data from various sources are listed in Tables A.2 and A.3 in Appendix A. Generally, the data compared quite favorably. Some trends of the comparison are noted below.

The historical data itself varied considerably from one sample time to the next, with no specific trend noted. The calcium and pH data of this study were often lower than in previous analyses. Certain recent values for the Mountain Dell well and the Doney Park #5 well varied significantly with previous values.

Water Quality Characterization

A comparison of data, such as follows, will not provide a clear understanding of the geochemical processes that created the values. In order to identify the

TABLE 5. ION BALANCE

Sample	Site Description	Total Anions (meq/1)	Total Cations (meq/1)	Balance %
1	Mountainaire Village	3.50	4.11	-8.0
2	Doney Park, Ranchos #2	4.85	5.22	-3.7
3	Lake Mary #5	6.70	7.00	-2.2
4	Woody Mountain #3	2.24	2.14	2.3
5	Kachino Village #1	4.65	4.18	5.3
6	Kachino Village #3	4.02	3.96	0.8
7	Doney Park, Koch Field #5	5.27	5.55	-2.6
8	Inner Basin #11	0.67	0.62	3.8
9	Raspberry Spring	0.50	0.46	4.1
10	Inner Basin #9	0.54	0.57	-2.7
11	Upstream/Hoxworth Spring	4.28	4.18	1.2
12	Babbit Spring	5.77	5.97	-1.7
13	Whitley Trailer Park	3.48	2.99	7.5
14	Upper Lake Mary 20' depth	0.88	0.86	1.4
15	Upper Lake Mary 3.5' depth	0.82	0.97	-8.0

TABLE 5. (continued)

Sample	Site Description	Total Anions (meq/1)	Total Cations (meq/1)	Balance %
16	Lake Mary #4	2.91	2.96	-0.9
17	Heckethorn Well	5.98	6.28	-2.4
18	Lower Lake Mary 2.5' depth	1.07	1.08	-0.4
19	Spring in Oak Creek Canyon	2.92	3.07	-2.5
20	Woody Mountain #5	2.33	2.40	-1.5
21	Woody Mountain #7	2.28	2.29	-0.2
22	Pine Grove Campground	5.10	5.10	0.0*
23	Marshall Lake	1.59	1.51	2.6
24	SW Center #8	6.72	6.99	-2.0
25	Harmony Hills Sedona	6.75	6.76	-0.1
26	Valley Vista Sedona	2.52	2.48	0.8
27	Walnut Canyon Nat'l Mon.	4.24	4.46	-2.5
28	Lake Mary #2	7.03	7.25	-1.5
29	Sunset Crator Nat'l Mon.	9.56	9.92	-1.8
30	Mountain Dell Well	5.22	5.25	-0.3

*Alkalinity value calculated for ion balance of zero.

geochemical process involved, a more rigorous analysis of the equilibrium relationship between the water and host mineral would be required. This type of analysis would include the calculation of saturation indices based on ion activities, ionic strengths and solubility products. However, using the knowledge of the aquifer material and flow regime, qualitative observations can be used to speculate about the origins of the water quality values.

The results of Table 4 are plotted in Figures 12 and 13. Figure 12 is a trilinear diagram as modified by Piper (1944). The majority of samples fall within the domain to be classified as Ca-Mg-HCO_3 water.

A small number of samples have elevated percentages of chloride and sulfate. Doney Park well #2 (sample no. 2) has significantly higher values of chloride, sulfate and sodium, the origin of which is unclear.

The Inner Basin sample nos. 8, 9 and 10 have a much larger sodium percentage. This can be attributed to the sediments of volcanic origin through which the water passes. Sample 23 (Marshall Lake) also has a higher sodium percentage. Evaporation of the lake may be concentrating the sodium values.

The alkalinity values in Table 4 are reported as $CaCO_3$. However, due to the normal pH values of all the

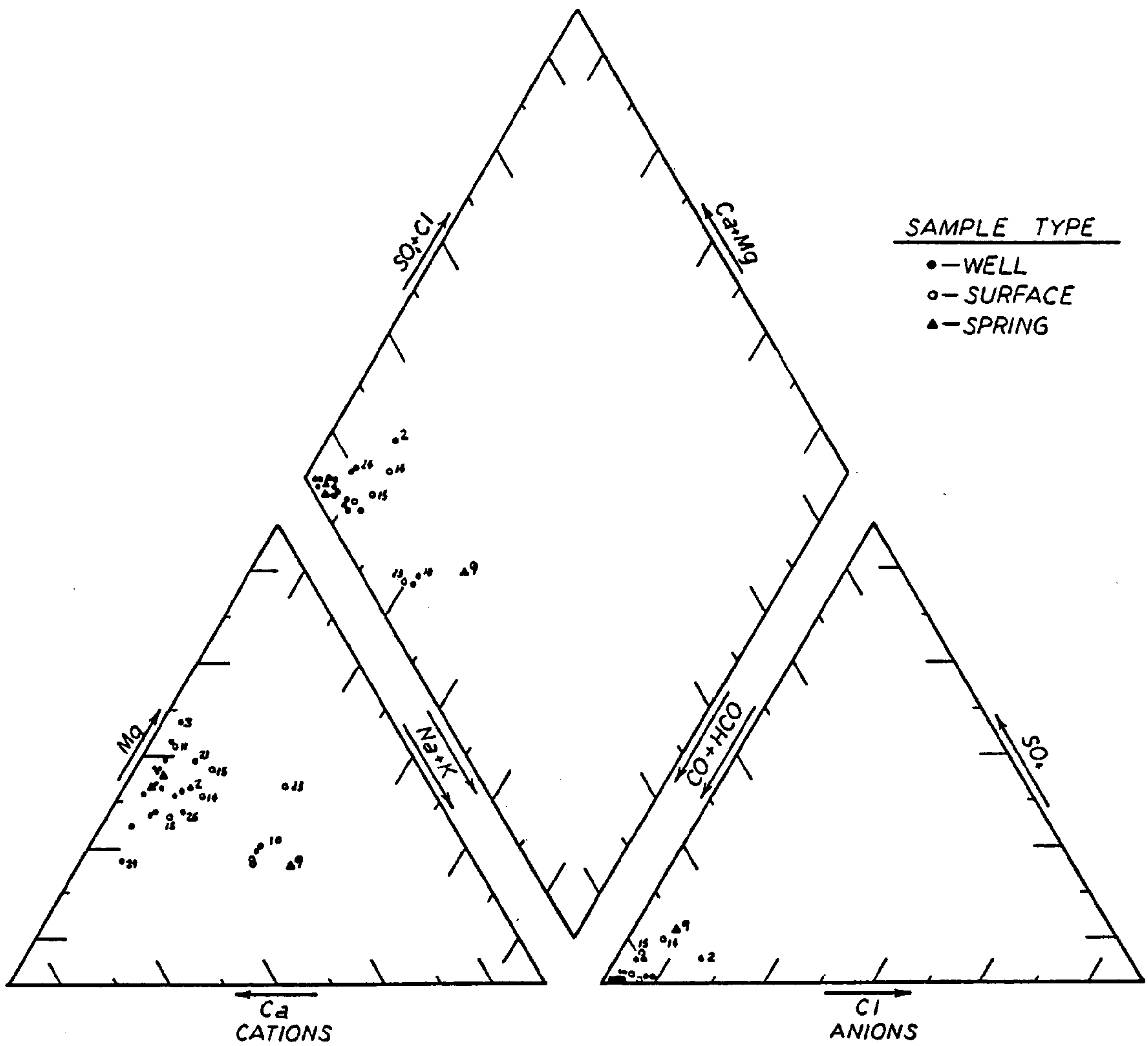

Figure 12. Trilinear Diagram of Sample Values.

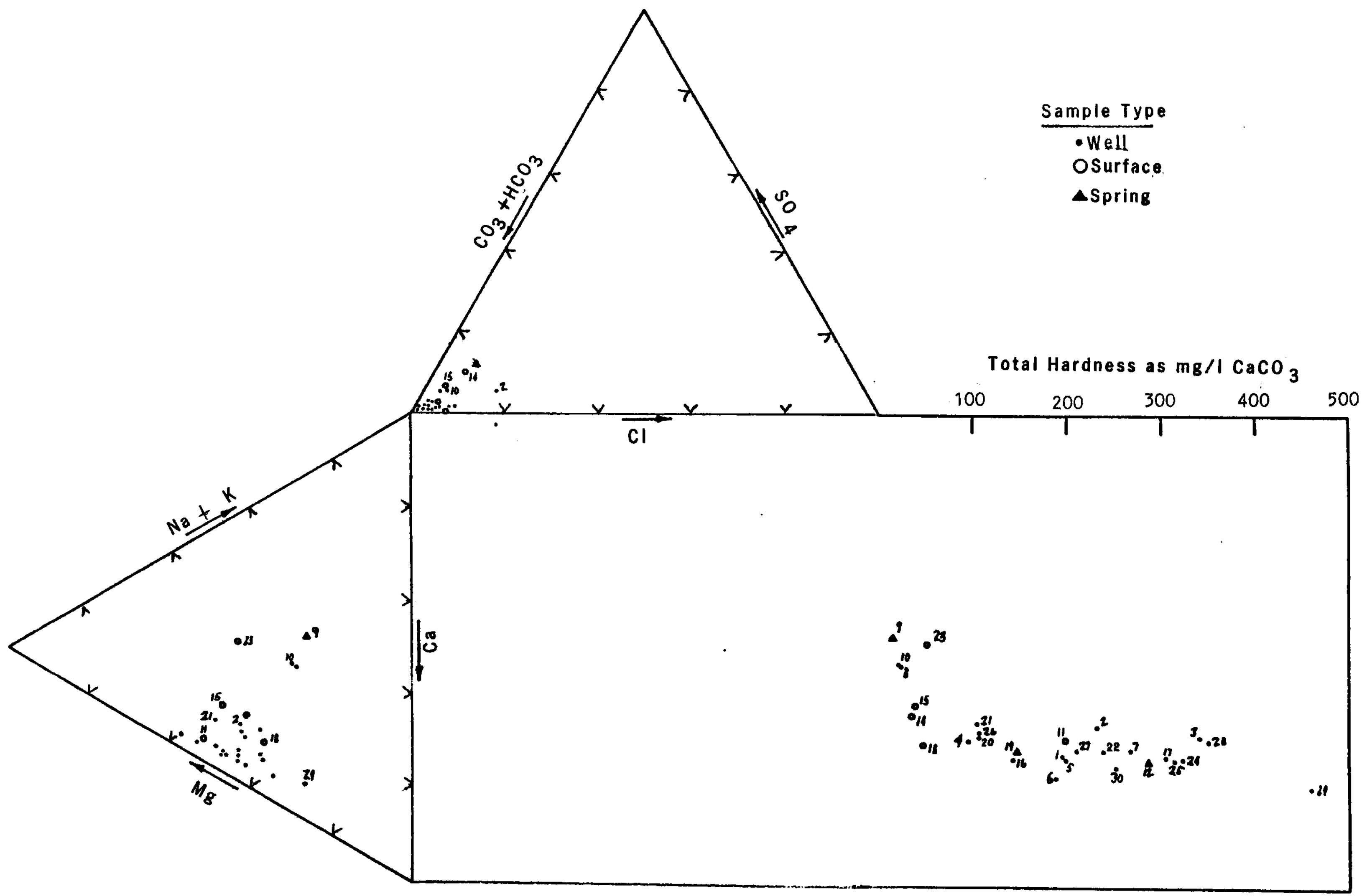

Figure 13. Durov Trilinear Diagram of Sample Values.

samples (below 8.3), it will be assumed that the alkalinity represents only bicarbonate ions.

The mechanism behind the calcium-magnesium-bicarbonate values is likely one of two sources, or both. Throughout the plateau region, recharge water infiltrates through fractures in the Kaibab Limestone, which is composed of dolomitic limestone. The limestone is soluble when in contact with water which contains dissolved CO_2. The primary aquifer in the area is composed of sandstone. However, the sandstone may be cemented with calcium-magnesium carbonate.

Figure 13 is a Durov diagram (Freeze, 1979). The advantage of this diagram over the trilinear diagram is that variations in the absolute value of certain parameters can be depicted. Total hardness was chosen as a horizontal axis for this diagram. It can be readily seen that the sample from Lake Mary well #4 has a significantly lower hardness than that of the other Lake Mary wells. The Woody Mountain wells also have a comparatively low hardness. This could perhaps confirm that the recharge area for the Woody Mountain well field is not the same as that of the other wells on the plateau.

The samples from the Kachino Village and Mountainaire wells have hardness values that fall within the values for Woody Mountain and those of the wells to the east (except for Lake Mary #4). This may indicate a mixing of recharge waters from the two areas. The values may also be due to a different (shorter) travel time for the recharge from a particular source. Water containing dissolved CO_2 will dissolve limestone until the water has become saturated with respect to the calcium carbonate mineral. The longer that the unsaturated water is in contact with the host rock, the greater the amount of mineral material dissolved.

Figures 14 through 22 are Schoeller diagrams (Schoeller, 1955) of the sample compositions. The diagrams are presented in order to further compare the samples from different locations. The samples were grouped on the diagrams by taking into account sample locations and possible hydrogeologic relationships, if any.

These diagrams can be used to directly compare compositions of the samples. For instance, Sample 16 (Lake Mary well #4) has significantly lower values for the parameters than the other Lake Mary wells.

In order to determine if there is a definite relationship between the calcium and magnesium values, their ratios were calculated (Table 6 and Figure 23). Theoretically, if the source rock for the ions is dolomite ($CaMg(CO_3)_2$), then the ratio of the ions (in meq/1)

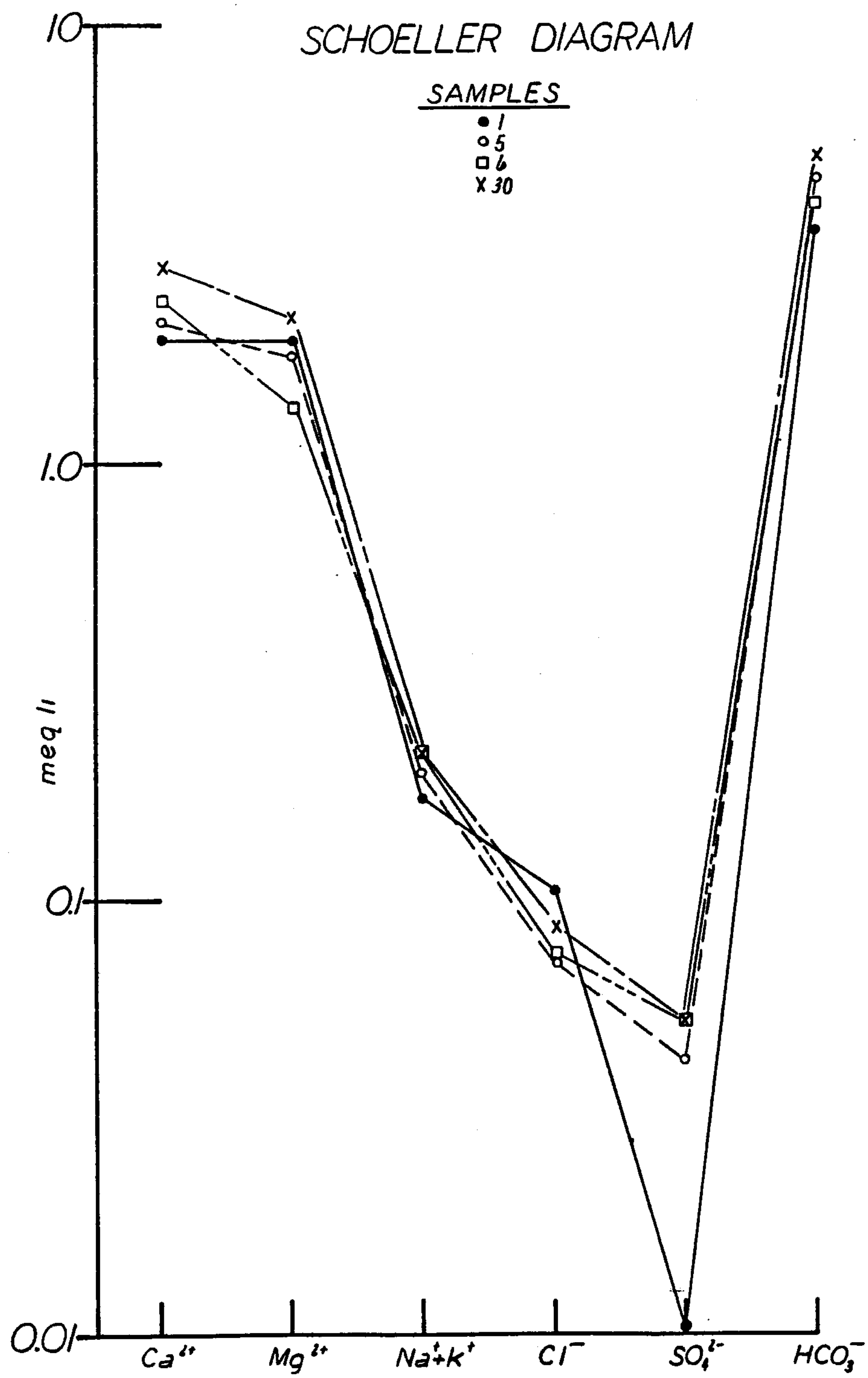

Figure 14. Schoeller Diagram for Sample Nos. 1, 5, 6, 30.

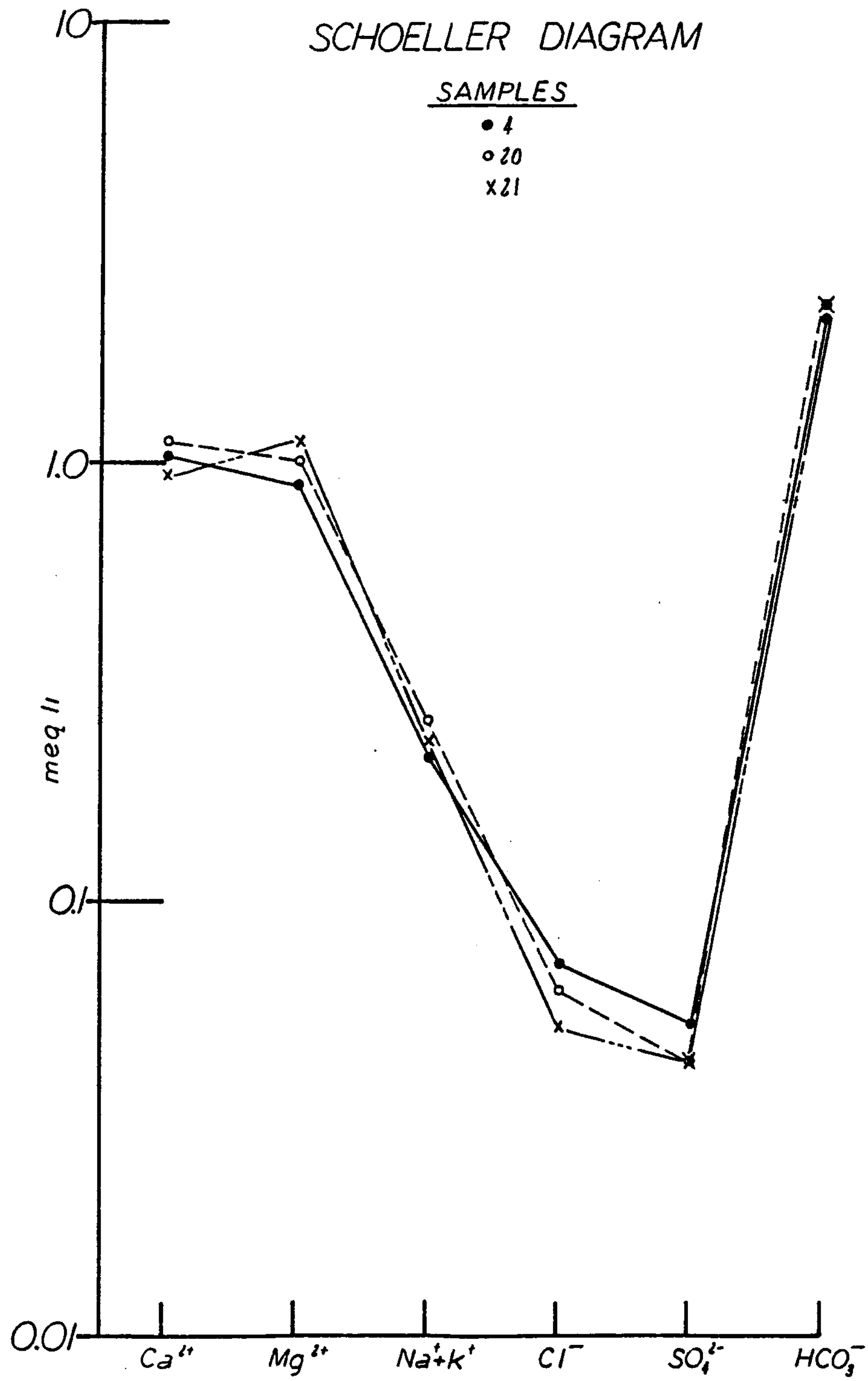

Figure 15. Schoeller Diagram for Sample Nos. 4, 20, 21.

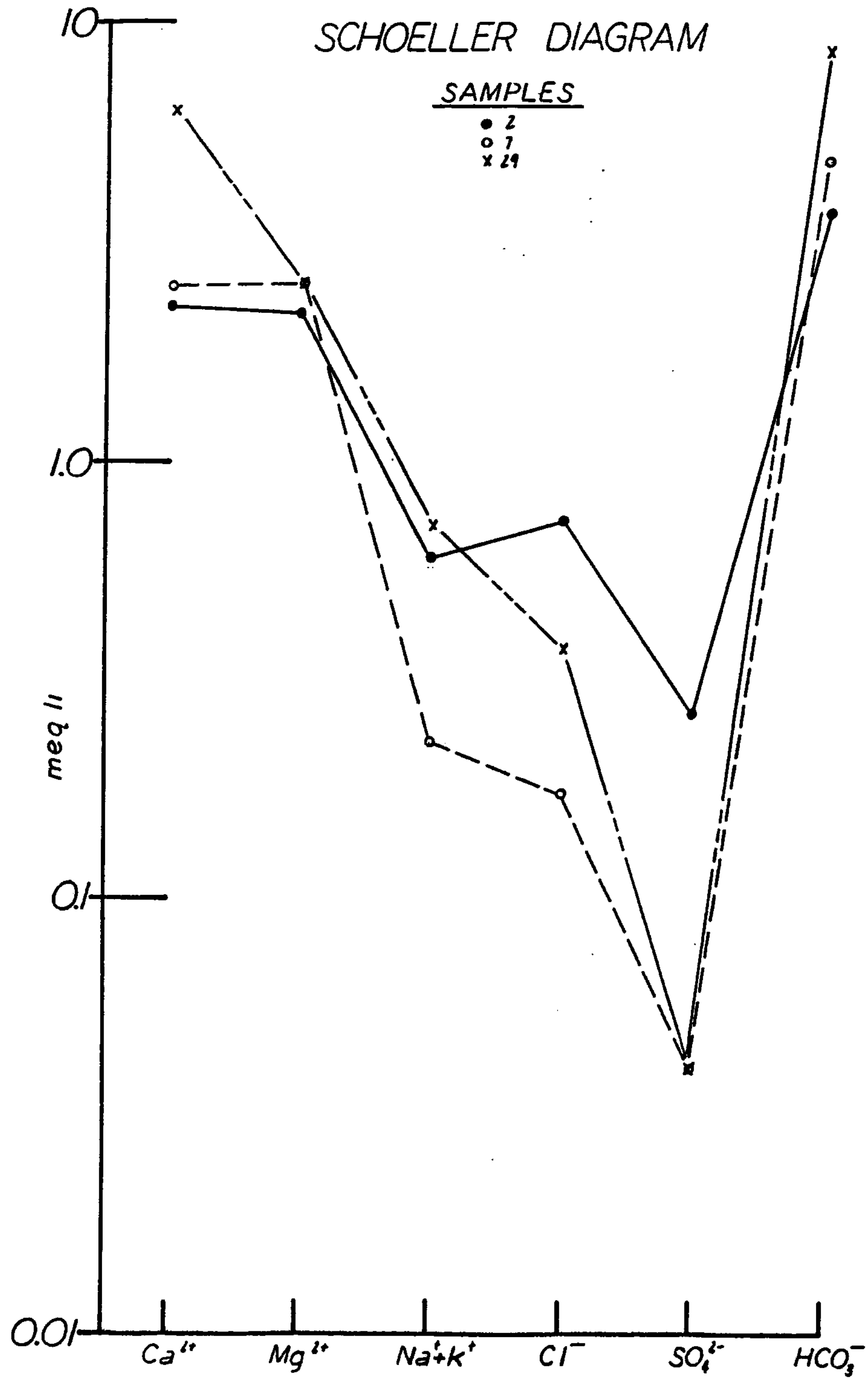

Figure 16. Schoeller Diagram for Sample Nos. 2, 7, 29.

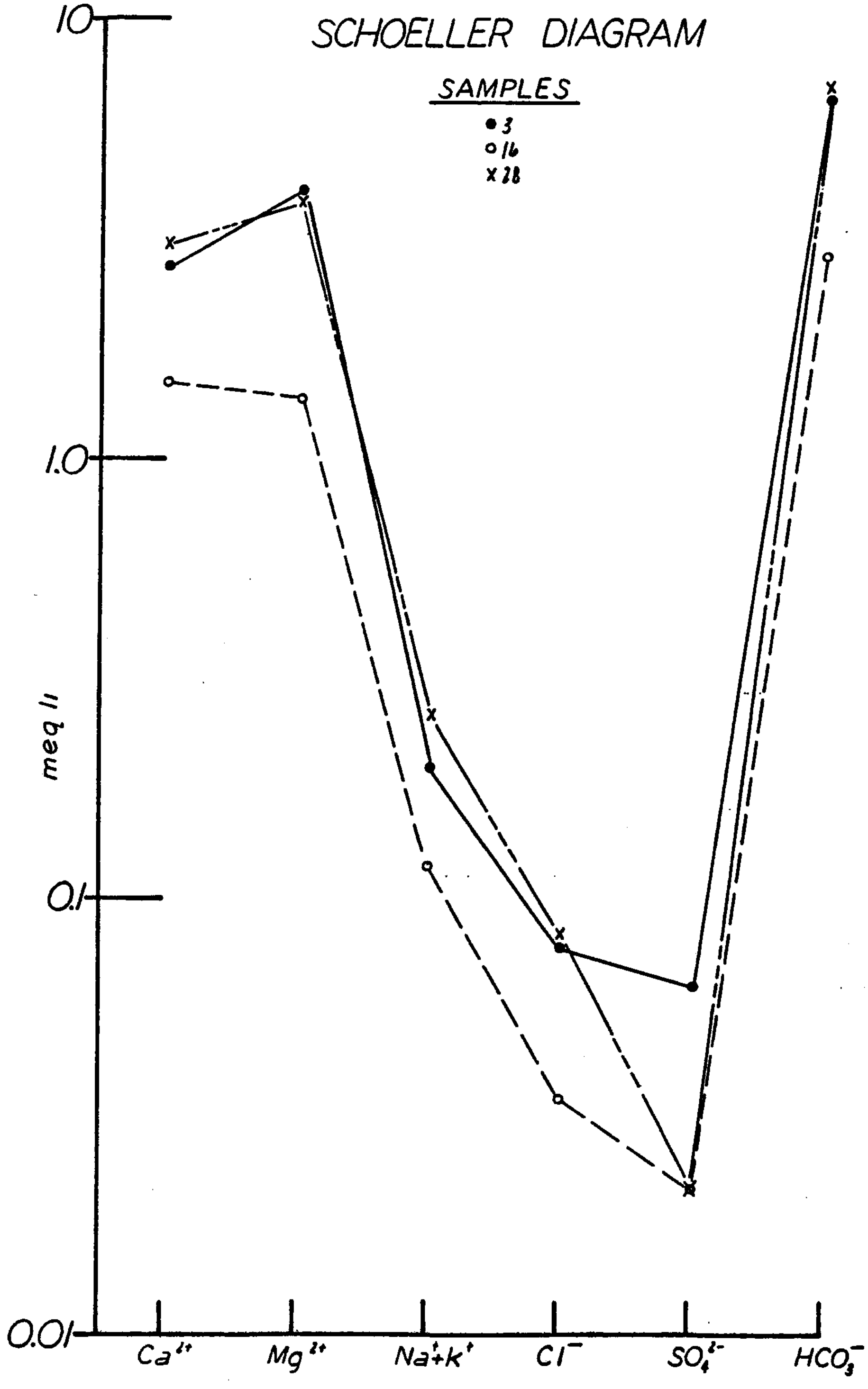

Figure 17. Schoeller Diagram for Sample Nos. 3, 16, 28.

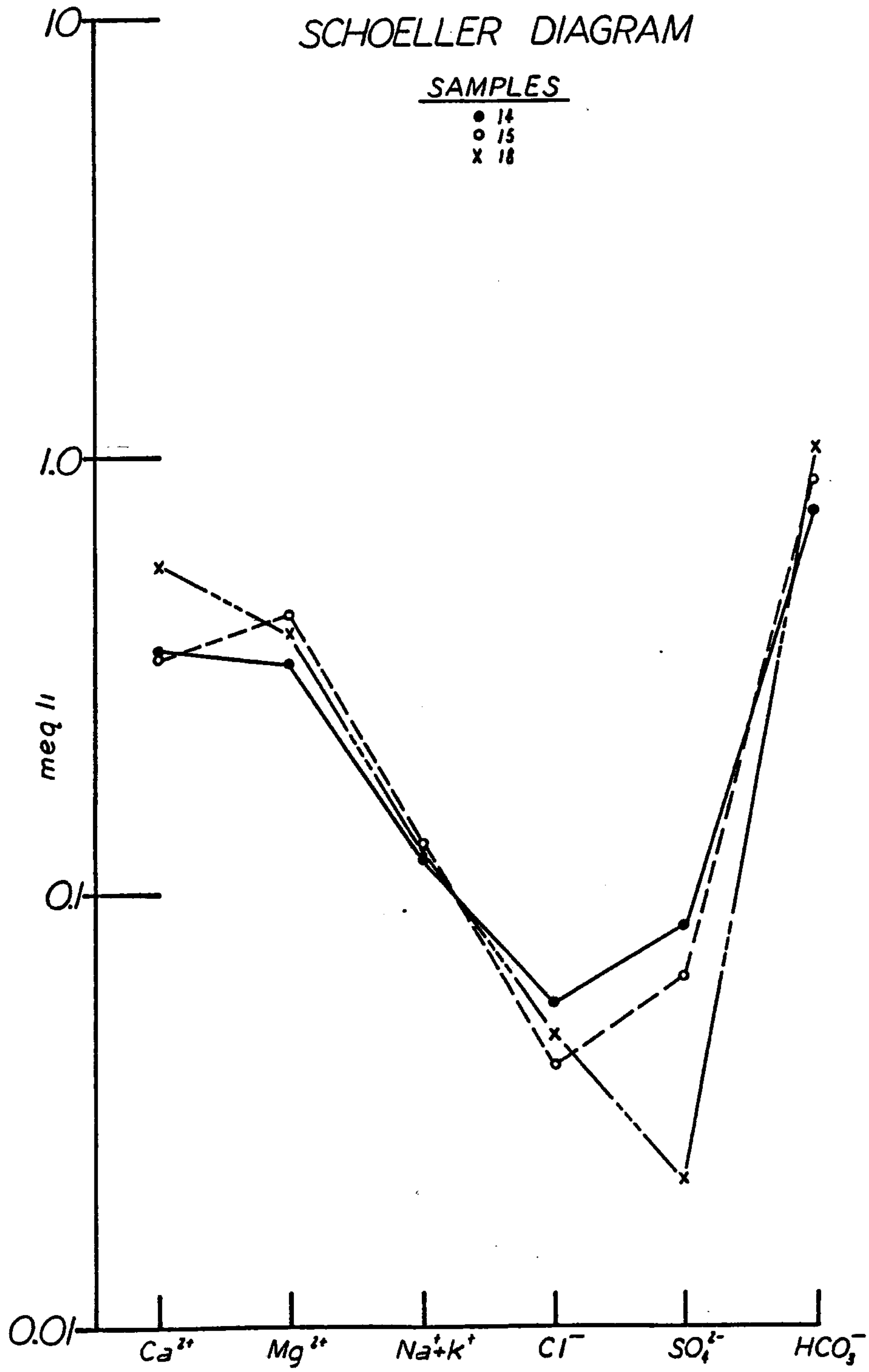

Figure 18. Schoeller Diagram for Sample Nos. 14, 15, 18.

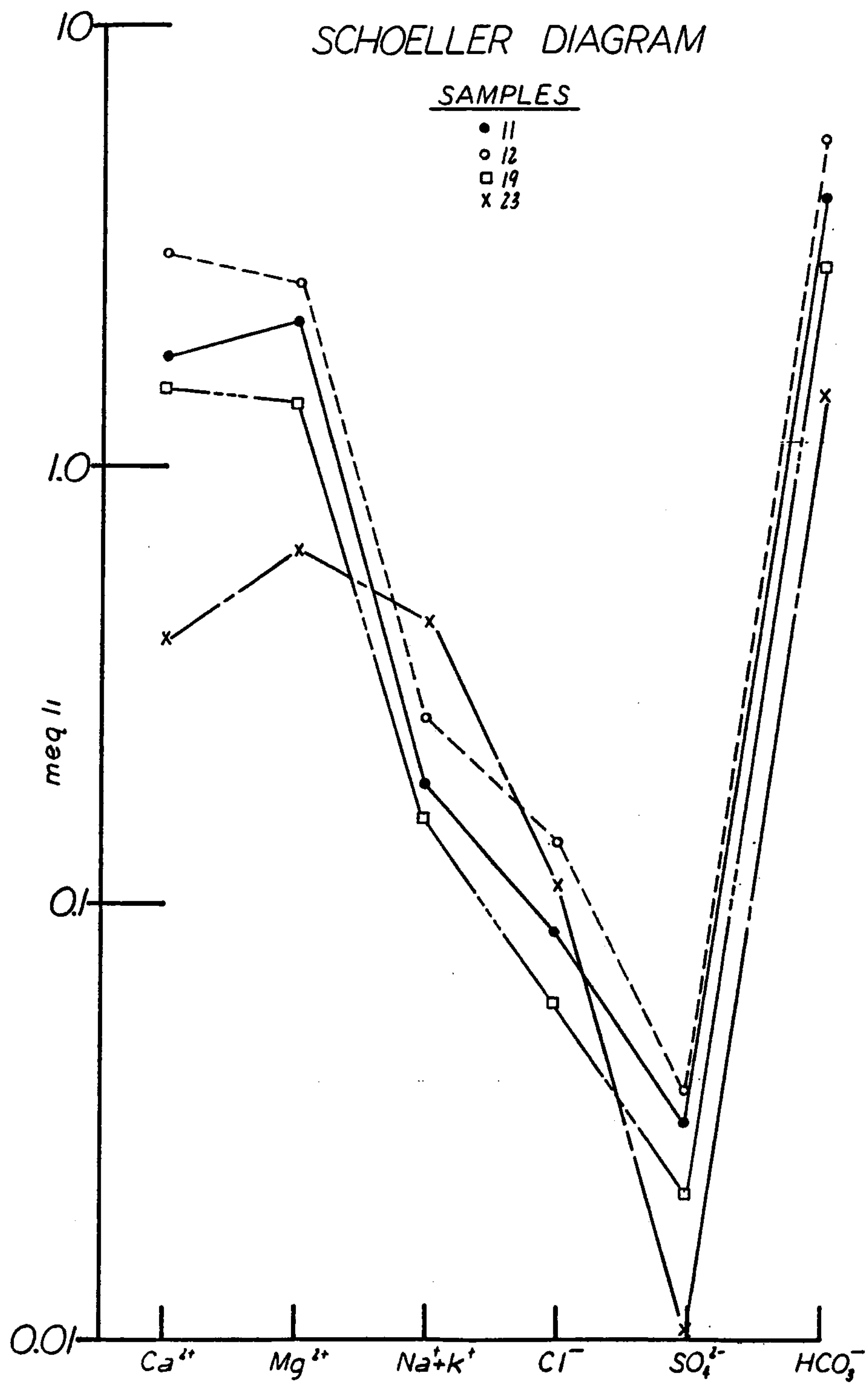

Figure 19. Schoeller Diagram for Sample Nos. 11, 12, 19, 23.

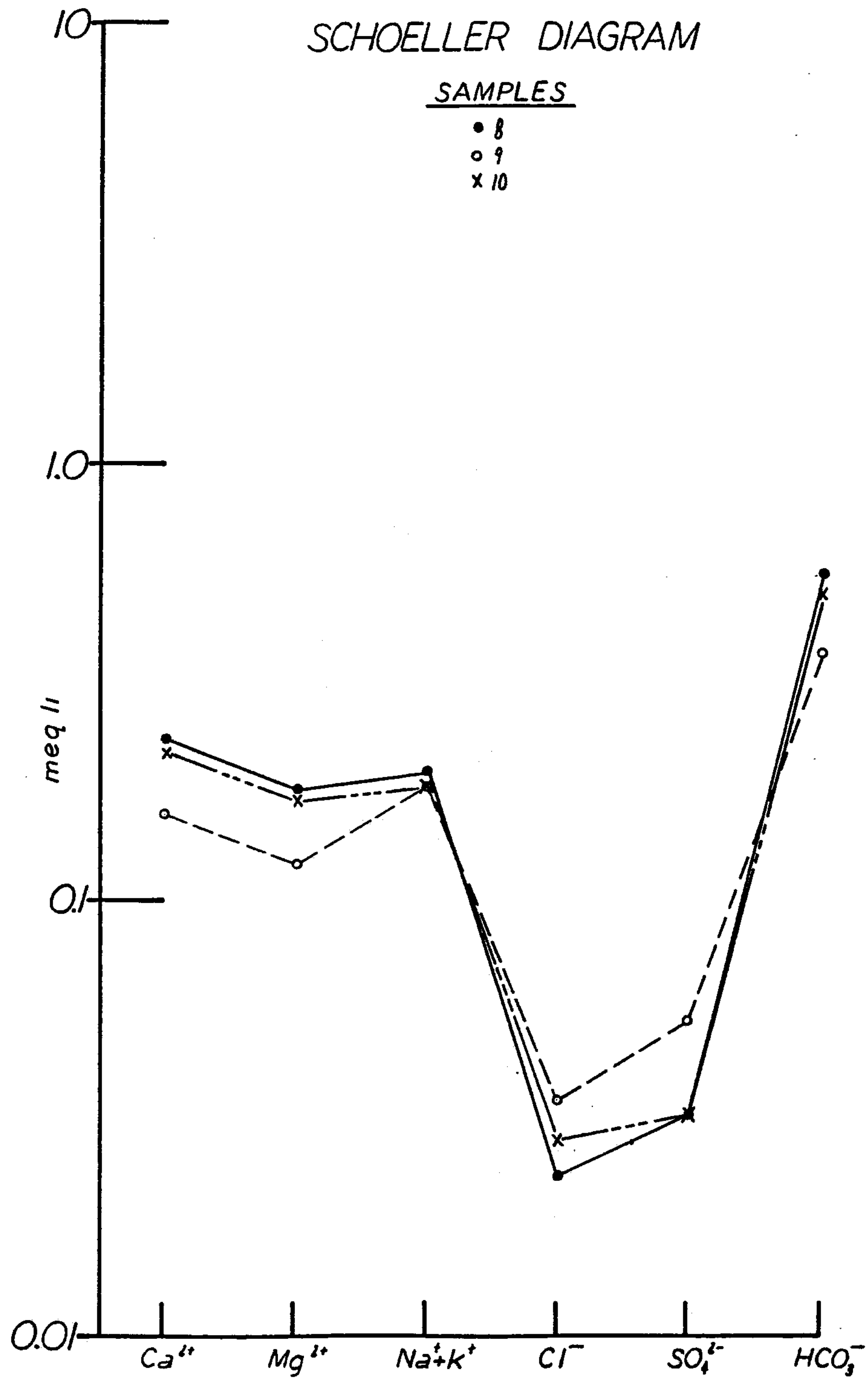

Figure 20. Schoeller Diagram for Sample Nos. 8, 9, 10.

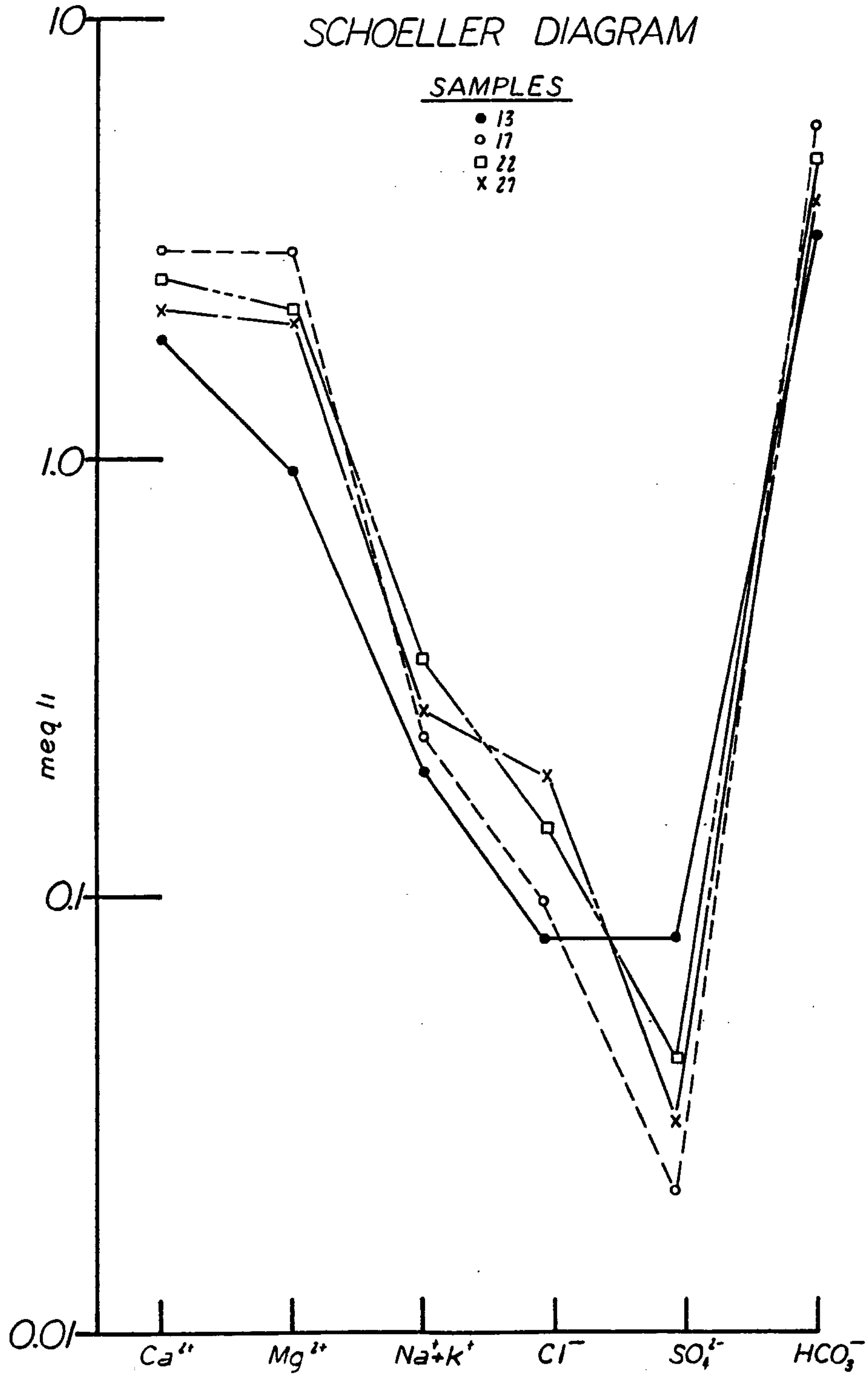

Figure 21. Schoeller Diagram for Sample Nos. 13, 17, 22, 27.

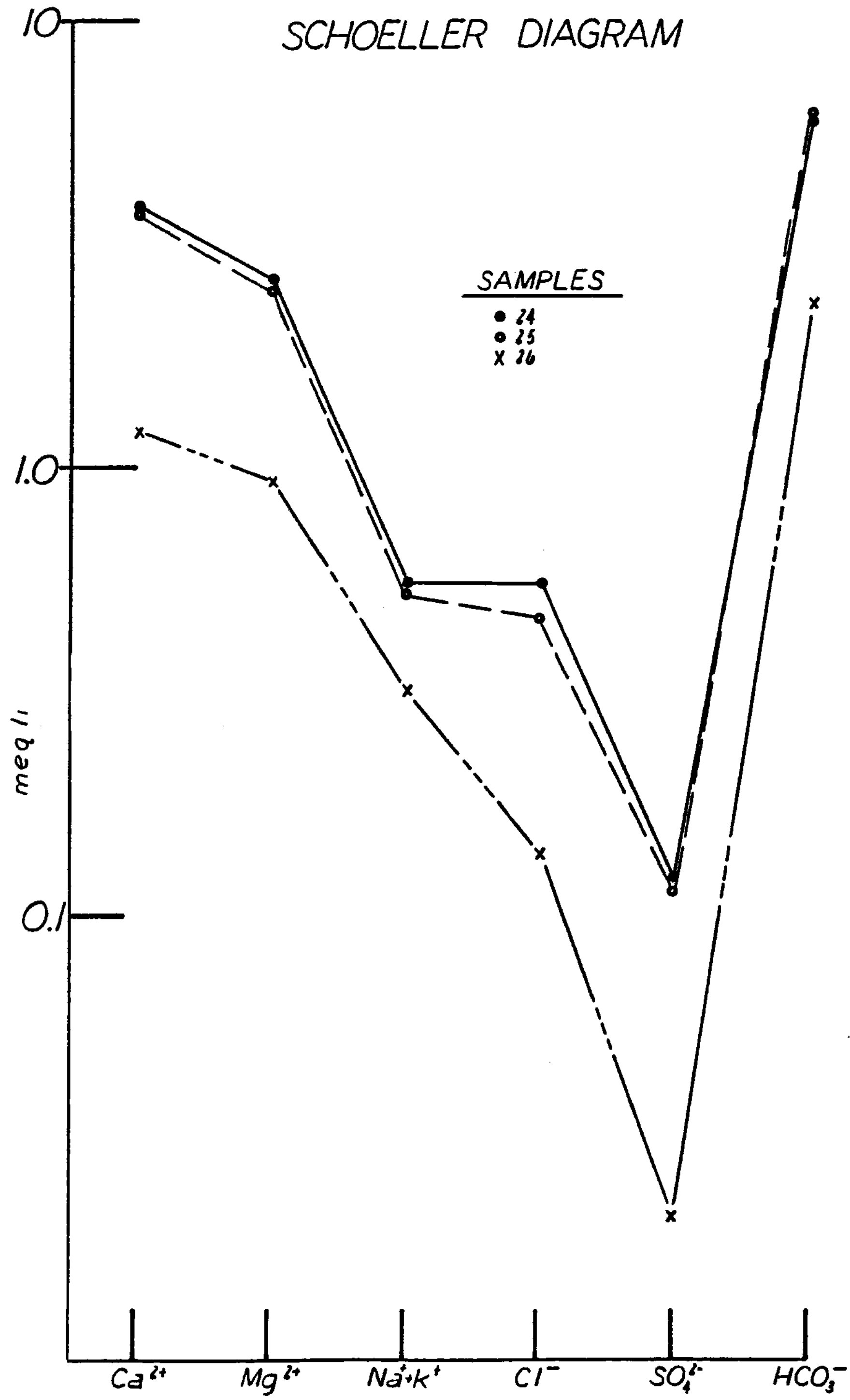

Figure 22. Schoeller Diagram for Sample Nos. 24, 25, 26.

TABLE 6. CALCIUM-MAGNESIUM ION RATIOS

Calculated From Concentration in meq/1

Sample	Ca/Mg	Sample	Ca/Mg
1	1.022	16	1.081
2	1.029	17	1.030
3	0.693	18	1.419
4	1.169	19	1.057
5	1.194	20	1.105
6	1.741	21	0.838
7	0.946	22	1.169
8	1.333	23	0.614
9	1.333	24	1.427
10	1.294	25	1.475
11	0.835	26	1.283
12	1.184	27	1.031
13	--	28	0.812
14	1.061	29	2.405
15	0.810	30	1.292

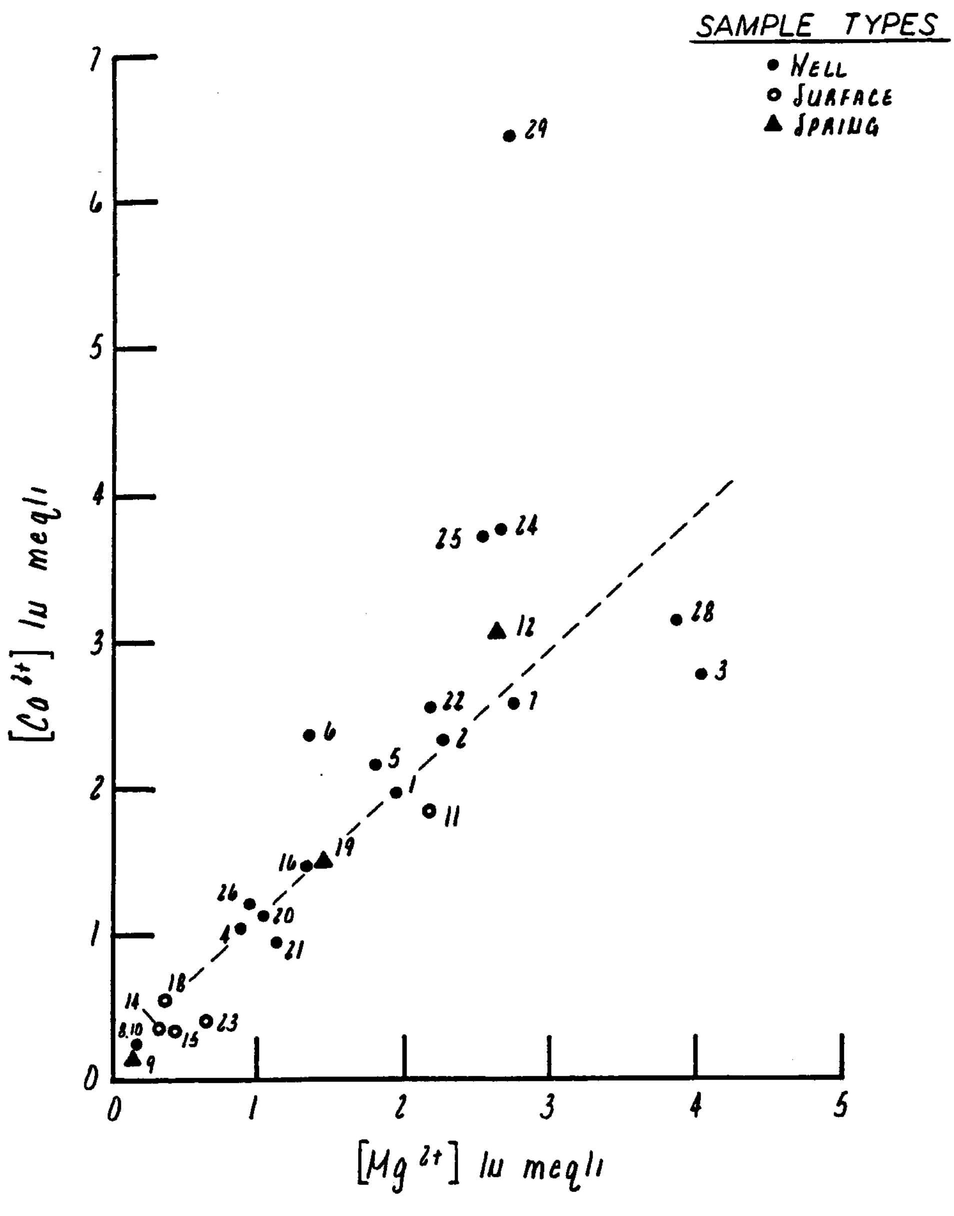

Figure 23. Calcium versus Magnesium Values.

should be one (Hem, 1970). However, the Ca/Mg ratio for dolomitic waters is actually slightly greater than would be found in dolomite due to the preferential dissolution of the calcium carbonate, which is almost always present in association with the dolomite. Most of the samples have ratios greater than one. Of the samples listed, twelve have Ca/Mg ratios between 1.0 and 1.2, which could presumably have been the result of the dissolution of dolomite.

Mapping of Nitrate And Silica Values

In order to verify the flow directions that are defined in Figure 10, maps of the silica and nitrate values were drawn using data from this study and the relevant data from Tables A.2 and A.3 in the Appendix A.

The City of Flagstaff sewage treatment plant discharges the secondary treated effluent into Rio de Flag and has so for 40 years. Presently the discharge rate is 3 mgd on an average annual basis. The effluent travels down the Rio de Flag until it reaches Big Fill Lake where it evaporates or seeps into the ground. If the ground-water flow from Big Fill Lake is to the north and northeast as shown in Figure 10, then the nitrate values to the north should be higher than those to the south. That is precisely what was found, although sample points to the north were sparse. The values (from Table A.4) are plotted on Figure 24.

Sandstone is chiefly composed of quartz and quartz has a low solubility at the pH and temperatures of typical groundwater. The solubility of quartz would only yield 5 to 15 ppm SiO_2 in ground water (Davis, 1966). Amorphous silica is more soluble (approximately 115 to 140 mg/1 at 25^oC, Freeze, 1979). Natural ground water usually falls within a narrow range between these two values, and concentrations within this range could depend on contact time (Mathess, 1982).

Samples were analyzed for silica to determine if results coincided with the travel direction of the ground water (i.e., larger silica values in the direction of flow due to increased travel time and dissolution). The values from Table A.5 were plotted on Figure 25. Only in the northwest area of Lower Lake Mary did this correlation seem to be meaningful.

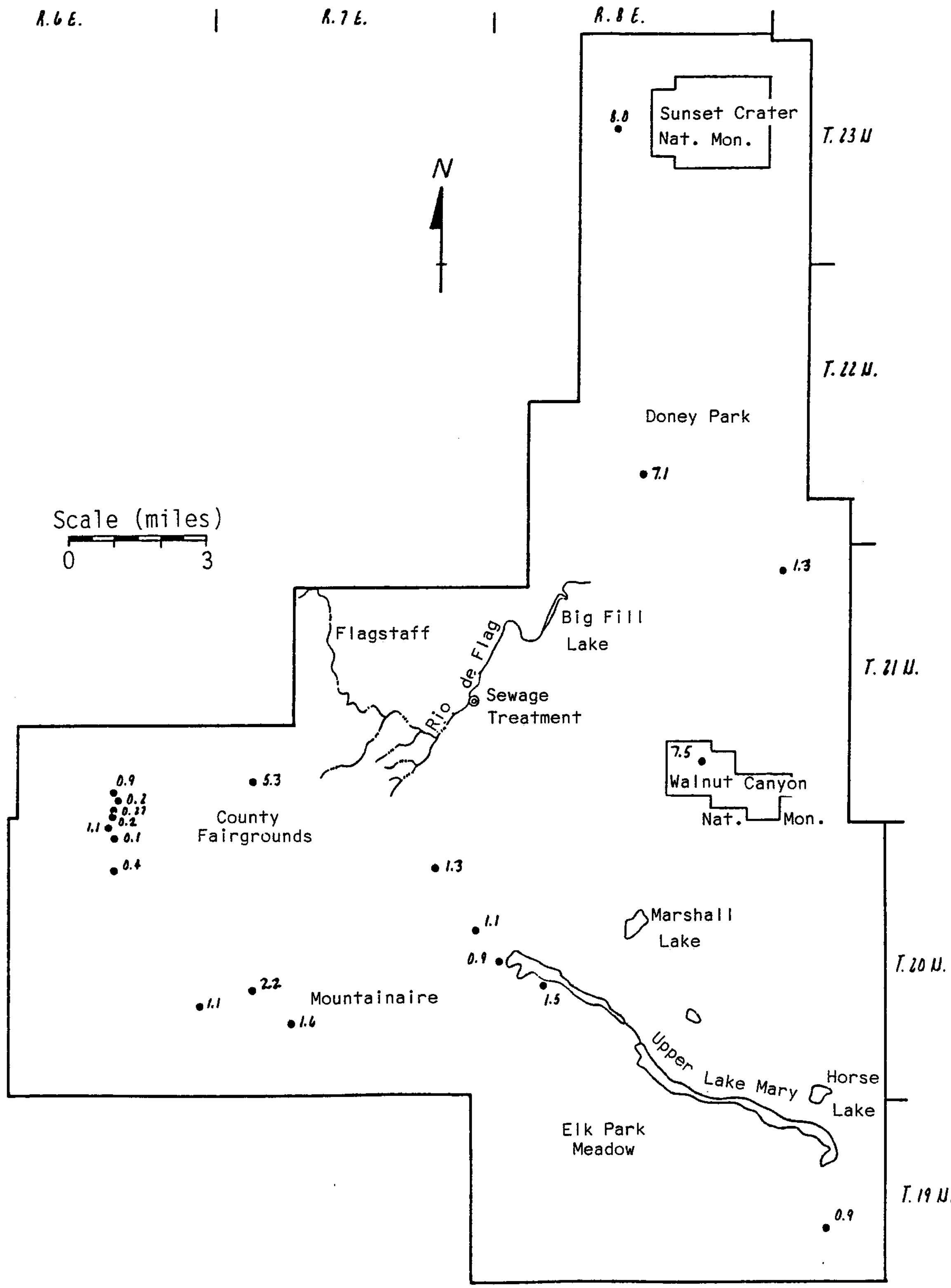

Figure 24. Map of Nitrate Values (as mg/l).

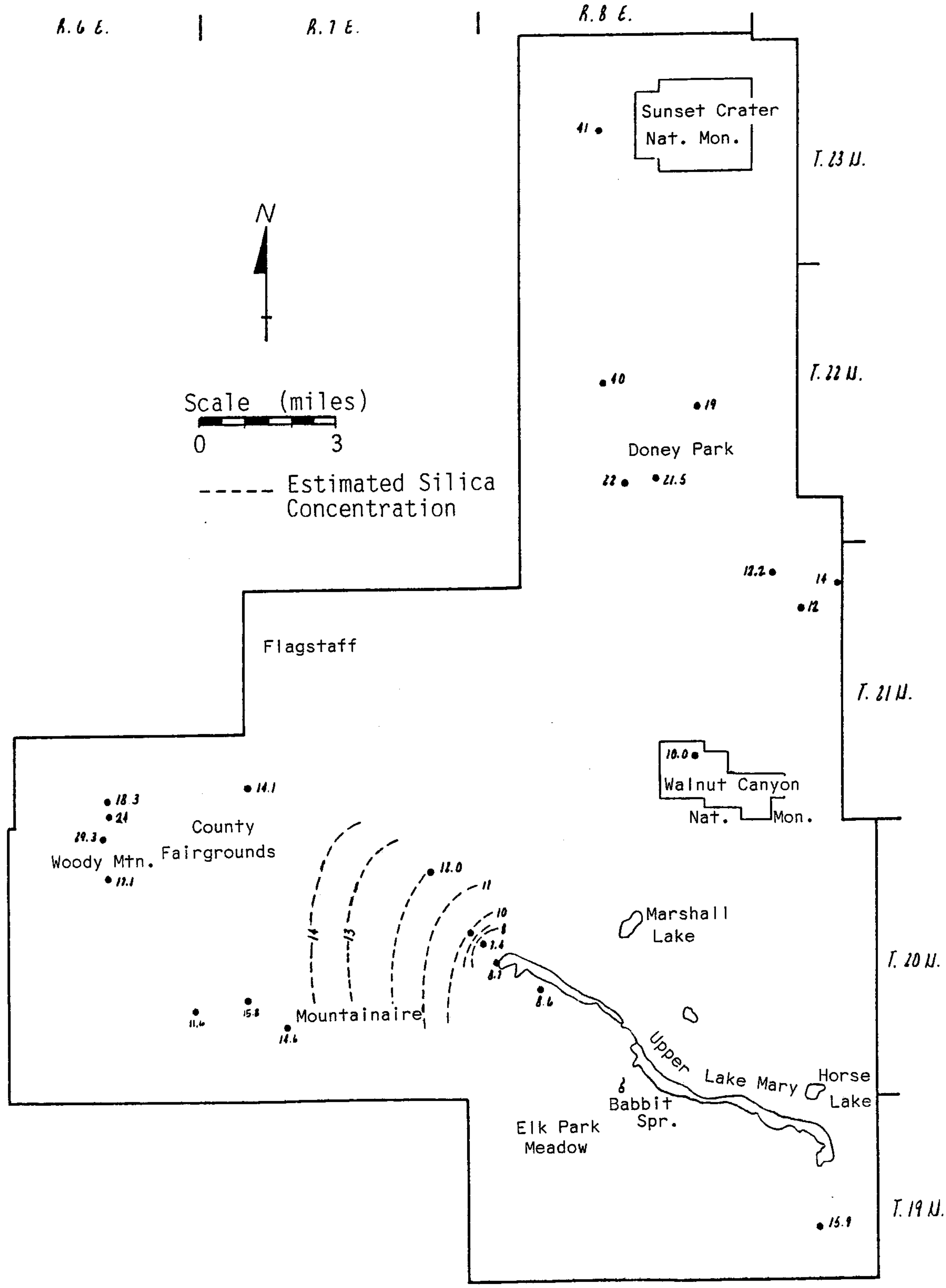

Figure 25. Map of Silica Values (as mg/l).

SECTION 5

ISOTOPE RESULTS AND RELATION TO RECHARGE OF THE LAKE MARY WELL FIELD

In certain situations, the stable isotopes deuterium (D or ^{2}H) and oxygen-18 (^{18}O) can be used to trace ground water back to its point of recharge. In addition, global events of the 1950s and early 1960s have resulted in the use of the unstable isotope tritium to evaluate the time for recharge waters to travel to discharge points. In order to discuss how these concepts relate to this study, it is necessary to review the theory behind these concepts.

Theory

The general theory for tracing recharge water is that when precipitation falls on the ground and infiltrates into the soil, it has a certain isotope composition that is a "fingerprint" of the climate and location of the recharge area. Once in the ground-water system, the isotope concentration will remain the same at normal ground-water temperatures. Thus, the stable-isotope composition of the ground water will be the same as that of the precipitation in the recharge area. Comparison of isotope values of precipitation from various parts of the basin will identify the recharge zone.

This is an ideal example, but deviations are useful when the proper hydrologic parameters are studied. Given more than one explanation for recharge to a well field, the isotopes can be used to determine the actual scenario. In this study, D and ^{18}O analysis can be used to determine the role of Lake Mary seepage in relation to the adjacent well field.

The Stable-Isotope "Fingerprint"

The relative abundance of deuterium and oxygen -18 as compared to the lighter isotopes H and ^{16}O is very small. The ratio of the heavy isotope to the light isotope is measured relative to a standard. The measurement unit is the delta value (δ) given in per mil and defined as:

$$\delta\ (^{o}/_{oo}) = \frac{R\ \text{sample} - R\ \text{standard}}{R\ \text{standard}} \times 1000,$$

where R = $^{18}O/^{16}O$ for oxygen and (D/H) for hydrogen (Hoefs, 1980). The standard for the hydrogen and oxygen measurements is that ratio termed Standard Mean Ocean Water (SMOW).

Hoefs (1980) termed isotope fractionation as the "partitioning of isotopes between two substances with different isotope ratios." The isotope fractionation of both oxygen and hydrogen is caused by the differences in vapor pressures of the different isotopic water molecules and their different diffusion velocities. The vapor pressure of HDO molecule is lower than that of H_2O, and the vapor pressure of $H_2{}^{18}O$ is lower than that of $H_2{}^{16}O$. During condensation, the concentration of the heavier isotopes is greater in the liquid than in the remaining vapor. Since the fractionation processes of both hydrogen and oxygen are the same, there is a direct relationship between their isotope ratios. This linear relationship is:

$$\delta D = 8 \delta {}^{18}O + 10. \quad \text{(Dansgaard, 1964).}$$

This relationship was derived from global precipitation measurements and is termed the meteoric water line. In addition, the ratio of the vapor pressures of the two isotopes at 25°C is 8 (Hoefs, 1980).

During condensation, the isotope ratio in the water droplet depends on the temperature and the isotope ratio of the original water vapor. The continental effect on isotope values in precipitation is an example. Water evaporates from the ocean with a high concentration of the lighter isotopes due to their higher vapor pressures. As the vapor moves inland, it cools and water with higher

δ values condenses. As this process continues, the vapor is being depleted of the heavy isotopes. Moving inland and continuously cooling and condensing, the remaining vapor has fewer heavy isotopes to fractionate out.

Atmospheric temperature is also related to altitude. Ideally, water that falls on a recharge zone will have an isotope ratio characteristic for the altitude of that zone in the basin. Precipitation in high, colder regions should be more depleted of heavy isotopes. This fact can be useful in determining the recharge zone in a mountainous area. Figure 26 contains scattergrams of δ D and δ ^{18}O versus elevation for two springs in the study area: Raspberry Spring of the Inner Basin and Babbit Spring of the plateau area near Lake Mary. These two data points are not sufficient to define the heavy to light isotope relationship with elevation in this region, but they do emphasize the greater depletion of heavy isotopes in waters of increasing elevation.

The evaporation process affects isotope fractionation differently than does condensation. There is greater kinetic energy during evaporation, so the difference in diffusion rate plays a more important role. The lighter isotopes have faster diffusion rates. The δ D and δ ^{18}O values both increase in the residual water.

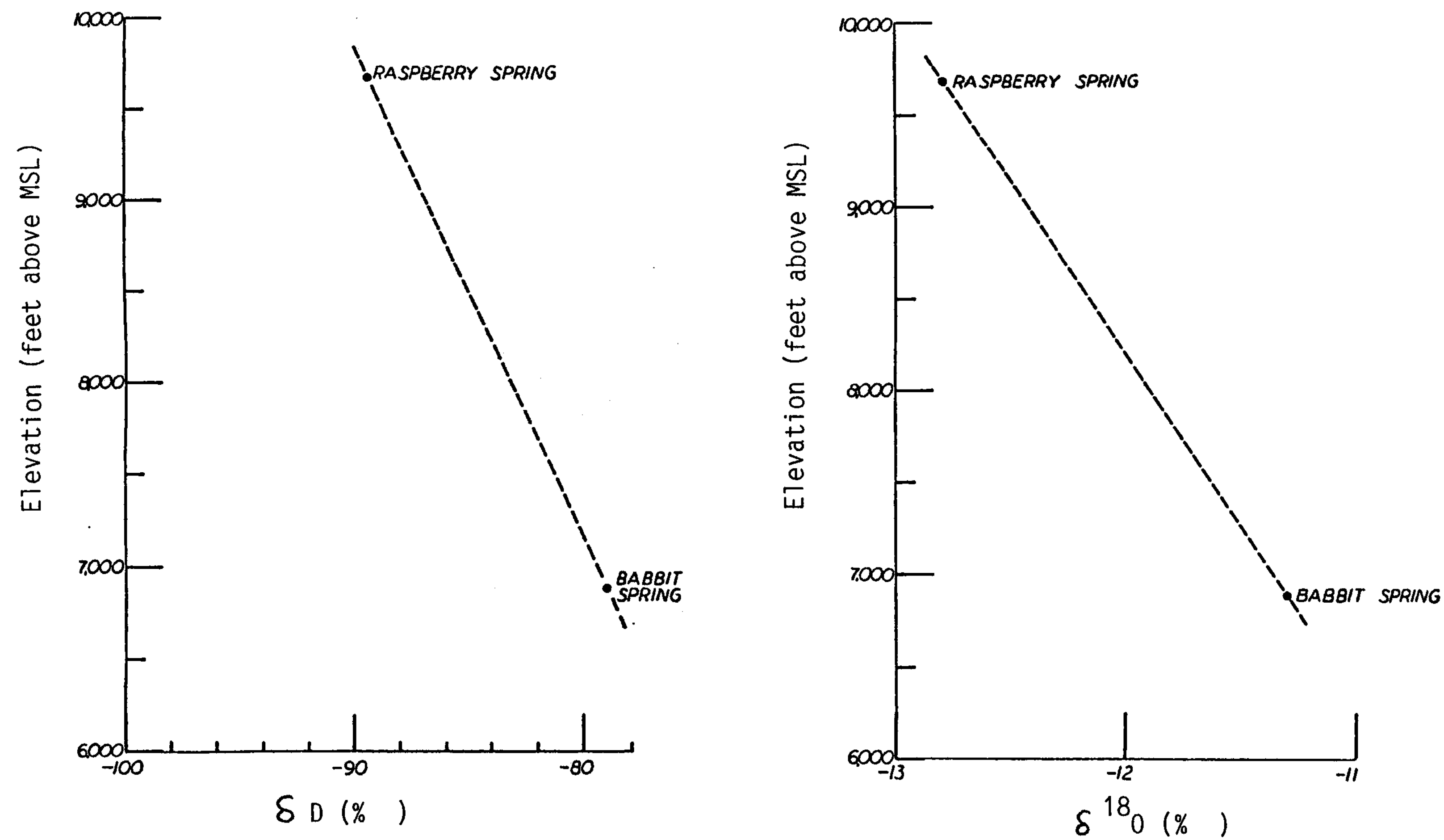

Figure 26. δD and $\delta^{18}O$ vs. Elevation for Spring Samples

This causes the $\delta D/\delta^{18}O$ line to shift to the right of the meteoric water line. Also, there is a greater amount of ^{18}O per quantity of D in the remaining waters. The slopes of the $\delta D/\delta^{18}O$ line changes from 8 to between 4 and 6 (Payne, 1972). The effect from the process of evaporation can be useful in understanding the relationship between a reservoir lake and the ground water; as in this study. As already mentioned, Upper Lake Mary loses approximately 28% of its inflow to evaporation. This should increase the concentration of the heavy isotopes and decrease the ratio of $\delta D/\delta^{18}O$.

In semiarid regions, such as the Flagstaff area, evaporation of the falling raindrops is likely to occur, especially during a light summer rain. This will have the same effect on the rainwater as evaporation of a lake. Light rains may not result in much recharge to the ground water. Heavier, colder rains, which contribute more to recharge, do not undergo as intense an evaporation (Dansgaard, 1964). Thus, successive rain events in one area will have different isotope ratios.

Ideally, precipitation with differing isotope ratios will mix due to hydraulic dispersion and a slow infiltration rate. Thus, the recharge to the ground water will have the same isotope fingerprint as that of the average precipitation that produces recharge.

Discussed earlier was the lack of isotope data for precipitation in the area of the Lake Mary reservoirs. These data would be most important for the area encompassing the ground-water mound, as this mound is thought to be a prime recharge source to the Lake Mary well field. As a practical solution for this lack of data, Payne (1972) suggested that the isotopic composition of springs in the area may be used to define the recharge if the knowledge of the springs' sources is sufficient. Both Babbit Spring and Hoxworth Spring are in the area described above. The source for both springs is water infiltrating into and moving through the alluvial deposits at the surface. Babbit Spring was sampled to provide a preliminary estimate of the isotopic composition of the rainfall. Hoxworth Spring had a very low flow rate, and was difficult to find, so a small stream was sampled which passed adjacent to the spring.

The Use of Tritium to Date Ground Water

Tritium is a radioactive isotope of hydrogen. Its half-life is 12.26 years. The existence of tritium can be used to date recent ground water from the time of recharge.

Tritium is naturally produced in the atmosphere, and a portion of that produced is incorporated in precipitation. Naturally produced levels of tritium in precipitation range between 5 to 20 TU (Payne, 1972). (1 TU = one tritium atom for every 10^{18} hydrogen atoms.)

Atmospheric tests of nuclear weapons in the 1950s and early 1960s produced large amounts of tritium in the atmosphere, far more than that produced naturally. Absolute values of tritium in precipitation were at a maximum in 1963 (Payne, 1972). These values were in the hundreds of TU. Recharge water since 1953 has been referred to as bomb tritium water (Freeze, 1979).

As a radioactive isotope, tritium levels can be used to provide absolute dates for ground-water travel time by using the equation for radioactive decay. However, this requires the precise value of the initial radioactivity of the recharge water. Yearly variations in tritium levels make this impractical.

For this study, samples were taken from five wells for tritium analyses. If the tritium values fall below 2-4 TU, then the well is assumed to be drawing water older than 1953 (from Freeze, 1979). This is based on the short half-life of tritium and the pre-bomb tritium levels of 5-20 TU. Values above 4 TU will be assumed to represent, at least in part, recharge water younger than 1953.

Isotope Results And Discussion

The results of the analyses for deuterium and oxygen-18 are in Table 7. The majority of the $\delta^{18}O$ values fall approximately in the $-11.0^{o}/_{oo}$ to $-12.0^{o}/_{oo}$ range. This applies to most of the sampled wells on the San Francisco Plateau. The elevations at these well heads range from 6430 feet above MSL to 6960 feet.

The δD values are relatively more scattered. More than half of the values fall within -77.8 to -84.5 range.

A scattergram of δD versus $\delta^{18}O$ values is given in Figure 27. The global meteoric line is drawn on the graph for reference purposes. It does not necessarily represent the meteoric line for this area. Data for a local meteoric line are not known to exist.

In general, the points on the graph do not fall along any well defined line. However, a number of points fall along a line that is below the meterioric line. The points 11, 12, 14, 15, 16, 18 and 23 fall close to a line defined by the equation $\delta D(^{o}/_{oo}) = 4.5 \delta^{18}O - 29.2 (^{o}/_{oo})$ with a correlation coefficient of 0.989. (Sample 17 is considered an anomaly and will be discussed later.) The deviation of this line, together with its slope of 4.5 suggest that the samples beyond the meteoric

TABLE 7. STABLE ISOTOPE DATA

Sample	Site Description	Date	$\delta^{18}O$ (±0.2‰)	δD (±2‰)
	WELLS			
1	Mountainaire Village	9/21/83	-11.2	-80.9
2	Doney Park, Ranchos #2	9/22/83	-11.1	-82.1
3	Lake Mary #5	9/22/83	-11.5	-80.7
4	Woody Mountain #3	9/22/83	-12.0	-79.1
5	Kachino Village #1	9/23/83	-11.0	-77.8
6	Kachino Village #3	9/23/83	-11.7	-78.6
7	Doney Park, Koch Fld. #5	9/23/83	-11.5	-80.7
8	Inner Basin #11	9/24/83	-12.8	-88.7
16	Lake Mary #4	9/27/83	- 7.6	-67.0
17	Heckethorn	9/27/83	- 5.3	-69.3
20	Woody Mountain #5	10/13/83	-11.6	-82.2
21	Woody Mountain #7	10/13/83	-11.6	-82.3
22	Pine Grove Campground	10/14/83	-11.6	-80.0
24	Sedona-SW Center #8	11/3/83	-11.0	-81.5
26	Sedona-Valley Vista	11/29/83	-11.8	-78.3
27	Walnut Canyon	11/30/83	-11.8	-90.5
28	Lake Mary #2	1/16/84	-11.8	-84.5
29	Sunset Crator	1/16/84	-11.7	-88.3
30	Jack's Hauling	1/16/84	-12.1	-86.9
	SPRINGS & SURFACE WATER			
9	Raspberry Spring	9/24/83	-12.8	-89.4
11	Upstream/Hoxworth Spg.	9/26/83	-10.8	-76.3
12	Babbit Spring	9/26/83	-11.3	-79.0
14	Upper Lake Mary/20'	9/27/83	- 7.1	-59.5
15	Upper Lake Mary/3'	9/27/83	- 6.9	-61.5
18	Lower Lake Mary	9/28/83	- 5.6	-56.8
23	Marshall Lake	11/3/83	- 1.2	-32.5

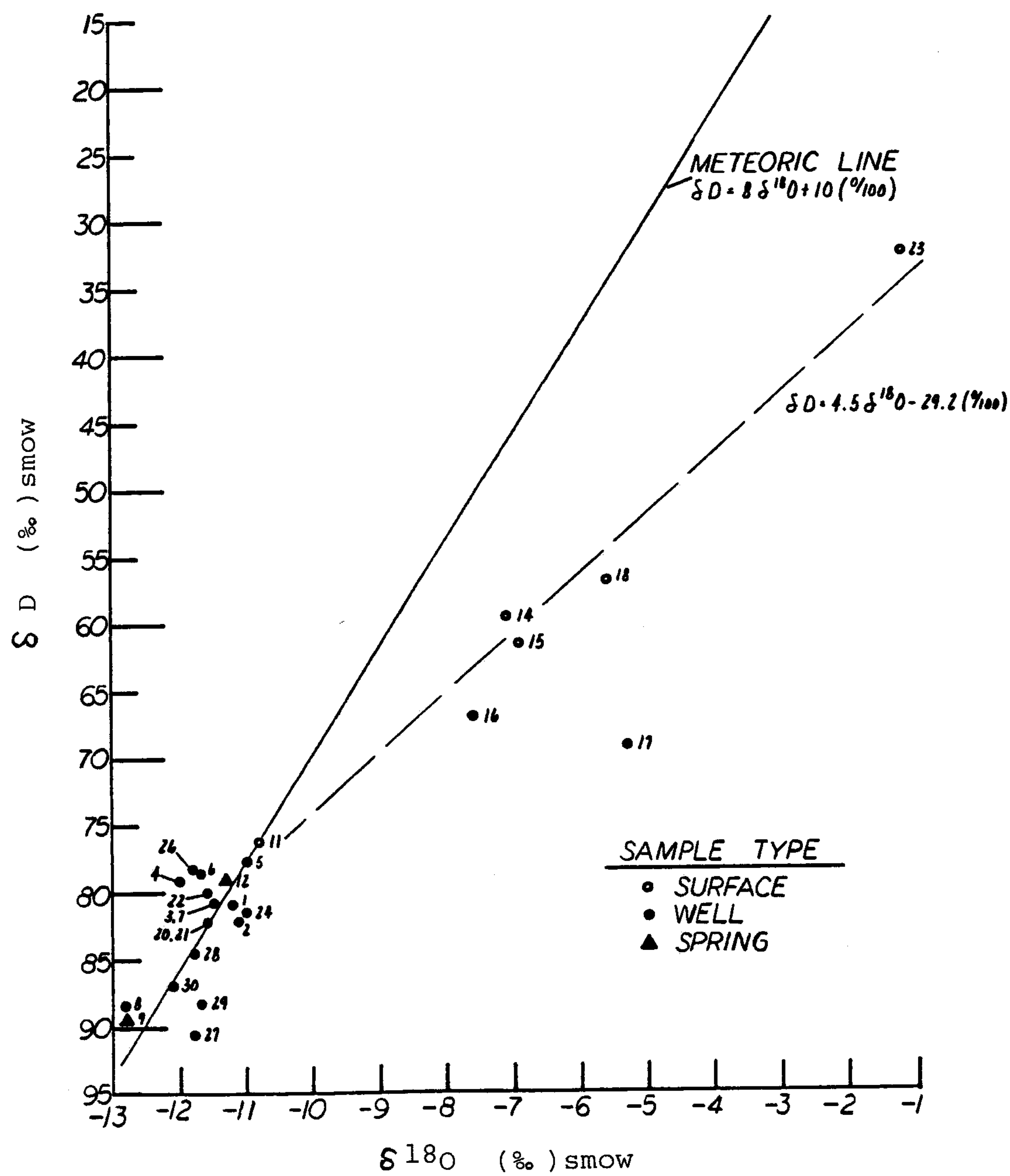

Figure 27. Deuterium and Oxygen - 18.

line are from bodies of water that have undergone evaporation. The samples 11, 14, 15, 18 and 23 represent surface water samples, including those from Upper and Lower Lake Mary. Sample 16 is Lake Mary well #4 near Lower Lake Mary and the Lake Mary fault (refer to Figures 6 and 7). The Babbit Spring sample (12) was included in the calculation of the line, because it should, theoretically, represent the value of precipitation at that location on the plateau. Thus, it is considered the starting point of the evaporation line.

The tritium values are reported below:

Sample No.	Site Description	Tritium (TU)
3	Lake Mary #5	0±3
6	Kachino Valley #3	6±3
16	Lake Mary #4	16±3
27	Walnut Canyon Nat'l Mon.	0.8±0.3
28	Lake Mary #2	0±3

Only samples from the Lake Mary #4 well and the Kachino Village #3 well have tritium values which suggest some recharge by bomb tritium water. If it is assumed that Lake Mary well #4 is drawing only bomb water younger than 1952, then the maximum tritium value the water could have had at the time of recharge was less than 120 TU (this assumes radioactive decay as the only reason for reduction of the value). This value may be considered low for bomb water. Thus, it is possibly that both of these wells are recharged by mixed waters of varying ages.

The remaining three wells are recharged by water older than 1953, as seen by their near zero values. These results can be used to interpret the effects of seepage from Lower and Upper Lake Mary on well field recharge.

As was discussed earlier, the limited number of samples taken cannot represent the variation of values with time and space. This is most especially true for surface water bodies. The surface water samples were taken in early fall, and most likely represent values more influenced by evaporation than at other seasons. However, in this study, the spread of values is large enough to make some preliminary judgments.

Lake Mary well #4 is drawing water that has undergone evaporation. It is the only well in the active Lake Mary well field to be receiving such water. Well #4 is also the only well in the well field drawing a portion of water that is younger than the initial bomb pulse of tritium.

Located on the west (upthrown) side of the Lake Mary fault, well #4 is not within the Lake Mary graben. However, it is only a few tens of meters from the Lower

Lake Mary shore. Although I believe that the data support the idea that well #4 is receiving recent recharge from the Lower Lake Mary, the exact pathway of this recharge can only be speculated.

It is possible that Lower Lake Mary overlies the Lake Mary fault. If this is definitely the case, recharge may be occurring from within the graben laterally through the Lake Mary fault; down through the fault and associated fractures directly from Lower Lake Mary; or only from the lake through fractures on the west side of the fault. The latter case would assume the fault is a barrier to ground water flow as suggested by Duren (1983).

The recharge to well #4 from Lower Lake Mary is in addition to recharge from the plateau area to the southwest. Both the tritium and stable isotope values suggest a mixing of the two waters. The Lake Mary well nos. 2 and 5 appear to only be receiving recharge from rain infiltration and ephemeral stream flow.

The Heckethorn well (sample no. 17) has an isotope value that indicates it is receiving recharge from a highly evaporated source. Given the directions of flow as determined by Figure 10, it does not appear as if this well would be receiving recharge from Lake Mary. The reason behind these isotopic values can only be speculated. Perhaps it is due to the tank set-up from which it was sampled, as discussed in Appendix B.

In order to investigate the possibility that seepage through the Lake Mary graben is reaching the Redwall Limestone and then moving laterally, possibly to the southwest, isotope samples were collected from two wells in Sedona. The isotope values resemble closely those of wells in the plateau regions above, nearer the recharge mound. It is possible that water from the recharge area on the plateau is reaching the Sedona wells. Although it is not known if the recharge mechanism is the fractures of the Lake Mary graben, it does not appear that seepage from the Lower and Upper Lake Mary reservoirs is the only recharge to the Sedona wells.

In addition to recharge through the Lake Mary graben, recharge may also be taking place through the Marshall Lake graben. The well at Walnut Canyon was considered to be a possible discharge point of this recharge. For that reason, isotope samples of Walnut Canyon well were compared with that of Marshall Lake and the Lower and Upper Lake Mary samples. These results do not appear to be comparable. The Walnut Canyon well is probably receiving recharge from another source, perhaps in the vicinity of the canyon.

SECTION 6

SUMMARY AND CONCLUSIONS

Previous studies of various well fields in the vicinity of Flagstaff had revealed a great deal of information concerning the hydrogeology of the area and its relation to the water supply development. However, certain physical constraints concerning recharge to the Lake Mary well field remained unclear. Perhaps the most important topic was whether the faults that define the adjacent Lake Mary graben are conductors of or barriers to ground-water flow. The graben could be an important channel for recharge to a properly designed well field if the faults are not barriers. An important source of recharge could be the Lower and Upper Lake Mary reservoirs, one of which is thought to lose 42% of its inflow by seepage into the graben.

In addition to the above problem, there was little recent work which involved chemically characterizing the various ground-water supplies. In order to develop further data on both of these topics, samples were taken from 30 springs, wells and surface water locations over a larger area of Flagstaff. The most concentrated sampling was in the region of the Lower and Upper Lake Mary reservoirs.

The samples were analyzed for the major ions and also nitrate, iron and silica. In addition, 26 of the samples were analyzed for the stable isotopes deuterium and oxygen-18. Five of the samples were analyzed for tritium in order to qualitatively date the ground water in the vicinity of the Lake Mary reservoirs.

Results of the chemical samples indicate that all of the waters sampled were calcium-magnesium-bicarbonate type water, with the exception of the Inner Basin well field, which contains a larger percentage of sodium and potassium ions. The waters varied considerably in hardness, with waters in the vicinity of the Lake Mary well field and those to the northeast composed of the highest calcium and magnesium values. Lake Mary well #4 contained lower hardness values than the other nearby wells.

Values of nitrate and silica were mapped over the study area. The values of nitrate, and to some degree, the values of silica confirmed the flow directions revealed by the static water level map.

The stable isotope results revealed a group of sample sites which were enriched in the heavier isotopes.

This type of trend indicates that those samples had undergone evaporation. All but one of those samples were from surface water, including samples from Lower and Upper Lake Mary. The other sample was from Lake Mary well #4, which is adjacent to Lower Lake Mary.

Only two wells yielded samples with significant tritium values indicating recent recharge. Lake Mary well #4 yielded the highest value of 16 TU.

Given the results of the chemical and isotopic analyses, it is evident that Lake Mary well #4 is receiving some portion of recharge from Lower Lake Mary. Results from a previous pump test on well #4 indicate that the Lake Mary fault may be a recharge boundary. However, there is not enough evidence to determine if the recharge is being drawn through the Lake Mary fault from the graben area, or if the recharge is coming through fractures in the upthrown side of the fault, near the well. It does not appear as if the other Lake Mary wells are receiving a significant amount of recharge from the Lake Mary reservoirs.

The results for sustained yield from the Lake Mary well field area in the Duren and Harshbarger reports are based upon different assumptions. The assumption of Duren, that no seepage from the Lake Mary reservoirs contributes to the developed Lake Mary well field, is incorrect based on the data from this study.

APPENDIX A

ADDITIONAL DATA TABLES

TABLE A.1 STATIC WATER LEVEL DATA FOR FIGURE 10

Local ID	Date	Elevation at Surface* (Feet)	SWL in Feet Below Surface	Elevation of SWL* (Feet)	Principal Aquifer Formation
(A-17-5)10cab	02/26/75	4480	653.0	3827	Redwall
(A-17-5)11ccb	07/83	4380	531	3849	Redwall
(A-17-5)11cdb	07/83	4415	563	3852	Redwall
(A-17-5)15aab	04/22/75	4375	497.3	3877.7	Supai
(A-17-5)15abd	04/01/83	4385	273.7	4111.3	Supai
(A-17-5)25bbd	03/14/74	4075	208.6	3866.4	Redwall
(A-17-6)18add1	04/22/75	4375	497.3	3877.7	Supai
(A-17-6)30abc	02/25/75	4335	450.8	3884.2	Supai
(A-17-6)30bb	04/08/83	4300	438.3	3861.7	Supai
(A-18-7)8ddc	01/30/78	6490	732.8	5757.2	Coconino
(A-18-7)15ccc2	01/09/81	6435	706.9	5728.1	Coconino
(A-18-7)22baa2	04/22/83	6455	706.0	5749	
(A-19-7)1ddd	03/10/77	7175	424.4	6750.6	Kaibab
(A-19-9)17dcd	12/67	6960	1320	5640	Coconino-Supai
(A-20-6)2bbc	12/14/83	7187	1076.0	6111	Coconino-Supai

TABLE A.1. (continued)

Local ID	Date	Elevation at Surface* (Feet)	SWL in Feet Below Surface	Elevation of SWL* (Feet)	Principal Aquifer Formation
(A-20-6)2bca	11/82			6053	Coconino-Supai
(A-20-6)11bba	11/82	7175	1083	6092	Coconino-Supai
(A-20-7)12ddb	11/82	6830	762	6068	Coconino
(A-20-7)20cca	12/03/79	6715	667	6048	Coconino-Supai
(A-20-7)30bbb	07/80	6675	613	6062	Coconino-Supai
(A-20-8)18bbb	03/06/84	6840	557.7	6282.3	
(A-20-8)18bcc	11/82	6837	501	6336	Coconino-Supai
(A-20-8)18cac	04/14/78	6830	527.5	6302.5	Coconino-Supai
(A-20-8)19aba	11/82	6809	322	6487	Coconino-Supai
(A-20-8)19dac	04/14/78	6795	273	6522	
(A-20-8)20ccd	11/82			6550	Coconino-Supai
(A-20-8)20dbc	11/82	6817	276.6	6540.4	Coconino-Supai
(A-20-8)27bad	09/81			5812	
(A-20-8)27cac	09/81			5866	Coconino-Supai

TABLE A.1. (continued)

Local ID	Date	Elevation at Surface* (Feet)	SWL in Feet Below Surface	Elevation of SWL* (Feet)	Principal Aquifer Formation
(A-21-6)35bcc	11/82	7130	1236	5894	Coconino-Supai
(A-21-6)35cba	12/20/83	7140	1243.0	5897	Coconino
(A-21-6)35ccb	11/82	7167	1247	5920	Coconino
(A-21-6)35ccc	11/82	7166	1103	6063	Coconino
(A-21-7)19aca	01/14/77	7070	1320.0	5750	Supai
(A-21-7)26abd	08/25/76	6795	1180.0	5615	Supai
(A-21-7)32bbc2	05/22/75	6900	975.0	5925	Coconino-Supai
(A-21-9)5ddd	07/21/75	6365	1270	5095	Supai
(A-21-9)6ca	1975	6430	1330	5100	Supai
(A-21-9)17acc	08/08/79	6440	1323	5117	Supai
(A-22-7)33cca2	08/07/79	7165	218.0	6947	Moenkopi
(A-22-7)34dca1	08/20/79	7230	200.2	7029.8	Moenkopi
(A-22-7)34dcb3	08/21/79	7230	302.5	6927.5	Kaibab
(A-22-8)23aab	04/25/71	6570	1585.0	4985	Supai

TABLE A.1. (continued)

Local ID	Date	Elevation at Surface* (Feet)	SWL in Feet Below Surface	Elevation of SWL* (Feet)	Principal Aquifer Formation
(A-22-8)27daa	09/24/80	6620	1510	5110	Supai
(A-22-9)29baa	12/17/73	6390	1383.0	5007	Supai
(A-23-7)28ddb2	08/30/78	9755	225.2	9529.8	Glacial
(A-23-7)28ddd	08/31/78	9774	238.2	9535.8	Glacial
(A-23-7)33aaa	08/30/78	9775	255.3	9519.7	Glacial
(A-23-7)33aab2	10/76	9793	143.0	9650	Glacial
(A-23-8)21aad	01/31/79	6970	1960.3	5009.7	Supai

*Elevation in feet above mean sea level.

TABLE A.2. HISTORICAL CHEMICAL DATA

Received from Scott (1984)
(All Values in mg/l Unless Otherwise Noted in Heading)

Local ID	Site Description	Date	Temp. °C	pH	Spec. Cond. (umhos/cm)	TDS*	Ca	Mg	K	Na	Total Hard. as $CaCO_3$	Total Alkalinity as $CaCO_3$	Cl	SO_4	NO_3	F	SiO_2	Fe	Zn	Ba
(A-21-6)35cba	Woody Mtn. #1	4/2/75		8.0		140	27	10		5	108	110	5	<6	<1	0.14		-	0.06	
		8/77		8.0		140	27	10		5	108	110	5	<6	<1	0.14			0.06	
		8/15/78		8.2		162**	25	11		6.5	106	106	4	<5	1	0.10			-	<1
		5/30/80						8.8		2.8		111	1.6	5.1	0.20				0.04	<0.5
(A-21-6)35ccb	Woody Mtn. #2	6/7/72		8.3			29	11		5	116	118	9	<6	20	0.05		-	0.1	
		5/20/74		7.9			31	10		4	134	116	3	7	<1	0.06		-	0.6	
		4/2/75		7.9		143	27	9		5	106	114	6	<6	<1	0.16		0.19	0.07	
		8/15/78		8.2		174**	25	11		7	108	108	4	4	1	0.12		-	-	
		8/20/82		7.87		120**	23.1	11.6		5.4	105.5	117	5.0	1.2	0.27			.04	-	<0.5
(A-21-6)35bcc	Woody Mtn. #3	6/7/72		8.3			24	9		4	100	112	5	<6	18	0.13		-	0.2	
		7/1/80		7.80		142.7	19.4	11.1		5.9	94.1	107.2	1.5	8.5				0.17	0.02	
(A-21-6)35ccc	Woody Mtn. #4	6/7/72		8.3			31	10		5	122	120	18	<6	31	0.04		-	0.3	
		5/20/74		8.2			29	8		5	108	116	3	6	<1	0.07		-	0.05	
		4/2/75		7.9			29	9		6	110	112	4	<6	<1	0.13		-	0.07	
		5/20/80		7.71		154.0	12.8	9.9		3.2	72.7	111.4	2.3	2.2	0.2	0.12		-	-	<0.5
(A-20-6)2bbc	Woody Mtn. #5	4/2/75		7.9			26	8		5	100	112	5	<6	<1	0.18		-	0.05	
		8/15/78		8.1		161**	24	12		8	106	108	5	<5	1	0.14		0.07	<0.05	
		12/8/81		7.74		151.0	22.1	12.8		4.8	108	94.0	7.9	1.6	<1	0.10				
(A-20-6)2bca	Woody Mtn. #6	4/2/75		7.9			27	6		5	94	100	5	<6	<1	0.24		0.06	0.10	
		5/22/80		7.64		177	13.7	5.5		2.6	56.8	93.5	1.3		0.10	0.12		0.22	0.07	
(A-20-6)11bba	Woody Mtn. #7	7/14/78	14	8.1	200	110**	23	12		6	108	108	3	<5	0.7	0.09		0.13	-	<1
		2/6/81		7.82		103	36.1	11.8		3.9	78.0	99.9	4.3	1.2	0.08	0.10		-	-	
(A-20-8)18bcc	Lake Mary #2	6/6/72		8.2			47	41		5	290	302	6	<6	63	0.13		-	0.05	
		4/2/75		7.5			74	35		6	332	350	5	<6	<1	0.17		-	0.07	
		5/30/80		7.85		371		41.9		3.8	318.5	373.6		4.4	0.30	0.10		-	0.01	
(A-20-7)12ddb	Lake Mary #3	12/16/71		8.1			42	26		10	216	238	5	7	1	0.09		-	<.05	
(A-20-8)19aba	Lake Mary #4	9/22/72		8.1			30	20		2	158	138	2	7	1	0.17		0.06	0.06	
		4/30/75					34	17		3	156	138	<1	<6	<1	0.13		-	0.06	
		3/13/78	11		275	161**	30	16		3	154	134	2	5		0.14		0.10	0.06	<1
		5/30/80		7.9		154	25.0	14.8		1.7	123.3	140.3	7.8	5.4	0.30	0.15		-	0.01	<0.5

TABLE A.2. (Continued)

Local ID	Site Description	Date	Temp. °C	pH	Spec. Cond. (umhos/cm)	TDS*	Ca	Mg	K	Na	Total Hard. as $CaCO_3$	Total Alkalinity as $CaCO_3$	Cl	SO_4	NO_3	F	SiO_2	Fe	Zn	Ba
(A-20-8)20dbc	Lake Mary #5	12/6/75		7.9		299**	66	35		7	314	332	2	<4	3	0.06		-	-	
		7/22/81		7.08		407.0	43.2	54.8		4.4	333.4	362.9	0.0	1.6	0.4	0.19		-	0.01	
	Raw Lake Mary Water	7/19/80			70	54	7	3.7	0.8	2	29		10	6	0.2	<0.1	14	0.38	0.01	
(A-23-7)33aab2	Inner Basin #9	8/24/78		7.3		48**	5	2		2	20	26	2	<5	0.6	0.44		-	0.08	<1
		1/2/79												<1	0.5	0.40				
		10/13/82		7.43		71.0	4.0	2.0		2.3	18.2		1.3		0.08	0.44		-	0.01	
(A-23-7)27cbd	Inner Basin #11	5/26/72		7.2			6	4		3	30	28	2	6	1	0.30		-	-	
		8/16/78		7.4		111**	5	2		4	20	26	3	<5	<0.5	0.24		-	-	<1
		10/17/80		6.46	73	110.1	0.9	1.7		3.3	9.2	26.3	1.2	4.7	0.1	0.30		-	-	<0.5
(A-23-7)28ddb1	Inner Basin #14	5/26/72		7.5			7	8		2	52	32	8	<6	22			-	0.07	
		8/16/78		7.3		86**	6	3		6	22	28	3	<5	0.7	0.14		-	-	<1
		11/2/79												<1	0.6	0.11				
		10/13/82		7.72		71.0	0.6	2.8		2.9	46.6	29	2.7	1.1	0.07	0.13		-	-	<0.5
(A-23-7)32aab	Flagstaff Spg. Inner Basin	9/19/79		7.1		41**	3	1		2	16	12	1	<1	<0.3	0.07		-	-	
(A-23-7)32dba	Snowslide Spg. Inner Basin	1/2/79												<1	<0.5	0.71				
		9/19/79				37**	4	1		2	22	12	1	<1	<0.5	0.10		-	-	<1
(A-23-7)27ccc	Raspberry Spg. Inner Basin	4/2/79												<1	0.8	0.32				
		9/19/79				68**	5	2		3	22		1	1.5	<0.5	0.30		0.07	-	<1

*Total dissolved solids determined from sum of constituents (unless otherwise noted).
**Determined from residue on evaporation.
-Below detection limit.

TABLE A.3. HISTORICAL CHEMICAL DATA

From Various Sources
(All Values in mg/l Unless Otherwise Noted in Heading)

Local ID	Site Description	Date	Temp. °C	pH	Spec. Cond. (umhos/cm)	TDS*	Ca	Mg	K	Na	Total Hard. as $CaCO_3$	Total Alkalinity as $CaCO_3$	Cl	SO_4	NO_3	F	Fe	Zn	Ba
[a](A-18-7)27cbb	Supai	9/7/65	17	7.2	197		17	7.7		12	74	82	8.0	6		<0.2			
[b](A-20-7)20cca	Kachino #3	11/29/78		7.8		162**	54	19		7	204	194	5	<5	3.9	0.10	0.60	0.22	<1
[b](A-20-7)30bbb	Kachino #1	9/22/78		7.8			45	21		5	200	190	3	<5	1	0.06	<0.05	0.06	<1
[b](A-20-7)30bdb	Kachino #2	9/22/78		7.9		188**	41	18		4	178	168	3	<5	2	0.09	<0.05	0.08	<1
[c](A-20-8)18bcc	Lake Mary #2	5/7/75		8.2			62	38	3.0	6.8							0.1		
		5/12/75		7.7			58	46	2.7	6.7							0.1		
[c](A-20-8)19aba	Lake Mary #4	5/7/75		8.4			29	14	2.6	3.3							0.1		
		5/12/75		8.0			25	18	2.5	3.7							0.1		
[b](A-21-7)32bbc2	Mountain Dell	2/7/83		7.45		238	89.2	36.7		3.8	373.0	324.5	4.3	19.0	0.72	<0.1	0.9	0.08	<0.5
[d](A-21-8)26dab	Walnut Canyon Nat'l. Mon.	8/19/70	15.5	8.0	418	214	42	26	0.8	4.0	212	203	5.0	3.0		0.1	0.0		
		10/9/80		7.12	397	194.7	59.2	25.0		2.7	250.8	208.0	0.0	5.0	1.5	0.17	<0.1	0.03	<0.5
[b](A-22-8)27daa	Doney Park Koch #5	8/26/82		7.35		270	60.6	11.1		5	196.8	254.5	12.7	2	0.7	0.1	<0.1	0.10	2.3
[e](A-23-8)21aab2	Sunset Crator Nat'l. Mon. #2	1/15/80				545	114	36		19	433	315	16	5	<0.1	0.34			

[a]McGavock (1968)

[b]State of Arizona, Department of Water Resources

[c]Harshbarger (1976)

[d]Office of Walnut Canyon National Monument

[e]Office of Sunset Crator National Monument

*TDS determined from sum of constituents unless otherwise noted

**Determined from residue on evaporation

TABLE A.4 NITRATE VALUES FOR FIGURE 24

Local ID	Date	Dissolved NO_3 (mg/1)	Site Description
(A-19-9)17dcd	10/14/83	0.9	Pine Grove Campground
(A-20-6)2bbc	10/13/83	1.1	Woody Mountain #5
(A-20-6)2bca	05/22/80	0.10	Woody Mountain #6
(A-20-6)11bba	10/13/83	0.4	Woody Mountain #7
(A-20-7)cca	09/23/83	2.2	Kachino Village #3
(A-20-7)12bba	09/27/83	1.3	Heckethorn
(A-20-7)28bcc	09/21/83	1.6	Mountainaire Village
(A-20-7)30bbb	09/23/83	1.1	Kachino Village #1
(A-20-8)18bcc	01/16/84	1.1	Lake Mary #2
(A-20-8)19aba	09/27/83	0.9	Lake Mary #4
(A-20-8)20dbc	09/22/83	1.5	Lake Mary #5
(A-21-6)35bcc	09/22/83	0.9	Woody Mountain #3
(A-21-6)35cba	05/30/80	0.20	Woody Mountain #1
(A-21-6)35ccb	08/20/82	0.27	Woody Mountain #2

TABLE A.4. (continued)

Local ID	Date	Dissolved NO_3 (mg/1)	Site Description
(A-21-6)35ccc	05/20/80	0.20	Woody Mountain #4
(A-21-7)32bbc2	01/16/84	5.3	Mountain Dell
(A-21-8)26dab	11/30/83	7.5	Walnut Canyon Nat'l Mon.
(A-21-9)6ca	09/22/83	1.3	Doney Park, Ranchos #2
(A-22-8)27daa	09/23/83	7.1	Doney Park, Koch #5
(A-23-8)21aab3	01/16/84	8.0	Sunset Crator Nat'l Mon.

TABLE A.5 SILICA VALUES FOR FIGURE 25

Local ID	Date	Dissolved SiO_2 (mg/1)	Well Description or Principal Formation
(A-19-9)17dcd	10/14/83	15.9	Pine Grove Campground
(A-20-6)2bbc	10/13/83	29.3	Woody Mountain #5
(A-20-6)11bba	10/13/83	17.1	Woody Mountain #7
(A-20-7)12bba	09/27/83	12.0	Heckethorn Well
(A-20-7)20cca	09/23/83	15.8	Kachino Village #3
(A-20-7)28bcc	09/21/83	14.6	Mountainaire Village
(A-20-7)30bbb	09/23/83	11.6	Kachino Village #1
(A-20-8)18bcc	01/16/84	10.0	Lake Mary #2
(A-20-8)18cac	09/26/83	7.4	Whitley Trailer Park
(A-20-8)19aba	09/27/83	8.7	Lake Mary #4
(A-20-8)20dbc	09/22/83	8.6	Lake Mary #5
(A-21-6)35bcc	09/22/83	18.3	Woody Mountain #3
(A-21-6)35ccb	08/10/78	24	Woody Mountain #2
(A-21-7)32bbc2	01/16/84	14.1	Mountain Dell

TABLE A.5 (continued)

Local ID	Date	Dissolved SiO_2 (mg/1)	Well Description or Principal Formation
(A-21-8)26dab	11/30/83	10.0	Walnut Canyon Nat'l Mon.
(a-21-9)6ca	09/22/83	12.2	Doney Park, Ranchos #2
(A-21-9)5ddd	09/06/78	14	Supai Formation
(A-21-9)8bcc	09/05/78	12	Supai Formation
(A-22-8)16dad	10/31/78	40	Supai Formation
(A-22-8)23aab	10/31/78	19	Supai Formation
(A-22-8)27caa	10/31/78	22	Supai Formation
(A-22-8)27daa	09/23/83	21.6	Doney Park, Koch #5
(A-23-8)21aab3	01/16/84	41.0	Sunset Crator Nat'l Mon. #3

APPENDIX B

SAMPLING AND ANALYTICAL METHODOLOGY

Samples for this study were taken from various sources, i.e., wells, springs and surface waters. Descriptions of sampling and analytical methods for these types of waters can be found in manuals from the U. S. Geological Survey (U.S.G.S., 1977, and Wood, 1976) and the American Public Health Association (1976). The methodology descriptions of importance for this study are reported below.

Sampling Methods

Sample no. 14 was taken at a depth of 20 feet near the dam for Upper Lake Mary. A Kemmerer thief-type sampler was used to collect the sample. The other surface water samples (11, 15, 18 and 23) were collected using a sample bottle over-turned at the proper depth.

Babbit Spring (sample no. 12) was sampled from a plastic pipe that had been inserted into the hillside. Samples from the other two springs (sample nos. 9 and 19) were collected directly into the sample bottles from the discharge point. Care was taken to collect a sample free of particulates from the surrounding strata.

When sampling wells, it is important that the water collected is characteristic of that within the aquifer medium and not stagnant water within the well. The wells were to be pumped until three times the volume of water within the well was removed. However, constraints on the amount that could be pumped at one time did not permit the full three well volumes to be pumped for sample nos. 2, 7 and 26.

Besides collecting samples that are not stagnant well water, it is important to collect samples that have not gone through pressure tanks or treatment systems. Four of the smaller wells could not be sampled prior to a storage or pressure tank. Sample nos. 17, 27 and 30 were taken from faucets on the discharge end of storage tanks. Wells filled these tanks on demand. The tank and well described by sample no. 27 were not open to the outside. Sample no. 13 was taken from a distribution system with a pressurized tank. The results from this sample were reported, but not used in the discussion section. All four wells were not pumped long enough to remove three water volumes.

Analytical Methods

Temperature, specific conductance, pH, and alkalinity measurements were made in the field at the time of sample collection. The other analyses were made in the laboratory.

Temperature measurements were made at the beginning of each sampling effort. A mercury filled thermometer with an accuracy of 0.1 degree celsius was used.

Specific conductance measurements were made using a Yellow Springs Instrument model 33 meter. Manufacturer's instructions were followed in the usage of the meter. The probe had a cell constant of one, and the accuracy of the probe and meter together was +/-5.5% of the reading. The results were corrected for the difference between the sample temperature and 25 degrees celcius by assuming a change in conductance of 2% per degree celcius.

Measurements of pH were made using a Digisense pH meter and combination pH probe. The accuracy of the meter was +/-0.01 pH unit, and the temperature difference was compensated for manually by setting the control to the temperature of the sample. The meter was operated according to the manufacturer's instructions. Samples were collected in 100 ml plastic beakers for measurement.

Alkalinity for each sample was originally measured using a Hach Chemical Co. digital titrator and sulfuric acid cartridge, and the pH meter described above. Poor analytical procedure resulted in erroneous data. The end point pH of 4.5, chosen to represent total alkalinity, was overshot in each titration in the field. Measurements of the amount of titrated acid were made, however, prior to and after the end point pH.

Rather than simply use the value of alkalinity that would bring the charge balance of ions for each sample to zero, two assumptions (although erroneous) were made in order to calculate the alkalinity from the data at hand. The first assumption was the original assumption that the total alkalinity end point was 4.5 pH for all samples. Actually, the end point for total alkalinity changes with the alkalinity concentration (Snoeyink, 1980). The second assumption was that there was a linear relationship between the amount of acid added to the sample and the resulting pH value in the pH range near the end point. The actual end point is the inflection point on a curve, not a point on a straight line. The alkalinity value as reported was then calculated using the data taken prior to and after the end point.

In the case of sample nos. 8, 9, 10, 14, 15 and 18, the alkalinity values reported were measured correctly, however some time after collection. Alkalinity within a sample may change due to precipitation of calcite if the measurement is not taken at the time of collection. Thus, the value of alkalinity required for a charge balance of ions is also reported and used in the discussion.

The analyses of sodium, potassium and iron were done on a flame atomic adsorption unit at the University of Arizona. Standard spikes were used to calibrate the instrument.

The analyses for calcium hardness, total hardness (from which magnesium values were derived), chloride, sulfate, nitrate, and silica were done using various methods and equipment supplied in the Hach Direct-Reading Engineer's Laboratory. Extreme care was taken to run the analyses according to the manufacturer's instructions. Standard's were analyzed as a quality control check.

The isotopes of deuterium and oxygen-18 were analyzed by staff members of the Isotope Laboratory at the College of Arts and Sciences, University of Arizona. The tritium analyses were done at the Weizmann Institute of Science, in Israel.

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