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# Geohydrology of Pipe Spring National Monument Area, Northern Arizona

Water-Resources Investigations Report 98—4263

*Prepared in cooperation with the*
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# Geohydrology of Pipe Spring National Monument Area, Northern Arizona

By MARGOT TRUINI

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 98—4263

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## CONVERSION FACTORS

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |
| acre | 0.4047 | hectare |
| acre-foot (acre-ft) | 0.001233 | cubic hectometer |
| gallon per minute (gal/min) | 0.06309 | liter per second |
| gallon per minute per foot [(gal/min)/ft] | 0.2070 | liter per second per meter |

Temperature is reported in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = 1.8(°C) + 32$$

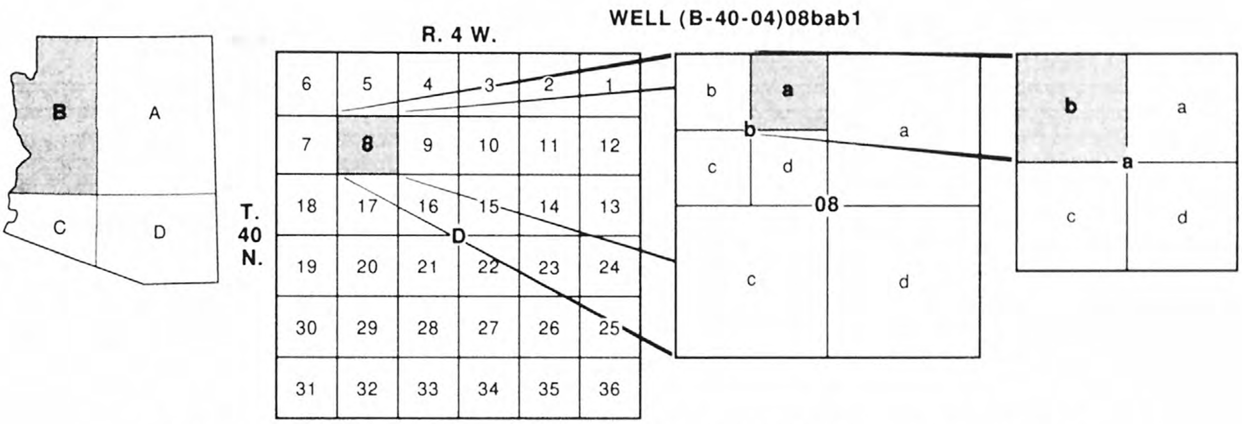
## ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (μg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C). Radioactivity is expressed in picocuries (pCi), which is the amount of radioactive decay producing 2.2 disintegrations per minute.

## VERTICAL DATUM

*Sea level*: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD OF 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called "Sea Level Datum of 1929."

## WELL-NUMBERING AND NAMING SYSTEM




**Quadrant B, Township 40 North, Range 4 West, section 8, quarter section b, quarter section a, quarter section b, well 1**

The well numbers used by the U.S. Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River Meridian and Base Line, which divide the State into four quadrants that are designated by capital letters A, B, C, and D in a counterclockwise direction, beginning in the northeast quarter. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes. In the example shown, well number (B-40-04)08bab1 designates the well as being in the NW1/4, NE1/4, NW1/4, section 8, Township 40 North, and Range 4 West.

# Geohydrology of Pipe Spring National Monument Area, Northern Arizona

*By* Margot Truini

## Abstract

Pipe Spring National Monument is on the Arizona Strip, an area between the Utah border to the north and the north rim of the Grand Canyon to the south. Four springs at the base of Winsor Point on Winsor Mountain (known collectively as Pipe Spring) are a part of the historical significance of the monument. The relation between declining discharges from springs in the monument and ground-water development north of the monument was studied to provide information that could be used for management of the monument resources.

Ground-water elevations from wells indicate that ground-water movement is from north to south along the west side of a branch of the Sevier Fault. Faulting in the area has downthrown permeable water-bearing sediments relative to impermeable sediments and is evinced by cliffs along the western and northern edges and flat-lying areas to the east. The Navajo Sandstone and Kayenta Formation are the primary water-bearing units on the west side of the fault. The semipermeable sediments of the Chinle and Moenkopi Formations on the east side of the fault inhibit ground-water movement from the west to the east side of the fault.

Ground water south of Moccasin Canyon is higher in total dissolved solids than ground water north of Moccasin Canyon. Wells north of Moccasin Canyon are open primarily in the Navajo Sandstone, and wells south of Moccasin Canyon are open primarily in the upper sandstone facies of the Kayenta Formation.

A water-budget estimate for the study area indicates a storage deficit of 780 acre-feet per year. This deficit suggests that some recharge may be occurring outside the study area. Oxygen and hydrogen stable-isotopic data suggest no isotopic variation in recharging waters in the study area and surrounding region. Radiocarbon and tritium activities indicate apparent ground-water ages at wells and springs are between 45 and 9,000 years.

## INTRODUCTION

Pipe Spring National Monument (hereafter referred to as the monument) is in northwestern Arizona on 40 acres within the Kaibab-Paiute Indian Reservation (fig. 1). Tunnel Spring, Main Spring, Cabin Spring, and Spring Room Spring are known collectively as Pipe Spring and are at the base of Winsor Point of Winsor Mountain. The springs are an integral part of the monument's historic setting, that of an early ranch homestead in desert country (Inglis, 1997). Ground water in the study area is used by the Kaibab-Paiute Indians, the town of Moccasin, and the National Park Service (NPS). The Kaibab-Paiute Tribe currently pumps ground water from Tribal Culinary well no. 2

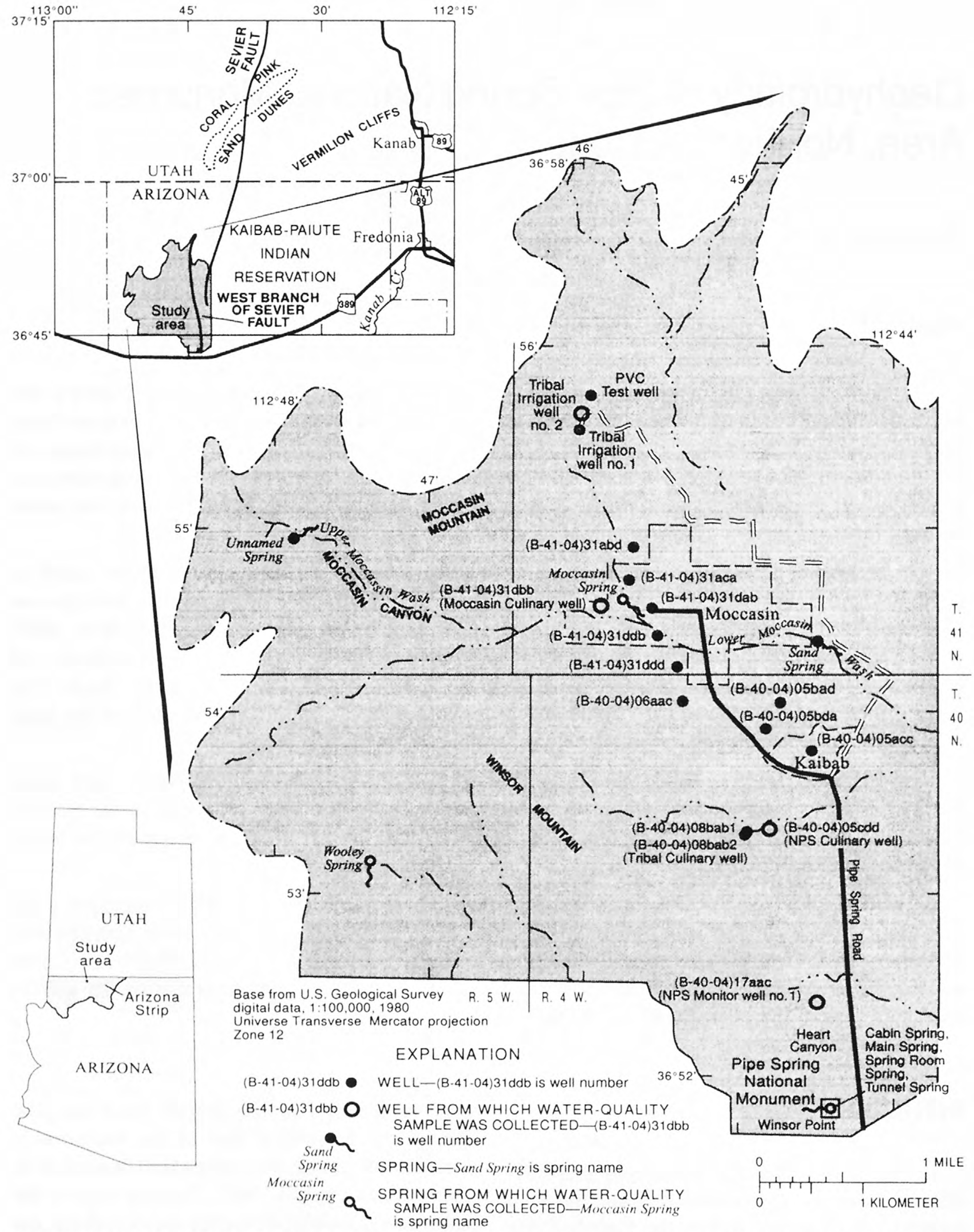



**Figure 1.** Study area and wells and springs, Pipe Spring National Monument area, northern Arizona.

limits for public supply (U.S. Public Health Service, 1962), and that ground water from the Navajo Sandstone was suitable for domestic use. He suggested that large-scale pumping of ground water from the Navajo Sandstone near Moccasin or the monument may decrease flow to the springs in these areas.

Levings and Farrar (1979) sampled selected springs and wells as part of a larger regional study. Samples were collected from Main Spring in the monument, Moccasin Spring, from an unidentified well between the monument and Moccasin, and from an unidentified well north of Moccasin. They determined that ground water from the Navajo Sandstone near Moccasin and the monument was of suitable chemical quality for domestic purposes. They also noted that ground water south of Moccasin had higher dissolved-solids concentrations than ground water north of Moccasin.

Barrett and Williams (1986) evaluated the declining spring flows in the monument and looked at spring-flow data from 1976 to 1986 with respect to water quality, precipitation, and geology. They concluded that the decline in spring flow probably was the result of ground-water pumping in the area rather than a natural variation in precipitation.

Inglis (1997) examined data collected from the springs at the monument, Moccasin Spring, the NPS Monitor well no. 1 (B-40-04)17aac, the NPS Culinary well (B-40-04)05cdd, and precipitation data, and was not able to determine a correlation between precipitation data and declining discharges. From August 1990 to June 1992, Inglis (1997) measured water levels at Tribal Culinary well no. 1 (B-40-04)08bab1 and the NPS Monitor well no. 1 (B-40-04)17aac, and spring discharges at the monument. He concluded that annual fluctuations in ground-water levels and spring discharges were caused by seasonal recharge and (or) seasonal pumping from wells, although he could not establish a correlation between local precipitation and spring discharges.

In 1997, the USGS assessed the feasibility of developing ground-water supplies on the Kaibab-Paiute Reservation (R.J. Hart and D.J. Bills, hydrologists, USGS, written commun., 1997). Part of this assessment included a seepage investigation of Moccasin Wash east of the study area and one of its tributaries Two Mile Wash. Results of the investigation showed that significant amounts of ground water discharges to the Moccasin Wash drainage system, and that riparian vegetation consumes a significant portion of the discharge during the summer.

## Acknowledgments

John Hiscock, Terry Strong, and the staff of Pipe Spring National Monument helped in collecting water samples from springs and wells and contributed historical information. The Kaibab-Paiute Tribe provided escorts on their land and access to wells. Residents of the town of Moccasin allowed access to wells for measurement of water levels and collection of water samples. Robert Rosé, a volunteer geologist for the NPS, shared his geologic experience and findings.

## DESCRIPTION OF THE STUDY AREA

The study area lies south of the Coral Pink Sand Dunes in Utah on the Arizona Strip. The Arizona Strip is the geographical area north of the Grand Canyon and south of the border with Utah (fig. 1). The monument is about 15 mi west of Fredonia, Arizona, and 20 mi southwest of Kanab, Utah. Winsor Mountain and Moccasin Mountain form the western and northern boundaries of the study area. The Vermilion Cliffs are to the north and east of the study area. The monument occupies 40 acres within the boundaries of the Kaibab-Paiute Indian Reservation at the base of the southern tip of Winsor Point of Winsor Mountain.

Perennial springs in the study area outside the monument include Moccasin Spring, an unnamed spring in Upper Moccasin Wash, Wooley Spring, and Sand Spring (fig.1). Water from Moccasin Spring is shared between the town of Moccasin and the Kaibab-Paiute Tribe. The unnamed spring in Upper Moccasin Wash, west of Moccasin, discharges at the contact between the Kayenta Formation and Navajo Sandstone. Wooley Spring, west of the monument, discharges from the uppermost part of the Kayenta Formation. Sand Spring, east of the town of Moccasin and north of the tribal village of Kaibab in Lower Moccasin Wash, discharges into Moccasin Wash.

The climate in the study area is semiarid. Precipitation averages 12 in./yr and occurs mostly as rainfall. Average temperatures range from about 40°F in the winter to about 90°F in the summer (John Hiscock, Superintendent, Pipe Spring National Monument, written commun., 1997).

## Physical Characteristics of Selected Springs

Tunnel Spring was developed before the monument was established. The spring is a horizontal 150 to170-foot-long tunnel hand dug into the Navajo Sandstone. The tunnel was dug around 1902 (John Hiscock, Superintendent, Pipe Spring National Monument, written commun., 1998). In 1987, the tunnel was opened, and a rock slide was found 40–50 ft beyond the opening. Beyond the rock slide, the tunnel may be saturated with water that has seeped through fissures and pore spaces in the Navajo Sandstone. Flow from the spring is conveyed by a pipeline outside the monument to meet a water-use agreement with the local cattlemen's association. The pipeline was reconstructed in 1988.

Cabin Spring is about 400 ft west of Winsor Castle and has not been developed. Cabin Spring discharges from a silty sandstone outcrop that may be near the contact between the siltstone-clay facies and sandstone facies of the Kayenta Formation (Robert Rosé, volunteer geologist, NPS, oral commun., 1998).

Main Spring, also known as Big Spring, is about 20 ft west of Winsor Castle and discharges into a channel that diverts flow through a horse trough into the western duck pond. Foundation drains convey seepage from the spring into the channel above the pond.

Spring Room Spring (formerly Parlor Room Spring) is inside Winsor Castle. Historic records indicate that at one time the spring opening was below the parlor room in the northwest corner of Winsor Castle. The spring water collects in the courtyard cistern, where it is diverted between Main Spring and Spring Room Spring. The water flows out of the building from Spring Room Spring through a trough and into the east pond in front of Winsor Castle.

Moccasin Spring is outside the monument about 3.5 mi north in the town of Moccasin. The spring seeps from the alluvium and generally is captured in a concrete cistern. Downstream from the cistern, the spring is diverted and the water is used by the town of Moccasin and the Kaibab-Paiute Tribe.

# EXISTING HYDROLOGIC DATA

Historical hydrologic and climatic data has been collected in an effort to monitor spring discharges, water levels, precipitation, and air temperature. Spring discharges were collected for springs at the monument from 1976 to the present (1998); however, only data from 1976 to 1996 are presented in this report. Water levels from well (B-40-04)06aac were measured by the USGS from 1976 to 1998. Daily climatological data for precipitation and air temperature were collected by the NPS from 1985 to the present (1998); however, only data from 1985 to 1996 were used in this study. Moving-average trend lines were used to define trends for spring discharges, air temperature, and precipitation.

Water-level data from (B-40-04)06aac show a decline of 5 ft from 1980 to 1992 and indicate declining water levels from 1980 to 1998 (fig. 2). Cumulative spring discharges for all four springs in the monument show annual cycles (fig. 3). A moving-average trend line shows declining spring discharges from 1977 to 1986 (fig. 3). Spring discharges were fairly steady from 1986 to 1996 but increased slightly from 1990 to 1994 (fig. 3). Average monthly precipitation and air temperatures also show annual cycles (fig. 4).

# APPROACH AND METHODS OF INVESTIGATION

Collection and analysis of hydrogeologic and water-chemistry data were designed to help describe ground-water movement, geologic characteristics and structural controls that affect flow, recharge and discharge areas, and ground-water ages, and were used to estimate a water budget. A hydrogeologic framework for the study area was developed on the basis of these data.

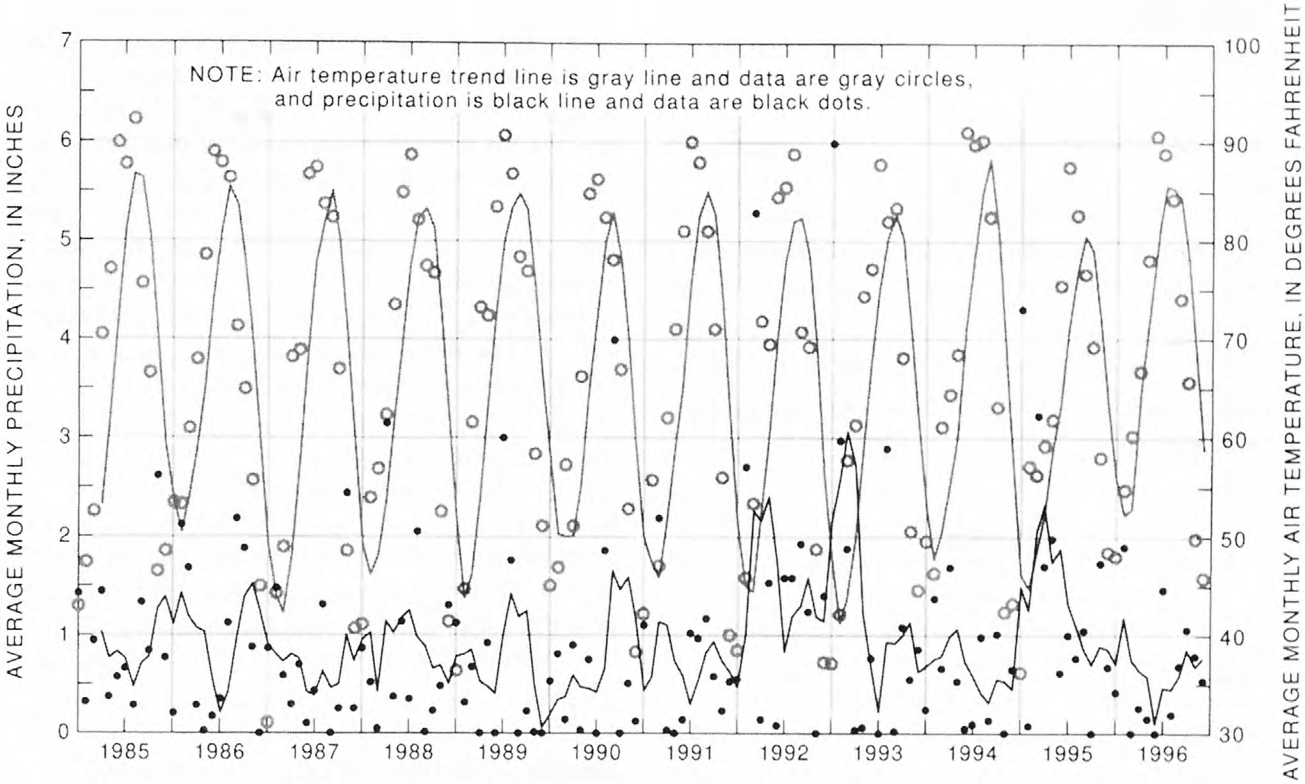



**Figure 4.** Moving-average trend lines for annual precipitation and air temperature, Pipe Spring National Monument area, northern Arizona. Trend lines were delineated using 4-month averages.

## Hydrogeologic Data

Hydrogeologic data were used to define the physical relation between the springs and ground-water system north of the monument. Existing water-level data from drillers' logs were used to identify locations where additional water-level measurements could be made. Ground-water levels were measured in wells using a steel or electric tape. Surface elevations for selected wells were measured using the global-positioning satellite (GPS) system. Well locations then were transferred to the appropriate USGS 1:24,000-scale topographic maps. Geologic sections were made using the topographic maps for well locations and drillers' logs for subsurface geologic contacts. Geologic data, well locations, and other geographic information, such as town, monument, and study-area boundaries, were digitized into a geographic-information system (GIS) data base to create working maps.

## Water-Chemistry Data

Water samples were collected and analyzed to help determine the relation between the ground-water flow near the springs in the monument and ground-water flow north of the monument. Samples were collected for analyses of major-ion, trace-element, and nutrient concentrations; stable-isotope ratios for oxygen ($^{18}O/^{16}O$), hydrogen ($^{2}H/^{1}H$), carbon ($^{13}C/^{12}C$); strontium ($^{87}Sr/^{86}Sr$); and activities of carbon-14 ($^{14}C$) and tritium ($^{3}H$).

Major-ion and trace-element analyses were used to determine the chemical compositions of ground water from different parts of the study area. Nutrient analyses were used as indicators of surface-water infiltration as a source of recharge to the aquifer. Stable-isotope data $^{18}O/^{16}O$ and $^{2}H/^{1}H$ were used to investigate sources of recharge. Carbon and Sr isotopic data were used to determine flow-path processes that control water-rock interactions. Analyses of $^{14}C$ and $^{3}H$ activities were used to determine apparent ground-water ages.

### Isotopic Nomenclature

Stable isotopes are measured relative to a standard in which the ratio of the two isotopes (for example $^{18}O/^{16}O$) is known. Deviation of the sample from the standard is expressed in parts per mil (‰) using the delta (δ) notation. Ratios of the stable isotopes also are expressed using delta notation:

$$\delta = \frac{R_x - R_{std}}{R_{std}} \times 1,000, \qquad (1)$$

where

$\delta$ = isotopic ratio, in per mil (‰),

$R_x$ = ratio of isotopes measured in sample, and

$R_{std}$ = ratio of same isotopes in the standard.

The standard used is Vienna Standard Mean Ocean Water prepared and distributed by the International Atomic Energy Agency (1969).

Natural background levels of $^{3}H$ in the atmosphere and ground water are about 5 tritium units (TU; Mazor, 1991); however, anthropogenic $^{3}H$ was produced from atmospheric thermonuclear tests that began in 1952. Anthropogenic $^{3}H$ peaked in about 1963 when atmospheric testing was banned (Mazor, 1991; Clark and Fritz, 1997). Consequently, semiquantitative age dating of ground water is possible. In 1998, water having less than 0.5 TU was recharged before 1953; water having greater than 10 TU typically can be assumed to have recharged after testing began. Water having greater than 0.5 TU and less than 10 TU probably is a mixture of pre- and post-bomb waters (Mazor, 1991; Clark and Fritz, 1997).

The geochemical mass-balance model NETPATH (Plummer and others, 1991) was used to translate $^{14}C$ data from percent modern carbon (pmc) to years. Several carbon-activity model routines that are written into the NETPATH code can be used. For the specification of this particular system, the model by Fontes and Garnier (1979) was used assuming (1) an open system (gas-solution equilibrium), which allows the model to back calculate an initial $^{13}C$ soil $CO_2$, and (2) solid-phase $\delta^{13}C$ values from the Navajo Sandstone near Black Mesa of -3.2‰ with a standard deviation of 3.7‰ (Lopes and Hoffmann, 1997).

The ionic radius of strontium (Sr; 1.13 Å) is only slightly larger than the ionic radius of calcium (Ca; 0.99 Å). This slight difference in size allows Sr to replace Ca in many minerals such as plagioclases, carbonates, and clays. The substituted Sr can go into solution by dissolution and ion exchange. The $^{87}Sr/^{86}Sr$ of a ground-water sample will indicate the net Sr input from the aquifer lithology.

### Sample Collection and Laboratory Analysis

Springs and wells were selected on the basis of their location relative to the monument, accessibility to the site, aquifer-unit association, and their location relative to the west branch of the Sevier Fault (fig. 1). Samples were collected from three springs at the monument (Cabin Spring, Spring Room Spring, and Tunnel Spring), and from Moccasin Spring. Ground-water wells developed in the Navajo Sandstone included the NPS Monitor well (B-40-04)17aac, the NPS Culinary well (B-40-04)05cdd, Moccasin Culinary well (B-41-04)31dbb, and Tribal Irrigation well no. 2. All wells and springs used for sampling are on the downthrown side (west side) of the west branch of the Sevier Fault. Wells sampled north of Moccasin are open to the Navajo Sandstone and the upper part of the Kayenta Formation. On the basis of drillers' logs, wells sampled south of Moccasin Canyon are open to the Navajo Sandstone; however, surficial geology and structural information indicate that these wells also are probably open to the sandstone facies of the Kayenta Formation.

Specific conductance, pH, dissolved oxygen, and water temperature were monitored during pumping until they stabilized to ensure that collected samples were representative of the water in the aquifer. Water samples were filtered using 0.1-micrometer filters for analysis of trace elements, major ions, nutrients, and strontium ($^{87}Sr/^{86}Sr$). Nitric acid ($HNO_3$) was used on site to acidify samples to a pH of less than 2 as a preservative for trace metals, most cations, and $^{87}Sr/^{86}Sr$.

Raw, unfiltered samples were collected to measure $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $^{3}H$ and $^{14}C$; and some major ions and nutrients. Oxygen and hydrogen isotope samples were collected in a 60-milliliter glass bottle filled to the top and sealed to prevent evaporation. Carbon-isotope samples were collected by filling 15.5-gallon containers slowly from the bottom and covering the top of the containers to prevent ambient carbon from dust and air mixing with the sample. Samples for analysis of $^{3}H$ were collected in 1-liter polyethylene bottles. Alkalinity was measured on site using filtered aliquots.

Samples for major ions, nutrients, and trace metals were analyzed by the USGS National Water Quality Laboratory (NWQL) in Arvada, Colorado. Analysis of $^{87}Sr/^{86}Sr$ was done by Shannon Mahon and Kyoto Futa of the USGS in Denver, Colorado. Samples for $^{3}H$ were analyzed by the USGS laboratory in Menlo Park, California, and samples for $^{18}O/^{16}O$ and $^{2}H/^{1}H$ were analyzed by the USGS laboratory in Reston, Virginia. Carbon isotope samples were analyzed by the Laboratory of Environmental Isotopes at the University of Arizona in Tucson.

# GEOHYDROLOGY

The Arizona Strip is part of the Colorado Plateau (Fenneman, 1931) that includes consolidated and unconsolidated rock formations that control the storage and movement of ground water in the area. The direction of regional ground-water flow is to the north following the regional dip of the beds (Blanchard, 1986; Heilweil and Freethey, 1992; Thiros and Borthers, 1993; and Lambert and others, 1995). Geologic units generally dip to the north-northeast about 3 to 5° and are incised by small stream systems that may contribute recharge to the ground-water system. Ground-water movement also is controlled by the Sevier, Hurricane, and Paunsaugunt Faults, which are major in scale in length and displacement (Blanchard, 1986).

## Geology

The monument is underlain by sedimentary rocks of early Triassic to Quaternary age. From oldest to youngest, these units are the Moenkopi and Chinle Formations of Triassic age; Moenave Formation, Kayenta Formation, and Navajo Sandstone of Jurassic age; and alluvial sediments of Quaternary age (fig. 5; Blanchard, 1986). The west branch of the Sevier Fault trends northward and southward in the study area (fig. 6; Gregory, 1950) and will be referred to in this report as the fault.

The upper Schnabkaib Member of the Moenkopi Formation (Stewart and others, 1972) crops out in the study area on the east side of the fault and is the only member of the Moenkopi Formation addressed in this report. The Schnabkaib Member consists of light-gray to light-green weathered interbeds of gypsiferous dolomitic, claystone, siltstone, and thin white interbeds of anhydrite (Robert Rosé, volunteer geologist, NPS, written commun., 1998).

The Shinarump Member of the Chinle Formation (Stewart and others, 1972) overlies the Moenkopi Formation and crops out on the east side of the fault north of Moccasin Wash and east of the monument where it forms cliffs. The Shinarump Member is a basal sandstone and conglomerate unit and underlies the Petrified Forest Member. The Petrified Forest Member is not well exposed in the area. The most complete section is at Blue Knolls on the Kaibab-Paiute Reservation outside the study area. The Petrified Forest Member underlies the Quaternary alluvium on the east side of the fault in the flat-lying areas of the northern half of the study area (fig. 7).

The Moenave Formation underlies the Kayenta Formation on the west side of the fault but is not exposed at land surface in the study area. The Moenave Formation consists of reddish-orange siltstone and fine- to coarse-grained sandstone (Olsen, 1989).

The Kayenta Formation is a reddish-orange-brown fluvial sandstone, siltstone, and shale with minor shale conglomerates and freshwater

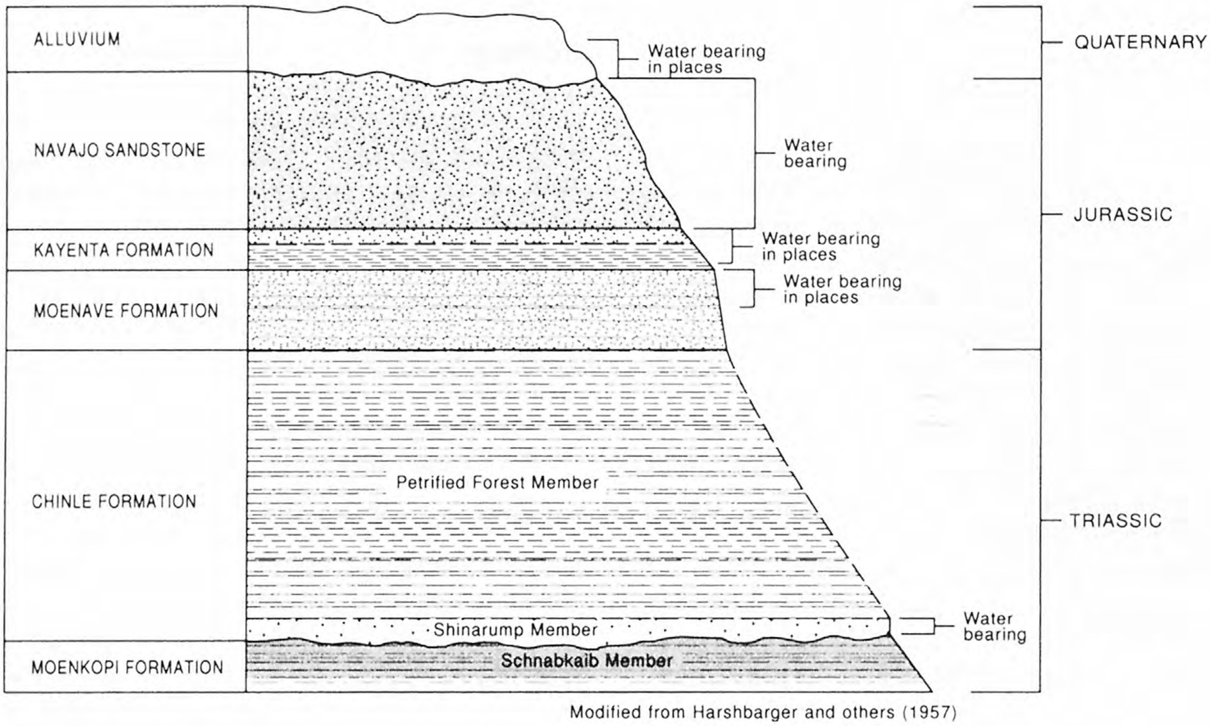



**Figure 5.** Stratigraphic columnar section, Pipe Spring National Monument area, northern Arizona.

limestone (Blanchard, 1986). North of Moccasin Canyon, the Kayenta Formation underlies the Navajo Sandstone and crops out in the western half of upper Moccasin Canyon. South of Moccasin Canyon, the contact between the Kayenta Formation and Navajo Sandstone is above land surface in some areas and below land surface in other areas (Robert Rosé, volunteer geologist, NPS, oral commun., 1998).

The Navajo Sandstone is a very fine to fine-grained, eolian, quartzose sandstone (Blanchard, 1986), commonly forms large-scale cliffs, and is characterized by high-angle crossbedding. The Navajo Sandstone crops out on the west side of the fault. Calcite nodules and vein deposits of iron oxide, which probably is hematite, are present in the formation (Cordova 1981; Robert Rosé, volunteer geologist, NPS, oral commun., 1998). The formation is thickest to the north of Moccasin Canyon (greater than 200 ft) and thins from Moccasin Canyon south to the monument (5 to 10 ft at Winsor Point).

The Quaternary alluvial sediments consist of well-sorted, fine-grained, red, unconsolidated sand. On the basis of drillers' logs, the alluvial sediments range from 8 to 90 ft in thickness. The sediments are exposed at land surface on both sides of the fault but cover a larger surface area on the east side (fig. 6). Upper and Lower Moccasin Washes have thick deposits on both sides of the fault where downcutting by surface-water flows has created unconsolidated sand cliffs 20 to 50 ft high.

## Ground-Water Hydrology

Ground water occurs in the consolidated and unconsolidated rocks in the study area. Faulting in

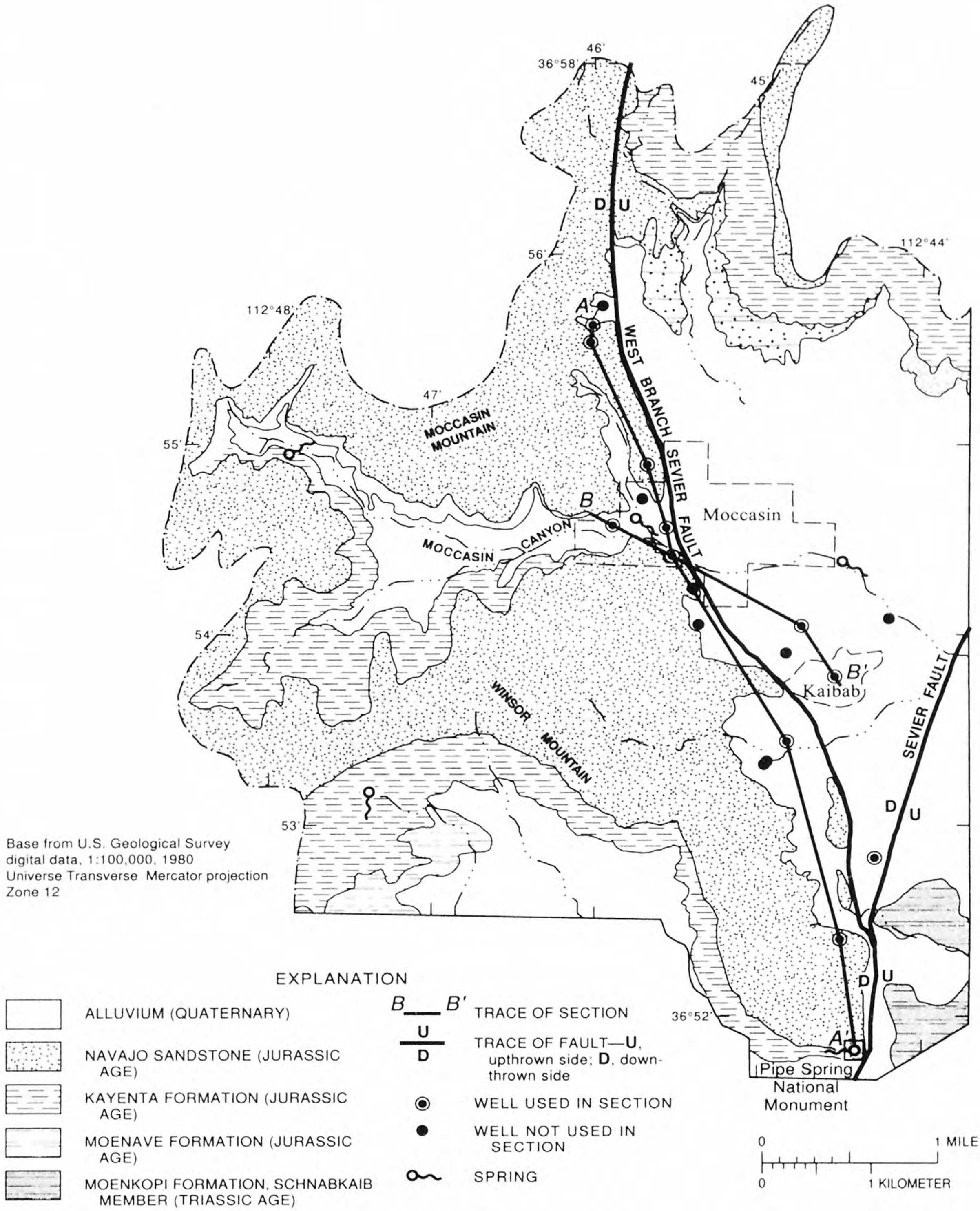



**Figure 6.** Surface geology and geologic structure, Pipe Spring National Monument area, northern Arizona (modified from Hemphill, 1956; Marshall, 1965; and Pillmore, 1956; by Robert Rosé, volunteer geologist, NPS, written commun., 1998).

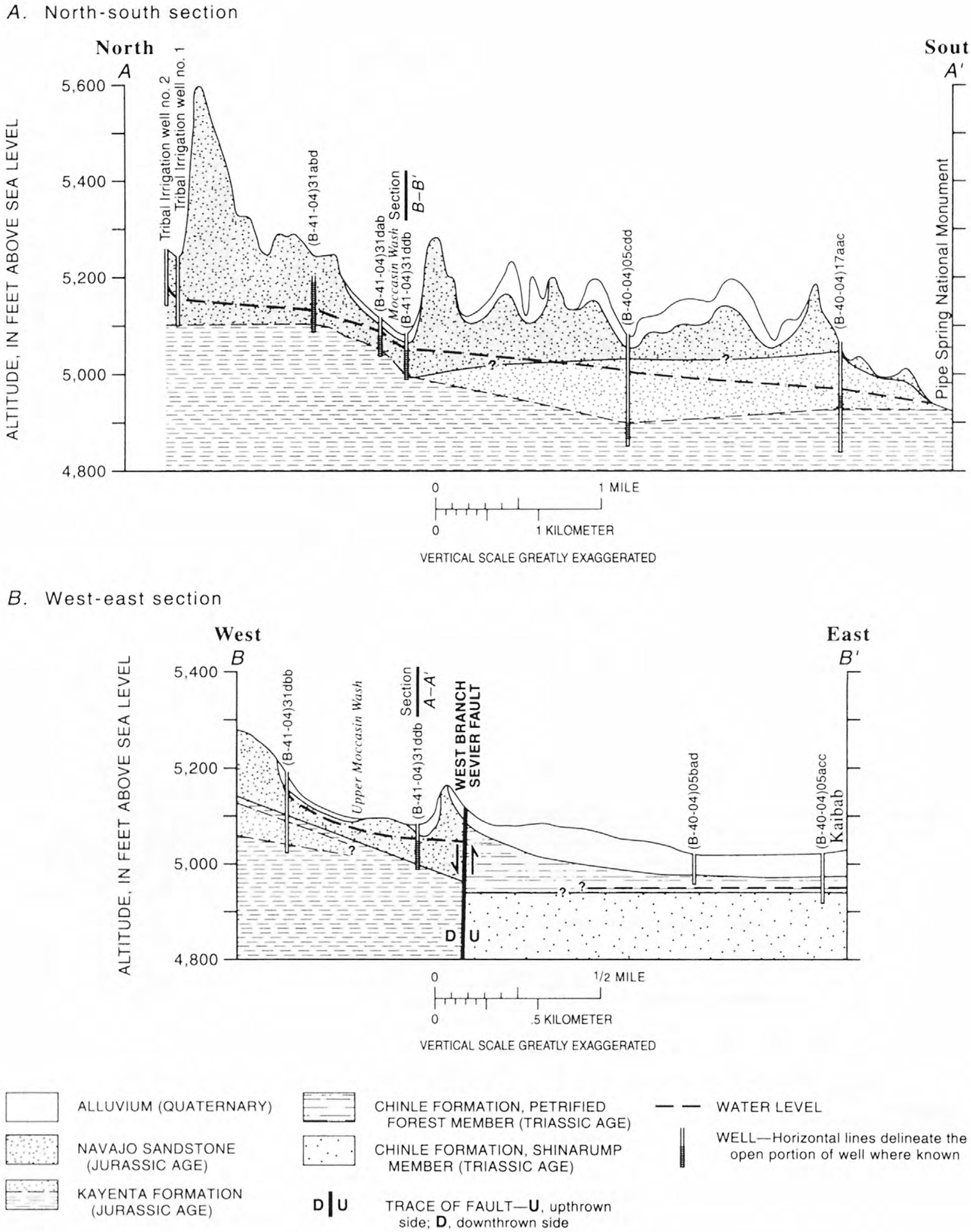



**Figure 7.** Geologic sections in the Pipe Spring National Monument area, northern Arizona. *A*, North-south section for the west side of the west branch of the Sevier Fault. *B*, West-east section showing lithology on either side of the west branch of the Sevier Fault. Traces of sections are shown on figure 6.

the area has juxtaposed permeable water-bearing sediments and semipermeable sediments along a north-south corridor characterized by high cliffs to the west and north and flat-lying areas to the east. Water-level data indicate that ground water flows toward the south along the downthrown (west) side of the fault (fig. 8). On the west side of the fault, water occurs in the Quaternary sediments, Navajo Sandstone, and Kayenta Formation (G.W. Levings, hydrologist, USGS, written commun., 1974). In the consolidated rocks on the west side of the fault, water movement probably is enhanced by a fractured zone associated with faulting. On the upthrown side (east) of the fault, water can occur in the Quaternary sediments and occurs in the Shinarump Member of the Chinle Formation (G.W. Levings, hydrologist, USGS, written commun., 1974). Sediments on the east side of the fault, however, are predominantly silty clays that probably act as a barrier to most ground-water flow from west to east across the fault (fig. 7).

Water discharges from the Quaternary alluvium at Moccasin Spring. The alluvium probably is hydraulically connected to underlying units because decreased spring discharges have been observed when wells north of Moccasin Spring were being used (Mike Heaton, resident, town of Moccasin, oral commun., 1998). Near Moccasin, ground water in the alluvial sediments may move across the fault from west to east and continue down lower Moccasin Wash. R.J. Hart and D.J. Bills (hydrologists, USGS, written commun., 1997) noted flow in lower Moccasin Wash of about 20 gal/min just east of the fault where water discharges at the land surface. The lack of water-level data precludes a complete characterization of ground-water movement in the alluvium.

The saturated parts of the Navajo Sandstone and the upper Kayenta Formation form the principal aquifer in the area. Ground water is under unconfined conditions. Depth to ground water ranges from about 30 ft in the Moccasin area to as much as 94 ft north and south of Moccasin. The Navajo Sandstone and Kayenta Formation are highly fractured from regional faulting in the area, which has created high secondary permeability. Pump-test data for NPS Culinary well (B-41-04) 05cdd has indicated higher-than-usual specific capacities of 12 (gal/min)/ft of drawdown (E.H. McGavock, hydrologist, USGS, written commun., 1974).

Below the sandstone facies of the Kayenta Formation, a semipermeable siltstone-clay facies acts as a barrier to vertical movement of ground water. Drillers logs indicate that most wells penetrate only the uppermost few feet of this siltstone-clay facies (fig. 7). At the monument, the surface exposure of the Kayenta Formation wraps around the southern tip of Winsor Point (Robert Rosé, volunteer geologist, NPS, oral commun., 1998), and the siltstone-clay facies may be a barrier to ground-water flow that causes ground water to discharge at springs in the monument. About 0.25 mi north of the monument in Heart Canyon, at a contact of the Kayenta Formation and Navajo Sandstone, there is no evidence of spring flow (Robert Rosé, volunteer geologist, NPS, written commun., 1998). This contact may be significant because if ground water is moving east toward the fault in the dipping beds of Winsor Mountain, discharge along the contact of the water-bearing units and the impermeable units north of Winsor Point would likely be evident. Lack of evidence of spring discharges in Heart Canyon may indicate that ground water in Winsor Mountain moves preferably along fractures in the subsurface rather than through the pores in the sandstone facies of the Kayenta Formation.

The Moenave Formation, which underlies the Kayenta Formation in the western part of the study area is water bearing in places. Because the Moenave Formation is not penetrated by wells used in this study, it was not included in this investigation.

The Shinarump Member of the Chinle Formation is a water-bearing unit on the east side of the fault and depths to water are greater than 60 ft. The hydraulic connection between the ground water in the Shinarump Member and the ground water in the Navajo Sandstone and Kayenta Formation on the west side of the fault is unknown. Ground-water movement across the fault from the Navajo Sandstone and Kayenta Formation to the Shinarump Member in the Moccasin area may be restricted by the semipermeable sediments of the Petrified Forest Member, which overlies the Shinarump Member (fig. 7). In the southern part of the study area, the units of the Chinle Formation are not present, and the Schnabkaib Member of the

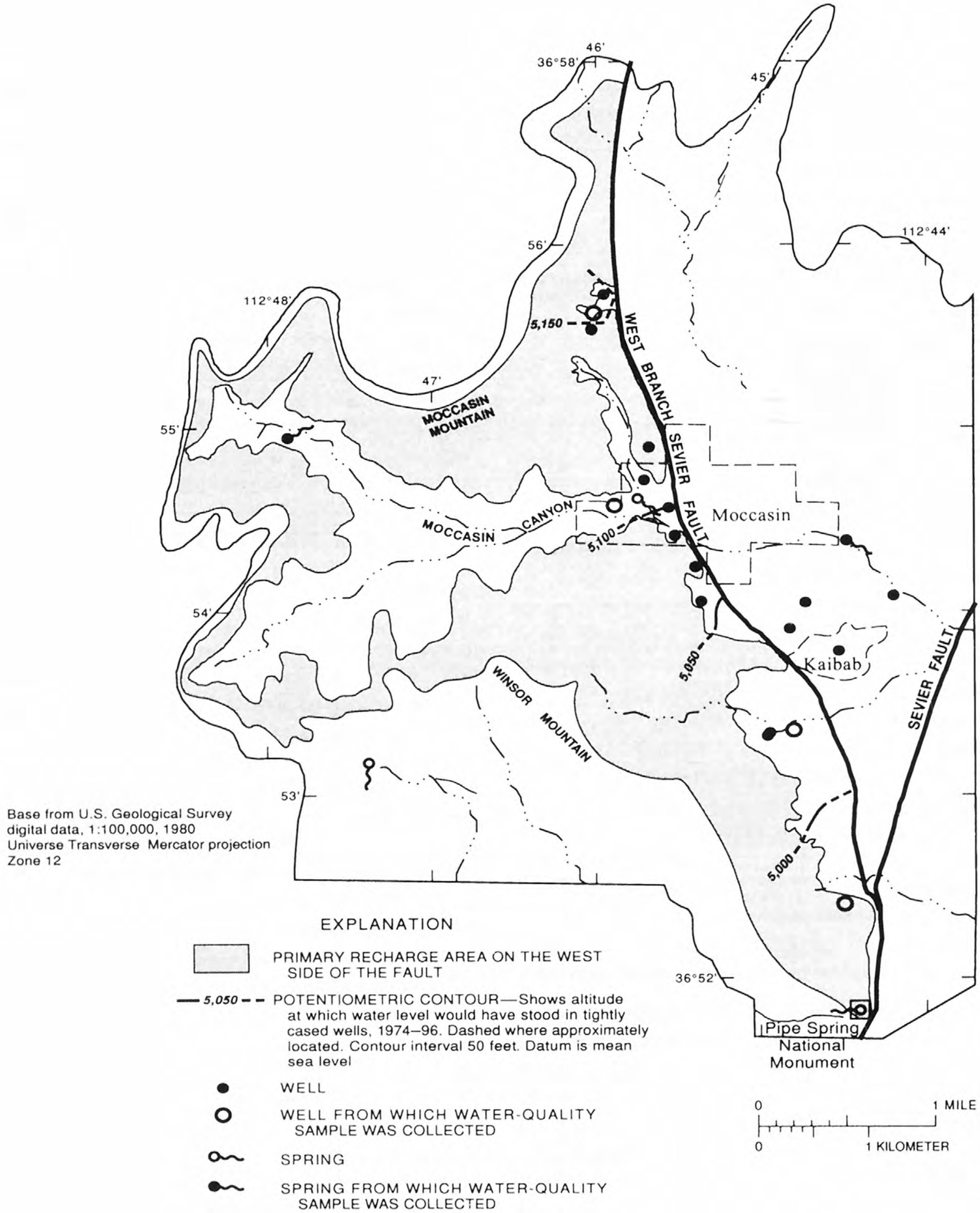



**Figure 8.** Potentiometric surface, 1974–96, and primary recharge area, Pipe Spring National Monument area, northern Arizona.

**Table 1.** Ground-water levels and elevations of springs and wells, Pipe Spring National Monument area, northern Arizona

[SM, Shinarump Member; CF, Chinle Formation; NS, Navajo Sandstone; KF, Kayenta Formation; Qa, Quaternary alluvium. Do. and do., ditto; PVC, polyvinyl chloride. Dashes indicate no data]

| Well number or name | Altitude of land surface, in feet | Water level, in feet | Date of water-level measurement | Site type | Water-bearing unit |
|---|---|---|---|---|---|
| (B-40-04)05acc | 5,020 | 69.0 | 04–28–70 | Well | SM; CF |
| (B-40-04)05bad | 5,020 | Dry | 1971 | Well | SM; CF |
| (B-40-04)05bda | 5,025 | Dry | 02–28–71 | Well | CF |
| (B-40-04)05cdd | 5,080 | 56.7 | 03–26–71 | Well | SM; CF |
| Do. | [1]5,082 | 56.7 | 03–25–71 | do. | Do. |
| (B-40-04)06aac | 5,140 | 80.4 | 07–22–75 | Well | ([2]) |
| Do. | do. | 80.0 | 07–27–76 | do. | Do. |
| Do. | do. | 81.1 | 12–14–77 | do. | Do. |
| Do. | do. | 81.0 | 03–08–79 | do. | Do. |
| Do. | do. | 79.9 | 01–04–80 | do. | Do. |
| Do. | do. | 79.2 | 01–07–81 | do. | Do. |
| Do. | do. | 80.0 | 03–03–82 | do. | Do. |
| Do. | do. | 83.4 | 12–01–82 | do. | Do. |
| Do. | do. | 81.3 | 02–08–84 | do. | Do. |
| Do. | do. | 81.0 | 04–03–85 | do. | Do. |
| Do. | do. | 80.8 | 02–26–86 | do. | Do. |
| Do. | do. | 81.4 | 03–30–87 | do. | Do. |
| Do. | do. | 82.3 | 05–18–88 | do. | Do. |
| Do. | do. | 82.4 | 03–21–89 | do. | Do. |
| Do. | do. | 82.5 | 04–11–90 | do. | Do. |
| Do. | do. | 83.5 | 11–07–90 | do. | Do. |
| Do. | do. | 84.2 | 06–25–92 | do. | Do. |
| Do. | do. | 83.4 | 10–29–92 | do. | Do. |
| (B-40-04)06aac—Cont. | 5,140 | 82.8 | 10–28–93 | Well | ([2]) |
| Do. | do. | 84.2 | 05–21–97 | do. | Do. |
| Do. | do. | 84.8 | 03–09–98 | do. | Do. |
| (B-40-04)08bab1 | 5,080 | --- | --- | Well | KF |
| (B-40-04)08bab2 | 5,082 | 74.6 | 05–29–75 | Well | KF |
| (B-40-04)17aac | 5,080 | 82.9 | 10–00–89 | Well | KF |
| Do. | [1]5,066 | 83.9 | 03–19–97 | do. | Do. |
| (B-41-04)31abd | 5,200 | 75.0 | 03–20–72 | Well | NS |
| (B-40-04)31aca | 5,170 | 10.5 | 02–10–72 | Well | NS |
| (B-40-04)31dbb | 5,180 | 32 | ([2]) | Well | NS |
| (B-41-04)31dab | 5,120 | 19.0 | 01–19–79 | Well | NS; KF |
| (B-41-04)31ddb | 5,120 | 18.0 | 03–21–79 | Well | NS; KF |
| Do. | [1]5,086 | 31.0 | 05–20–97 | do. | Do. |
| (B-41-04)31ddd | 5,160 | 36.0 | 08–11–76 | Well | NS; KF |
| Do. | [3]5,100 | 47.2 | 05–21–97 | do. | Do. |
| Tribal Irrigation well no. 1 | 5,240 | 94.0 | 06–18–97 | Well | NS |
| Tribal Irrigation well no. 2 | 5,238 | 69.0 | 06–18–97 | Well | NS |
| Tribal PVC test well | 5,238 | 87.6 | 11–07–96 | Well | ([2]) |
| Wooley Spring | 5,225 | --- | --- | Spring | KF |
| Sand Spring | 4,980 | --- | --- | Spring | Qa |
| Pipe Spring | 4,960 | --- | --- | Spring | KF |
| Moccasin Spring | 5,130 | --- | --- | Spring | Qa |
| Do. | 5,120 | --- | --- | Spring | Do. |

[1]Altitude measured by global-positioning system.

[2]Unknown.

[3]Well location plotted on U.S. Geological Survey 1:24,000 topographic map for new altitude.

**Table 2.** Water budget, Pipe Spring National Monument study area, northern Arizona

| **Inflows to the Navajo Sandstone for the study area:** | Quantity of water, in acre-feet per year | |
|---|---|---|
| 1. Volume of annual precipitation | 3,000 | |
| 2. Average recharge assuming 10 percent of annual precipitation | | 300 |
| **Outflows for the study area:** | | |
| 1. Total spring discharge (1996) | | 190 |
| 2. Total well discharge (1996) | | 700 |
| 3. Evapotranspiration | | 190 |
| Total discharge | | 1,080 |
| Inflows minus outflows equals ground-water storage deficit, in acre-feet per year | -780 | |

An additional water budget for south of Moccasin Canyon was calculated using only the exposed surface of the Navajo Sandstone on Winsor Mountain (2.2 $mi^2$; table 3) to determine if the springs and wells south of Moccasin Canyon could be part of a smaller ground-water system separate from the ground-water system in the Moccasin area. Although uncertainties exist in the water-budget components, the water-budget calculations indicate that this recharge source is not sufficient to maintain the outflow of ground water that discharges at springs near the monument and wells south of Moccasin Canyon (table 3).

## GROUND-WATER CHEMISTRY AND FLOW

Results of major-ion and trace-element analyses revealed two general ground-water compositions in the study area (fig. 9). Springs discharging from the monument, and NPS Culinary well (B-40-04)05cdd and NPS Monitor well no. 1 (B-40-04)17aac have significantly higher dissolved-solids concentrations than do Moccasin Spring, Moccasin Culinary well (B-41-04)31dbb, and Tribal Irrigation well no. 2. The sediments of the Kayenta Formation, however, may contribute higher concentrations of dissolved solids to the ground water south of Moccasin Canyon than do the sediments of the Navajo Sandstone north of Moccasin Canyon. Increases in dissolved solids in ground water south of Moccasin Canyon also could be due to the slower ground-water velocity as indicated by the smaller slope of the hydraulic gradient (fig. 7*A*). Little work has been done on the mineralogy of the Kayenta Formation; however, gypsum may be contributing sulfate to ground water south of Moccasin Canyon. Sulfate concentrations increase from less than 6 mg/L in upgradient areas to as much as 47 mg/L in downgradient areas (table 4). Figure 10 shows the slope of the line for the dissolution of gypsum if gypsum were the only contributor of calcium and sulfate ions to the ground water. The deviation from the slope of the line indicates that other sources, such as calcite (which is present as nodules in the Navajo Sandstone), are contributing calcium to the ground water.

Data for $^{14}C$ and $\delta^{13}C$ provided information on apparent ground-water ages (years since recharge). Samples for analysis of $^{14}C$ and $\delta^{13}C$ were collected from Tribal Irrigation well no. 2, Moccasin Culinary well (B-41-04)31dbb, NPS Culinary well (B-40-04)05cdd, and Cabin Spring. Uncertainties for the estimated ground-water ages were determined by a sensitivity analysis using NETPATH (Plummer and others, 1991). Data were used from Tribal Irrigation well no. 2 (49.1 pmc) using $\delta^{13}C$ values of -3.2‰ ± 3.7‰ and soil-gas $\delta^{13}C$ values between -12.00‰ and -20.00‰ (table 5; Lopes and Hoffmann, 1997). The sensitivity analysis includes results from models by Ingerson and Pearson (1964), Fontes and Garnier (1979), and Eichenger (1983).

NETPATH overcorrected when a soil-gas $\delta^{13}C$ of -20‰ was used. A soil-gas $\delta^{13}C$ value between -16‰ and -18 ‰ is consistent for soils vegetated with desert plants (Galimov, 1985). Sensitivity of mass-balance equations to changing soil-gas $\delta^{13}C$ and carbonate $\delta^{13}C$ yielded $^{14}C$ ages of 311 years to more than 9,000 years.

On the basis of NETPATH results, apparent ages of ground water decrease along the flow path, which indicates the southern part of the study area

**Table 4**. Physical and chemical data for water samples from wells and springs, Pipe Spring National Monument area, northern Arizona

[°C, degree Celsius; mg/L, milligrams per liter; µS/Ccm, microsiemens per centimeter; µg/L, micrograms per liter; pCi/L, picocuries per liter; --, no data; <, less than; pmc, percent modern carbon]

| Station name | Township/range section | Date | Temperature, water (°C) | pH, water, whole, field (standard units) | pH, water, whole, laboratory (standard units) | Hardness, total (mg/L as $CaCO_3$) | Alkalinity, water, dissolved, fix end, field ($CaCO_3$) | Specific conductance, laboratory (µS/cm) | Alkalinity, laboratory (mg/L as $CaCO_3$) | Calcium, dissolved (mg/L as Ca) |
|---|---|---|---|---|---|---|---|---|---|---|
| Tunnel Spring | (B-40-04)17ddb2 | 12-10-96 | 15.0 | 7.9 | 7.7 | 210 | 190 | 530 | 189 | 49 |
| Cabin Spring | (B-40-04)17ddb3 | 12-10-96 | 14.5 | 7.6 | 7.8 | 200 | 180 | 521 | 182 | 48 |
| Spring Room Spring | (B-40-04)17ddb1 | 12-10-96 | 14.5 | 7.3 | 8.2 | 210 | 190 | 511 | 164 | 49 |
| NPS Culinary well | (B-40-04)05cdd | 03-20-97 | 15.0 | 7.7 | 7.7 | 200 | 193 | 564 | 184 | 45 |
| NPS Monitor well no. 1 | (B-40-04)17aac | 03-19-97 | 17.0 | 7.6 | 7.6 | 200 | 194 | 534 | 190 | 48 |
| Moccasin Culinary well | (B-41-04 )31dbb | 03-20-97 | 17.0 | 8.8 | 7.9 | 87 | 110 | 209 | 88 | 21 |
| Tribal Irrigation well no. 2 | | 05-20-97 | 16.0 | 8.1 | 7.9 | 86 | -- | 200 | 86 | 20 |
| Moccasin Spring | (B-41-04)31adc | 12-10-96 | 12.5 | 8.0 | 7.9 | 88 | 84 | 203 | 86 | 21 |

| Station name | Date | Magnesium, dissolved (mg/L as Mg) | Sodium, dissolved (mg/L as Na) | Potassium, dissolved (mg/L as K) | Chloride, dissolved (mg/L asCl) | Fluoride, dissolved (mg/L as F) | Sulfate, dissolved (mg/L as $SO_4$) | Silica, dissolved (mg/L as $SiO_2$) | Arsenic, dissolved (µg/L as As) | Barium, dissolved (µg/L as Ba) | Beryllium, dissolved (µg/L as Be) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tunnel Spring | 12-10-96 | 21 | 31 | 3.3 | 24 | 0.20 | 44 | 13 | 3 | 57 | <0.50 |
| Cabin Spring | 12-10-96 | 20 | 30 | 3.4 | 26 | 0.20 | 43 | 13 | 3 | 56 | <0.50 |
| Spring Room Spring | 12-10-96 | 21 | 30 | 3.1 | 24 | 0.20 | 43 | 14 | 2 | 59 | <0.50 |
| NPS Culinary well | 03-20-97 | 22 | 34 | 4.1 | 31 | 0.20 | 47 | 12 | 4 | 60 | <0.50 |
| NPS Monitor well no. 1 | 03-19-97 | 20 | 28 | 3.5 | 24 | 0.23 | 42 | 13 | 3 | 56 | <0.50 |
| Moccasin Culinary well | 03-20-97 | 8.8 | 4.9 | 3.7 | 4.7 | <0.10 | 5.6 | 12 | 2 | 34 | <0.50 |
| Tribal Irrigation well no. 2 | 05-20-97 | 8.8 | 3.8 | 3.5 | 3.7 | <0.10 | 3.8 | 12 | 1 | 41 | <0.50 |
| Moccasin Spring | 12-10-96 | 8.7 | 4.3 | 3.8 | 4.2 | <0.10 | 4.6 | 12 | <1 | 35 | <0.50 |

| Station name | Date | Boron, dissolved (µg/L as B) | Cadmium, dissolved (µg/L as Cd) | Chromium, dissolved (µg/L as Cr) | Cobalt, dissolved (µg/L as Co) | Copper, dissolved (µg/L as Cu) | Iron, dissolved (µg/L as Fe) | Lead, dissolved (µg/L asPb) | Maganese, dissolved (µg/L as Mn) | Molybdenum, dissolved (µg/L as Mo) | Nickel, dissolved (µg/L as Ni) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tunnel Spring | 12-10-96 | 168 | <1.0 | <5.0 | <3.0 | <10 | 4.0 | <10 | <1.0 | <10 | <10 |
| Cabin Spring | 12-10-96 | 170 | <1.0 | <5.0 | <3.0 | <10 | <3.0 | 10 | <1.0 | <10 | <10 |
| Spring Room Spring | 12-10-96 | 172 | 3.0 | <5.0 | <3.0 | <10 | <3.0 | 20 | <1.0 | <10 | <10 |
| NPS Culinary well | 03-20-97 | 157 | <1.0 | <5.0 | <3.0 | <10 | <3.0 | 12 | <1.0 | 10 | <10 |
| NPS Monitor well no. 1 | 03-19-97 | 156 | <1.0 | <5.0 | <3.0 | <10 | <3.0 | <10 | <1.0 | 20 | <10 |
| Moccasin Culinary well | 03-20-97 | 28 | <1.0 | <5.0 | <3.0 | <10 | <3.0 | 20 | <1.0 | <10 | <10 |
| Tribal Irrigation well no. 2 | 05-20-97 | 32 | <1.0 | <5.0 | <3.0 | <10 | 4.0 | <10 | <1.0 | <10 | <10 |
| Moccasin Spring | 12-10-96 | 29 | <1.0 | <5.0 | <3.0 | <10 | <3.0 | 10 | <1.0 | <10 | <10 |

| Station name | Date | Silver, dissolved (µg/L as Ag) | Strontium, dissolved (µg/L as Sr) | Vanadium, dissolved (µg/L as V) | Antimony, dissolved (µg/L as Sb) | Lithium, dissolved (µg/L as Li) | Selenium, dissolved (µg/L as Se) | Nitrogen, nitrate, dissolved (µg/L as N) | Nitrogen, ammonia, dissolved (µg/L as N) | Nitrogen, nitrite, dissolved (µg/L as N) | Nitrogen, ammonia+organic, total (µg/L as N) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tunnel Spring | 12-10-96 | 1.0 | 340 | <6 | <1.0 | 33 | 2 | 3.59 | <0.015 | 0.010 | <0.20 |
| Cabin Spring | 12-10-96 | 1.0 | 320 | <6 | <1.0 | 32 | 2 | 3.79 | <0.015 | 0.010 | <0.20 |
| Spring Room Spring | 12-10-96 | 1.0 | 330 | <6 | <1.0 | 32 | 2 | -- | -- | -- | -- |
| NPS Culinary well | 03-20-97 | <1.0 | 350 | <6 | 1.0 | 28 | 3 | -- | <0.015 | <0.010 | <0.20 |
| NPS Monitor well no. 1 | 03-19-97 | <1.0 | 330 | <6 | <1.0 | 28 | 2 | -- | <0.015 | <0.010 | <0.20 |
| Moccasin Culinary well | 03-20-97 | <1.0 | 82 | <6 | <1.0 | <4 | <1 | -- | <0.015 | <0.010 | <0.20 |
| Tribal Irrigation well no. 2 | 05-20-97 | <1.0 | 71 | <6 | <1.0 | <4 | <1 | -- | <0.015 | <0.010 | <0.20 |
| Moccasin Spring | 12-10-96 | 2.0 | 74 | <6 | <1.0 | <4 | <1 | -- | <0.015 | <0.010 | <0.20 |

**Table 4**. Physical and chemical data for water samples from wells and springs, Pipe Spring National Monument area, northern Arizona—Continued

| Station name | Date | Nitrogen, $NO_2+NO_3$, dissolved (mg/L as N) | Phosphorus, total (mg/L as P) | Phosphorus, dissolved (mg/L as P | Phosphorus, ortho, dissolved (mg/L as P | Specific conductance (μS/cm) | Tritium, total (pCi/L) | Solids, sum of constituents, dissolved (mg/L) | Tritium, 2 sigma water, whole, total (pCi/L) | $H^2/H^1$ stable isotope ratio (per mil) | $O^{18}/O^{16}$ stable isotope ratio (per mil) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tunnel Spring | 12-10-96 | 3.60 | <0.010 | <0.010 | 0.010 | 550 | <0.1 | 315 | 1.0 | -94.3 | -12.84 |
| Cabin Spring | 12-10-96 | 3.80 | 0.020 | 0.010 | 0.010 | 503 | <0.1 | 310 | 1.0 | -95.3 | -12.88 |
| Spring Room Spring | 12-10-96 | -- | -- | -- | -- | 555 | <0.1 | 283 | 1.0 | -94.0 | -12.89 |
| NPS Culinary well | 03-20-97 | 5.30 | 0.040 | 0.030 | 0.040 | 538 | 1.3 | 329 | 1.0 | -95.4 | -12.97 |
| NPS Monitor well no. 1 | 03-19-97 | 3.90 | <0.010 | 0.010 | 0.020 | -- | <0.1 | 311 | 1.0 | -94.9 | -12.91 |
| Moccasin Culinary well | 03-20-97 | 2.00 | <0.010 | <0.010 | 0.010 | 254 | <0.1 | 122 | 1.0 | -96.6 | -13.12 |
| Tribal Irrigation well no. 2 | 05-20-97 | 2.20 | 0.012 | <0.010 | 0.020 | 200 | <0.1 | 117 | 1.0 | -96.7 | -13.15 |
| Moccasin Spring | 12-10-96 | 2.00 | 0.010 | <0.010 | 0.020 | 199 | <0.1 | 119 | 1.0 | -96.2 | -13.07 |

| Station name | Date | Strontium $^{87}Sr$ ratio | Carbon-13 ratio (per mil) | Carbon-14 (pmc) |
|---|---|---|---|---|
| Tunnel Spring | 12-10-96 | -- | -10.4 | 74.4+/-0.6 |
| Cabin Spring | 12-10-96 | 0.71009+/-0.000011 | -- | -- |
| Spring Room Spring | 12-10-96 | 0.71014+/-0.000010 | -9.9 | 72.4+/-1.2 |
| NPS Culinary well | 03-20-97 | 0.71008+/-0.000011 | -- | -- |
| NPS Monitor well no. 1 | 03-19-97 | 0.71008+/-0.000009 | -9.3 | 40.4+/-1.6 |
| Moccasin Culinary well | 03-20-97 | 0.71011+/-0.000011 | -9.5 | 49.1+/-0.9 |
| Tribal Irrigation well no. 2 | 05-20-97 | 0.71011+/-0.000011 | -- | -- |
| Moccasin Spring | 12-10-96 | -- | -10.4 | 74.4+/-0.6 |

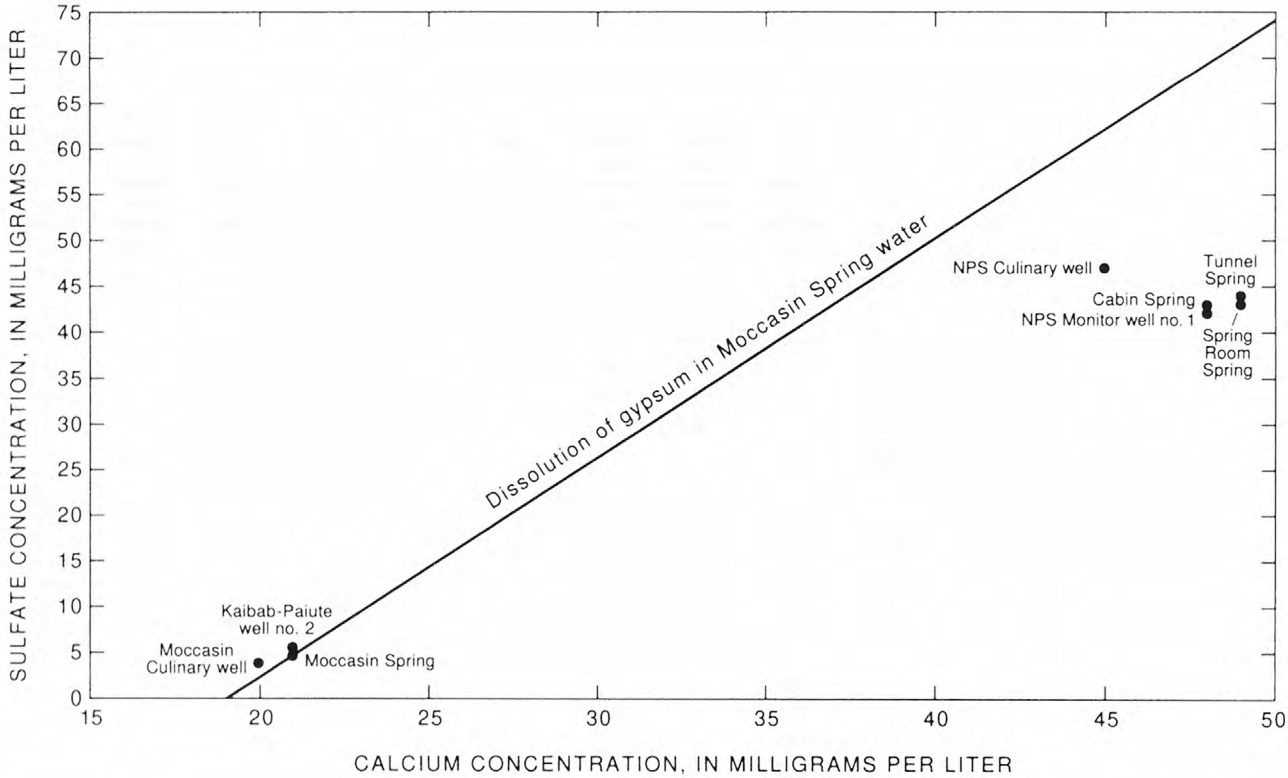



**Figure 10.** Relation of sulfate and calcium concentrations in water from wells and springs, Pipe Spring National Monument area, northern Arizona.

**Table 5.** Sensitivity analysis of carbon-14 ages for water from Tribal Irrigation well no. 2, Pipe Spring National Monument area, northern Arizona

[The $^{14}C$ activity of carbon dioxide was 100 percent modern carbon (pmc) in all models. $\delta^{13}C$, in per mil; $A_o$, initial $^{14}C$ activity at Tribal Irrigation well no. 2 in pmc; OC, overcorrected. Measured $^{14}C$ was 72.4 pmc]

| Calcite | Ingerson and Pearson (1964) | | Fontes and Garnier (1979) | | Eichenger (1983) | |
|---|---|---|---|---|---|---|
| $\delta^{13}C$ | $A_o$ | $^{14}C$ corrected age, in years | $A_o$ | $^{14}C$ corrected age, in years | $A_o$ | $^{14}C$ corrected age, in years |
| **Initial $\delta^{13}C$ in soil gas (carbon dioxide) at -12 per mil** | | | | | | |
| 0.5 | 80.00 | 4,036 | 153.81 | 9,440 | 75.88 | 3,598 |
| -3.2 | 71.59 | 3,117 | 72.76 | 3,251 | 65.52 | 2,385 |
| -6.9 | 50.98 | 311 | 50.98 | 311 | 39.59 | OC |
| **Initial $\delta^{13}C$ in soil gas (carbon dioxide) at -15 per mil** | | | | | | |
| .5 | 64.52 | 2,257 | 83.42 | 4,382 | 61.2 | 1,796 |
| -3.2 | 53.39 | 819 | 61.11 | 1,808 | 48.61 | OC |
| -6.9 | 32.10 | OC | 243.64 | OC | 24.59 | OC |
| **Initial $\delta^{13}C$ in soil gas (carbon dioxide) at -20 per mil** | | | | | | |
| .5 | 47.78 | OC | 48.73 | OC | 46.00 | OC |
| -3.2 | 37.50 | OC | 37.11 | OC | 33.98 | OC |
| -6.9 | 19.85 | OC | 18.68 | OC | 15.08 | OC |

may receive some younger ground water from a nearby recharge source or sources. Data for $^{14}C$ from Tribal Irrigation well no. 2 and Moccasin Culinary well (B-41-04)31dbb (49.1 and 40.4 pmc, respectively) yielded apparent $^{14}C$ ages of between 200 and 9,000 years. The large uncertainty is because the model is sensitive to values of $\delta^{13}C$ in the carbonate minerals and the soil-gas $\delta^{13}C$ (table 5). NETPATH overcorrected $^{14}C$ data from NPS Culinary well (B-40-04)05cdd and Cabin Spring (74.4 and 72.4 pmc, respectively). Age-dating younger ground water for $^{14}C$ that has been out of contact with the atmosphere for less than 200 years generally is difficult unless specific data are available such as soil-gas $\delta^{13}C$ and carbonate $\delta^{13}C$ (L.N. Plummer, hydrologist, USGS, oral commun., 1998).

Surface-water drainage west of NPS Culinary well (B-40-04)05cdd may be contributing recharge to the ground water in the area near the well. Water from this well has the highest concentration of nitrate (5.3 mg/L; table 4) in the study area. Lack of irrigation, animal waste, or septic systems near the well suggest that the nitrate is coming from upgradient sources or that there is a natural source. Nitrate can accumulate in the soil if sufficient infiltration/percolation is not available to keep the soils leached of soluble salts (Hem, 1992). NPS Culinary well (B-40-04)05cdd was the only well that contained detectable amounts of $^{3}H$. The 1.3 pCi of $^{3}H$ translates to less than 0.5 TU, which typically indicates submodern or pre-1952 water (Clark and Fritz, 1997). The presence of $^{3}H$, however, could indicate that some younger water is mixing with older water from upgradient areas.

Recharge from a common source for ground water in the study area is indicated by the small range in $\delta^{18}O$ data (-12.8 to -13.1‰) and the range in $\delta^{2}H$ data (-94.0 to -96.6‰; table 4; fig. 11). Some ground-water recharge probably occurs outside the study area; however, stable-isotope data indicate that the regional precipitation does not have a varied isotopic signature. Spring and well data plot below the global meteoric water line (Craig, 1961a, b; fig. 11). The signature of water from Wooley Spring may have resulted from instream-evaporative processes. The sample was collected downstream from the point of discharge because access to the spring was not possible. A white precipitate that may have been deposited by evaporative processes was observed along the banks of Wooley Spring.

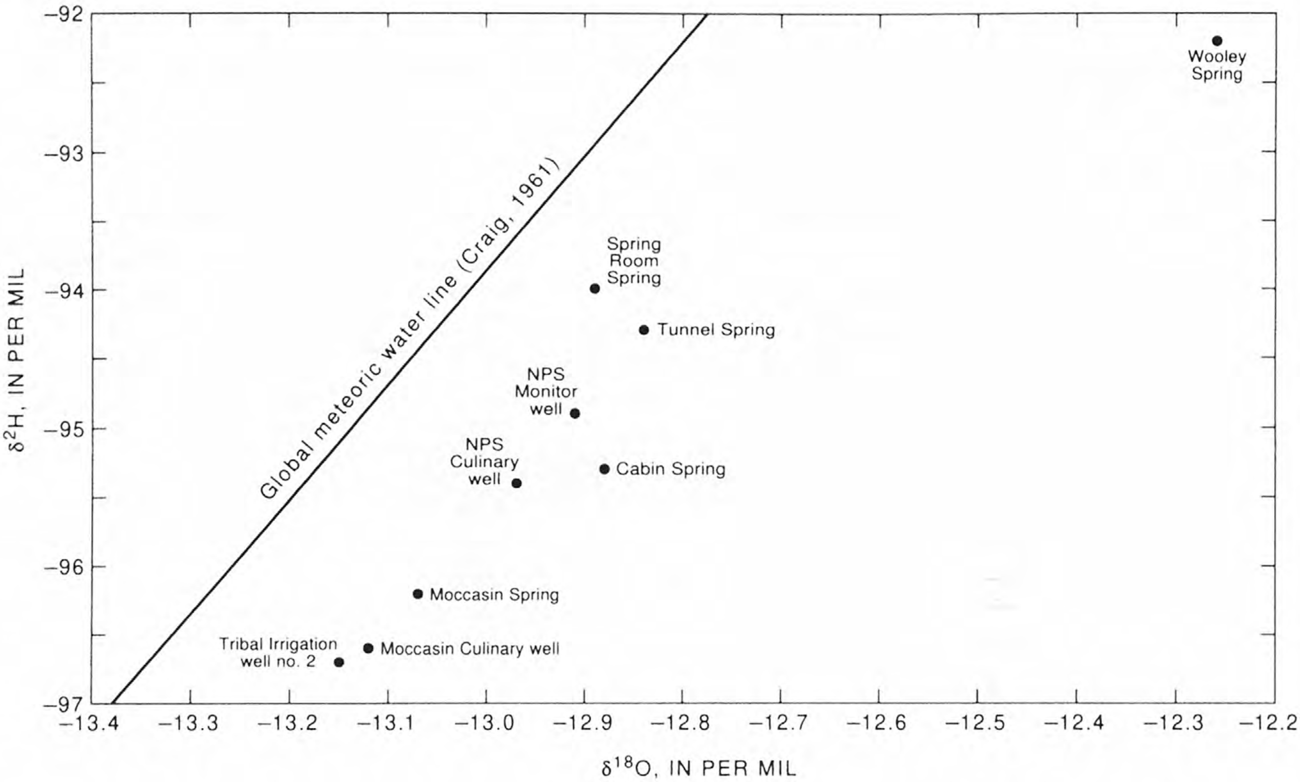



**Figure 11.** Oxygen and hydrogen isotopes in water from selected wells and springs, Pipe Spring National Monument area, northern Arizona.

Travel times for ground water along the north-south corridor were estimated on the basis of an average porosity of 30 percent (Cordova, 1981; Blanchard, 1986) for fractured Navajo Sandstone, an estimated hydraulic conductivity of 5 ft/d (Lopes and Hoffman, 1997), and the hydraulic gradients along the flow path. Estimated velocity between the tribal irrigation wells and wells north of Moccasin is about 30 ft/yr, and the estimated travel time is 180 years. The hydraulic gradient is larger in the Moccasin area and yields an estimated velocity of 170 ft/yr and a travel time of 15 years. Between Moccasin and the monument, the estimated velocity slows to 30 ft/yr yielding a travel time of 620 years. These velocities suggest that once water has reached the saturated zone, ground water may take about 800 years to travel from the area of the tribal irrigation wells to the monument, which is a distance of 5 mi. Using the average hydraulic gradient from the tribal irrigation wells to Pipe Spring National Monument, the velocity for the entire flow path is about 44 ft/yr, which yields a travel time of 600 years.

## SUMMARY AND CONCLUSIONS

Pipe Spring National Monument in northern Arizona, lies in a semiarid region of sparse water supplies. Springs at the monument were an important source of water for prehistoric and historic people in the region for the past 8,000 years. Current water users in the area are the NPS, the Kaibab-Paiute Indians, and the residents of the town of Moccasin. Most of the domestic water demands are met by wells north of the monument. This study was done to describe the hydrogeologic framework and provide a better understanding of how monument springs relate to the local ground-water system. Results of the study indicate local ground-water movement is north to south along a corridor on the west side of the fault where ground water flows primarily through the fractured consolidated rocks of the Navajo Sandstone and Kayenta Formations, and discharges at Moccasin Spring and springs in the monument.

On the west side of the fault, the permeable Navajo Sandstone and Kayenta Formation have been downthrown relative to the semipermeable Chinle and Moenkopi Formations on the east side of the fault. West-to-east movement of ground water across the fault in the consolidated rocks is restricted by the Petrified Forest Member of the Chinle Formation in the northern part of the study area and the Schnabkaib Member of the Moenkopi Formation in the southern part of the area. On the west side of the fault, the Navajo Sandstone is the primary water-bearing unit in the northern part of the study area, and the sandstone facies of the Kayenta Formation is the primary water-bearing unit in the southern part. Lack of ground-water development on Winsor and Moccasin Mountains restricts defining ground-water movement in these areas.

An estimated water budget indicates ground-water discharge from springs and wells in the area exceeds recharge from local precipitation by 780 acre-ft/yr. The ground-water storage deficit for the area indicates a component of recharge probably is occurring outside the study-area boundary. On the basis of a separate water budget calculated for just the Winsor Mountain area, ground-water discharge from wells and springs exceeds local recharge from precipitation by 30 acre-ft/yr. Although uncertainties exist in the water-budget components, this deficit indicates that recharge occurring in the Winsor Mountain area alone is not sufficient to maintain the outflow of ground water that discharges at springs near the monument and to wells south of Moccasin Canyon.

Chemical and isotopic data for ground water reveal differences in the composition of ground water sampled north of Moccasin Mountain and ground water sampled south of Moccasin Mountain. The sandstone facies in the Kayenta Formation may contribute more dissolved solids to the ground water than sediments from the Navajo Sandstone. The higher dissolved solids also could be due to the slower velocity of ground water in the southern part of the study area. Travel time for ground water from tribal irrigation wells north of Moccasin to Moccasin is estimated to be 180 years, and travel time for ground water from south of Moccasin to the monument is estimated to be 620 years. Radiocarbon and $^{3}H$ data indicate apparent ground-water ages between 45 and 9,000 years old. Only small amounts of $^{3}H$ were detected in ground water along the north-south corridor. On the basis of $^{14}C$ data, ground water north of Moccasin Canyon is older than ground water south of Moccasin Canyon. The younger ground-water ages south of Moccasin Canyon indicate that some local ground-water recharge may be occurring in the area. The small ranges in $\delta^{18}O$ and $\delta^{2}H$ data indicate a common recharge source for the study area.

On the basis of hydrogeologic and chemical data, spring flow at the monument is part of a ground-water system that supplies water to the tribal irrigation wells north of Moccasin Canyon, wells and springs in the Moccasin area, and wells south of Moccasin Canyon. Ground-water flow in the study area is controlled to a large degree by geologic structure that is dominated by the Sevier Fault. Some ground-water recharge occurs outside the study area; however, stable-isotope data indicate that the regional precipitation does not have a varied isotopic signature. Water withdrawals north of Moccasin Canyon and in the Moccasin area may eventually affect spring flow in the monument. On the basis of ground-water travel times, however, significant increases in withdrawal rates from present rates may be required to produce effects on spring flow. Recharge south of Moccasin Canyon, in addition to recharge from other areas, may be sufficient to balance ground-water withdrawals near Moccasin. Monitoring of additional wells and springs in the area and geophysical investigations designed to develop a better understanding of the subsurface structure in the Moccasin area would provide information needed to better estimate the effects of ground-water development on spring flow in the monument.

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