Prepared in cooperation with the National Park Service

Aqueous Geochemistry of Waters and Hydrogeology of Alluvial Deposits, Pinnacles National Park, California

Open-File Report 2022–1026

U.S. Department of the Interior
U.S. Geological Survey

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B

C

D

Cover: U.S. Geological Survey (USGS) photographs from Pinnacles National Park showing (*A*) Balconies Cave pool (September 30, 2016), taken by Kathleen Scheiderich, USGS; (*B*) Windmill above well SC-1 (May 15, 2018), taken by Claire Tiedeman, USGS; (*C*) Precipitation sampling jugs (October, 2016), taken by Kathleen Scheiderich, USGS; (*D*) Well CHA-4 (June 1, 2020), taken by Claire Tiedeman, USGS.

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U.S. Geological Survey, Reston, Virginia: 2022

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Suggested citation:
Scheiderich, K., Tiedeman, C.R., Hsieh, P.A., 2022, Aqueous Geochemistry of Waters and Hydrogeology of Alluvial Deposits, Pinnacles National Park, California: U.S. Geological Survey Open-File Report 2022–1026, 39 p., https://doi.org/10.3133/ofr20221026.

Data release citations:
Scheiderich, K.D., 2021, Geochemistry of rocks, precipitation, and water sources from Pinnacles National Park, California, 2016-2017: U.S. Geological Survey data release, https://doi.org/10.5066/P9BMM0XG.

Tiedeman, C.R., and Hsieh, P.A., 2021, Passive Seismic Data Collected for the Horizontal-to-Vertical Spectral Ratio (HVSR) Method, Pinnacles National Park, California, 2018-2020: U.S. Geological Survey data release, https://doi.org/10.5066/P9AMDH71.

Tiedeman, C.R., Ingebritsen, S.E., and Hsieh, P.A., 2021, Streamflow data collected by the wading method, Pinnacles National Park, California, 2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9IZXRC0.

ISSN 2331-1258 (online)

Acknowledgments

The authors thank Paul Johnson of the National Park Service (NPS) for his support and encouragement of this study, including providing information about scientific studies at Pinnacles National Park, leading the authors on field visits to park features relevant to this study, and arranging access to monitoring and sampling locations. We are grateful to NPS specialist Valerie Nuttman for undertaking the labor of the precipitation sampling. We also acknowledge Carole Johnson and Eric White of the U.S. Geological Survey (USGS) for providing training on the horizontal-to-vertical spectral ratio method and the use of Tromino seismometers, and for assistance with analyzing and interpreting the seismic data, as well as Kate Jacques, Ane Slabic, and Rachel Mixon of the USGS, who were invaluable to the collection and field processing of the water samples. Steven Ingebritsen and Yousif Kharaka, emeritus scientists with the USGS, provided colleague reviews that substantially improved this report.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	Acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
	Flow rate	
million liters per year	0.2642	million gallons per year
million liters per year	0.8107	acre-foot per year (acre-ft/yr)
liter per minute (L/min)	0.2642	gallon per minute (gal/min)
	Hydraulic Conductivity and Velocity	
meter per second (m/s)	3.281	foot per second (ft/s)
	Precipitation	
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L). Milliequivalent per liter (mEq/L) is used for ionic constituents and is calculated using concentration of solute in milligrams multiplied by the valence, then divided by the molarity. Concentrations of chemical constituents in solid materials are given in micrograms per gram (µg/g), micrograms per kilogram (µg/kg) or weight percent as oxide (%).

Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (iE) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Abbreviations

SWRCB	California State Water Resources Control Board
CCC	Civilian Conservation Corps
GPS	Global Positioning System
HVSR	horizontal-to-vertical spectral ratio
HDPE	high density polyethylene
ICP-MS	inductively-coupled plasma mass spectrometer
LDPE	low density polyethylene
MCL	maximum contaminant level
NPS	National Park Service
NWQL	National Water Quality Laboratory
QA/QC	Quality assurance / quality control
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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Abstract

A cooperative study between the National Park Service (NPS) and the U.S. Geological Survey (USGS) characterized groundwater quality and hydrogeology in parts of Pinnacles National Park. The water-quality investigation assessed the geochemistry of springs, wells, surface water, and precipitation and analyzed geochemistry of rock formations that affect the water chemistry through water-rock interaction. The hydrogeology investigation used geophysical and groundwater level data to characterize groundwater-flow processes in the alluvial deposits of Bear Valley and the Chalone Creek watershed.

Analysis of aqueous geochemical parameters in water samples from perennial springs, water-supply wells, and surface waters was conducted for samples collected after the dry season (autumnal) and after the wet season (vernal) to assess changes in geochemistry due to changes in groundwater levels or flow resulting from precipitation. The chemistry of bulk precipitation collected during the wet season was also analyzed. Bedrock samples were analyzed for geochemical parameters to help constrain groundwater sources, flow paths, and weathering. The geochemical investigations show a correspondence between the source rock and the spring-water chemistry that can be attributed to the mineralogy of the source rock. The narrow range of strontium isotopes in water samples, sourced in geochemically and mineralogically disparate rocks, indicates that the bedrock groundwater is relatively old and has reached quasi-steady state with respect to weathering of susceptible minerals.

Groundwater-level monitoring indicated that the water table is shallow—from 0 to 10 meters (m) below land surface. In southern Bear Valley and in the Chalone Creek alluvium, water levels rose and declined by several meters over each annual cycle of this study. In northern Bear Valley, water levels rose modestly over two wet seasons but declined during a third wet season. In Bear Valley, groundwater/surface-water interaction occurs along the perennial reach of Sandy Creek. Groundwater discharges to the upstream part of the reach, becomes surface water and is partly consumed by evapotranspiration, and infiltrates farther downstream. In the Chalone Creek alluvium, runoff-generated surface-water flow in intermittent stream reaches is a major component of groundwater recharge. After the onset of significant streamflow, creek water rapidly recharges groundwater until water levels rise to nearly the creek level. Groundwater levels generally remain high throughout the wet season, then gradually decline after the creek becomes dry.

Introduction

Pinnacles National Park lies in a remote arid setting in the southern part of the Gabilan Range, a small mountain range in the inner Coast Ranges of California (fig. 1). The land was established as a National Monument in 1908 and became a National Park in 2013. Pinnacles National Park employs about 40 people. During the past decade, an average of about 230,000 people have visited annually with no major temporal trends in visitation except for fewer visitors in 2019 due to a government shutdown and in 2020 due to COVID-19 (Christopher Symons, National Park Service, written commun., 2021). Unique natural features of the park include its pinnacles and talus caves, which are formed from volcanic rocks that are approximately 23.5 million years old (Matthews, 1976). These rocks were produced by the Neenach Volcano, which was severed by movement along the San Andreas Fault. The separated volcanic rocks include the Pinnacles Volcanics, which lie on the Pacific Plate in Pinnacles National Park, and the Neenach Volcanics, which lie on the North American Plate and are offset 315 kilometers (km) to the south.

Pinnacles National Park is bordered almost entirely by private land used for grazing, agriculture, and rural homes. A small parcel of land belonging to the California State Land Commission borders the southern tip of the park. Domestic and agricultural water supply near the park is heavily dependent on groundwater because surface-water resources are scarce in this arid climate. In recent years, land-use changes, such as the introduction of water intensive crops, have caused increased use of groundwater in areas bordering the park.

Within the park, groundwater is the sole source of water supply for staff and visitors, and is obtained from wells completed in granitic, volcanic, and sedimentary rocks. In 2019 and 2020, groundwater use in the park was approximately 8.4 million liters per year, (L/yr; 2.2 million gallons per year, gal/yr; 6.8 acre-feet per year, acre-ft/yr) (Casey Heninger, National Park Service, written commun., 2021). Groundwater also is an important water source for plants and animals. Groundwater emanates from several perennial springs throughout the park, which, in the dry season, are the sole source of flow in a few perennial stream reaches (perennial reach locations are described in section, "Physical Setting"). These areas of groundwater discharge provide water supply for wildlife and habitat for plants and aquatic animals.

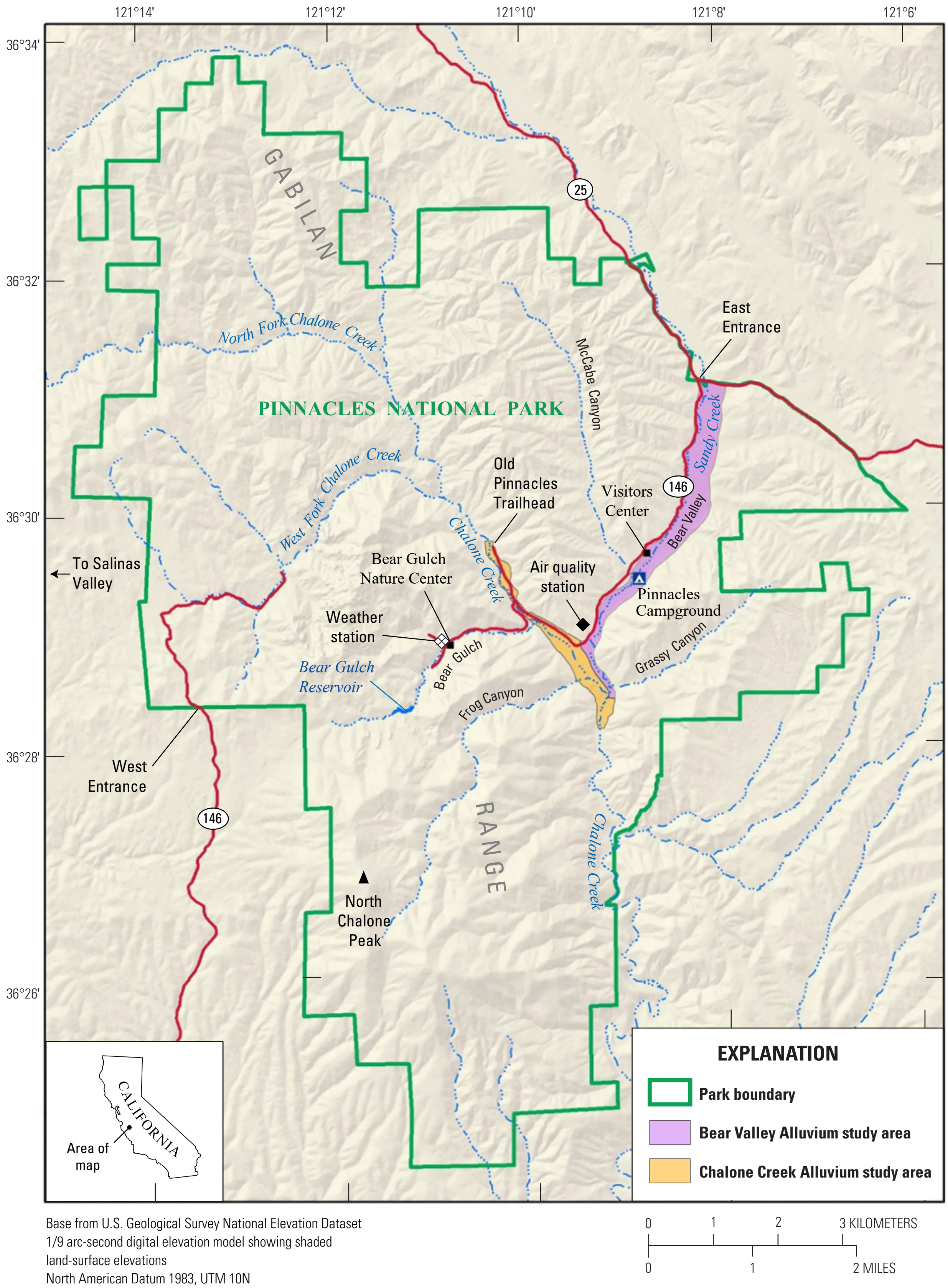


Figure 1. Map of Pinnacles National Park, California.

Purpose and Scope

The strong dependence on groundwater for Pinnacles National Park visitors, staff, plants, and animals and the increased stress on groundwater in the areas surrounding the park led the National Park Service (NPS) to propose an investigation of park groundwater resources. The NPS requested that the U.S. Geological Survey (USGS) conduct a study of current hydrogeologic and water-quality conditions to provide park managers with baseline information and a better understanding of park groundwater resources. In response to this request, the NPS and USGS entered into an Interagency Agreement in 2016 to conduct the hydrogeology and water-quality study. The USGS assumed responsibility for data collection and interpretation, and the NPS assumed responsibility for providing access to data-collection sites and knowledge about the park and previous relevant investigations. The water-quality investigations began in 2016 and the hydrogeology investigations began in 2018. The hydrogeology and water-quality investigations concluded in 2021 and this report describes the findings of those studies.

The goal of the water-quality investigation was to assess the current water quality and provide further baseline information on the geochemistry of environmental water sources in the park, building upon the study of Borchers and Lyttge (2007). For this purpose, many groundwater sources within the park were located and sampled for comprehensive geochemical analysis. Named springs discussed in previous reports and located on USGS topographic maps (North Chalone Peak, U.S. Geological Survey, 1995) were sampled, as well as others that were located and sampled based on reconnaissance and discussions with park personnel (fig. 2). In addition, eight supply and monitoring wells and two surface-water sources were sampled (fig. 2), and bulk precipitation was collected and analyzed. The geochemistry of surface-water and groundwater sources is related to the geochemistry of underlying rock formations through water-rock interaction, so an effort also was made to assess the geochemistry of the underlying rock formations.

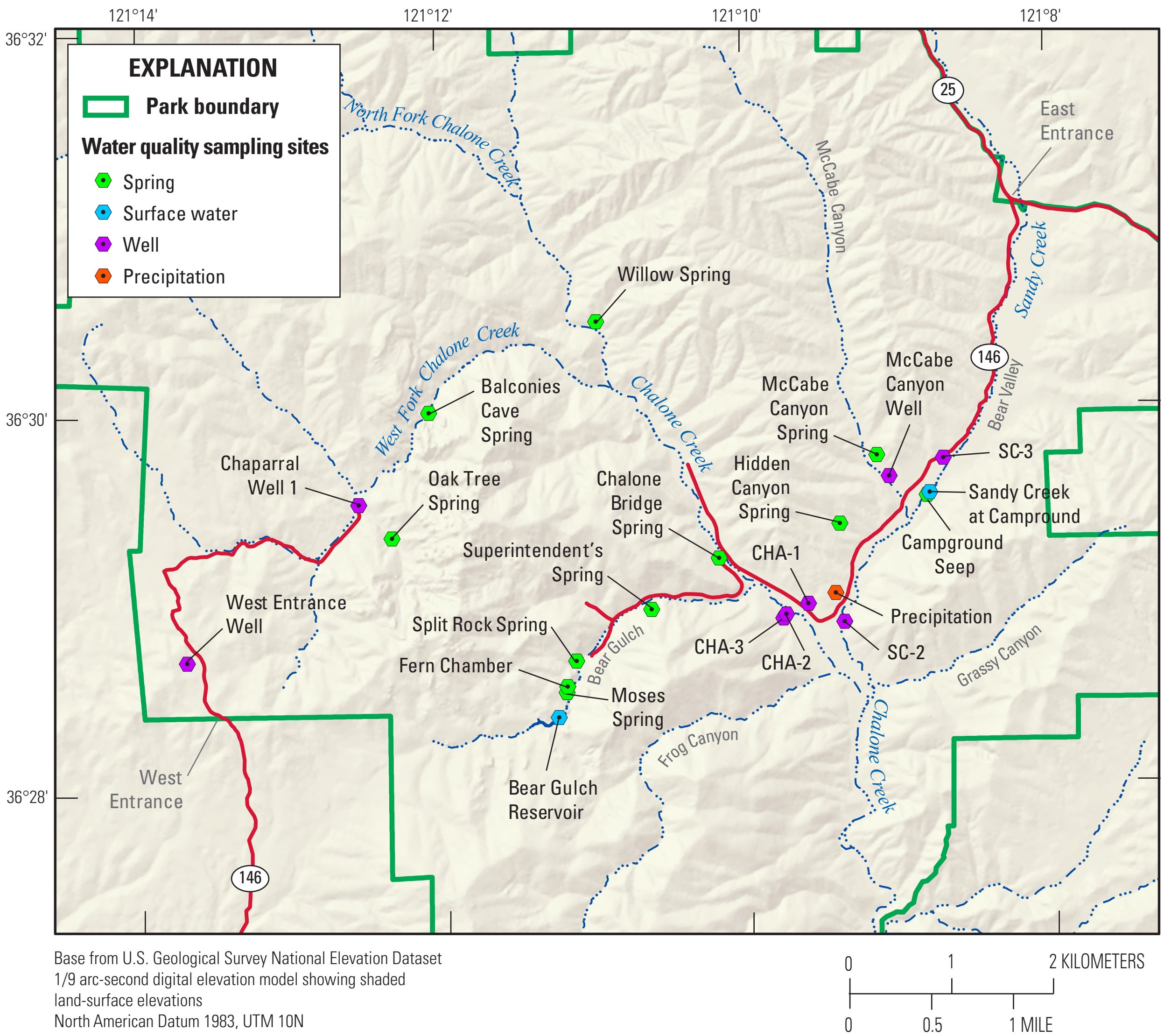


Figure 2. Map of water-quality sampling sites, Pinnacles National Park, California.

The hydrogeology investigation focused on collecting and interpreting geophysical and groundwater-level data to gain understanding of groundwater-flow processes in alluvial deposits of Bear Valley and the Chalone Creek watershed (fig. 3). Although groundwater in the alluvium is not used for human water supply at the park, shallow groundwater and associated soil moisture are an important water source for plants and animals. At the outset of the study, investigation of groundwater flow in bedrock at the park was also considered. All water supply at the park is drawn from wells completed in the bedrock, and the NPS is concerned about the sustainability of this resource. However, a bedrock groundwater investigation was not immediately feasible for two reasons: (1) there were no existing monitoring wells in the bedrock on the eastern side of the park, where groundwater sustainability is of most interest, and (2) installing enough bedrock monitoring wells to assess groundwater flow was not possible under the project budget.

Previous Investigations

Previous groundwater studies at Pinnacles National Park have addressed the issue of increasing water supply for visitors and staff. Evenson (1962) focused on the Chalone Creek alluvium as a potential water source. At the time of his study, springs served as the park water supply and their yield was barely sufficient for the Pinnacles National Monument campground and headquarters facilities. Evenson (1962) described groundwater flow processes in the Chalone Creek alluvium and drilled a test well near the current location of maintenance facilities along the road to Old Pinnacles Trailhead (fig. 1). Although drilling mud invaded the surrounding alluvial deposits during development of this well, it yielded tens of liters per minute. Evenson (1962) concluded that groundwater in the Chalone Creek alluvium was the “most readily available source of water” in Pinnacles National Monument. Akers (1967) conducted a broader assessment of existing and potential sources of groundwater supply and suggested two locations for new wells to be drilled into bedrock, both along the Chalone Creek Fault. The abandoned Stone Boundary well (fig. 3, table 1) is near one of the locations.

Conwell & Associates (1993) conducted a geologic survey to evaluate potential sites for drilling a deep well east of the Chalone Creek Fault in an area near the Stone Boundary well (see fig. 4 for location of Chalone Creek Fault and other geologic information). They applied seismic refraction along a 240 meter (m) transect across the Chalone Creek alluvium to determine the fault contact between rhyolite to the west and fanglomerate (conglomerate deposited as an alluvial fan) to the east. Their results indicated that the fault lies within an 80-m-wide zone along the transect. Outcrop studies and borehole information from a previously drilled test well indicated that the fault dips 60 degrees to the east. Based on these results, they recommended a location for a new test borehole that would ensure its completion in rocks east of the fault. Well CHA-1 (fig. 3, table 1), also known as the Pillar well, is near this recommended location. This well currently provides water supply to park headquarters facilities.

Subsequent hydrologic investigations at Pinnacles National Park have focused on flood potential (Meyer, 1995), spring water quality (Borchers and Lyttge, 2007), and stream water quality (Booth, 2013). At the request of and in collaboration with the NPS, USGS scientists conducted a water-quality study of seven springs that were determined to be key resources in the park. The criteria used to determine key resource status is whether the springs flow perennially to streams, or “provide sufficient aquatic habitat in parts of intermittent stream channels,” and included the following springs—Willow, McCabe Canyon, Oak Tree, Chalone Bridge, Superintendent’s, Moses, and Split Rock (fig. 2; Borchers and Lyttge, 2007). Important findings included arsenic (As) and uranium (U) concentrations that exceeded the U.S. Environmental Protection Agency (EPA) maximum contaminant level (MCL) for these elements in some of the springs and oxygen-isotope evidence for post-precipitation evaporation in Willow Spring and McCabe Canyon Spring. Another important finding was that tritium concentrations in the springs support an interpretation of relatively old groundwater, as the samples had not been affected by precipitation falling after 1952. Booth (2013) conducted a water-quality assessment of the perennial and intermittent freshwater streams in the park as part of the San Francisco Bay Area Inventory and Monitoring Network. However, this study did not perform a comprehensive geochemical study, instead focusing primarily on physicochemical parameters.

Approach

Baseline water quality was assessed by collecting samples for geochemical analyses from springs and groundwater wells at locations throughout the central part of Pinnacles National Park (fig. 2), as well as from a perennial reach of Sandy Creek and from Bear Gulch Reservoir. Sampling was done at the end of the dry season (September 28–30, 2016; denoted autumnal samples) and at the end of the wet season (May 24–26, 2017; denoted vernal samples) to capture the range of geochemical conditions that might be a result of seasonal recharge. The analyses include nutrients, major anions and cations, minor elements, and strontium isotopes.

The hydrogeology investigation was conducted in parts of the alluvial deposits within Bear Valley and Chalone Creek watershed. The creek draining Bear Valley is unnamed on USGS topographic maps but has been named Sandy Creek by the NPS. We adopt the name Sandy Creek in this report. The Bear Valley alluvium study area is defined as the alluvium between the east entrance of the park and the confluence of Sandy Creek with Chalone Creek (figs. 1, 3). The Chalone Creek alluvium study area was defined as the alluvium extending from slightly northwest of the Old Pinnacles Trailhead to slightly south of the confluence with Sandy Creek (figs. 1, 3). These boundaries are somewhat arbitrary and delimit an area that was easily accessible for data collection. The hydrogeology investigation involved monitoring groundwater levels in wells, applying a geophysical (seismic) method to estimate the thickness of the alluvial deposits, and conducting aquifer tests. The resulting data were used to develop a conceptual understanding of groundwater flow and its interaction with streams.

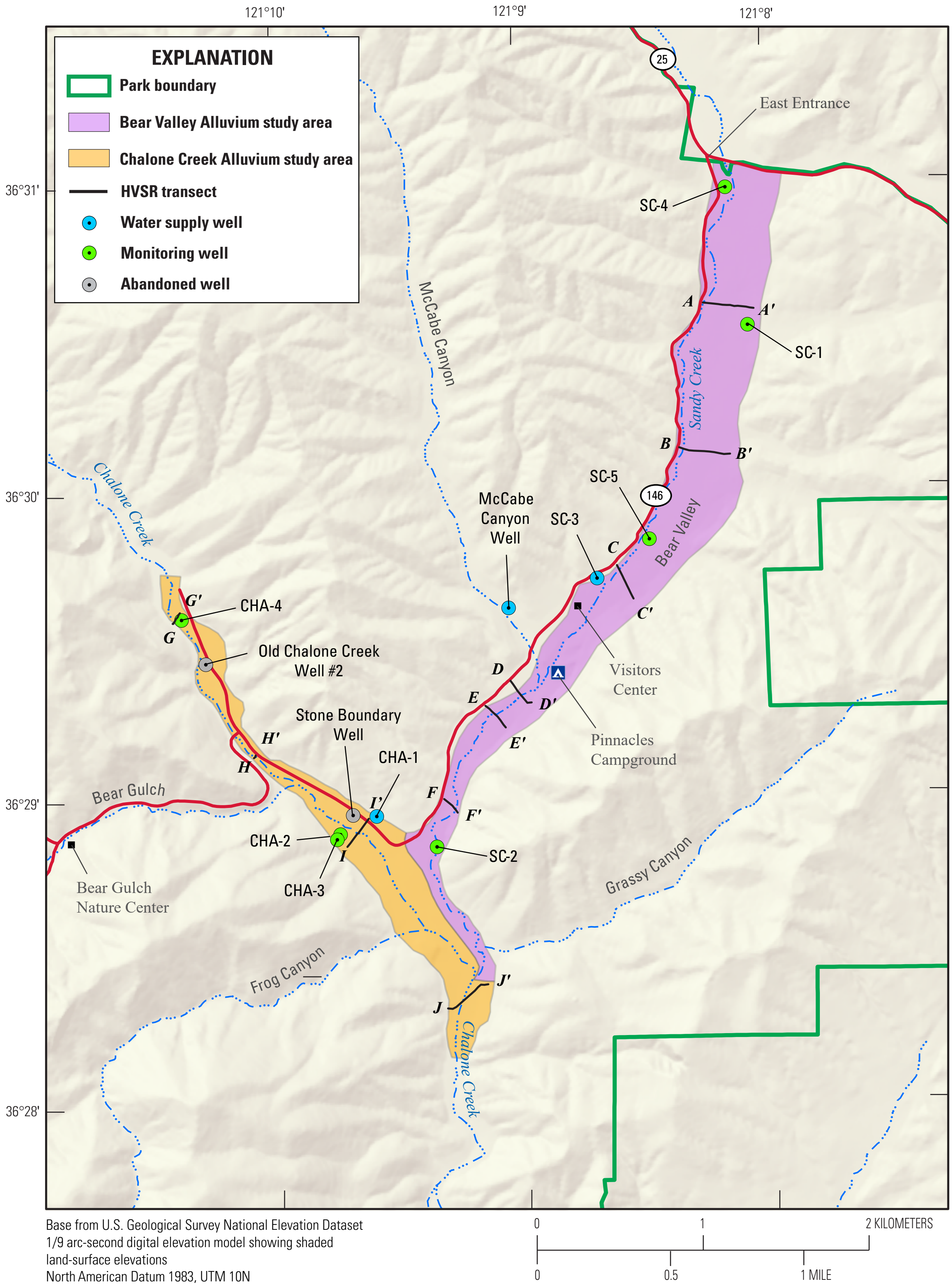


Figure 3. Map showing alluvium study areas, wells within these areas, and transects along which passive seismic data were collected for horizontal-to-vertical spectral ratio (HVSR) analysis, Pinnacles National Park, California.

Table 1. Monitoring and water supply wells in Pinnacles National Park, California.

[Well locations shown in figures 2 and 3. Well names in parentheses are names commonly used by the National Park Service. CHA in well name denotes wells in Chalone Creek alluvium. SC in well name denotes wells in Bear Valley alluvium. N/A, not available; ID, identification; USGS, U.S. Geological Survey; cm, centimeter; m, meter]

Well name	Type	USGS site ID	Year drilled	Diameter (cm)	Completed depth (m)	Depth of screened interval(s) (m)	Borehole geologic information (depth below land surface)	Source of well information
CHA-1 (Pillar well)[1]	Water supply	362857121093601	1993	15	97.5	73.2–97.5	Sandy clay to 1.5 m; granite to 97.5 m	Martin (2009)[2], well-completion report
CHA-2[1]	Monitoring	362854121094501	N/A	5	7.2	1.8–4.6	N/A	This study
CHA-3[1]	Monitoring	362853121094601	N/A	5	6	1.5–2.9 3.3–6.0	N/A	This study
CHA-4	Monitoring	362935121102301	2019	5	8.7	4.1–8.7	Coarse sand and gravel with minor silt to 9.4 m; bedrock at 9.4 m	This study
SC-1	Monitoring	363032121080401	N/A	15	27	N/A	N/A	National Park Service
SC-2 (Pinnacles Land & Cattle Co. well)[1]	Monitoring	362851121092201	N/A	N/A	19.5	N/A	Alluvium to 14.0 m; clay to 19.5 m	Martin (2009)[2]
SC-3 (Pinnacles Campground well)[1]	Water supply	362943121084201	2008	13	61	30.5–36.6 54.9–61.0	Sand to 9.1 m; decomposed granite to 33.5 m; granite and cemented sand to 62.5 m	Martin (2009)[2], well-completion report
SC-4	Monitoring	363058121080901	2019	5	14.3	5.2–14.3	Fine to coarse sand with minor gravel to 14.6 m; clay and angular rocks at 14.6 m	This study
SC-5	Monitoring	362951121082901	2019	5	16.2	4.0–16.2	Fine sand and silt to 20.7 m	This study
Stone Boundary	Abandoned[3]	N/A	1968	N/A	18.3	N/A	Alluvium to 12.2 m; bedrock to 18.3 m	Martin (2009)[2]
Old Chalone Creek Campground #2	Abandoned[3]	N/A	1968	41	11	N/A	Alluvium to 11.0 m; bedrock at 11.0 m	Martin (2009)[2]
West Entrance[1]	Water supply	362841121134201	2001	N/A	128	N/A	Completed in granitic rocks	Martin (2009)[2]
Chaparral well 1[1]	Water supply	362931121123301	1965	N/A	102.1 or 104.5	N/A	Likely completed in fault zone of fractured breccias and tuffs underlain by rhyolite and overlain by limestone and granodiorite	Martin (2009)[2]
Chaparral well 2	Monitoring	N/A	1965	N/A	102.1 or 104.5	N/A	Likely completed in fault zone of fractured breccias and tuffs underlain by rhyolite and overlain by limestone and granodiorite	Martin (2009)[2]
McCabe Canyon	Former water supply	362937121090301	N/A	N/A	16.5	N/A	N/A	This study

[1]Wells sampled for the geochemical study.

[2]Larry Martin, National Park Service, written commun., 2009.

[3]Two abandoned wells are listed because their geologic information was used in this study.

Description of Study Area

Physical Setting

Pinnacles National Park encompasses approximately 108 square kilometers (km^2) across San Benito and Monterey Counties, California. It is bounded by the Gabilan Range and Salinas Valley to the west and by the San Andreas Fault system to the east (figs. 1, 4). The climate is Mediterranean, with cool moderately wet winters and hot dry summers. Average annual precipitation was 422 millimeters (mm) from 1948 to 2005 (Western Regional Climate Summary, 2021a) and 277 mm from 2006 to 2020 (Western Regional Climate Summary, 2021b; average calculated from monthly summary time series data). Vegetation on the landscape is predominantly chaparral, consisting of dense shrubs with few or no trees (Davis and others, 2013). Oak woodlands are adjacent to stream channels where soils are deeper than in the chaparral zones.

Pinnacles National Park topography is characterized by gently sloping valley bottoms, steeply incised canyons, and rock outcrops that form pinnacles and cliffs. Land-surface altitudes range from approximately 240 m at the southern boundary to 1,007 m at the summit of North Chalone Peak in the southwest. Land-surface altitudes of wells sampled for water geochemistry range from 295 m at wells CHA-2 and CHA-3 to 606 m at the west entrance well. Topography is gentle within the Bear Valley and Chalone Creek alluvium study areas, with altitudes in both areas ranging from about 280 to 360 m.

Most of the Pinnacles National Park lies in the watershed of Chalone Creek, with headwaters located to the west and north of the park. The creek exits the park in the southeast, eventually flowing west and joining the Salinas River. Major tributaries of Chalone Creek include the North Fork and West Fork of Chalone Creek, Bear Gulch, and Sandy Creek (fig. 1). The headwaters of Sandy Creek in Bear Valley are approximately 7 km northwest of the east entrance. The portion of Bear Valley within the park is approximately 5 km long.

Most streamflow at the park is ephemeral (occurring in response to direct runoff from precipitation) or intermittent (receiving groundwater discharge during part of the year in addition to storm runoff). Perennial streamflow occurs in portions of Sandy Creek, Chalone Creek, Bear Gulch, and McCabe Canyon Creek. These reaches are not precisely mapped so their approximate locations are described here rather than shown in figures 1–3. The perennial reach of Sandy Creek extends from slightly north of well SC-5 to slightly south of the confluence with the creek draining McCabe Canyon. Perennial portions of Chalone Creek in the central part of the park include a short reach just upstream of State Highway 146 bridge across the creek and a reach south of the confluence with Sandy Creek. Bear Gulch receives outflow from Bear Gulch Reservoir and flows perennially in a few reaches downstream. McCabe Creek flows perennially along a reach upstream of its confluence with Sandy Creek. Most perennial flow rates are low (Tiedeman and others, 2021). Surface-water resources also include Bear Gulch Reservoir (fig. 1), upstream of the park headquarters. The reservoir is not used for water supply because of poor water quality.

Geology

Figure 4 shows the generalized geologic structures that are relevant to movement of groundwater in Pinnacles National Park. The central part of the park is composed of volcanic rocks, with sedimentary units to the east and northeast and granitic rocks to the northwest and southeast. A down-dropped fault block (graben), bounded by Chalone Creek Fault to the east and Pinnacles Fault to the west, preserved the younger (early Miocene, 23.5 mega-annum; Ludington and others, 1987) extrusive calc-alkaline igneous rocks of the Pinnacles Volcanics (andesite, dacite, and rhyolite flows, and rhyolite breccias and tuffs; Matthews, 1976). Miocene sedimentary rocks lie to the east of the graben, and the basement rocks of the Gabilan Range (Cretaceous granite-granodiorite) bound the graben on the west. To simplify the complex stratigraphy of the Pinnacles Volcanics, it can be subdivided into two major rock units—breccia/tuff units and massive rocks such as rhyolite flows and andesite (Matthews, 1976). The breccias are composed of lithic fragments of rhyolite, with a volcanic matrix, that likely formed as a submarine slump or turbidite on the flanks of the erupting volcanic vent (Ludington and others, 1987). Differential erosion of the rhyolite units, compared to the more resistant breccias of the Pinnacles Volcanics, has produced the distinct “pinnacles” for which the park is named.

The major structural elements are the Pinnacles Fault and the Chalone Creek Fault, northwest-southeast trending early Miocene traces of the San Andreas Fault (Matthews, 1976), with the preserved graben in between (fig. 4; Ludington and others, 1987). Right-lateral movement along the San Andreas Fault system split the early-Miocene volcanic center, with offset of 315 km between the eastern side (Neenach Volcanics, currently near Lancaster, Calif.) and western side (Pinnacles Volcanics). Tectonic activity on the faults is further responsible for the unusual talus caves, formed by massive blocks. The highly fractured breccias and tuffs are generally close to the larger mapped faults (Akers, 1967).

Sedimentary rocks, mainly poorly consolidated, massive or poorly bedded arkosic gravel and conglomerates of middle to late Miocene age, are found to the east of the Chalone Creek Fault (Andrews, 1938; Rosenberg and Wills, 2016). A recent geologic map identifies the main sedimentary unit in the park as the Bickmore Canyon Arkose (Rosenberg and Wills 2016; Wills and others, 2016; Russell Graymer, U.S. Geological Survey, written commun., January 2017). These rocks were previously referred to as Temblor Formation and (or) Monterey Formation (Andrews, 1938; Evenson, 1962; Akers, 1967). The lower Bickmore Canyon is marine and includes lenses of diatomite, whereas the upper part reflects non-marine and estuarine deposition. Among the non-marine sediments is a granitic fanglomerate, likely derived primarily from Gabilan Range igneous rocks. The fanglomerate contains coarse, angular clastics derived from a nearby source with high relief; compositionally both the granites and Pinnacles

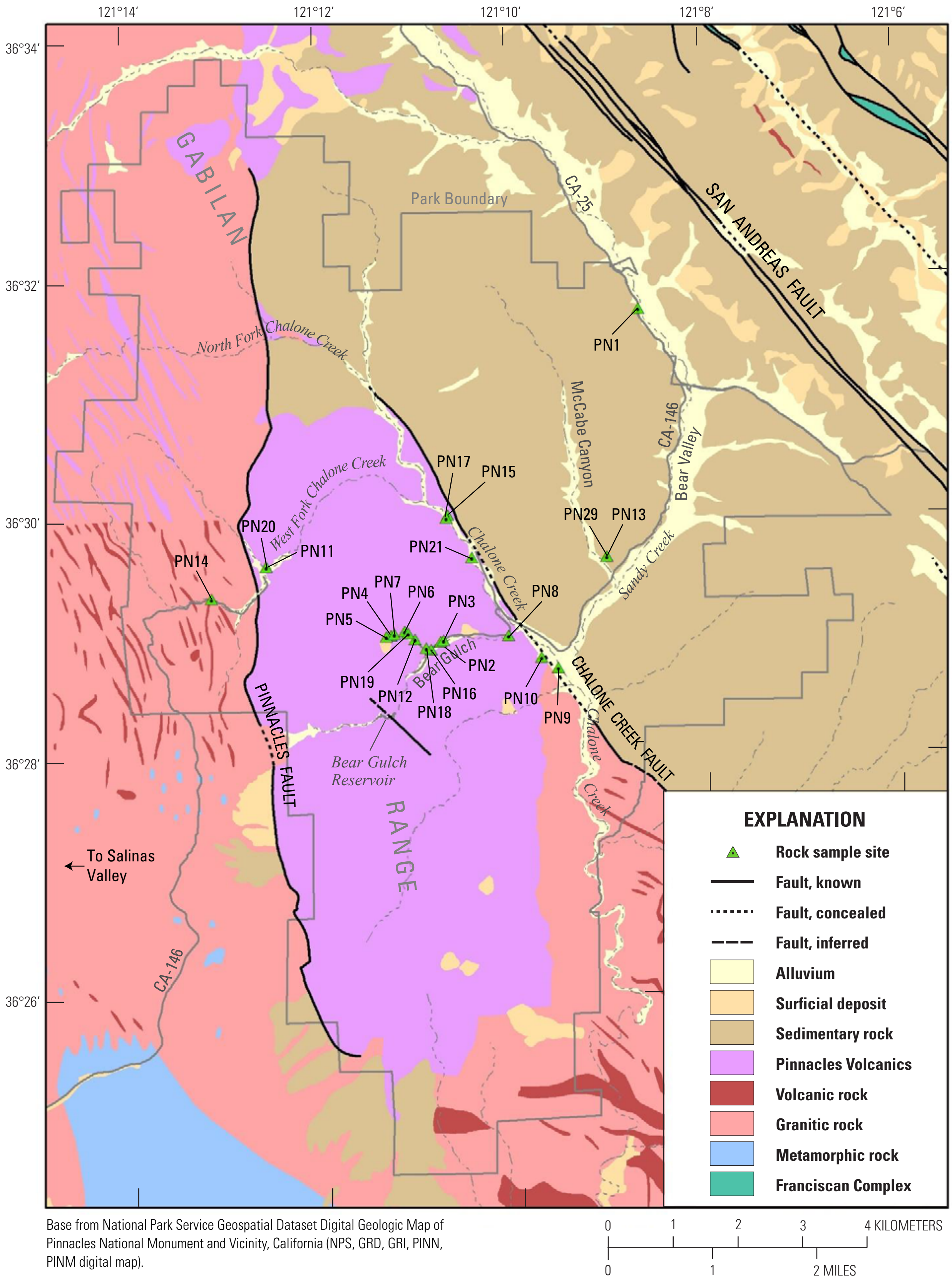


Figure 4. Map showing generalized surficial geology of Pinnacles National Park, California. Modified from National Park Service (2010).

Volcanics are represented in the conglomerate fragments (Andrews, 1938; Ryder and Thomson, 1989; Wills and others, 2016; Russell Graymer, U.S. Geological Survey, written commun., January 2017). Quaternary alluvium is found in and near creek beds and tributary channels. Along Chalone Creek, alluvium consists mostly of coarse sand, gravel, and boulders. Alluvium along Sandy Creek is finer, consisting mostly of sand and silt.

Springs

Most springs in Pinnacles National Park are low-flow springs that occur in fractures and bedding planes of volcanic rocks (for example, Superintendent's Spring, Split Rock Spring, Oak Tree Spring; fig. 2). High-flow springs and low-flow seeps occur on the northeastern side of Chalone Creek (for example, Willow Spring, Hidden Spring) and may discharge from "perched water" in sedimentary strata (Evenson, 1962). The similar topographic altitude of many of these springs may indicate structural or stratigraphic control. The springs contribute to the surface flow of perennial streams and are a primary source of water to flora and fauna in the dry seasons. Samples of the springs revealed that the groundwater, based on tritium results, has not been affected by infiltration of precipitation after 1952 (Borchers and Lyttge, 2007). Photographs of selected springs are presented in appendix 1.

Previously Studied Springs

Oak Tree Spring lies on the hillslope east of the main Juniper Canyon Trail in a concrete cistern casing constructed by the Civilian Conservation Corps (CCC) (Borchers and Lyttge, 2007; fig. 2), emanating from the volcanic breccia/tuff at less than 4 liters per minute (L/min; Akers, 1967). It is the only spring within the Pinnacles National Park boundary on the western side of the park. Samples were collected directly from the cistern.

Superintendent's Spring is located approximately 100 m up a steep, north-facing slope to the south of the former Superintendent's residence in Bear Gulch, near the Nature Center/Ranger Station. The flow is exceedingly low (less than 1 L/min, as estimated by Borchers and Lyttge, 2007), and appears to emanate from beneath the roots of a large coast live oak tree (fig. 1.3). On both sampling trips, it was necessary to remove colluvium from the area between and downslope of the tree roots to allow sufficient flow to collect a sample. Superintendent's Spring flows downslope through possibly carbonate-cemented mossy berms, a unique feature that was also noticed at Hidden Spring. The spring likely originates in the fractured breccias.

Moses Spring is a low-volume spring that flows out of an orifice in the wall of volcanic breccia bordering the High Peaks/Bear Gulch Cave Trail, and likely contributes to the base flow of Bear Gulch. Its flow was measured as 5.7 L/min by Borchers and Lyttge (2007). The water was sampled where it flows over a rocky lip directly onto the main trail to the cave.

Split Rock Spring was formerly the water supply for the park headquarters. The spring is piped to flow into a large concrete cistern near the headquarters buildings in Bear Gulch. The cover of the cistern is hidden and locked but is located on a flat area covered with boulders just off the High Peaks trail approximately 500 m up from the Moses Spring parking lot. The water was sampled directly from the inflow pipe. Although the flow is low (less than 7 L/min, Akers, 1967; less than 3 L/min, Borchers and Lyttge, 2007), at the time of sampling, several centimeters (cm) of standing water had pooled on the floor of the cistern, where most of the flow leaves the cistern and joins the base flow of Bear Creek. It appears that the water is sourced along fracture planes in the breccias.

Chalone Bridge Spring fills a sunken concrete cistern (constructed by the CCC). The cistern is difficult to locate on the steep and densely vegetated hillside immediately on the western side of State Highway 146 bridge over Chalone Creek, and the cistern cover has been partially buried under debris flows and vegetation; the presence of water is revealed by the green rushes growing below the cistern. The spring's location near the main Chalone Creek Fault implies it is sourced in the fractured volcanic breccias/tuffs. The flow is apparently low (estimated less than 0.5 L/min; Borchers and Lyttge, 2007). The cistern was less than half full during both sampling events, but this may also be due to a leaky casing and loss of water to the surrounding soil. Samples were collected from water in the cistern.

Willow Spring was formerly a water supply for the old Chalone Campground and is accessed via the North Wilderness Trail about 1 km beyond the Old Pinnacles trailhead (fig. 1). The spring discharge flows down a small side canyon. It was not possible to find the source owing to dense poison-oak brush and steep slopes; samples were collected above the valley floor where the water was about 20 cm deep and flowing freely. Akers (1967) indicated that Willow Spring flows at a near-constant rate of approximately 150 L/min from the fault contact between the Temblor Formation and the volcanic breccia and tuffs of the Pinnacles Volcanics (Larry Martin, National Park Service, written commun., 2009). Borchers and Lyttge (2007) estimated a much lower flow rate of 23 L/min.

McCabe Spring is located on the eastern slope of McCabe Canyon, less than 1 km from the gated access point on State Highway 146. Borchers and Lyttge (2007) identified McCabe Canyon Spring as a perennial spring with flow of approximately 6 L/min, and both sampling trips during the current study found ample water pooling underneath the overhanging slope from whence the spring presumably flows (fig. 1.2). Much of the floor of the canyon in this area is marshy and damp, indicating other springs and seeps contributing to the flow in McCabe Creek. McCabe Canyon has a long history of use and cultivation by the Native peoples of the Amah Mutsun and Chalon groups of the Ohlone People (National Park Service oral commun., October 2017; amahmutsun.org). Culturally significant plants such as deergrass and sedges, that currently thrive in McCabe Canyon, were managed by the inhabitants, and presumably used as resources. McCabe Canyon Spring and other seeps in the canyon are at a similar altitude to Willow Spring, and previous studies suggested a common source at the boundary between the sedimentary strata (now called Bickmore Canyon arkose) and the Pinnacles Volcanics (Akers, 1967; Larry Martin, National Park Service, written commun., 2009).

Additional Springs

Hidden Spring is a very low-volume, likely perennial spring in Hidden Spring Canyon that opens on the northern side of State Highway 146, approximately 0.5 km southwest of McCabe Canyon (fig. 2). The spring is on the western side of Hidden Spring Canyon, about 0.3 km from the road, and has mossy carbonate berms similar to Superintendent's Spring, surrounded by sedges and deergrass. Hidden Spring emanates from a small overhang in the slope, which is composed of loosely consolidated sandstone, and pools before flowing downslope under colluvium of mud and leaves (fig. 1.1). The colluvium was dug out to allow sufficient flow for sampling. There was a strong sulfur smell to the water.

Campground Seep is a poorly defined expanse of muddy/marshy ground heavily vegetated with reeds, sedges, deergrass, and other water-loving plants, atypical of the park and for this climate (except for similar occurrences in McCabe Canyon). It is composed of multiple seeps located on the southeastern side of a road into the campground (fig. 2). Water emanates diffusely from a hillslope composed of sedimentary rocks on the southeastern side of Bear Valley. The seeps contribute to the baseflow of Sandy Creek. Water was sampled by sinking the sampling buckets into the mud and allowing the sediment to settle before collecting the remaining, relatively clear water.

Samples from Balconies Cave were collected from a pool of water (approximately 9 × 5 m and 1 m deep) that collects underneath a chamber on the northern side of the Balconies Cave Trail to the east of the main Balconies Cave entrance (fig. 1.4). The source of the water is unknown; it could be percolated rainwater dripping down rock fractures, groundwater sourced from a spring, or some combination. Regardless of source, the water is likely interacting with the massive rhyolite and other Pinnacles Volcanics rocks. A source of water at Balconies Cave was also noted in previous reports (Larry Martin, National Park Service, written commun., 2009). The water flows diffusely out of the pool and down the trail away from the cave.

Fern Chamber is a pool of water hidden behind tall ferns just off the Moses Spring Trail. The water drips from crevices in the rock face (breccia) and pools beneath the cliff. Borchers and Lyttge (2007) considered this to be the likely source of Moses Spring, although its location below Moses Spring makes that unlikely. More likely, both Fern Chamber and Moses Spring receive flow from the same fracture system within the breccias. Samples were collected from the center of the pool using a dipper bucket and pole.

Surface Water

Surface water is scarce within in Pinnacles National Park and includes Bear Gulch Reservoir and perennial reaches of streams. Only two surface-water locations were sampled, Bear Gulch Reservoir and the perennial portion of Sandy Creek in Bear Valley. Bear Gulch Reservoir was constructed by the CCC in 1935 as a flood-control measure and for aesthetic purposes; it now serves as storage for firefighting and habitat for California red-legged frogs (*Rana draytonii*). Bear Gulch Reservoir sits above Bear Gulch Cave in the Pinnacles Volcanics and leaks water into Bear Gulch; the USGS North Chalone Peak quadrangle map (USGS, 1995) shows several springs that likely flow into the reservoir. However, these springs are on private land and sampling was not possible. Sandy Creek was sampled just below the bridge into the eastern side of the campground.

Wells

Four water-supply wells completed in bedrock provide water for Pinnacles National Park visitors and staff (table 1). Well SC-3 (wells in Bear Valley have the prefix SC, denoting Sandy Creek), also known as the Pinnacles Campground well, is completed in granitic fanglomerate and supplies campground and visitor-center facilities (figs. 2, 3). The driller's log for well CHA-1 (wells in Chalone Creek watershed have the prefix CHA), also known as the Pillar well, indicates that, beneath the shallow alluvium, granite was encountered over the full length of the borehole. At the location of well CHA-1, the mapped surficial geology indicates sedimentary rocks, but the Pinnacles Volcanics and granitic rocks are nearby (fig. 4). Well CHA-1 supplies the park headquarters facilities in Bear Gulch. Chaparral well 1, completed in volcanic rocks, and the west entrance well, completed in granitic rocks, provide water to visitor facilities on the western side of the park (fig. 2). The McCabe Canyon well (figs. 2, 3) served as water supply for a former occupant of the canyon. During this study, it was uncapped and flowed continuously at a rate of about 1.4 L/min, with the discharge flowing to nearby McCabe Creek. This well is believed to penetrate the sedimentary rocks.

At the beginning of this study, there were four wells completed in the alluvium that could be used as monitoring wells. Well SC-1 in Bear Valley (fig. 3) has an inoperable windmill situated above it and is pumped periodically with a submersible pump to provide water for horses owned by the NPS. Well SC-2 was formerly used by the Pinnacles Land and Cattle Company. Wells CHA-2 and CHA-3 in Chalone Creek alluvium were originally constructed as monitoring wells. In December 2018, borehole video surveys of wells CHA-2 and CHA-3 provided the well-construction information in table 1. Because of the wellhead configurations at wells SC-1 and SC-2, it was not possible to conduct borehole video surveys of these wells.

In November 2019, wells SC-4, SC-5, and CHA-4 were drilled to provide additional locations for monitoring groundwater levels in the Bear Valley alluvium and Chalone Creek alluvium (fig. 3, table 1). Well SC-4 is near the east entrance. Well SC-5 is 200 m northeast of the visitor center, roughly at the midpoint between wells SC-4 and SC-2. Well CHA-4 is near the farthest upstream location in the Chalone Creek alluvium that is accessible to vehicles. The three wells were constructed in the same manner, but the depths of the well elements differ (fig. 5).

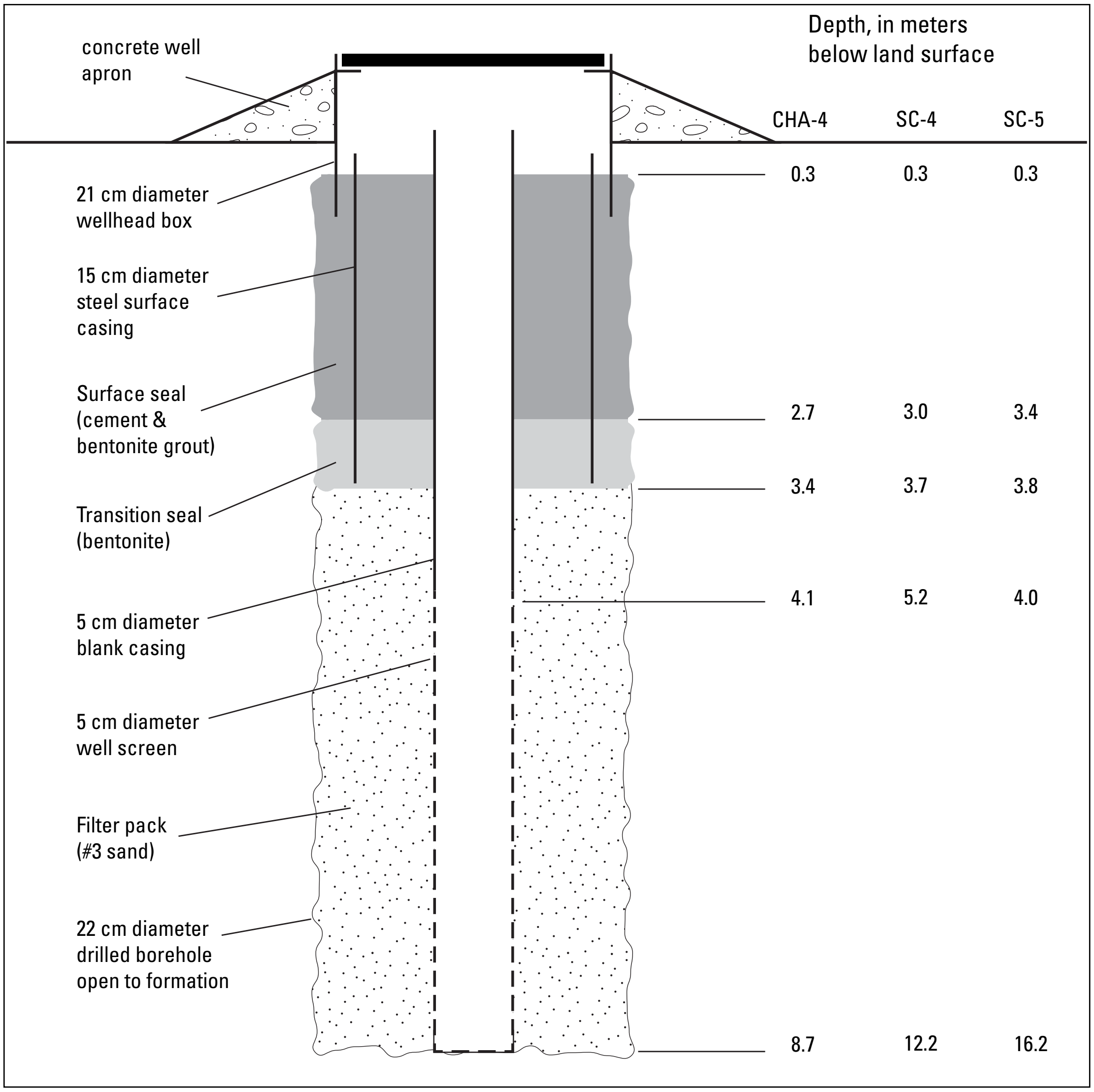


Figure 5. Schematic construction diagram for wells CHA-4, SC-4, and SC-5, Pinnacles National Park, California. Locations of wells are shown in figure 3. cm, centimeter.

Geochemistry

Sampling Protocols

Water Samples

During the field campaigns, bulk water was collected by using a hand-operated vacuum pump (SoilMoisture Equipment) or a dipper bucket and swing arm to fill acid-cleaned, 1-gallon low density polyethylene (LDPE) jugs. The jugs and buckets were rinsed and emptied with ambient water three times before final sample collection. Water temperature, conductance, and pH were analyzed in a fresh sample of water using a hand-held probe that was calibrated twice daily using the supplied calibration standards (Hach multimeter). The jugs were then carried back to a staging tent for immediate subsampling into sampling bottles (seven different sample types were collected at each location). Any required sample treatment (acidification, filtration, chilling) was performed using the USGS National Water Quality Laboratory (NWQL) Field Manual protocols. Chilled samples were stored with ice in a cooler. GPS coordinates of each site at the time of sampling were recorded with a handheld Garmin 64S GPS unit. Quality assurance and quality control and NWQL field and other method references are available at https://nwql.usgs.gov/rpt.shtml?pubs-twri and in the data dictionary (Scheiderich, 2021). Minor elements were analyzed on the Nexion300 inductively-coupled plasma mass spectrometer (ICP-MS) at USGS laboratories in Menlo Park, Calif. Strontium isotopes were analyzed by thermal ionization mass spectrometry using standard methods of the USGS Menlo Park Metal Isotope Laboratory (Bullen and others, 1996). All data are available in the associated data release (Scheiderich, 2021).

Rock Samples

Hand-sample specimens of the Pinnacles Volcanics and sedimentary rocks were collected in autumn 2017. Samples (fig. 4) were collected using a rock hammer from outcrop or float, and locations recorded using a handheld Garmin 64S GPS unit. The samples were later cut into billets and sent for thin-sectioning, powdering, and energy-dispersive X-ray fluorescence analysis by the Analytical Services Section of the USGS Minerals Group in Denver, Colo. (Taggart, 2002; Scheiderich 2021).

Precipitation

Bulk precipitation (rain plus dry deposition) collectors, composed of clean 1-gallon LDPE jugs and high density polyethylene (HDPE) funnels, were placed on a 1.5 m tall platform near the air quality station in Pinnacles National Park (fig. 1). The sampling bottles were replaced after major storm events or approximately every 2 weeks from November 2016 to May 2017. Seven bottles contained sufficient water for geochemical analysis, which consisted of tritium, strontium, and ICP-MS measurements. Nutrient, cation/anion, and oxygen-isotope analyses were not possible on these samples because of the open nature of the sampler. Precipitation chemistry data for this time interval were obtained from National Atmospheric Deposition Program (2020).

Results of Geochemical Analyses

pH, Hardness, and Specific Conductance

The sampled waters all exhibited neutral pH to slightly alkaline (maximum pH of 8.1 in Chaparral well 1), except Hidden Spring, which had a slightly acidic pH of 6.6. Hardness of the water varied considerably; many of the springs and wells fall into the moderately hard category (61–120 mg/L $CaCO_3$). Exceptions include the west entrance well water, with an extreme hardness of 450 mg/L $CaCO_3$; water samples from Sandy Creek and well SC-2 were also extremely hard. In contrast, water samples from McCabe Canyon well and Spring, Moses Spring, Fern Chamber, and Willow Spring were all soft (<60 mg/L $CaCO_3$). Specific conductance (measured in microsiemens per centimeter at 25° Celsius, µS/cm at 25°C), a measure of the electrical conductance of water at 25°C, which is related to the concentration of dissolved solids, is influenced by anthropogenic inputs, local geology, precipitation and evapotranspiration, and water temperature (for example, Olson and Cormier, 2019). Vernal and autumnal values at most locations were less than 500 µS/cm at 25°C, which is considered ideal for the support of aquatic life (Booth, 2013). Values of specific conductance at three locations in Pinnacles National Park were greater than the California State Water Resources Control Board recommendation of 900 µS/cm at 25°C (west entrance well, well SC-2, and the vernal sample from Sandy Creek; available at https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/ddw_secondary_standards.pdf). Seasonal variations in specific conductance were less than 10 percent for most of the springs, except Balconies Cave (25 percent change, with the values in the vernal sample being higher than the autumnal sample). Change in specific conductance at Sandy Creek was 35 percent, with the values in the vernal sample being higher than the autumnal sample. Specific conductance in the autumnal sample was 34 percent higher than the vernal sample in Bear Gulch Reservoir, although remaining very low. Specific conductance in the vernal sample was 8 percent higher than in wells SC-2 and SC-3 although specific conductance in the autumnal sample was higher in wells CHA-1 and CHA-2. At Bear Gulch Reservoir, evaporation and less dilution by inflow are likely the cause of the higher values of specific conductance at the end of the dry season (Olson and Cormier, 2019). For the wells, the general trends are influenced by the hydrogeology of the two aquifers. The coarse alluvium of the Chalone Creek aquifer (well CHA-2) experiences rapid recharge after precipitation events. As water levels decline over the dry season, water remaining within the aquifer may become more concentrated in dissolved ions. Slower recharge of the Bear Valley alluvium by precipitation might be reflected in the relatively constant specific conductance values; the finer grained material there would result in slower ion exchange (Hem, 1985). The reason for a large vernal increase in specific conductance along the perennial section of Sandy Creek is somewhat obscure. No rainfall was recorded for the month prior to sampling, so the higher value might represent baseflow conditions, but why it is higher than the baseflow in autumn remains enigmatic given the limited data. The study of stream parameters in 2012 also found consistently high specific conductance levels (median 780–967 µS/cm) in perennial and intermittent sections of Sandy Creek (Booth, 2013); median specific conductance values were low for the other creeks.

Anions and Cations

The major anion and cation composition of a water sample was used to classify waters by their chemistry, using a trilinear diagram (fig. 6; Piper, 1944; Appelo and Postma, 2005). The springs, wells, and surface water in the Pinnacles National Park were dominated by bicarbonate as the major anion (>50 percent on a milliequivalent per liter basis, mEq/L), with the exceptions of Hidden Spring and Campground Seep, which had similar milliequivalent percentages of sulfate and bicarbonate (33–45 percent each). Dominant cations varied more; many of the springs were dominated by sodium (Na) and potassium (K), with exceptions being Balconies Cave, Superintendent's, and Oak Tree Springs, which were dominated by calcium (Ca). Dry season (autumnal samples) versus wet season (vernal samples) seemed to affect only small changes in the relative percentages of the anions and cations present. Most sites experienced less than 2 percent change, with a maximum change of 4 percent in Ca for Balconies Cave, with the vernal sample being higher than the autumnal sample; and with Na and K expressing more variability from wet to dry than Ca and magnesium (Mg). These small changes were not enough to shift classification of the water type. The west entrance well is Ca dominated, with higher Mg than Na+K, although Chaparral well 1 has equivalent percentages of Ca and Na+K, with almost no Mg. The eastern side wells are Na and K dominated. Surface water in Bear Gulch Reservoir is Na and K dominated, whereas Sandy Creek has nearly equal percentages of Ca and Na+K, and subequal Mg.

The composition of the solid materials, in terms of four major oxides, provides insight into the dominant cations in the water (fig. 7). The rhyolites and associated rocks group tightly in the high-Na_2O+K_2O region of the ternary composition diagram, although the granodiorite has a higher percentage of Ca than other igneous rocks in the park. The west entrance well water, sourced from granodiorite, has more Ca than any water sourced from the rhyolite. This is likely a consequence of the rhyolite composition being dominated by Na- and K-feldspars (and possibly glasses; Nesbitt and Young, 1984), while the granodiorite has a larger component of Ca-rich plagioclase. All rock samples measured are low in Mg.

Further comparison of seasonal variations in the major cations and anions, and silica, was done by stacking the components (as milliequivalents per liter [mEq/L]). Arranging the sites according to the presumed lithology (Hem, 1985) allows the influence of lithology on groundwater chemistry to be visualized (fig. 8). For example, the west entrance well (in granodiorite) is distinct in having larger concentrations of cations and anions than any waters sourced in the more felsic terrain of the park. High bicarbonate concentrations are considered typical of groundwater associated with igneous terrain, particularly fractured and brecciated tuffs, whereas high chloride is commonly associated with dissolution of volcanic glasses (White and others, 1980). These variations in chemistry are driven by the dominant weathering reactions of minerals, which release soluble cations. In the case of rhyolites, the dominant reaction is alkali feldspars weathering to kaolinite (shown in reaction 1 as the ideal equation for a pure albite endmember in reaction with carbon dioxide; for example, Nesbitt and Young, 1984):

$$2NaAlSi_3O_8 + 11H_2O + 2CO_2 = Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3 + 4H_4SiO_4 \quad (1)$$

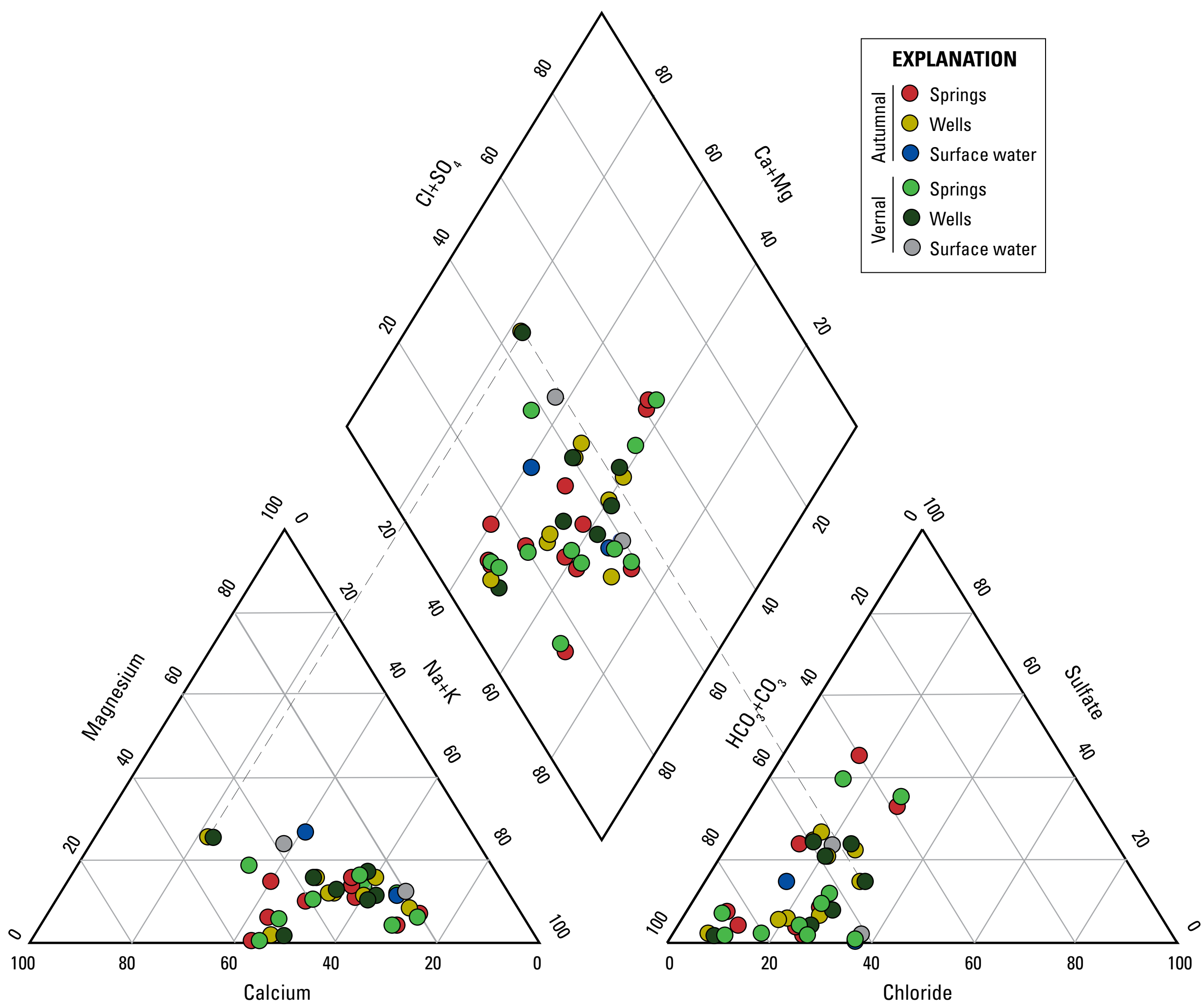


Figure 6. Trilinear diagram showing aqueous chemistry in the vernal and autumnal samples from springs, wells, and surface water in Pinnacles National Park, California. The trilinear diagram was generated using an Excel macro (Halford, 2002). The dashed lines tie together the points for west entrance well, as a visual aid.

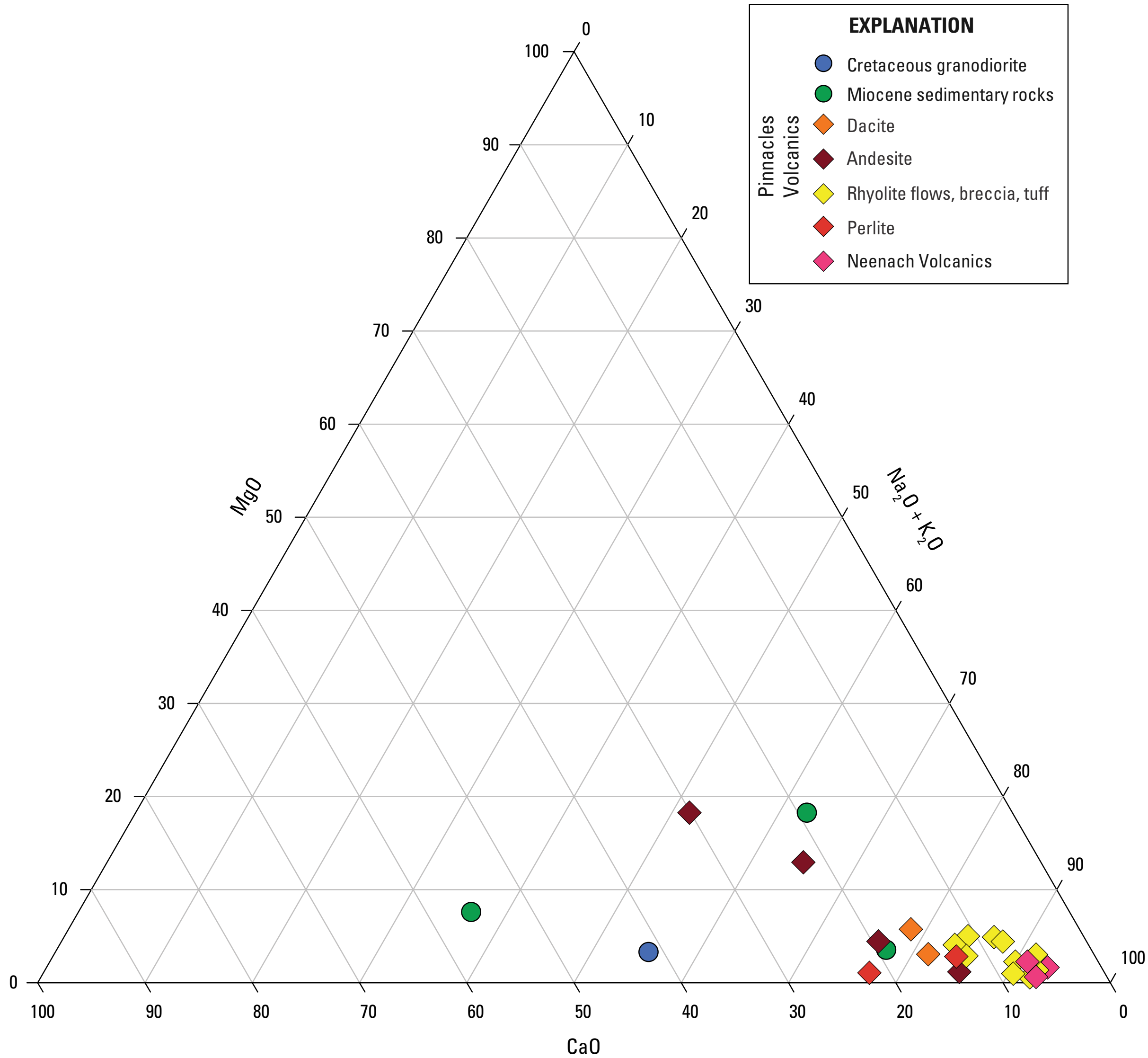


Figure 7. Ternary diagram showing normalized percentages of major elements calcium (CaO), magnesium (MgO), and sodium plus potassium ($Na_2O + K_2O$), as oxides in the solid materials from Pinnacles National Park, California.

A similar ideal reaction can be written for the K-rich feldspars. For the granodiorite, the dominant reaction may be weathering of calcic plagioclase to kaolinite (reaction 2):

$$CaAl_2Si_2O_8 + 2H_2O + CO_2 + H^+ = Al_2Si_2O_5(OH)_4 + Ca^{2+} + HCO_3^- \quad (2)$$

Seasonal changes in geochemistry due to recharge, dissolution/precipitation of soluble minerals, and flushing of soluble cations/anions is not evident at most of the sites sourced in bedrock or more indurated sedimentary rock. This implies that over much of the upland park area, most of the water from precipitation events is lost to overland flow and evapotranspiration, without rapid or significant infiltration. Based on changes in geochemistry (increases in specific conductance, bicarbonate, sulfate, or Ca), Balconies Cave, Superintendent's, and Chalone Bridge Springs may be receiving some direct input from precipitation and percolation through colluvium. The sites sourced in the alluvium show a wide range of chemical profiles. This range might be an effect of grain size or sorting in the unsaturated zone, which affects the pore space and therefore solute transfer (Hem, 1985), as well as the different rates of recharge of the two alluvial aquifers. Further, the travel times of the flow paths through the fracture system in the volcanic breccias and the sedimentary strata are probably much longer than the time interval between the samplings, as evidenced by the stability of the chemistry across seasons as well as the likely age of groundwater in the system (older than 60 years; Borchers and Lyttge, 2007). There is a similarity between the chemistry of the Campground seep area and the dry season sample of Sandy Creek, indicating that this seep area contributes to Sandy Creek baseflow. Sandy Creek and well SC-2 experience significant seasonal changes in specific conductance and milliequivalent concentrations (particularly of sulfate and Ca). Although the Bear Gulch Reservoir sits within the volcanic terrain, its low specific conductance and low concentration of major ions indicates that it may be replenished primarily by precipitation, with minimal input from groundwater.

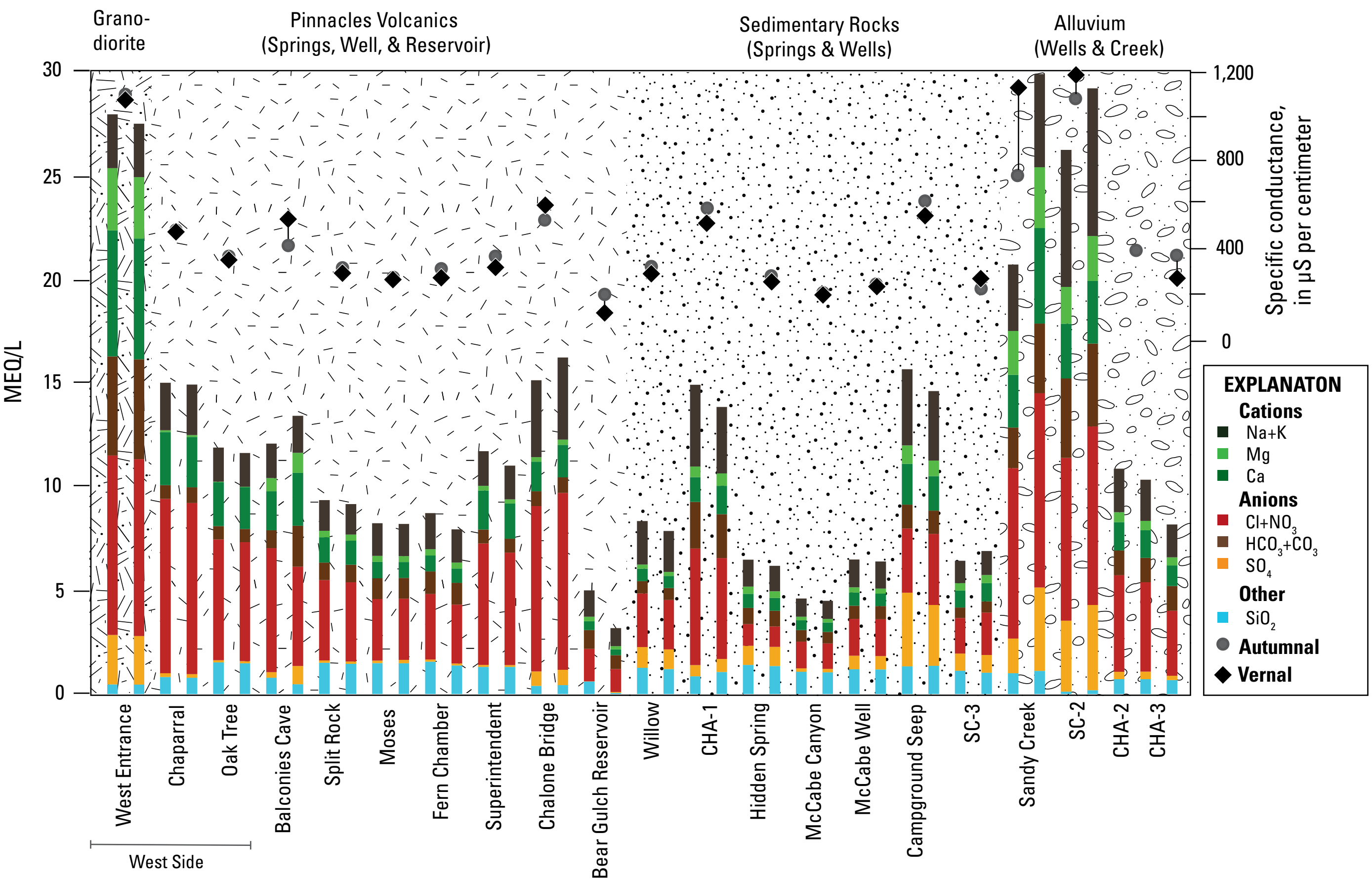


Figure 8. Diagram showing major components of water chemistry (cations, anions, silica) in milliequivalents per liter (mEq/L). For each site, two bars are paired, where the autumnal sample is the left bar and the vernal sample is the right bar. Well CHA-2 has only an autumnal sample. Specific conductance is shown in the secondary Y-axis (right) in µS/cm, where it is apparent that it tracks with total milliequivalents per liter for a site. The sites are shown on a backdrop of the lithology in which they are presumably sourced. Locations of wells and springs are shown in figures 2 and 3. µS/cm, microsiemens per centimeter.

Precipitation Chemistry

Bulk precipitation was collected at the Pinnacles Air Quality Monitoring station, as previously outlined. The concentrations of major elements are shown with the precipitation data for the collection period, at the dates on which the samples were removed (fig. 9). Variations in chemical composition of precipitation and throughfall at Pinnacles National Park have previously been attributed to seven different sources of aerosols, including biomass burning (K), marine aerosols (Na, Ca, and Mg), dust (Al, Si, Fe, Ca, and Mg), and vehicle emissions (iron [Fe]) (Dadashazar and others, 2019). Concentrations of Na, Ca, and Mg are comparable to but generally higher than published data for bulk precipitation in other locations, whereas K was significantly elevated (Appelo and Postma, 2005). High concentrations indicate a large amount of aerosol particulate matter, as proposed by Dadashazar and others (2019). These authors suggest that sea salt aerosols contribute about 40 percent of the total particulate matter in the park, whereas dust contributes 10 percent. In our sample set, however, the ratio of Na/Ca in the bulk precipitation (average value = 0.32) bears little resemblance to seawater (Na/Ca = 26), with much higher Ca than seawater. This suggests that dust and coarse particulates were elevated during the study period. There is insufficient information to relate the samples to specific aerosol contributors, but patterns are evident in the element concentrations across different storm events; for example, Ca, K, and Si tend to correlate.

Constituents and Parameters of Concern

The EPA sets a maximum contaminant level (MCL) for many inorganic and organic contaminants in drinking water (https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#Inorganic; table 2). Most of the sampled sites in Pinnacles National Park are “environmental,” which we operationally define as non-drinking water sources. Although most of the sampled sites in

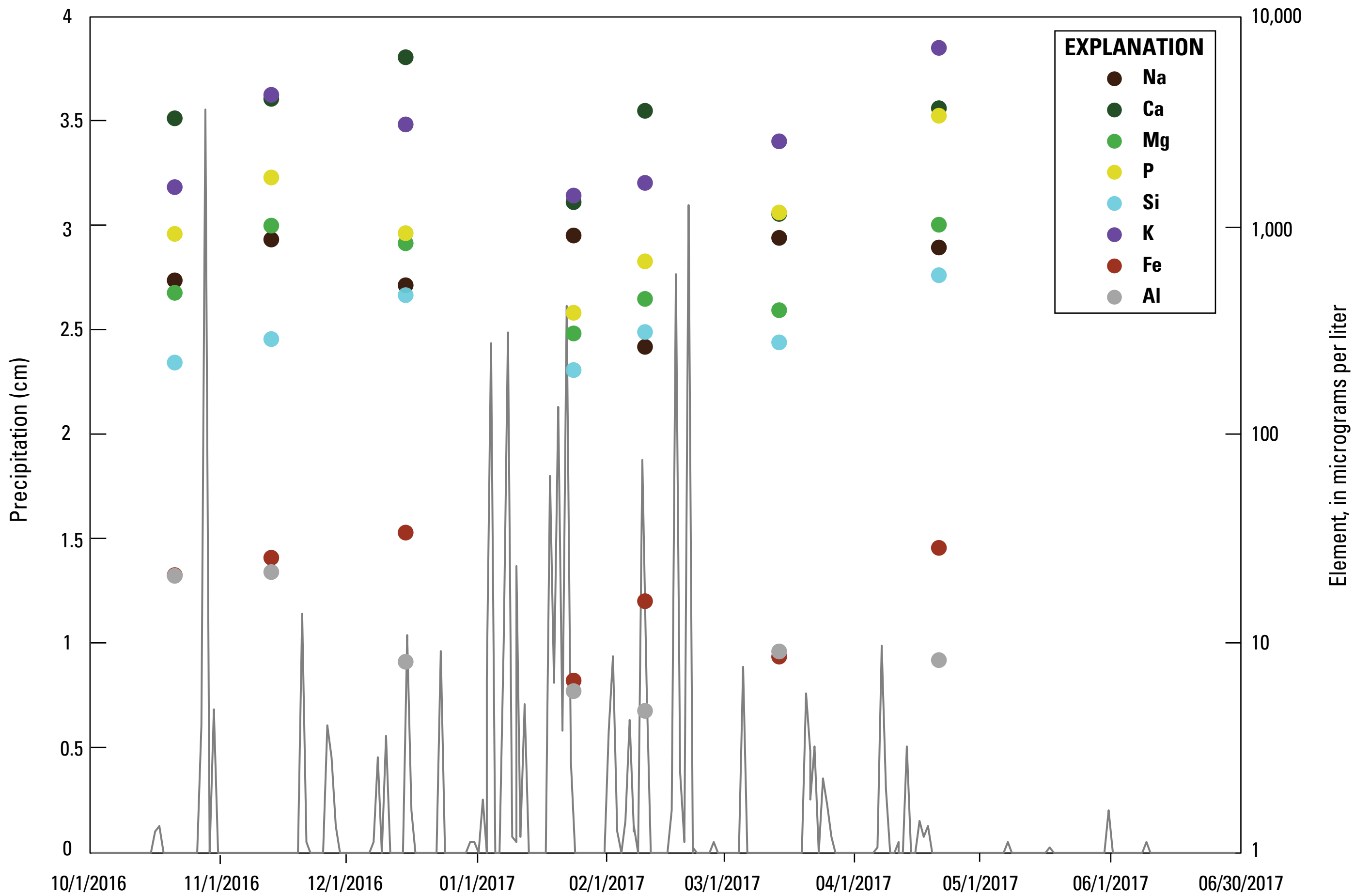


Figure 9. Graph showing chemistry of bulk precipitation, collected from November 1, 2016 to June 30, 2017, Pinnacles National Park, California. Log scale for major element concentrations on right-Y axis in micrograms per liter (µg/L). Daily precipitation totals were obtained from National Atmospheric Deposition Program (2020). cm, centimeters.

the park are not used for the drinking water supply, comparison of the environmental samples collected in this study to MCLs is nonetheless of interest (table 2), as there are no similarly established contaminant limits for environmental samples. Some contaminants with an established MCL are not listed in table 2 either because the samples had values that are uniformly close to or less than the detection limits for these elements (Cd, Cr) or the contaminants were not measured (F, Se, Tl, Hg). The California State Water Resources Control Board (SWRCB) secondary standards list includes a number of elements/parameters that are of interest due to aesthetics such as taste or odor (https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/ddw_secondary_standards.pdf). The median values listed in the table are across the sampled water sources. The highest value for each parameter at every site is given in table 2.1.

Arsenic concentrations were greater than the MCL in Hidden Spring, Split Rock Spring, Oak Tree Spring, and Chaparral well 1 (appendix 2). Other environmental samples approaching the arsenic MCL for drinking water include Moses, Fern Chamber, Superintendent's, and Balconies Cave. Similarly elevated As concentrations were identified by Borchers and Lyttge (2007), suggesting that the As is geogenic, with a possible source being sulfide minerals within the volcanic units. One sample of pumice-lapilli tuff had 21 µg/g As, which is higher than the crustal average of 4.8 µg/g (Rudnick and Gao, 2003). Chaparral well 1 exceeded the drinking water MCL for uranium (U); Chalone Bridge Spring and Oak Tree Spring approach the MCL (29.6 and 22.4 µg/L, respectively), and Superintendent's Spring and well CHA-2 were near 10 µg/L, on average. Again, Borchers and Lyttge (2007) found similar results, suggesting a geogenic source, within the volcanic rock units of the park, some of which had U concentrations greater than crustal averages (2.7 µg/g; Rudnick and Gao, 2003). A uranium anomaly has been previously identified in the flow-banded rhyolite and lapilli tuff units of the Pinnacles Volcanics (Butler and others, 1962). Uranium is a common substitute for other elements in igneous minerals such as biotite. High concentrations of both U and As are unusual, as they have different geochemical behavior.

Given the status of Chaparral well 1 as a drinking water supply, park authorities were informed of the exceedances of As and U in the untreated supply water. The NPS has acted to

Table 2. Drinking water maximum contaminant and action levels and other constituents/parameters of concern.

[ng/L, nanogram per liter; mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemens per centimeter at 25°C; N/A, not available; MCL, maximum contaminant level]

Constituent/ parameter	MCL or action level	Units	Pinnacles maximum	Pinnacles minimum	Median value
U.S. Environmental Protection Agency MCL					
Arsenic (As)	10	µg/L	23	0.28	4.83
Barium (Ba)	2	mg/L	0.094	<0.003[1]	0.007
Nitrate (as N)	10	mg/L	3.3	<0.04[1]	0.22
Nitrite (as N)	1	mg/L	0.016	<0.001[1]	0.002
Uranium (U)	30	µg/L	85.4	<0.01[1]	1
U.S. Environmental Protection Agency Action Level					
Copper (Cu)	1.3	mg/L	0.005	<0.001[1]	0.0012
Lead (Pb)	0.015	mg/L	0.00018	<0.00003[1]	0.00001
California State Water Resources Control Board Secondary MCL					
Aluminum (Al)	0.2	mg/L	0.051	0.001	0.003
Chloride (Cl)	250	mg/L	170	19	29.5
Iron (Fe)	0.3	mg/L	1.12	0.04	0.11
Manganese (Mn)	0.05	mg/L	1.32	<0.01[1]	0.02
Specific conductance	900	µS/cm	1,210	170	360
Sulfate (SO_4)	250	mg/L	200	2.3	26.3
Zinc (Zn)	5.0	mg/L	0.15	0.002	0.0023
Other					
Boron (B)	N/A	µg/L	430	21	37
Lanthanum (La)	N/A	ng/L	74	0.4	2.7
Lithium (Li)	N/A	µg/L	230	7.4	49.2
pH	N/A	N/A	8.1	6.5	7.5

[1]Value below detection limit.

cease using this well for drinking water supply, and to provide drinking water for visitors through other means.

McCabe Canyon Spring was the only location with consistently high nitrate concentrations, but these were still well below the EPA MCL. The highest nitrate concentrations sampled by Booth (2012) were also in McCabe Canyon Creek (0.83 mg/L) and could be derived from contributions of upstream springs. Nitrite was less than EPA limits of 10 mg/L in all samples. Elevated nitrite/nitrate concentrations are generally the result of runoff from fertilized areas, natural deposits nitrified by soil bacteria, or sewage; anthropogenic and natural sources of nitrite/nitrate in the park do not appear to be substantial. Barium (Ba) concentrations are less than the EPA limit. Concentrations were highest in the west entrance well, completed in granitic rocks, which tend to have higher Ba concentrations than crustal average (624 µg/g, Rudnick and Gao, 2003). One sample of loosely consolidated sandstone had 0.14 weight percent BaO (1,200 µg/g), much higher than most other rocks in the park, possibly from sedimentary barite.

Copper (Cu) and lead (Pb) concentrations in sampled park waters are low; the highest concentration of Pb was in well SC-3, used for water supply in the campground. All Cu and Pb concentrations are under the EPA action levels (table 2); if these levels are exceeded in drinking water supply systems then corrosion control measures must be undertaken. The low Cu and Pb concentrations suggest that these constituents are not mobilized effectively due to the circumneutral pH of the circulating waters. Concentrations of these elements in rock materials were also low with maximum values of 3.8 and 4.4 µg/g, respectively, compared to 28 and 18 µg/g for crustal average (Rudnick and Gao, 2003).

Other elements that are not regulated by the EPA may still be of concern when considering water quality for beneficial use. Several of these are listed by the State of California as elements of concern with a secondary MCL (table 2). Boron is often a contaminant from agricultural uses but also has natural sources; although the high concentration in Sandy Creek suggests a runoff contribution, the concentrations are still less than the California secondary MCL. Iron (Fe) and manganese (Mn) are occasionally quite high, but there is no discernible pattern to the high concentrations of either element, other than that they do not correlate. Generally, Fe and Mn were higher in the sedimentary and alluvially influenced water samples, likely because Fe and Mn are common constituents of igneous and sedimentary minerals and are relatively mobile and redox-active (Hem, 1985).

Strontium Isotopes and Groundwater Sources

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) can be useful tracers of water-rock interaction, water-source mixing, groundwater movement, and salinity (Clark and Fritz, 1997). Strontium is a divalent cation that substitutes for Ca^{2+} in many rock types and minerals and behaves similarly to Ca and other divalent exchangeable cations during weathering and water-rock interaction. It has four isotopes, with ^{88}Sr comprising 82.6 percent, ^{86}Sr 9.9 percent, and ^{84}Sr 0.6 percent. The other isotope, ^{87}Sr (7 percent), is the daughter product of ^{87}Rb decay through beta emission, with a half-life of 48.8×10^9 years (Bullen and Kendall, 1998). The larger ionic radius of rubidium (Rb) means that it will be excluded from certain minerals (carbonates, plagioclase feldspars) and preferentially substitute for K in others (biotite, K-feldspars). Potassium-rich rocks thereby have high ^{87}Rb and consequently higher ^{87}Sr. This generates varying initial Rb/Sr ratios and initial $^{87}Sr/^{86}Sr$, which evolve over time as Rb decays. Thus, the $^{87}Sr/^{86}Sr$ in waters will depend on the $^{87}Sr/^{86}Sr$ and Sr concentrations of the underlying rock types, the age and area of exposure of rock types, their dominant minerals and susceptibility to chemical weathering, and mixing of water derived from different rock types (Faure and Mensing, 2005). For example, ^{87}Sr-depleted ocean basalts have $^{87}Sr/^{86}Sr = 0.703$ (less radiogenic), while continental rocks (^{87}Sr-enriched, more radiogenic) are higher (0.710 to 0.740), and seawater is intermediate, 0.709, with secular (long-term, non-periodic) variation over geologic time (for example, Palmer and Elderfield, 1985).

For this study, the Sr isotope composition was measured in all the water samples, bulk precipitation (4 samples), a suite of Pinnacles Volcanics rocks, one sample of granodiorite, three sedimentary rocks and, for comparison, several samples from the separated half of the original volcano (Neenach Volcanics). The analysis of $^{87}Sr/^{86}Sr$ in the rocks was performed on hydrofluoric acid digests of whole-rock powders.

Most of the rocks in Pinnacles National Park are rhyolitic, with greater than 67 percent SiO_2 and composed of quartz, K-feldspar, and a lesser amount of Na-rich plagioclase and accessory biotite. The granodiorite is compositionally between rhyolite and dacite, with similar quantities of quartz, K-feldspar, and Na-plagioclase, and accessory amphibole and biotite. A few rocks classify as dacitic and andesitic with greater than 60 percent SiO_2 with lower quartz and higher plagioclase, amphibole, and biotite concentrations. Andesites are dominated by Na-Ca feldspars and have little to no quartz or K-feldspar (Matthews, 1978) which, in the case of Pinnacles National Park, is reflected by relatively non-radiogenic Sr isotope values (0.7054). The rocks span a large range of $^{87}Sr/^{86}Sr$ values, from 0.704 to 0.712, with a direct correlation to K_2O percentage and Rb/Sr ratio, as expected (fig. 10, top and bottom). The sedimentary rocks have low Rb/Sr, but otherwise are in line with the $^{87}Sr/^{86}Sr$ of surrounding materials.

The Sr-isotope values from the water samples and precipitation have a very small range (0.7076–0.7088; fig. 11), spanning just a portion of the wider range established by the solid materials (0.704–0.712). The water Sr isotopes show no correlation to Ca/Sr, Ca/Si, or Sr concentration, as might be expected (for example, Banner, 2004; figs. 11, 12). The range of water values also is less than the value for modern seawater (0.70925). There are only minor differences between autumnal and vernal Sr isotope values. Importantly, there are no distinct groupings in isotope values that might indicate groundwater pathways through different rock types, other than the high Sr-isotope value of the west entrance well, sourced in granodiorite. Small changes in Ca/Sr are evident seasonally but are not correlated with Sr-isotope changes (fig. 12).

The three major geologic matrices (Pinnacles Volcanics, sedimentary strata, and alluvium) do not generate distinct groupings in the water Sr isotopes (fig. 12). Several possibilities could contribute to the highly consistent water Sr-isotope values. First, the alluvium is composed of eroded Pinnacles Volcanics and sediments, while the sedimentary strata are themselves composed of clastics derived in part from the Pinnacles Volcanics, admixed with granite/granodiorite (Ryder and Thomson, 1989; Wills and others, 2016). Second, the springs that arise from the sedimentary strata may be associated with a structural or stratigraphic boundary that would allow mixing and homogenization of Sr isotope values across lithologies. However, a mixing line for Sr isotopes, if it does exist, is likely to be very steep, given the small ranges in Sr-isotope values and Ca/Sr or Sr concentrations. Bear Gulch Reservoir does not bear much similarity to the Sr isotopes in precipitation, although we have postulated that its primary input was from rainfall, based on the cation/anion concentrations. Instead, it bears a high resemblance to the waters in the nearby springs sourced in the fault breccias.

Precipitation in the park has an average Sr-isotope value of 0.7085, with an average Sr concentration of 19 μg/L. Although this concentration is low compared to the groundwater, it could contribute up to a fifth of the isotope composition of certain springs with lower Sr concentrations around 100 μg/L. A simple isotope mixing calculation indicates that, because the concentration of Sr in rainwater alone (<2 μg/L; Banner, 2004) is low compared to the concentrations in dry deposition (dust about 22,000 μg/kg Sr and marine aerosols about 7,000 μg/L Sr), these two components cannot contribute more than 0.1 percent of the Sr to bulk precipitation. Extending this calculation indicates that the Sr isotopic composition of rain is most likely to be within the narrow range of 0.7084–0.7086. The similarity of bulk precipitation to groundwater and surface-water Sr isotopes, and to the average value for $^{87}Sr/^{86}Sr$ in the rocks, indicates that Sr isotopes in the groundwater have reached an approximately steady-state value. The relatively long residence time of water in the groundwater system implies that the Sr isotope composition of bulk precipitation has not varied significantly over the same time frame.

There are several potential drivers of the relatively homogeneous set of Sr-isotope values and the appearance of a quasi-steady-state. In keeping with the low-flow rates of nearly all the springs, it is possible that the residence time of water within both the Pinnacles Volcanics and in the

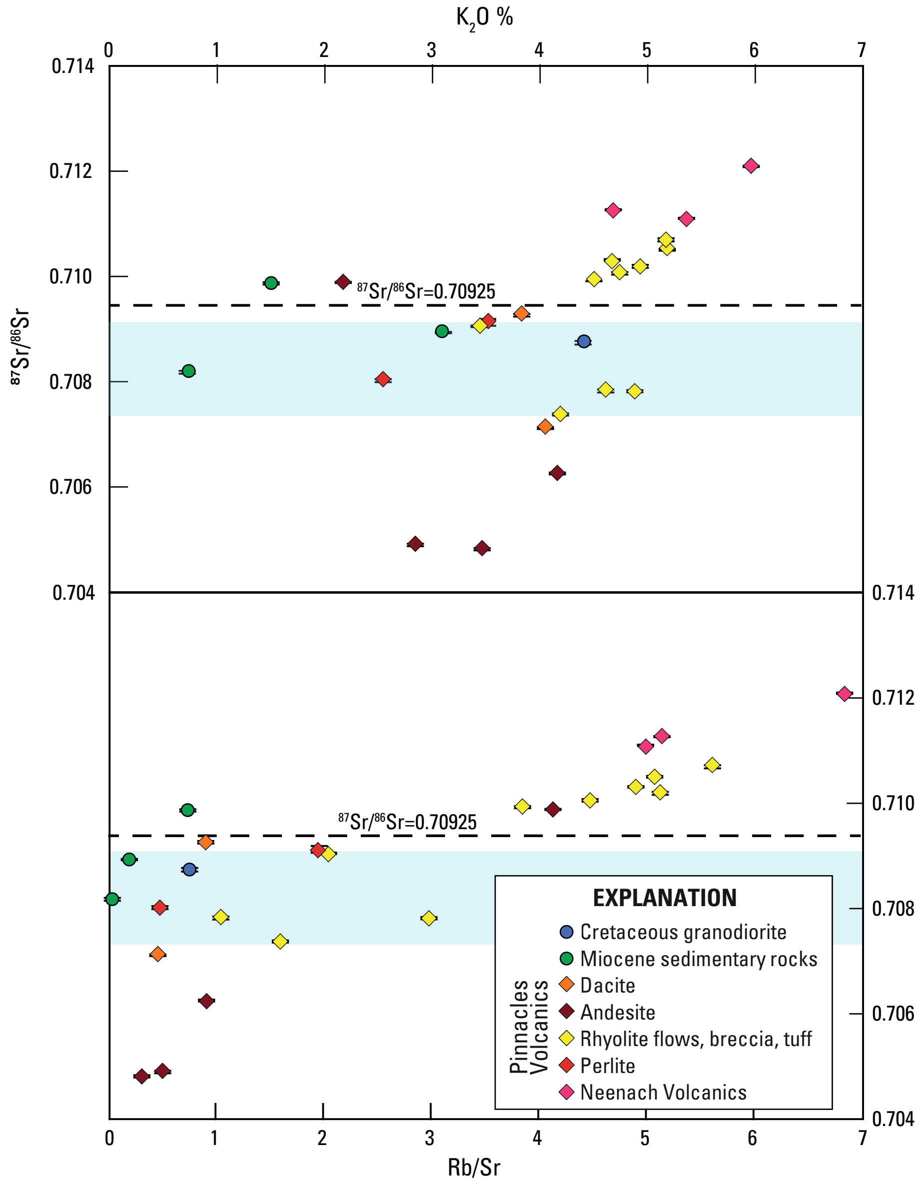


Figure 10. Graphs showing strontium isotopes ($^{87}Sr/^{86}Sr$) compared to percentage of K_2O in powdered whole rock from Pinnacles National Park, California (top graph). Strontium isotopes ($^{87}Sr/^{86}Sr$) compared to Rb/Sr ratio in powdered whole rock (bottom graph). Errors (two standard deviations, less than 0.00001) for internal measurements are smaller than the symbol size. Dashed line in both panels is the Sr isotope value for modern seawater (0.70925), while the blue shading delineates the range of Sr isotope values in waters from Pinnacles National Park.

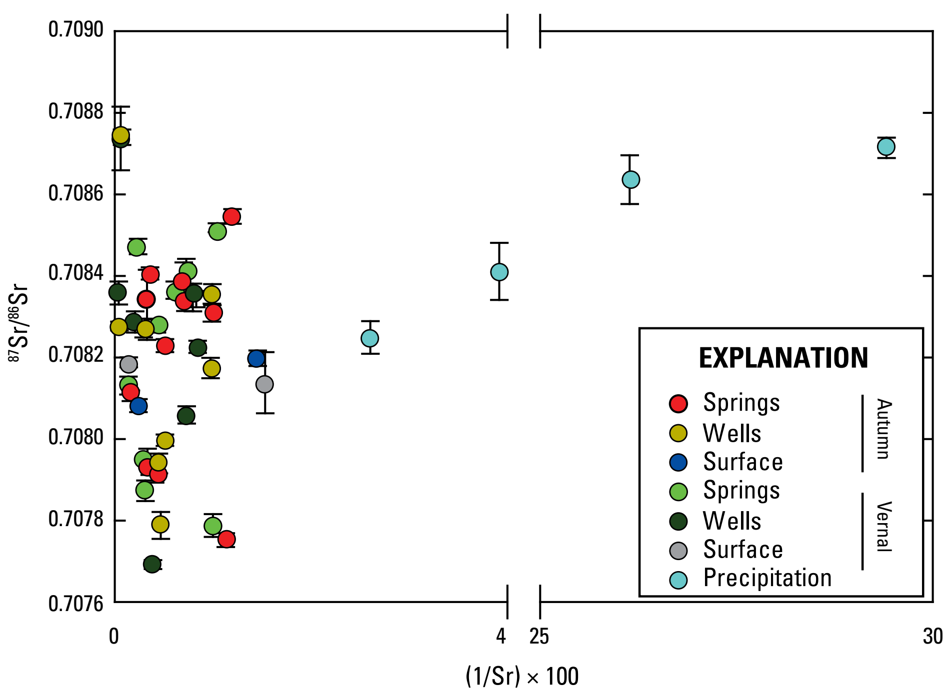


Figure 11. Graph showing strontium isotope values in all aqueous samples compared to inverse of strontium concentration (1/Sr, µg/L). Error bars for $^{87}Sr/^{86}Sr$ are ± two standard deviations of the internal measurement error.

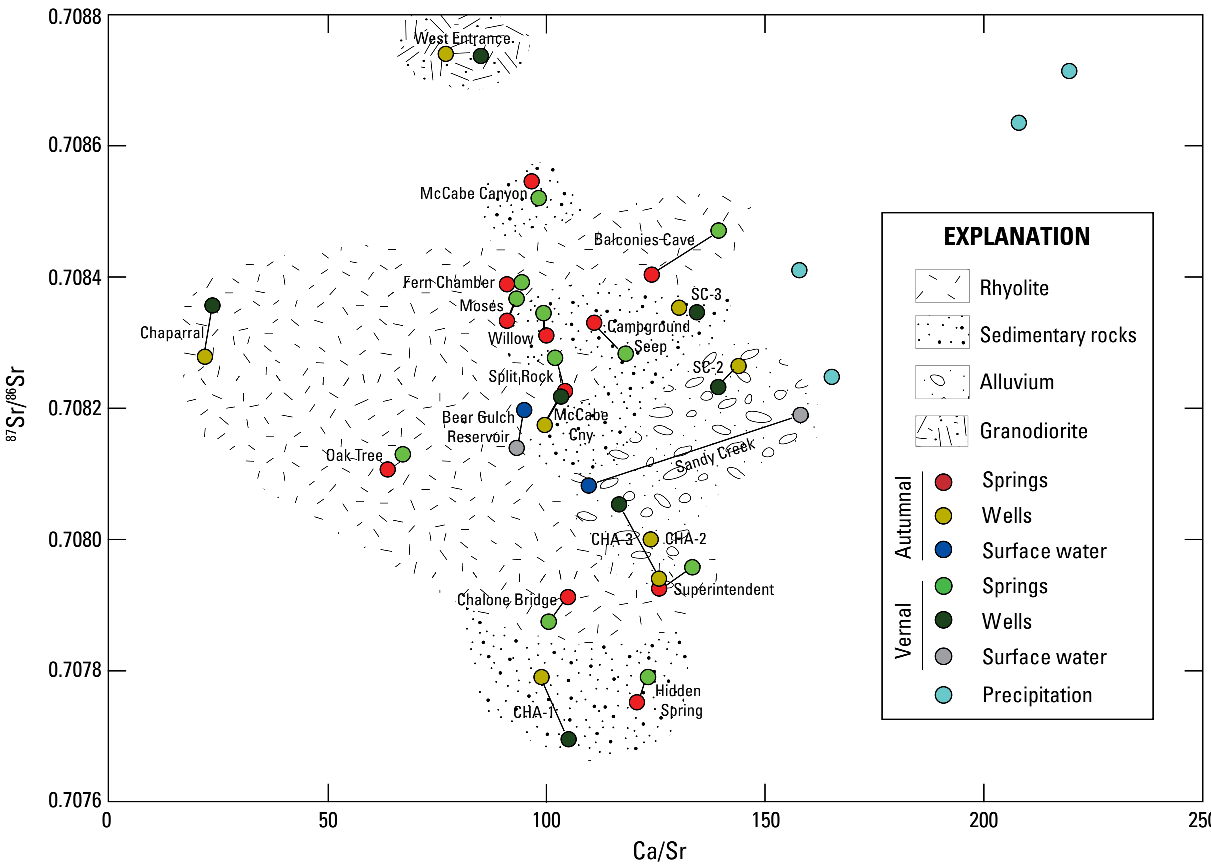


Figure 12. Graph showing strontium isotope values ($^{87}Sr/^{86}Sr$) versus Ca/Sr in all aqueous samples. Error bars are omitted for clarity. The wells and springs are shown on a backdrop of the rock material in which they are sourced (as in fig. 8). The autumnal and vernal samples for each sampling location are connected by a line, except for locations where the two samples plot very close to one another.

sedimentary strata is very long with respect to weathering rates of susceptible minerals (in accordance with Bowen's reaction series: Bullen and others 1996, 1997; Nimz, 1998). Although plagioclase feldspars are more resistant to weathering than alkali feldspars, alkali feldspars generally have higher Rb/Sr than plagioclase (due to Rb substitution for K). Accordingly, the rhyolites and associated rocks (breccias) would have higher initial quantities of Rb-rich feldspar, compared to the andesite and granodiorite (which would however contain greater quantities of high Rb/Sr biotite).

Slow flow rates in fractured-rock groundwater systems allow plagioclase to develop alteration coatings that inhibit dissolution and Sr removal, allowing for a stronger influence of more radiogenic Sr from alkali feldspar on $^{87}Sr/^{86}Sr$ ratios (Nimz, 1998). The system Sr isotope ratio has slowly converged towards an "equilibrium" value with time, however, as the most susceptible minerals are lost (Biotite, high Rb/Sr) or are passivated (for example, plagioclase, very low Rb/Sr). The long contact of rock surfaces with groundwater then promotes dissolution of more-resistant minerals such as quartz (virtually no Rb/Sr) and alkali feldspars (somewhat higher Rb/Sr). The samples from Sandy Creek saw a shift in conductance (as discussed previously; seen in figure 12 as a shift in Ca/Sr) between the wet and dry seasons that might be evidence for a pool of exchangeable Sr that is isotopically relatively homogeneous as, despite the large increase in Sr, there was little change in Sr-isotope ratio.

Hydrogeology of Bear Valley Alluvium and Chalone Creek Alluvium

The hydrogeology investigation focused on the Bear Valley alluvium and Chalone Creek alluvium study areas (figs. 1, 3). In both study areas, groundwater flows in a southerly direction, following the drainages of the creeks. The water table is generally at shallow depths—less than 10 m below land surface. Over an annual cycle, water levels generally rise during the wet season (late autumn to early spring) and decline during the dry season. However, this general pattern does not occur regularly, particularly in northern Bear Valley.

The investigation involved conducting field activities to characterize alluvium thickness and hydraulic conductivity, and monitoring groundwater levels in the Chalone Creek alluvium and Bear Valley alluvium from April 2018 to January 2021. The groundwater-level variations were used to develop an understanding of groundwater flow and its interaction with surface water in both alluvium study areas.

Alluvium Characteristics

Thickness

Thicknesses of the Bear Valley alluvium and Chalone Creek alluvium are needed for developing a conceptual understanding of groundwater flow. Alluvium thickness is defined as the depth below land surface of the bedrock underlying the alluvium. Bedrock depths are available for a few wells that penetrated bedrock (wells CHA-1, CHA-4, SC-3, Chalone Creek Campground well No. 2, and the Stone Boundary well; table 1). Given these sparse borehole data, a geophysical investigation was conducted to provide additional bedrock depth estimates. The horizontal-to-vertical spectral ratio (HVSR) seismic method was applied at points along six transects in Bear Valley alluvium and four transects in Chalone Creek alluvium (fig. 3) and at the locations of several existing and abandoned wells. This method uses ambient (passive) seismic noise in the range of 0.1 to 1 Hertz (Hz), measured with a three-component seismometer (Lane and others, 2008; Johnson and Lane, 2016). Ambient seismic noise in this frequency range is generated by ocean waves, large regional storms, and tectonic sources. The data are processed to determine the fundamental seismic resonance frequency, which is obtained by analyzing the spectral ratio of the vertical and horizontal components of the seismic noise. This resonance frequency is related to alluvium thickness by equation 3 (Lane and others, 2008):

$$f_0 = V_s / 4Z, \qquad (3)$$

where

f_0 = the fundamental resonance frequency (Hz),
V_s = the average shear-wave seismic velocity (meters per second, m/s) of a sediment layer overlying bedrock, and
Z = sediment thickness (m).

On a graph of the ratio of horizontal and vertical amplitude spectrums (H/V) versus frequency, f_0 is the frequency at which a prominent peak occurs (for example, fig. 13*A*). The method performs best when there is a strong contrast (>2:1) in acoustic impedance (product of material density and *Vs*) at the boundary between alluvium and bedrock. Prior to collecting the ambient seismic data, the minimum *Vs* contrast at this boundary was estimated to be 2.7 for Chalone Creek alluvium and 3.5 for Bear Valley alluvium (appendix 3). Because the density of rock is greater than that of alluvium, the acoustic impedance contrasts will be somewhat larger than the *Vs* contrasts, indicating the conditions for applying the HVSR method were satisfied.

Ambient seismic data were collected along the 10 transects (fig. 3) and at the existing and abandoned well locations during November 2018, February 2019, and February and March 2020 (Tiedeman and Hsieh, 2021). Data were collected with Tromino three-component seismometers, using model TEP-3C in 2018 and 2019 and model Tromino BLU in 2020. Data were collected for 20 to 30 minutes at each point. Seismic data from each point measurement were processed using the commercial software program Grilla version 8.0 to obtain f_0. At 81 points along the 10 transects, an interpretable peak in H/V and an associated f_0 were obtained. The quality of the peaks was subjectively rated as good (52 peaks), fair (17 peaks), or poor (12 peaks). To be retained, a peak rated as poor was required to meet a criterion of consistency with peaks for adjacent points on the transect. Peaks rated as poor were mostly near the ends of a transect. Examples of peaks rated as good, fair, and poor are shown in figure 13.

To calculate *Z* from f_0 measured along the transects, estimates of *Vs* for the Chalone Creek alluvium and Bear Valley alluvium are needed (equation 3). *Vs* estimates were obtained from equation 3 with *Z* and f_0 as inputs, with f_0 obtained by applying the HVSR method at wells with known or inferred bedrock depths, as discussed in appendix 3. This yielded average, minimum, and maximum *Vs* estimates for Chalone Creek and Bear Valley alluvium (appendix 3). These *Vs* were used to estimate average, minimum, and maximum depths to bedrock along the transects (figs. 14, 15).

The Bear Valley alluvium is thickest in the north and thins towards the confluence of Sandy and Chalone Creeks (fig. 14). The maximum estimated thickness of 34 m (range of 28–41 m) occurs in the center of the northern transect *B–B′*. At the southernmost transect (*F–F′*), the maximum thickness is 18 m (range of 15–22 m). The width of the alluvial basin narrows from the north (where it is about 300 m wide) to the south (about 120 m wide). Along transects *A–A′*, *B–B′*, *C–C′*, and *F–F′*, the HVSR data show a bedrock surface profile that is shallowest at the endpoints, near the base of the hillslopes bordering the alluvial deposits, and deepest near the center of the transect (fig. 14). For transects *D–D′* and *E–E′*, the bedrock is shallowest at the northwestern endpoints and deepens with distance along the transect. Depth to bedrock could not be estimated at points close to the base of the hillslope in the southeast due to lack of access or data that did not produce a useable f_0. The southeastern endpoints of transects *D–D′* and *E–E′* are each about 40 m from the base of the hillslope, and it is expected that the bedrock surface becomes shallower towards this hillslope.

The thickness of Chalone Creek alluvium tends to increase from north to south (fig. 15). Transects *G–G′* and *H–H′* have similar maximum thicknesses of about 12 m (range 9–15 m) and transect *I–I′* has maximum thickness of 15 m (range 12–18 m). At transect *J–J′* the maximum estimated thickness at the data points is 20 m (range 15–25 m), but the alluvium might be thicker in the center of the transect, where its thickness could not be estimated because of lack of access. Along Chalone Creek, the width of the alluvium is narrow upstream of the confluence with Bear Gulch (transects *G–G′* and *H–H′*) and wider downstream of this confluence (transects *I–I′* and *J–J′*). Topographic maps indicate that the width of alluvium again narrows south of transect *J–J′*.

Hydraulic Conductivity

The hydraulic conductivity of the Chalone Creek alluvium was estimated by conducting two aquifer tests using wells CHA-2 and CHA-3. Both tests were performed on April 16,

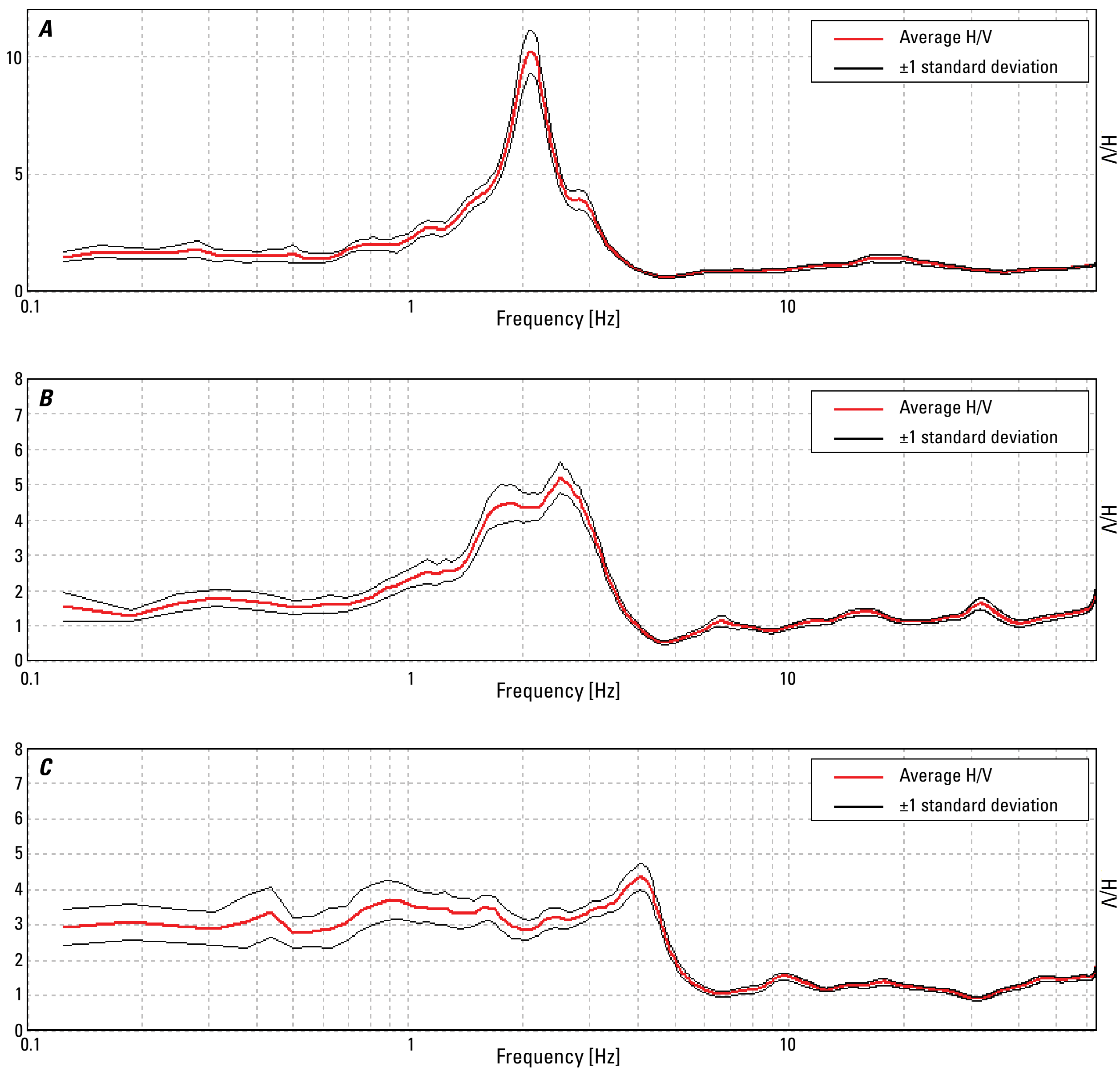
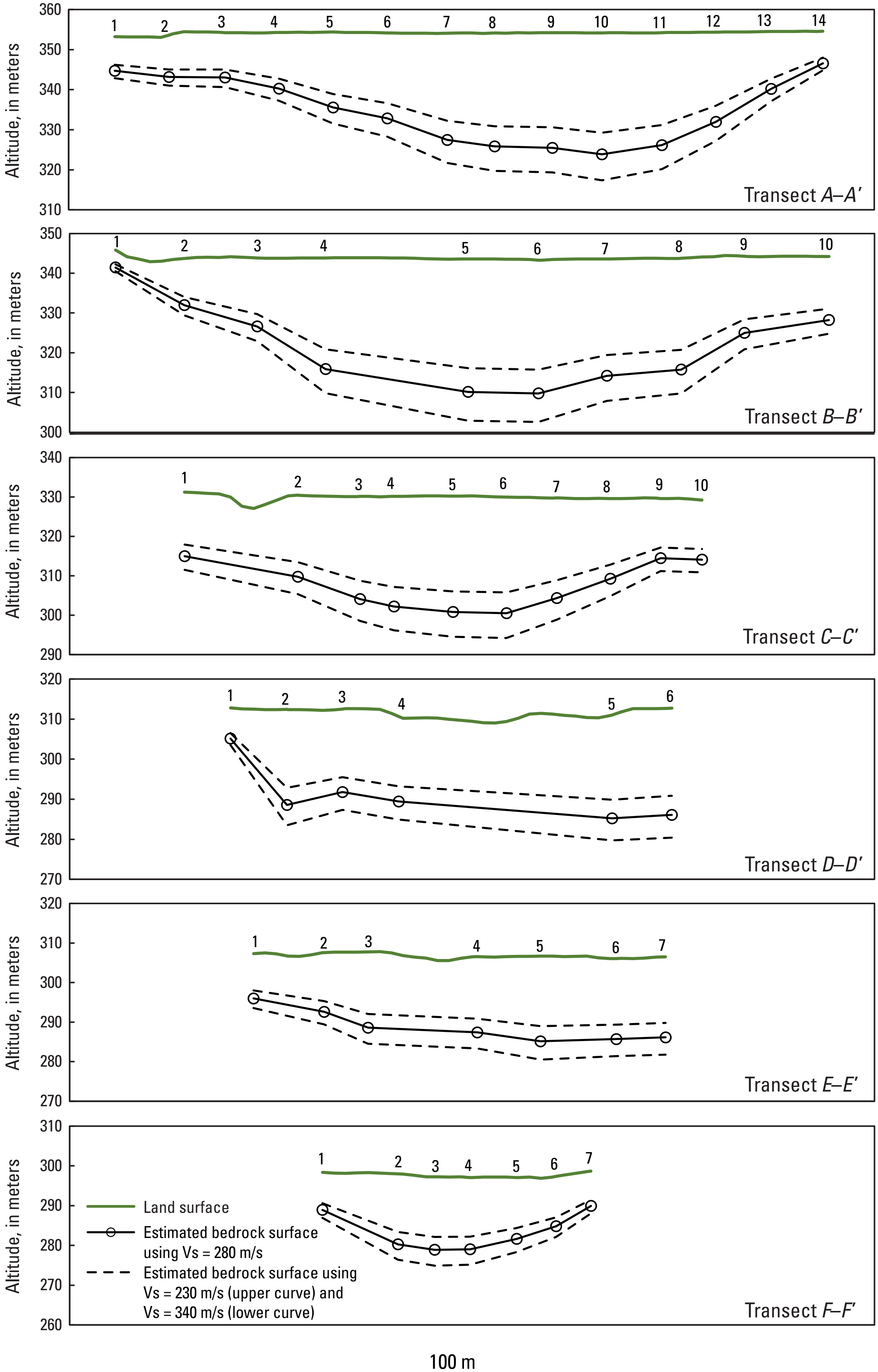


Figure 13. Example plots of the ratio of the horizontal (H) and vertical (V) amplitude spectrums, showing H/V peaks that identify the fundamental resonance frequency f_0. The plots show data from three points on transect *B–B′*: (*A*) Point 5, rated good. (*B*) Point 4, rated fair. (*C*) Point 3, rated poor. Red curves are the average H/V ratio and black curves are ± 1 standard deviation. Location of transect *B–B′* is shown in figure 3 and locations of points 3, 4, and 5 are shown in figure 14.

Figure 14. Cross sections showing altitude of bedrock surface estimated by the horizontal-to-vertical spectral ratio (HVSR) seismic method along transects in Bear Valley alluvium, Pinnacles National Park, California. Numbers indicate locations of points at which passive seismic data were collected. The point numbers correspond to point names in Tiedeman and Hsieh (2021). Transect locations are shown in figure 3.


Transect A–A′
Transect B–B′
Transect C–C′
Transect D–D′
Transect E–E′
Transect F–F′
Altitude, in meters
Land surface
Estimated bedrock surface using Vs = 280 m/s
Estimated bedrock surface using Vs = 230 m/s (upper curve) and Vs = 340 m/s (lower curve)
100 m

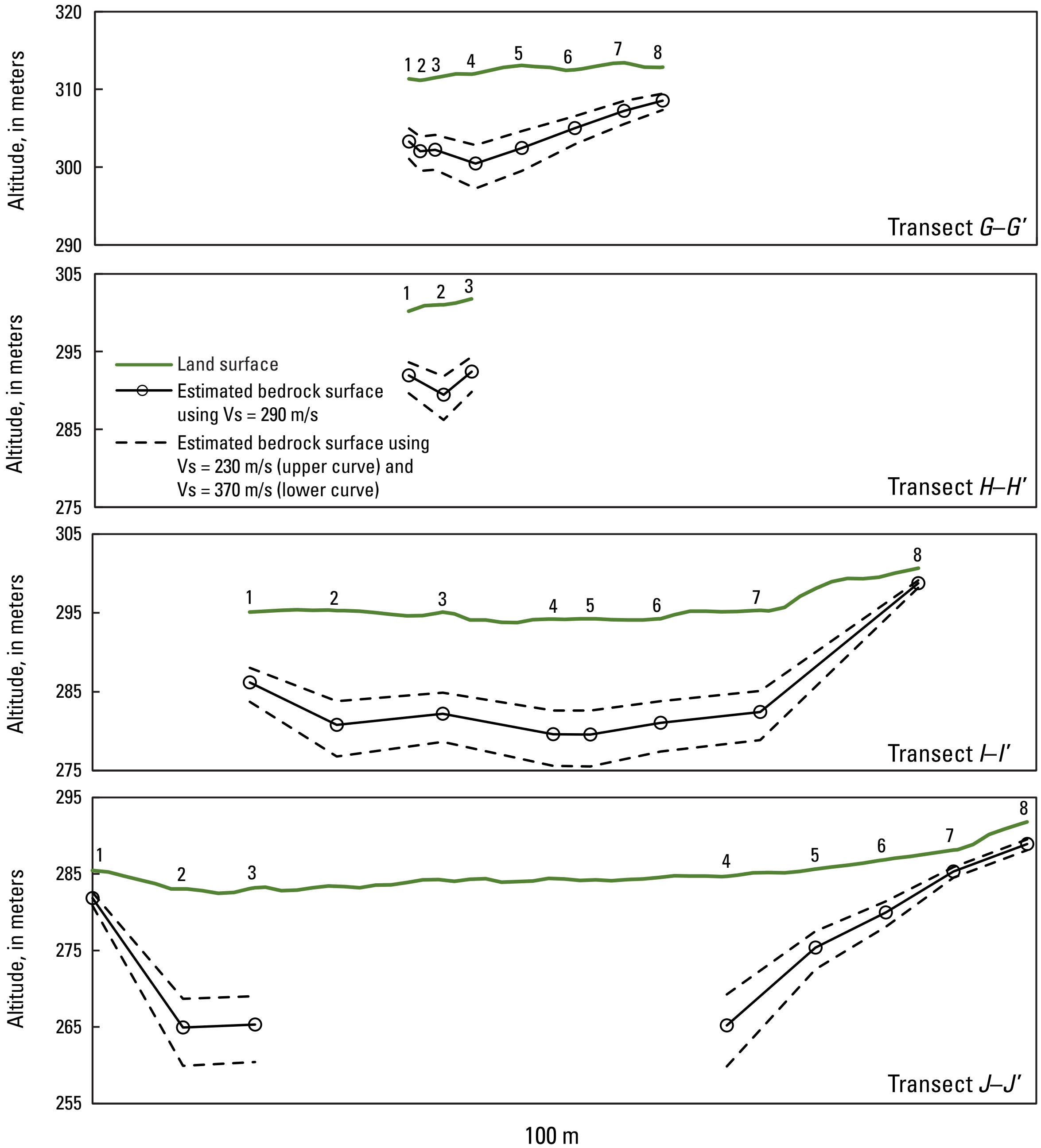


Figure 15. Cross sections showing altitude of bedrock surface estimated by the horizontal-to-vertical spectral ratio (HVSR) seismic method along transects in the Chalone Creek alluvium, Pinnacles National Park, California. Numbers indicate locations of points at which passive seismic data were collected. The point numbers correspond to point names in Tiedeman and Hsieh (2021). Transect locations are shown in figure 3. m, meters.

2019. In the first test, a Grundfos Redi-Flo2 pump was lowered into well CHA-2 to withdraw water at a constant rate. Water levels in wells CHA-2 and CHA-3 were measured manually using a Solinst 102M Mini Water Level Meter. In the second test, the pump was lowered into well CHA-3 to withdraw water at a constant rate and water levels were measured in wells CHA-2 and CHA-3. The duration of each test was 1 hour. In both tests, the pumped water was conveyed through a hose to approximately 50 m away from the pumped well and discharged onto the surface of the alluvium. The pumping rate was determined by measuring the time needed to fill a bucket to the 18.9 L (5 gal) mark.

Drawdown is the difference between the water-level altitude prior to pumping and the water-level altitude during pumping. In both tests, drawdown in the pumped well stabilized after approximately 10 minutes from the start of pumping. There was no drawdown in the unpumped well, which was 36 m from the pumped well.

Hydraulic conductivity of the Chalone Creek alluvium near wells CHA-2 and CHA-3 is computed according to the Thiem equation (Fetter, 1994; equation 4):

$$HC = \frac{Q}{2\pi sb} ln \frac{r_e}{r_w}, \quad (4)$$

where

HC = hydraulic conductivity,
Q = pumping rate,
s = stabilized drawdown,
b = length of the well screen,
r_w = well radius, and
r_e = effective radius of influence.

The Thiem equation was derived under the assumption that the pumped well is screened over the full thickness of a confined aquifer. As the conditions at wells CHA-2 and CHA-3 do not fully satisfy this assumption, the computed hydraulic conductivity should be considered an order-of-magnitude estimate rather than a high-precision result.

Values of Q, s, b, and r_w are given in table 3. The effective radius of influence (r_e) is defined as the radial distance from the pumped well beyond which there is no drawdown. The value of r_e is unknown, but its upper limit can be set at 36 m, which is the distance from the pumped well to the unpumped well, where there was no drawdown. As an alternative, a smaller value of 5 m was also assumed for r_e. As shown in table 3, decreasing the value of r_e from 36 m to 5 m decreases the calculated hydraulic conductivity by approximately 30 percent. The hydraulic conductivities of both wells are on the order of 10^{-3} m/s, which is consistent with representative values for gravel and coarse sand (Domenico and Schwartz, 1990).

Groundwater Levels

Groundwater levels in monitoring wells SC-1, SC-2, CHA-2, and CHA-3 were measured from April 2018 to February 2021 (figs. 16, 17). Discrete measurements were collected throughout the full period of record. Continuous measurements were collected in wells CHA-2 and CHA-3 starting in June 2018, and in wells SC-1 and SC-2 for selected time periods starting in December 2019. Discrete and continuous measurements were collected in wells SC-4, SC-5, and CHA-4 from late autumn 2019 to February 2021 (figs. 16, 17). All discrete measurements were collected using a Solinst 102M Mini Water Level Meter. Continuous measurements were collected at a frequency of 15 minutes in wells CHA-2, CHA-3, CHA-4, SC-4, and SC-5 using In-Situ Rugged

Table 3. Data for computing hydraulic conductivity from aquifer tests conducted in wells CHA-2 and CHA-3, Pinnacles National Park, California.

[L/min, liter per minute; m, meter; m/s, meter per second]

Pumped well	Pumping rate, Q (L/min)	Stabilized drawdown, s (m)	Length of well screen, b (m)	Well radius, r_w (m)	Effective radius of influence, r_e (m)	Hydraulic conductivity, HC (m/s)
CHA-2	27.0	0.064	2.8	0.0254	5	2.1×10^{-3}
					36	2.9×10^{-3}
CHA-3	25.8	0.125	4.1	0.0254	5	7.1×10^{-4}
					36	9.7×10^{-4}

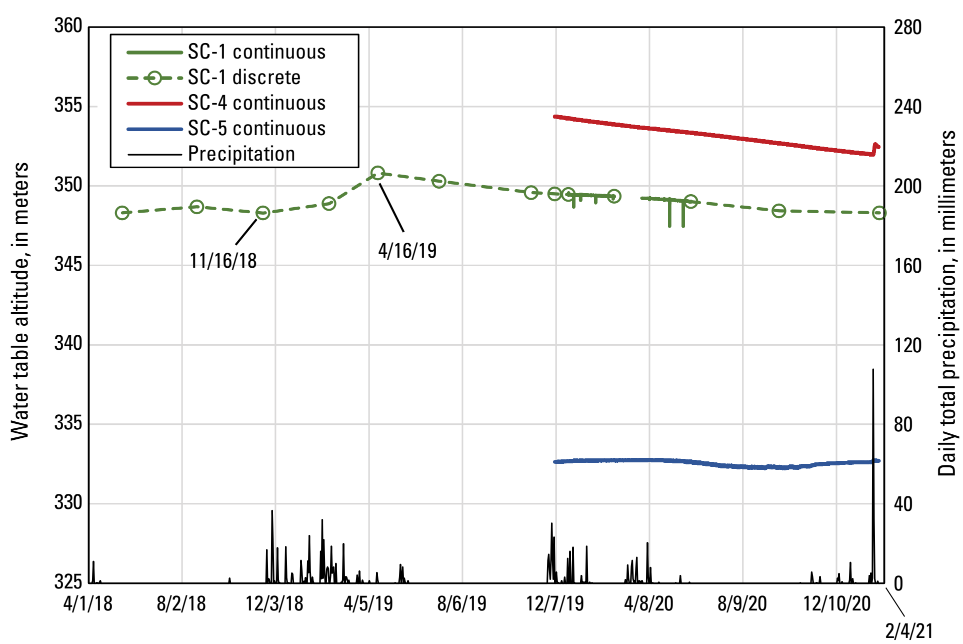


Figure 16. Hydrograph showing water-table altitudes in wells SC-1, SC-4, and SC-5 and daily total precipitation at the Pinnacles National Park weather station, California, April 1, 2018 to February 4, 2021. Discrete measurements not shown during periods of continuous measurement. The temporary downward spikes in the continuous data for well SC-1 reflect pumping to supply water for Pinnacles National Park horses.

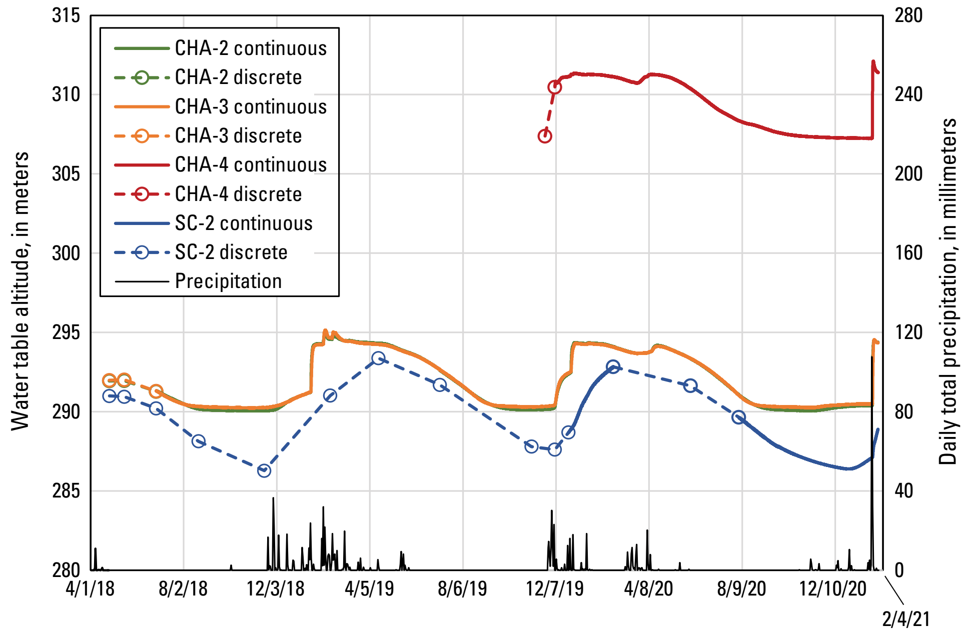


Figure 17. Hydrograph showing water-table altitudes in wells CHA-2, CHA-3, CHA-4 and SC-2, and daily total precipitation at the Pinnacles National Park weather station, California, April 1, 2018 to February 4, 2021. Discrete measurements not shown during periods of continuous measurement.

TROLL 100 instruments, which contain an absolute pressure transducer and a datalogger. Each Rugged TROLL 100 had a range of 9 m of water pressure. Barometric pressure was recorded at a 15-minute frequency using an In-Situ Baro TROLL suspended about 0.3 m below land surface in well CHA-2. Groundwater pressure data were processed to remove barometric effects and converted to altitudes. Continuous measurements were collected in wells SC-1 and SC-2 using vented pressure transducers (Process Measurement & Controls Inc. Miniature Submersible Depth / Level Transducer model MTM 3211) with 10.5 m water pressure range. These transducers were connected to a Campbell Scientific CR10x datalogger at land surface.

Bear Valley Alluvium

In the northern part of the Bear Valley alluvium study area, the water-level response to precipitation depends on the soil-moisture content above the water table as well as on the temporal distribution and intensity of precipitation events. At the end of the dry season, soil moisture is low. Therefore, infiltration from precipitation events during the early part of the wet season (late autumn) serves to increase the soil moisture, and little to no infiltration reaches the water table. Recharge to the groundwater system occurs only when soil moisture is raised to the level allowing infiltration to reach the water table. During the 2018–2019 wet season, discrete water-level measurements at well SC-1 show that the water table rose 2.5 m from November 16, 2018 to April 16, 2019 (fig. 16), indicating that there was sufficient precipitation to recharge the groundwater system. However, discrete measurements might miss periods of rapid rises and declines, so the response of the water table to individual precipitation events is unknown.

The continuous data at wells SC-1 and SC-4 during the 2019–2020 wet season provide a contrasting example, showing no rise in water levels during the wet season. Instead, water levels declined throughout the wet season. During and after rainy days, water levels showed no response to precipitation. The 2019–2020 wet season had less total precipitation (299 mm) than the 2018–2019 wet season (446 mm). In 2019–2020, it is likely that very little, if any, of the infiltration reached the water table. In well SC-5, the water levels do not decline as much as those in wells SC-1 and SC-4. Well SC-5 is adjacent to the perennial reach of Sandy Creek, which is sustained by groundwater discharge with occasional contributions from runoff. Because of the hydraulic connection with the nearby creek, water levels in well SC-5 have little temporal variation.

Another interesting example is provided by an extreme precipitation event that occurred in California from January 27–28, 2021, caused by an atmospheric river making landfall from the Pacific Ocean. The Pinnacles National Park weather station recorded 108 mm of precipitation on January 27, 2021, and 33 mm of rain on January 28, 2021. This precipitation led to a 0.6 m water-level rise in well SC-4 over 48 hours starting on January 28, 2021 (fig. 18*A*). This response indicates that infiltration from this event, and possibly from antecedent precipitation, raised the soil moisture to the point where recharge to the water table could occur. In well SC-5, water levels rose 0.1 m (fig. 18*B*) and the water-level rise began earlier than in well SC-4, perhaps driven by an increase in the stage of Sandy Creek along the deeply incised, adjacent perennial reach, resulting in the creek recharging the groundwater.

The seasonal water-level trends at well SC-2, near the confluence with Chalone Creek, were similar to those in Chalone Creek alluvium, rather than those observed in the northern part of Bear Valley alluvium (fig. 17). Discrete measurements indicate that the water table rose by as much as 7 m during the wet seasons. During and after the large rainfall event on January 28, 2021, water levels in well SC-2 rose about 1.5 m over 5 days (fig. 18*C*). The similarity of the trends in well SC-2 to those in wells CHA-2 and CHA-3 indicates that water levels at well SC-2 are strongly affected by the water levels in Chalone Creek alluvium.

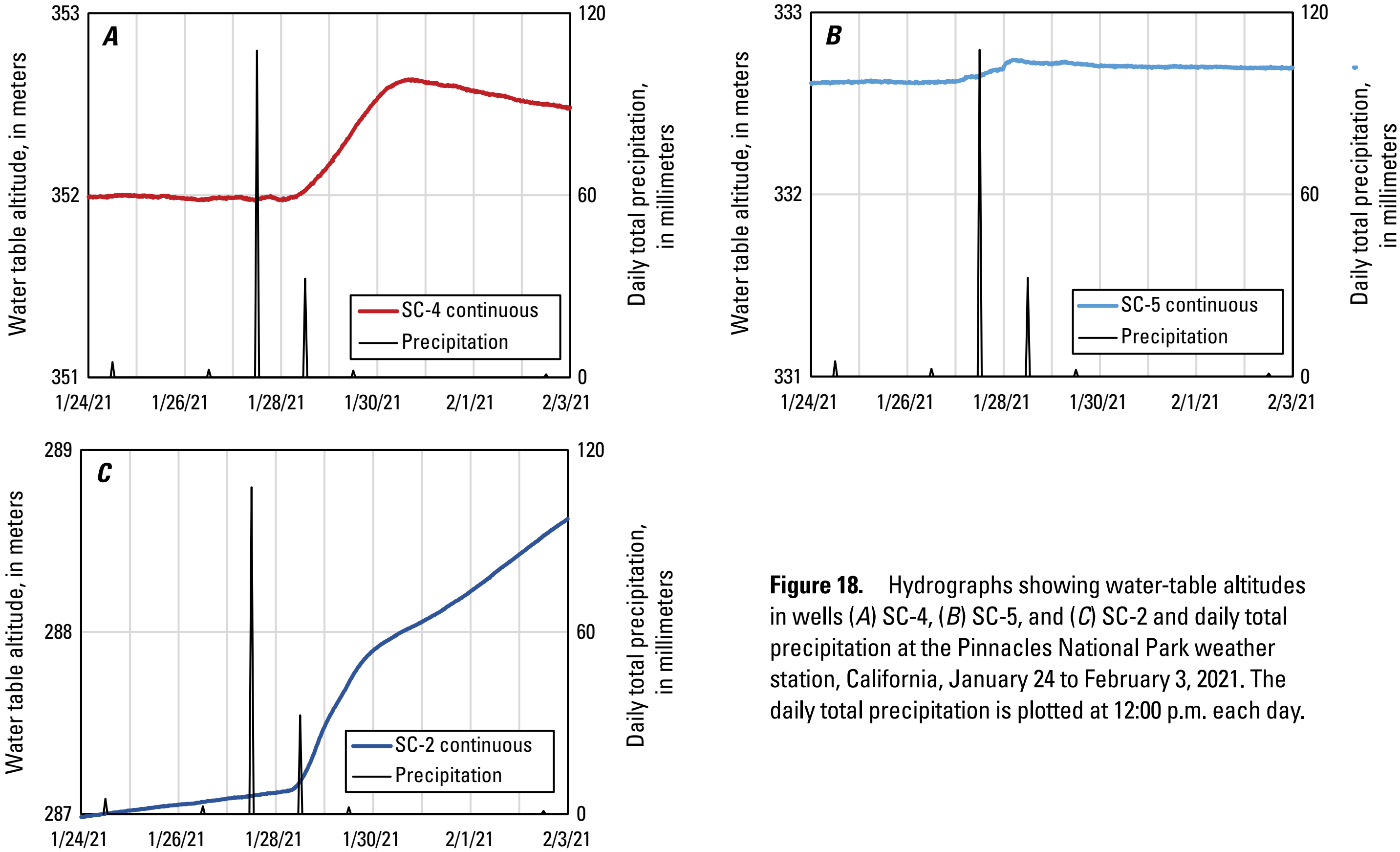


Figure 18. Hydrographs showing water-table altitudes in wells (*A*) SC-4, (*B*) SC-5, and (*C*) SC-2 and daily total precipitation at the Pinnacles National Park weather station, California, January 24 to February 3, 2021. The daily total precipitation is plotted at 12:00 p.m. each day.

Chalone Creek Alluvium

Groundwater levels in Chalone Creek alluvium exhibit greater seasonal variation than those in northern Bear Valley (fig. 17). They also respond more rapidly to recharge from precipitation and streamflow. Over the 2.5-year record of continuous data for wells CHA-2 and CHA-3, the water table rose by as much as 5 m during the wet seasons and then gradually declined through the dry seasons (fig. 17). The period of record for well CHA-4 is shorter, but similar water-table variations were observed. The groundwater altitude was often nearly identical in wells CHA-2 and CHA-3 (fig. 17) because the two wells are close to each other (fig. 2) and the alluvium has high hydraulic conductivity (table 3). However, during the wet season, there were small differences in the water table at these two wells that provide insight about groundwater responses to precipitation and creek flow.

During the 2018–2019 wet season, the water table gradually increased by about 1 m in wells CHA-2 and CHA-3 from November 2018 through mid-January 2019 (figs. 17, 19), likely owing to recharge from precipitation and increased groundwater flow from upgradient. An abrupt change in water levels began at 12:30 a.m. on January 17, 2019, with a rapid water-level rise of 2.9 m in well CHA-2 over 72 hours (fig. 19). This rise is attributed to rapid infiltration of Chalone Creek streamflow causing focused recharge. Data from a stream intermittency sensor 850 m downstream of well CHA-2 corroborate this conclusion, showing that Chalone Creek began to flow on January 15, 2019 (time unknown) (Michael Bogan, University of Arizona, written commun., 2019). Therefore, the onset of surface-water flow was from 24 to 48 hours prior to the start of the abrupt water-level rise in the wells. This lag time likely represents the transit time of water through the unsaturated zone. Another corroborating factor is that the water-level rise in well CHA-3, farther from the creek, lagged that in well CHA-2 (fig. 19, inset).

Following the large rise in mid-January 2019, water levels in wells CHA-2 and CHA-3 remained high throughout the wet season (fig. 19), likely because Chalone Creek was continuously flowing. Additional significant water-level rises began on February 2 and February 14, 2019, with greater rises in well CHA-3 than in well CHA-2. Well CHA-3 is close to the hillslope, and the larger rise there indicates that runoff and shallow flow down the hillslope contributed to enhanced groundwater recharge. During February 2019, water levels in well CHA-3 remained higher than in well CHA-2, indicating a groundwater-flow component toward the creek and groundwater discharge into the creek.

Starting in early March 2019, water levels in well CHA-2 were slightly higher than those in well CHA-3, indicating a reversal in the groundwater-stream interaction, with Chalone Creek again recharging the aquifer. This is supported by a stream stage measurement on April 16, 2019, showing that the stage was higher than the water levels in wells CHA-2 and CHA-3 (fig. 19). Groundwater levels declined slowly in both wells until late April 2019, when the slope of the water-level decline steepened, likely because of cessation of creek flow, and the water-table altitudes in wells CHA-2 and CHA-3 soon became identical (figs. 17, 19).

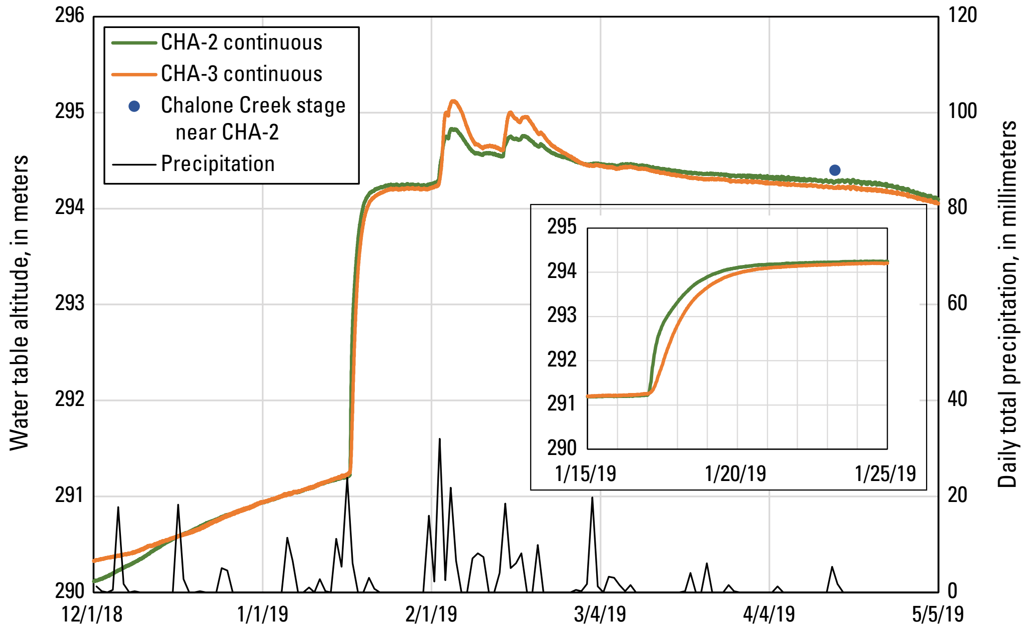


Figure 19. Hydrographs showing water-table altitude in wells CHA-2 and CHA-3 and daily precipitation at the Pinnacles National Park weather station, California, December 1, 2018 to May 5, 2019, and approximate Chalone Creek stage on April 16, 2019.

During December 2019, two distinct water-level rises occurred in wells CHA-2 and CHA-3 (fig. 20). Water levels rose 2.2 m from December 4 to December 26, 2019, then rose 1.8 m from December 26 to December 31, 2019. The first rise was likely caused by recharge from precipitation and groundwater flow from upgradient. Visual observations showed that Chalone Creek was not flowing near well CHA-2 on December 5 or December 23, 2019, but was flowing near well CHA-4. Furthermore, water levels in well CHA-4 rose 3.1 m (fig. 17) from November 22, and December 5, 2019, indicating that this part of the alluvium was recharged by the creek earlier than near well CHA-2. The second water-level rise in wells CHA-2 and CHA-3, during December 2019, was steeper than the first, and the rise in well CHA-3 lags that in well CHA-2 (fig. 20). These rises are attributed to rapid infiltration of creek water.

Through late January 2021, water levels in Chalone Creek alluvium had rebounded very little from the previous dry season, prior to the atmospheric river event that produced 108 mm of precipitation on January 27, 2021 (fig. 17). In response to this large precipitation event, water levels in well CHA-4 rose nearly 5 m in 24 hours, and water levels in wells CHA-2 and CHA-3 rose 4 m in 48 hours (fig. 21*A*, *B*). These rises are attributed predominantly to infiltration of creek water. The rise in well CHA-4 occurred more rapidly than those in wells CHA-2 and CHA-3, likely because the aquifer volume is smaller near well CHA-4, where the alluvial channel deposits are narrower and thinner (fig. 15).

During each summer of this study, the water-table altitude in wells CHA-2 and CHA-3 declined to about 290 m and remained at nearly that level for 2 to 3 months, until the wet season began and water levels started to rise (fig. 17). This seasonally

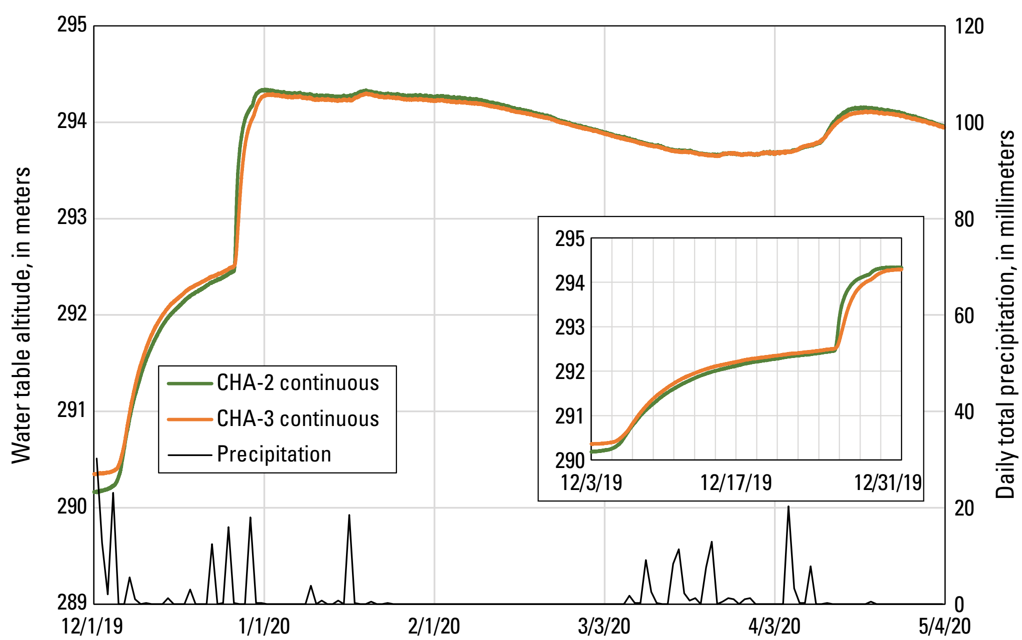


Figure 20. Hydrograph showing water-table altitude in wells CHA-2 and CHA-3 and daily total precipitation at the Pinnacles National Park weather station, California, December 1, 2019 to May 4, 2020.

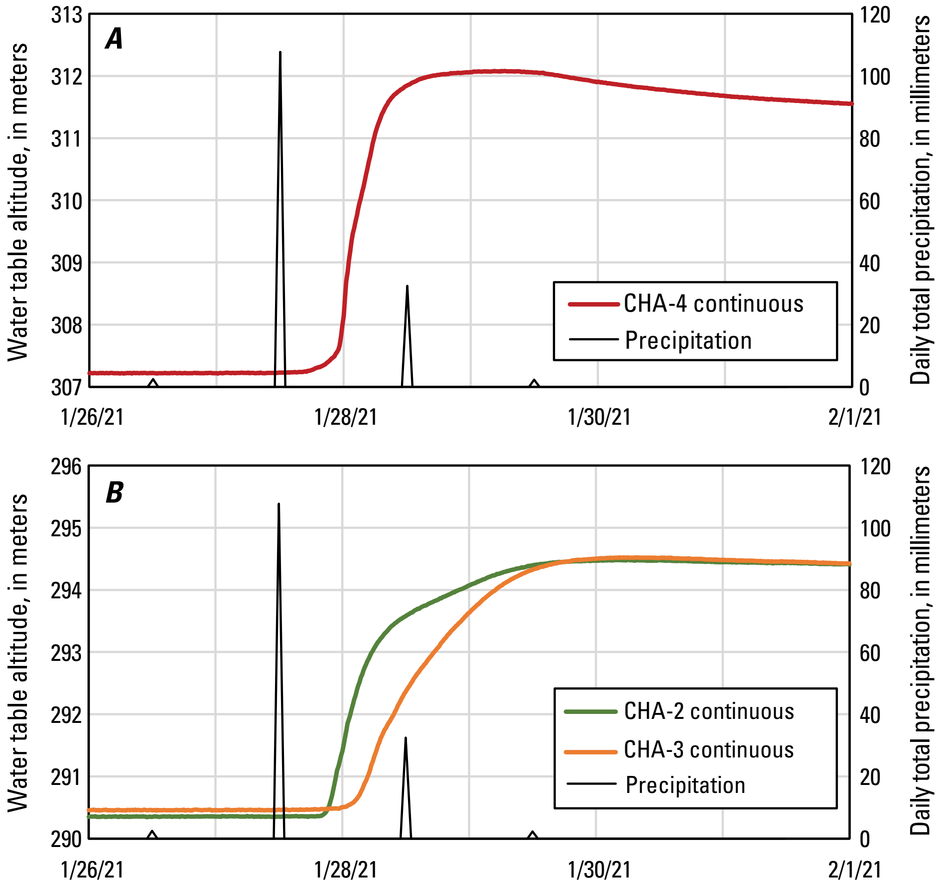


Figure 21. Hydrograph showing water-table altitude in wells (*A*) CHA-4 and (*B*) CHA-2 and CHA-3 and daily total precipitation at the Pinnacles National Park weather station, California, January 26 to February 1, 2021. Daily total precipitation is plotted at 12:00 p.m. each day.

stable water table at both wells suggests the presence of a low-permeability layer at about an altitude of 290 m. A landfill existed near wells CHA-2 and CHA-3 prior to the NPS acquiring the land; it was removed around 2001 and the void was filled with alluvium. The low-permeability layer may be associated with the former landfill; for example, it could be a clay liner that was not completely removed or a compressed soil layer below the depth of removed material. Groundwater does not readily drain from this layer, so water levels remain relatively constant. The difference in summer water-table altitude between wells CHA-2 and CHA-3 (fig. 22) indicates the top of the low-permeability layer is about 0.2 m lower in well CHA-2 than in well CHA-3.

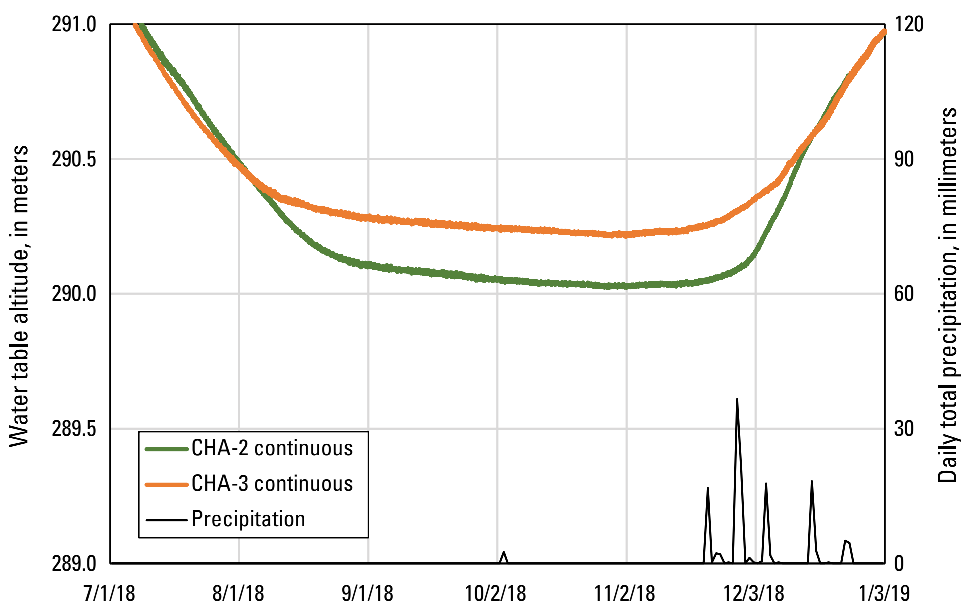


Figure 22. Hydrograph showing water-table altitude in wells CHA-2 and CHA-3 and daily total precipitation at the Pinnacles National Park weather station, California, July 1, 2018 to January 3, 2019.

Groundwater Flow

In both alluvium study areas, groundwater flows in a southerly direction, following the creek drainages. As shown in the previous section, over an annual cycle water levels in the Bear Valley and Chalone Creek alluvium generally rise during the wet season (late autumn to early spring) and decline during the dry season. However, this general pattern does not occur regularly every year, particularly in Bear Valley. During the period of this study, water levels rose and declined several meters in the Chalone Creek alluvium and the southern part of Bear Valley whereas smaller water-level changes occurred in northern Bear Valley.

The rise and decline of the water table are controlled by inflow into and outflow from the groundwater system. For both alluvium study areas, inflow to the system includes recharge from precipitation infiltrating into the ground and reaching the water table, recharge from streamflow entering the study area or generated by runoff in the study area, groundwater entering the study area from alluvium upstream of the study area or in tributary canyons, and groundwater entering the alluvium from surrounding bedrock (fig. 23). Outflow includes groundwater flow exiting the study area, groundwater consumption (evapotranspiration) by vegetation along the creek channel, intermittent pumping (in Bear Valley alluvium only), and groundwater discharge to surface-water flow that exits the study area. During periods when inflow is greater than outflow, the water table rises. Conversely, when inflow is less than outflow, the water table declines. The data collected during this study are insufficient for identifying the contribution of individual inflow and outflow components to changes in water levels, with the exception of creek recharge in Chalone Creek alluvium.

Groundwater flow to and from perennial reaches of Sandy and Chalone Creeks is an internal exchange and does not contribute to inflow to or outflow from the study areas. At the upstream portion of a perennial reach, groundwater discharges into the creek channel to become surface flow. Conversely, at the downstream portion of a perennial reach, surface flow in the creek infiltrates into the ground to become groundwater. From a groundwater perspective, surface flow in a perennial creek reach can be considered as the surface manifestation of groundwater flow. During the wet season, runoff also can contribute to surface-water flow in perennial reaches.

The interaction of groundwater and surface water is an important process in the alluvial flow systems of both Bear Valley and the Chalone Creek watershed. In Bear Valley, the primary interaction occurs over the perennial reach of Sandy Creek, which was observed to be greater than 1 km in length, extending from slightly north of well SC-5 to slightly south of the confluence with the creek draining McCabe Canyon. To the north and south of this perennial reach, the Sandy Creek stream channel is usually dry, and surface-water flow does not occur frequently. The data collected during this study suggest that there is little interaction between groundwater and surface water in the intermittent reaches of Sandy Creek.

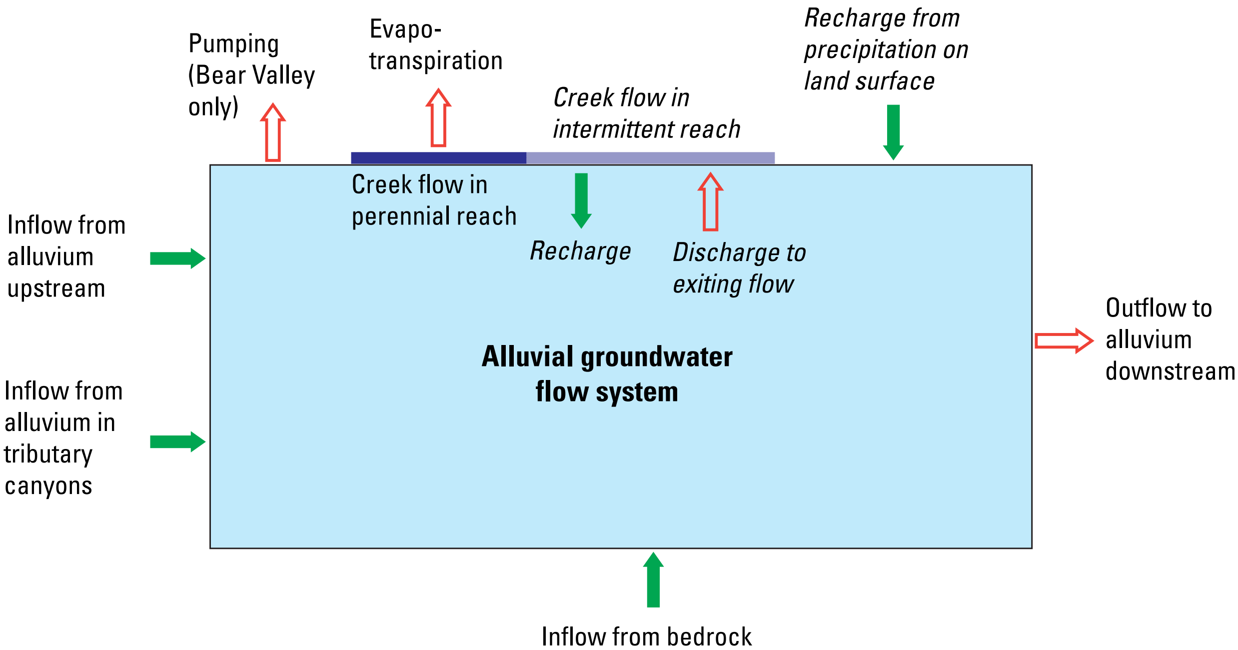


Figure 23. Diagram showing groundwater inflows to (solid green arrows) and outflows from (open red arrows) the alluvium study areas. Flows in italics occur only during the wet season. Recharge from intermittent creek reaches is considered an inflow only if the creek flow entered from upstream of the study area or was generated as runoff within the study area. Recharge of creek water that originated as groundwater discharge to the creek within the study area is not considered an inflow.

By contrast, in the Chalone Creek alluvium, recharge of runoff-generated surface-water flow in intermittent stream reaches is a major component of the interaction between groundwater and surface water. Because of its greater relief, the Chalone Creek watershed generates larger, more frequent streamflow in the wet season compared to Bear Valley. This flow can rapidly infiltrate into the unsaturated zone owing to the permeable sediments. The water-level data show that rapid recharge begins shortly after the onset of creek flow in intermittent reaches, with creek water filling up the unsaturated zone. This filling continues over approximately 1 to 3 days, until groundwater levels in the alluvium are near the level of the creek, at which time the saturated groundwater flow system is hydraulically connected with the surface-water flow. Afterwards, the creek tends to continually recharge the groundwater system during wet-season periods when precipitation is minor or absent. When large precipitation events occur, groundwater levels can rise above the creek level, causing groundwater discharge to the creek. At the end of the wet season, when the creek becomes dry, groundwater gradually drains from the alluvium, and water levels decline.

Near the confluence of Bear Valley and Chalone Creek, groundwater flow in the southern part of the Bear Valley alluvium is strongly controlled by groundwater conditions in the Chalone Creek alluvium. The similar trends in water levels in wells SC-2, CHA-2, and CHA-3 (fig. 17) indicate that the substantial seasonal water-level changes in Chalone Creek alluvium strongly influence water levels at the southern end of Bear Valley, where well SC-2 is located. The rise of Chalone Creek alluvium groundwater levels during the wet season reduces outflow of groundwater from southern Bear Valley, causing water levels in southern Bear Valley to also rise. Conversely, the decline of Chalone Creek groundwater levels during the dry season increases groundwater outflow from southern Bear Valley, causing its water table to decline. Water-level declines in the dry season are greater in well SC-2 than in wells CHA-2 and CHA-3 (fig. 17). This is likely because the low-permeability layer stabilizing water levels at wells CHA-2 and CHA-3 is a local feature. Downgradient of this location, the water table in Chalone Creek alluvium likely declines by a greater amount during the dry season than at wells CHA-2 and CHA-3.

Summary

At Pinnacles National Park, groundwater is the sole source of water supply for staff and visitors and is an important water source for plants and animals where groundwater discharges to perennial springs and stream reaches. The cooperative study between the National Park Service (NPS) and the U.S. Geological Survey (USGS) that is described in this report was designed to improve understanding of the groundwater quality and the hydrogeology in parts of Pinnacles National Park. The water-quality investigation assessed the geochemistry of springs, wells, surface water, and precipitation as well as analyzed the geochemistry of rock formations that affect the water chemistry through water-rock interaction. The hydrogeology investigation focused on collecting and interpreting field data to gain an understanding of groundwater flow processes in the alluvial deposits of Bear Valley and the Chalone Creek watershed.

Groundwater quality in the park is generally good, with neutral pH and low-to-moderate hardness levels and specific conductance in most of the perennial springs and wells. Concentrations in most of the environmental and water-supply samples are less than the limits for U.S. Environmental Protection Agency (EPA) contaminants of concern in drinking water. The exception is Chaparral well 1, where the untreated supply water exceeds the EPA limits for arsenic and uranium. Contaminants in the park are likely geogenic in nature, and there is little anthropogenic contamination of either water supplies or perennial springs. Precipitation may contribute significant percentages of soluble cations as dust/particulates.

The groundwater within the fracture system of the Pinnacles Volcanics and in the sedimentary formations is inferred to be quite old, and experiences little seasonal variation. These waters likely move quite slowly, based on low apparent discharge rates and lack of seasonal change in discharge rates and groundwater chemistry. This is likely due to low recharge rates and poor connectivity between the fractures within the Pinnacles Volcanics and the structural/stratigraphic boundary in the sedimentary rocks to the east of the Chalone Creek Fault. These old groundwaters appear to have reached a steady state with respect to their geochemistry, based on Sr and Sr isotope values.

The Bear Valley alluvium and Chalone Creek alluvium were characterized by collecting field data to estimate alluvium thickness and hydraulic conductivity. To estimate thickness, passive seismic data were collected along transects across the Bear Valley and Chalone Creek. These data were analyzed with the horizontal-to-vertical spectral ratio seismic method, which allows estimating the depth to bedrock, equivalent to alluvium thickness. The Bear Valley alluvium is thickest in the north. At the deepest point on a northern transect, the alluvium thickness estimate is 28–41 m (range accounts for uncertainty) and at the deepest point on a southern transect, the thickness estimate is 15–22 m. The Chalone Creek alluvium thickness tends to increase from north to south. At the deepest points on transects, the alluvium is estimated to be 9–15 m thick in the north and 15–25 m thick in the south.

Two aquifer tests were conducted in the Chalone Creek alluvium using wells CHA-2 and CHA-3. Analyses of these tests with the Thiem equation yielded an estimated hydraulic conductivity on the order of 10^{-3} meters per second, consistent with expected values for gravel and coarse sand.

Groundwater levels were monitored by collecting discrete and continuous data at four monitoring wells in Bear Valley alluvium and three monitoring wells in the Chalone Creek alluvium. The water table was generally at shallow depths—from 0 to 10 m below land surface. Over an annual cycle,

water levels typically rose during the wet season in the winter and early spring and declined during the dry season. However, this general pattern does not occur every year. Water-level variations were substantially different in northern Bear Valley than in southern Bear Valley and the Chalone Creek alluvium. In northern Bear Valley, water levels rose 2.5 m during the 2018–2019 wet season, did not rise during the 2019–2020 wet season, and rose abruptly by 0.6 m after a single intense storm during January 2021. In southern Bear Valley and the Chalone Creek alluvium, water levels changed by about 5 to 7 m over an annual cycle. During the wet season, rapid water-level rises occurred in response to some precipitation events and to the onset of flow in intermittent reaches of Chalone Creek. Following the wet season, water levels gradually declined throughout the dry season.

In both study areas, groundwater flows in a southerly direction, following the creek drainages. The rise and decline of the water table are controlled by inflow to and outflow from the groundwater system. For both alluvium study areas, inflows include recharge from precipitation infiltrating into the ground and reaching the water table, recharge from streamflow that does not originate as groundwater in the study area, and groundwater entering from alluvium or bedrock outside of the study area. Outflows include groundwater exiting the study area, groundwater discharge to surface water that exits the study area, evapotranspiration, and pumping (Bear Valley only). Groundwater flow to and from perennial creek reaches is an internal exchange and does not contribute to inflow to or outflow from the study area. Groundwater levels rise when total inflows exceed total outflows and decline when outflows exceed inflows. The data collected during this study are insufficient for identifying the contribution of individual inflow and outflow components to changes in water levels, excluding creek recharge in Chalone Creek alluvium.

The interaction of groundwater and surface water is an important process in the alluvial flow systems of Bear Valley and the Chalone Creek watershed. In Bear Valley, the primary interaction occurs along the perennial reach of Sandy Creek. Groundwater discharges to the upstream portion of the creek, becomes surface water, is partly consumed by evapotranspiration, and recharges groundwater farther downstream. In the Chalone Creek alluvium, recharge of runoff-generated surface-water flow in intermittent stream reaches is a major component of the interaction between groundwater and surface water. Shortly after the onset of significant creek flow in these reaches, creek water rapidly recharges the groundwater system until groundwater levels are close to the level of the creek. The creek then slowly recharges the groundwater system when precipitation is minor or absent, and groundwater discharges to the creek when water levels rise above creek level owing to large precipitation events. At the end of the wet season the creek becomes dry, and groundwater gradually drains from the alluvium by flowing downgradient.

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Appendixes

Appendix 1. Photographs of Selected Springs

All photographs, Kathleen Scheiderich, U.S. Geological Survey. Date of photographs is included in figure captions.

Figure 1.1. Hidden Spring, before removal of colluvium (September 28, 2016).

Figure 1.3. Superintendent's Spring (September 29, 2016).

Figure 1.2. McCabe Canyon Spring (September 28, 2016).

Figure 1.4. Balconies Cave pool (September 30, 2016).

Appendix 2. Constituents of Concern in Wells, Springs, and Surface Water

Table 2.1. Maximum measured value for constituents of concern (as given in table 2 of the main text) at each location, Pinnacles National Park, California.

[Complete geochemistry data are available in Scheiderich (2021). Location of wells are shown in figure 2. U.S. Geological Survey (USGS) site IDs are used in the USGS NWIS database (U.S. Geological Survey, 2021, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN). bdl, below detection level; ng/L, nanogram per liter; mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemens per centimeter at 25°C.]

Constituent	USGS site ID	NO_3 (mg/L as N)	NO_2 (mg/L as N)	Ba (mg/L)	U (µg/L)	Cu (mg/L)	Pb (mg/L)	As (µg/L)	B (µg/L)	Fe (mg/L)	Mn (mg/L)	Al (mg/L)	Li (µg/L)	La (ng/L)	SO4 (mg/L)	Zn (mg/L)	Cl (mg/L)	Specific Conductance (µS/cm)
								Wells										
West Entrance	362841121134201	0.33	0.011	0.094	0.90	0.003	0.00004	3.7	51	0.41	0.01	0.001	31	3.5	120	0.008	170	1,130
Chaparral well 1	362931121123301	0.04	0.001	0.004	85.4[1]	0.005	0.00006	23[1]	21	0.26	0.01	0.001	230	1.6	8.6	0.15	27	480
SC-3	362943121084201	0.04	0.001	0.012	0.01	bdl	0.00018	0.55	38	0.82	0.10	0.001	23	0.9	41	0.004	19	260
SC-2	362851121092201	0.29	0.016	0.006	0.30	0.005	0.00003	0.99	430	0.17	1.32	0.001	51	0.4	200	0.013	140	1,210
McCabe Canyon	362937121090301	0.04	0.001	0.044	0.01	bdl	bdl	0.28	54	1.12	0.07	0.002	31	0.7	32	0.002	23	240
CHA-1	362857121093601	0.05	0.001	0.027	0.02	0.002	bdl	0.89	290	0.93	0.15	0.001	58	0.5	30	0.009	80	580
CHA-2	362853121094601	0.10	0.002	0.017	8.9	0.001	bdl	5.3	54	0.06	0.01	0.027	51	43	17	0.006	42	390
CHA-3	362854121094501	0.22	0.001	0.021	3.4	0.001	0.00009	4.8	57	0.07	1.04	0.039	48	46	18	0.003	42	380
								Springs										
Oak Tree	362920121122001	1.1	0.001	bdl	22.4[1]	0.001	bdl	19[1]	21	0.14	bdl	0.001	120	0.8	4.9	0.003	22	360
Willow	363000121120501	0.04	0.001	0.007	0.12	0.002	0.00004	6.1	35	0.15	0.03	0.051	30	74	48	0.002	21	310
Balconies Cave	363000121120501	0.65	0.002	0.034	5.95	0.002	bdl	8.1[1]	31	0.16	bdl	0.006	58	7.3	43	0.003	70	550
Chalone Bridge	362912121101101	0.04	0.001	0.006	29.6[1]	0.004	0.00004	4.8	68	0.09	0.41	0.011	200	2.7	36	0.002	27	550
Superintendent's	362856121103801	1.5	0.011	0.009	10.7	0.001	0.00006	7.1	41	0.10	0.13	0.020	86	9	4.4	0.002	23	370
McCabe Canyon	362944121090801	3.3	0.015	0.003	0.85	bdl	bdl	3.6	23	0.04	0.07	0.002	7.4	2.1	7.9	0.002	18	170
Hidden Canyon	362922121092301	bdl	bdl	0.003	0.01	0.001	0.00003	22[1]	29	0.23	0.12	0.010	54	5.9	45	0.008	28	260
Campground Seep	362932121084702	0.08	0.004	0.019	0.12	0.003	bdl	4.5	220	0.14	0.23	0.016	53	18	170	0.018	41	640
Fern Chamber	362832121111201	0.10	0.002	0.006	0.19	0.001	0.00005	8.9[1]	25	0.07	bdl	0.008	100	15	4.9	0.003	39	290
Moses	362830121111201	0.95	0.001	0.005	1.75	0.001	bdl	11[1]	26	0.05	bdl	0.002	97	2.0	7.7	0.002	35	280
Split Rock	362840121110801	0.87	0.001	0.005	3.0	0.005	0.00016	16[1]	28	0.07	bdl	0.003	89	2.9	5.6	0.005	30	300
								Surface Water										
Bear Gulch Res.	362822121111501	0.04	0.001	0.010	0.21	bdl	0.00003	1.5	37	0.14	0.03	0.023	15	58	2.3	0.004	32	200
Sandy Creek at Campground	362932121084701	0.50	0.006	0.042	2.82	0.004	bdl	7.2	210	0.28	0.14	0.003	53	3.5	190	0.004	120	1,150

[1]Uranium (U) and arsenic (As) values approach or exceed the MCL for U and As in drinking water

Appendix 3. Seismic Velocities

Compressional-Wave and Shear-Wave Velocities for Assessing Viability of Horizontal-to-Vertical Spectral Ratio Method

Results of a seismic refraction survey conducted along a transect across Chalone Creek near the Peaks View parking area (Conwell & Associates, 1993) were used to assess whether a sufficiently strong contrast in acoustic impedance exists for the horizontal-to-vertical spectral ratio (HVSR) method to be viable in the Chalone Creek alluvium. The survey estimated the location of the fault contact between rhyolite to the west and fanglomerate to the east (fig. 4), as well as the alluvium–rock contact, using contrasts in compressional wave seismic velocities (*Vp*) for the different geologic units. Estimates of *Vp* are shown in table 3.1. Shear wave seismic velocity (*Vs*) can be calculated from *Vp* by using *Vp*/*Vs* ratios reported in other studies (Castagna and others, 1985; Brocher, 2005; Al-Tahini and others, 2007; Brocher, 2008; Zhang and others, 2014). Using the *Vp* estimates and reported ranges of *Vp/Vs* for each geologic unit yielded estimated ranges of *Vs* (table 3.1). Using these ranges, the minimum contrast in *Vs* between the alluvium and fanglomerate is 2.7 and that between the alluvium and rhyolite is 3.9. Because the density of rock is greater than that of alluvium, the acoustic impedance contrasts will be somewhat larger than the *Vs* contrasts.

For the Bear Valley alluvium, Gibbs and Fumal (1994) estimated *Vs* for alluvial sediments in a borehole at Webb Ranch about 1.6 kilometers north of the Pinnacles National Park east entrance (table 3.1). Bear Valley sediments are underlain by fanglomerate. Using the *Vs* ranges for these geologic units, the estimated minimum contrast in *Vs* between the alluvium and bedrock is 3.5.

Shear-Wave Velocities for Estimating Alluvium Thickness

For calculating Z from f_0 measured along the transects, it is preferable to use *Vs* estimates from measurements in the Pinnacles alluvial deposits, rather than from calculations using *Vp* and *Vp*/*Vs* as was done for assessing acoustic impedance contrasts. *Vs* can be calculated using equation 3 by acquiring ambient seismic data and determining f_0—the frequency at which a prominent peak occurs—at locations of boreholes with known depth to bedrock (*Z*). In Bear Valley, well SC-3 is the only well drilled into bedrock. The well log indicates sand from 0 to 9.1 meters (m) depth, decomposed granite from 9.1 to 33.5 m, and granite and cemented sand below 33.5 m (table 1). Applying the HVSR method at this well yielded a strong peak with f_0 = 3.5 Hz. Assuming that the sand and decomposed granite have a large acoustic impedance contrast yields *Vs* = 130 m/s; assuming instead that the decomposed granite and granite have a large contrast yields *Vs* = 470 m/s. Both these values are outside of the expected range for fine- to medium-grained Bear Valley alluvium (table 3.2). At wells SC-2 and SC-4, bedrock was not encountered, but drilling penetrated clay that is possibly weathered rock, indicating proximity to the bedrock surface. *Vs* was calculated at these two wells by assuming that the drilled depth equals the alluvium thickness, yielding values in the expected range (table 3.2). The minimum, maximum, and average *Vs* (table 3.2) from the set of values at Webb Ranch (Gibbs and Fumal, 1994), wells SC-2 and SC-4 were used to estimate a range of thicknesses along the transects in the Bear Valley watershed.

In the Chalone Creek alluvium, the HVSR method was applied at well CHA-4, the Stone Boundary well, and Old

Table 3.1. Seismic velocity data for assessing shear wave velocity contrast between alluvium and bedrock, Pinnacles National Park, California.

[m/s, meters per second; *Vs*, shear wave velocity; *Vp*, compressional wave velocity]

Seismic velocity (m/s)	Geologic unit	Source
	Vp	
300–430	Chalone Creek alluvium	Pinnacles seismic refraction survey (Conwell & Associates, 1993)
2,280	Fanglomerate	Pinnacles seismic refraction survey (Conwell & Associates, 1993)
2,740	Rhyolite	Pinnacles seismic refraction survey (Conwell & Associates, 1993)
	Vp/Vs	
1.4–3.0	Coarse-grained Holocene alluvium	Brocher (2008), San Francisco Bay area field data
1.5–1.7	Cemented sandstone	Al-Tahini and others (2007)
1.5–1.9	Sandstone	Castagna and others (1985)
2.8	Fanglomerate	Brocher (2005), empirical equation for felsic rocks
1.5–2.0	Rhyolite-dominated volcanic rocks	Zhang and others (2014)
2.3	Rhyolite	Brocher (2005), empirical equation for felsic rocks
	Vs	
230	Bear Valley alluvium	Gibbs and Fumal (1994), Webb Ranch site, thickness-weighted average
100–300	Chalone Creek alluvium	Calculated from *Vp* and *Vp*/*Vs* in this table
810–1,570	Fanglomerate	Calculated from *Vp* and *Vp*/*Vs* in this table
1,190–1,890	Rhyolite	Calculated from *Vp* and *Vp*/*Vs* in this table

Table 3.2. Data for determining and evaluating shear wave seismic velocities (*Vs*) to use in estimating alluvium thickness along transects, Pinnacles National Park, California.

Value type	Shear wave seismic velocity (*Vs*) (m/s)	Source
Values for geologic units		
Bear Valley alluvium	230	Gibbs and Fumal (1994), Webb Ranch site, thickness-weighted average
Fine- and medium-grained alluvium	190–320	Brocher (2008), San Francisco Bay area field data
Course-grained Holocene alluvium	250–730	Brocher (2008), San Francisco Bay area field data
Values for wells		
SC-3	130 or 470	Calculated using equation 3 and data in Tiedeman and Hsieh (2021)
SC-2	340	Calculated using equation 3 and data in Tiedeman and Hsieh (2021)
SC-4	280	Calculated using equation 3 and data in Tiedeman and Hsieh (2021)
CHA-4	370	Calculated using equation 3 and data in Tiedeman and Hsieh (2021)
Stone Boundary well	280	Calculated using equation 3 and data in Tiedeman and Hsieh (2021)
Old Chalone Creek well #2	230	Calculated using equation 3 and data in Tiedeman and Hsieh (2021)
Values used to estimate transect thicknesses in Bear Valley alluvium		
Minimum	230	*Vs* values for Webb Ranch, SC-2, and SC-4
Average	280	*Vs* values for Webb Ranch, SC-2, and SC-4
Maximum	340	*Vs* values for Webb Ranch, SC-2, and SC-4
Values used to estimate transect thicknesses in Chalone Creek alluvium		
Minimum	230	*Vs* values for well CHA-4, Stone Boundary well, and Old Chalone Creek well #2
Average	290	*Vs* values for well CHA-4, Stone Boundary well, and Old Chalone Creek well #2
Maximum	370	*Vs* values for well CHA-4, Stone Boundary well, and Old Chalone Creek well #2

Chalone Creek well #2 and yielded good-quality peaks. Using the f_0 values and bedrock depths for these wells (table 1) yielded *Vs* consistent with expected values for coarse-grained alluvium (table 3.2). The minimum, maximum, and average *Vs* values from these three well locations (table 3.2) were used to estimate a range of thicknesses along transects in the Chalone Creek watershed.

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Moffett Field Publishing Service Center
Manuscript approved March 3, 2022
Edited by Mitchell Phillips
Layout and illustration support by Cory Hurd

Scheiderich—**Aqueous Geochemistry of Waters and Hydrogeology of Alluvial Deposits, Pinnacles National Park, California**—Open-File Report 2022–1026

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20221026