U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Geologic Setting, Geohydrology, and Ground-Water Quality near the Helendale Fault in the Mojave River Basin, San Bernardino County, California

Prepared in cooperation with the
MOJAVE WATER AGENCY

USGS
science for a changing world

Water-Resources Investigations Report 03-4069

Geologic Setting, Geohydrology and Ground-Water Quality near the Helendale Fault in the Mojave River Basin, San Bernardino County, California

By Christina L. Stamos, Brett F. Cox, John A. Izbicki, *and* Gregory O. Mendez

---

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 03-4069

Prepared in cooperation with the

MOJAVE WATER AGENCY

7208-24

Sacramento, California
2003

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, *Secretary*

U.S. GEOLOGICAL SURVEY
Charles G. Groat, *Director*

For additional information write to:

District Chief
U.S. Geological Survey
Placer Hall, Suite 2012
6000 J Street
Sacramento, California 95819-6129
http://ca.water.usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
square foot (ft^2)	0.09290	square meter
square foot per day (ft^2/d)	0.09290	square meter per day
gallons per minute (gal/min)	0.06309	liters per second
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (ºF) may be converted to degrees Celsius (ºC) as follows:

$$^{o}C=(^{o}F-32)/1.8.$$

VERTICAL DATUM

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

ABBREVIATIONS

δD	delta deuterium
$\delta^{18}O$	delta oxygen-18
^{14}C	carbon-14
L	liter
MCL	Maximum Containment Level
min	minute
per mil	parts per thousand
pmc	percent modern carbon
PVC	polyvinyl chloride
SMCL	Secondary Maximum Containment Level
TU	tritium units

Organizations

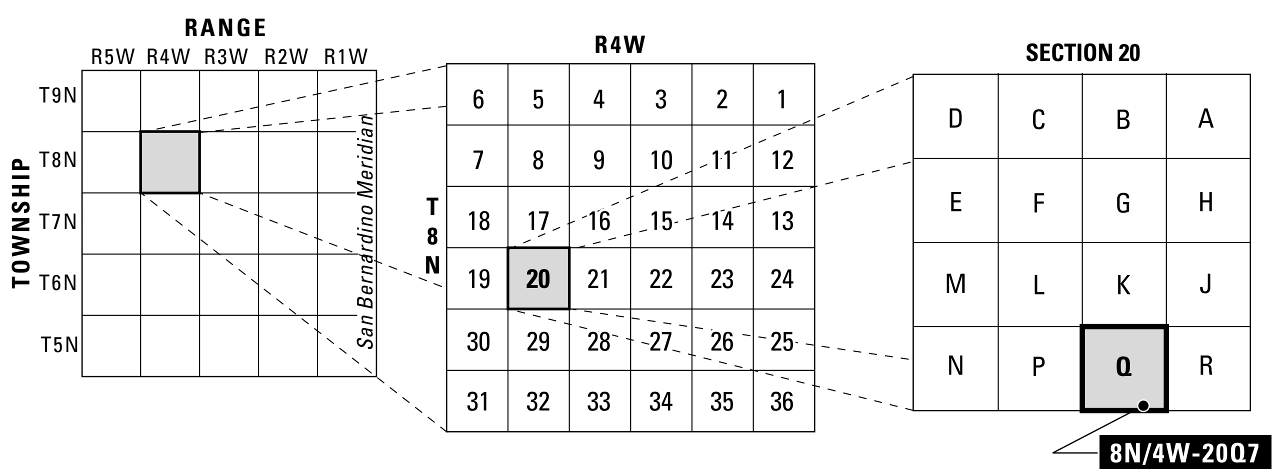
MWA	Mojave Water Agency
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water

Stratographic Units

Qoa	older alluvium of the ancestral Mojave River (Pleistocene)
Qra	recent alluvium of the Mojave River (Holocene)
QTof	older fan and stream deposits (Pliocene and Pleistocene)
QTp	playa deposits (Pliocene or early Pleistocene)
Qya	younger alluvium of the Mojave River (Pleistocene and Holocene)
Qyf	younger fan deposits (PLeistocene and Holocene)

WELL-NUMBERING SYSTEM

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the San Bernardino base line and meridian (S) Well numbers consist of 15 characters and follow the format 008N004W20Q007S. In this report, well numbers are abbreviated and written 8N/4W-20Q7. Wells in the same township and range are referred to only by their section designation, 20Q7. The following diagram shows how the number for well 8N/4W-20Q7 is derived.



Well-numbering diagram (Note: maps in this report use abbreviated well numbers such as **"20Q7"**)

Geologic Setting, Geohydrology, and Ground-Water Quality near the Helendale Fault in the Mojave River Basin, San Bernardino County, California

By Christina L. Stamos, Brett F. Cox, John A. Izbicki, *and* Gregory O. Mendez

ABSTRACT

The proximity of the Mojave River ground-water basin to the highly urbanized Los Angeles region has resulted in rapid population growth and, consequently, an increase in the demand for water. The Mojave River, the primary source of surface water for the region, normally is dry—except for periods of flow after intense storms; therefore, the region relies almost entirely on ground water to meet its agricultural and municipal needs. The area where the Helendale Fault intersects the Mojave River is of particular hydrogeologic interest because of its importance as a boundary between two water-management subareas of the Mojave Water Agency. The fault is the boundary between the upper Mojave River Basin (Oeste, Alto, and Este subareas) and the lower Mojave River Basin (Centro and Baja subareas); specifically, the fault is the boundary between the Alto and the Centro subareas. To obtain the information necessary to help better understand the hydrogeology of the area near the fault, multiple-well monitoring sites were installed, the surface geology was mapped in detail, and water-level and water-quality data were collected from wells in the study area.

Detailed surficial geologic maps and water-level measurements indicate that the Helendale Fault impedes the flow of ground water in the deeper regional aquifer, but not in the overlying floodplain aquifer. Other faults mapped in the area impede the flow of ground water in both aquifers. Evidence of flowing water in the Mojave River upgradient of the Helendale Fault exists in the historical record, suggesting an upward gradient of ground-water flow. However, water-level data from this study indicate that pumping upstream of the Helendale Fault has reversed the vertical gradient of ground-water flow since predevelopment conditions, and the potential now exists for water to flow downward from the floodplain aquifer to the regional aquifer.

Sixty-seven ground-water samples were analyzed for major ions, nutrients, and stable isotopes of oxygen and hydrogen from 34 wells within the study area between May 1990 and November 1999. Dissolved-solids concentrations in water samples from 14 wells in the floodplain aquifer ranged from 339 to 2,330 milligrams per liter (mg/L) with a median concentration of 825 mg/L. Concentrations in water from 11 of these wells exceeded the U.S. Environmental Protection Agency (USEPA) Secondary Maximum Contaminant Level (SMCL) of 500 mg/L. Dissolved-solids concentrations of water from nine wells sampled in the regional aquifer ranged from 479 to 946 mg/L with a median concentration of 666 mg/L. Concentrations in at least one sample of water from each of the wells in the regional aquifer exceeded the USEPA SMCL for dissolved solids. Arsenic concentrations in water from 14 wells in the floodplain aquifer ranged from less than the detection limit of 2 micrograms per liter (μg/L) to a maximum of 34 μg/L with a median concentration of 6 μg/L. Concentrations in water from six of the 14 wells exceeded the USEPA Maximum Contaminant Level (MCL) for arsenic of 10 μg/L. Arsenic

concentrations in water from nine wells in the regional aquifer ranged from less than the detection limit of 2 to 130 μg/L with a median concentration of 11 μg/L. Concentrations in water from five of these nine wells exceeded the USEPA MCL for arsenic. Dissolved-solids concentrations in water from seven wells completed in the igneous and metamorphic basement rocks that underlie the floodplain and regional aquifers ranged from 400 to 3,190 mg/L with a median concentration of 1,410 mg/L. Concentrations in water from all but one of the seven wells sampled exceeded the USEPA SMCL for dissolved solids. Concentrations in water from the basement rocks exceeded the USEPA SMCL for arsenic of 10 μg/L in five of the seven wells. The high concentrations of arsenic, dissolved solids, and other constituents probably occur naturally.

Stable isotopes of oxygen and hydrogen indicate that before pumping began in the early 1900s, the floodplain aquifer near Helendale was recharged by infiltration of winter stormflows originating in the headwaters of the Mojave River, and the regional aquifer was recharged by the infiltration of surface flow from small streams near the front of the San Gabriel and San Bernardino Mountains and (or) by infiltration of runoff from local mountains within the southern Mojave Desert.

Tritium, the radioactive isotope of hydrogen, was present in water from every well sampled in the floodplain aquifer indicating that the water was recharged after 1952. Water from most wells in the regional aquifer and the underlying basement rocks did not contain tritium, which indicates that it was recharged prior to 1952. Carbon-14, a naturally occurring isotope of carbon, was used to estimate the approximate age of the water from wells in the regional and underlying basement rocks. In general, uncorrected carbon-14 activities increase with depth and are fairly young near and downgradient from the Helendale Fault. The uncorrected carbon-14 activities indicate that the water in the regional aquifer was recharged between about 6,980 and 17,500 years ago and that the water in the basement rocks was recharged between 8,000 to 10,800 years ago. The great age of the water in the regional aquifer reflects the long flow paths and times of travel from the recharge areas near the northern front of the San Gabriel and San Bernardino Mountains. It is also possible that a small amount of this recharge may have been from infiltration of runoff from streams draining local mountains within and surrounding the study area during past climatic and hydrologic conditions that were different than those that exist in the present-day Mojave Desert.

INTRODUCTION

The Mojave River Basin is located in the western part of the Mojave Desert in southern California (fig. 1) and has a desert climate that is characterized by high summer temperatures, low humidity, and low precipitation. The proximity of the basin to the highly urbanized Los Angeles region has led to a rapid growth in population, and consequently, to an increase in the demand for water. The Mojave River is the primary source of surface water in the basin, but it is not dependable for water supply because significant flows occur only after intense storms. As a result, ground water is used for agricultural and municipal needs.

Ground-water withdrawal since the early 1900s has resulted in discharge (primarily from pumping wells) that exceeds recharge (natural and artificial). This reliance on ground water has resulted in overdraft conditions since the mid 1940s (Stamos and others, 2001). For the purposes of this report, overdraft occurs when ground-water discharge (natural discharge plus pumpage) exceeds recharge, resulting in a net reduction in ground water stored in the aquifer system.

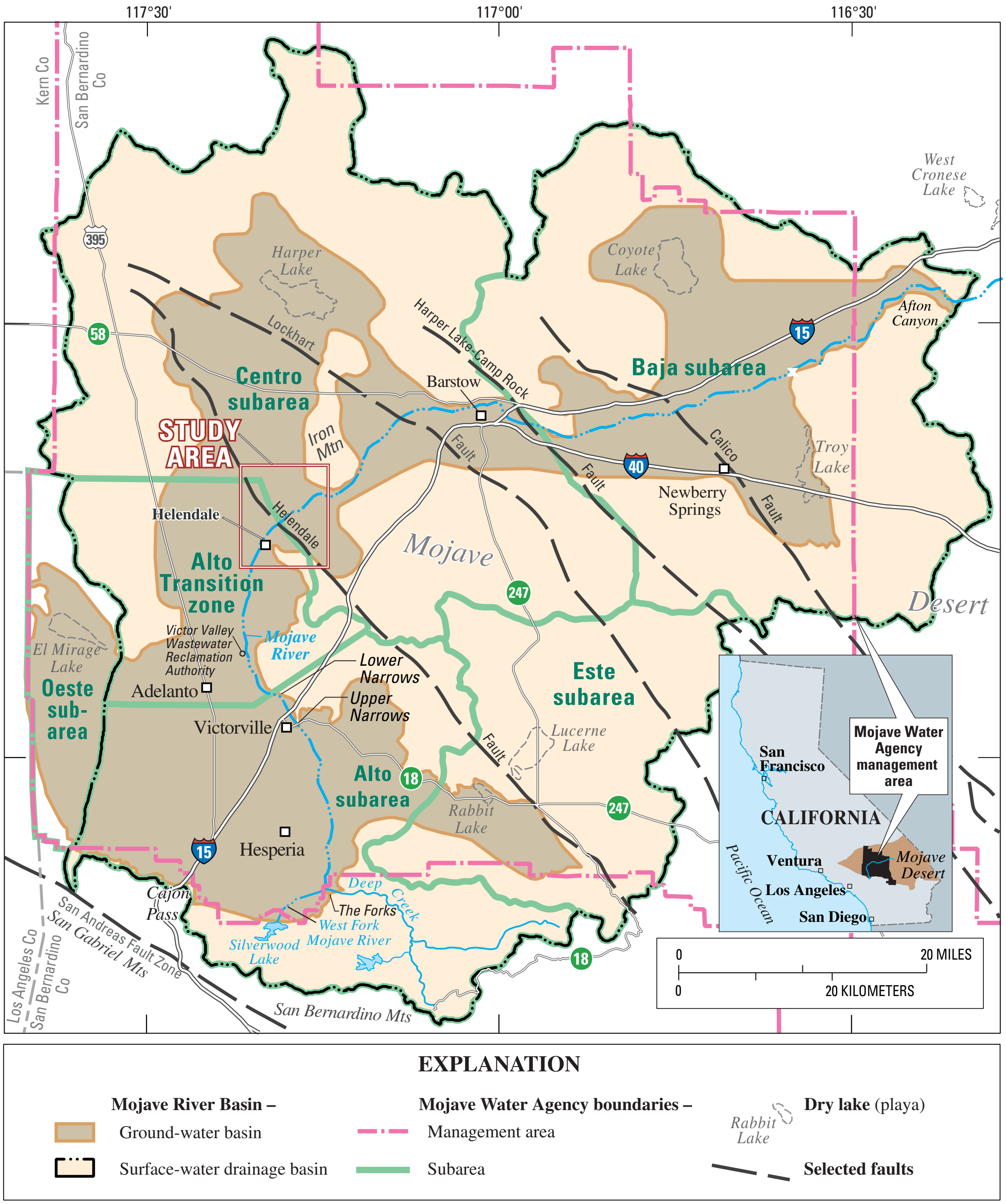


Figure 1. Location of study area.

In 1990, the city of Barstow and a local water company filed a complaint in the California Supreme court alleging that the cumulative water production from upstream communities between 1931 and 1990 overdrafted the Mojave River ground-water basin; the complaint resulted in the adjudication of the basin (Mojave Water Agency, 1996). At the core of the complaint was the assertion that the ground-water supplies of the downstream users were affected by withdrawals in the upstream parts of the basin. In 1993, a physical solution was submitted to the court that required users to initially reduce their pumpage by 20 percent over 5 years, followed by possible subsequent annual reductions in pumpage. The physical solution also required that each subarea within the Mojave River ground-water basin provide a specific quantity of water to the adjoining downstream subarea.

The area where the Helendale Fault crosses the Mojave River is of particular hydrogeologic interest because of its importance as a boundary between two water-management subareas of the Mojave Water Agency (MWA). The Helendale Fault is the boundary between the upper Mojave River Basin (Oeste, Alto, Transition zone of the Alto, and Este subareas) and the lower Mojave River Basin (Centro and Baja subareas); specifically, it is the boundary between the Alto and the Centro subareas (fig. 1). Previously published water-level maps by Stamos and Predmore (1995), Mendez and Christensen (1997), and Smith and Pimentel (2000) show that in most areas of the Mojave River Basin, ground-water flow mainly is toward the Mojave River, but in the area downgradient of the Helendale Fault, ground-water flow is away from the Mojave River toward Harper Lake and downstream toward the city of Barstow.

This study was done in cooperation with the MWA for the purposes of mapping the surficial geology near the Helendale Fault, defining the vertical and horizontal extent of the aquifers in the area, and determining how the Helendale Fault affects ground-water flow and water quality. Water samples were analyzed to determine the concentrations of dissolved constituents and the approximate ages and source(s) of recharge of the water in the alluvial aquifers and underlying basement rocks. This report presents the data collected for this study and the interpretation of field work done near the Helendale Fault. The field work included detailed mapping of the geology of the area, drilling and installation of multiple-well monitoring sites for gathering data from the aquifer system at discrete intervals, and collecting water-level and water-quality data.

Description of Study Area

The study area is located in the Mojave River ground-water basin approximately 100 mi northeast of Los Angeles, California (fig. 1). The area is centered where the Mojave River intersects the Helendale Fault—the westernmost of several long, northwest-trending faults that cross the central and western Mojave Desert. The headwaters of the Mojave River lie 30 to 40 mi to the south, in the high mountains of the central Transverse Ranges that were uplifted along the San Andreas Fault during the past several million years (Meisling and Weldon, 1989; Matti and Morton, 1993). The study area covers an area of about 30 mi^2 that spans from about 3 mi upstream to about 4 mi downstream from the Helendale Fault.

For management purposes, the MWA subdivided the Mojave River surface-water drainage basin unit into several subareas—Oeste, Alto Transition zone of the Alto (hereinafter referred to as the Transition zone), Este, Centro, and Baja (fig. 1). The study area straddles the Helendale Fault, which is the boundary between the upper Mojave River Basin (Oeste, Alto, and Este subareas) and the lower Mojave River Basin (Centro and Baja subareas).

The principal sources of natural recharge to the ground-water basin are the Mojave River, and to a lesser extent, small ephemeral streams and washes (Izbicki and others, 1995; Stamos and others, 2001). The Mojave River bisects the study area and, when sufficient surface water is present, recharges the aquifer system. However, significant recharge occurs only during episodic stormflows, usually in the winter; during the rest of the year, most of the river is usually dry. The floodplain aquifer near Helendale is recharged primarily by the infiltration of winter stormflows from the Mojave River. Since 1981, the discharge of treated municipal wastewater by the Victor Valley Wastewater Reclamation Authority (fig. 1) has maintained perennial flow in the Mojave River upstream from the study area and, as a result, has increased the amount of recharge going into the floodplain aquifer in the

Transition zone. Discharge from Victor Valley Wastewater Reclamation Authority ranged from about 260 acre-ft in 1981 to about 7,300 acre-ft in 1995 (Stamos and others, 2001).

Because of the limited availability of surface water, water supply in the area is derived entirely from ground water. Within the study area, some ground water is pumped for agriculture, but most is pumped for municipal supply. Upstream of the Helendale Fault, about 5,400 acre-ft/yr is pumped for municipal supply at Helendale (including the community of Silver Lakes) (fig. 1).

Acknowledgments

Appreciation is expressed to the San Bernardino County Flood Control District and Lockheed Martin Corporation for allowing access to their property for test drilling. In addition, appreciation is expressed to local land owners who allowed access to their property for water-level measurements and water-quality sample collection. The authors also thank the following U.S. Geological Survey personnel who assisted with data collection: Lowell F.W. Duell, Charles Lamb, Dennis Clark, Jill N. Densmore, Gregory Smith, Steven Crawford, and John C. Tinsley

Data-Collection Techniques

Several field investigations performed specifically for this study aided in the understanding of the subsurface hydrogeology. The conclusions in this report are a blend of the knowledge gained through detailed geologic mapping, the installation of multiple-well monitoring sites, the collection and analysis of aquifer-test data, water-level data, and water-quality data. A summary of well location and construction information and the type of data collected from 58 wells in and near the study area is presented in table 1. To download a file containing site identification numbers for these wells, click here; for the retrieval of water-level and water-quality data from the U.S. Geological Survey (USGS) National data base, go to http://waterdata.usgs.gov/ca/nwis/. The drilling techniques and procedures followed for the collection of the water-level and water-quality data are discussed in the following sections.

Multiple-Well Monitoring Sites

Prior to this study, water-level measurements and water samples for geochemical analysis were obtained exclusively from irrigation or domestic wells, the depths of which were uncertain in many cases. Multiple-well monitoring sites were installed for this study to measure water levels and to take water-quality samples from specific depths within the aquifer system in the Helendale area. During the drilling of the boreholes for the monitoring wells, a detailed log of the subsurface geology was recorded and used to interpret the hydrology of the aquifer system and the geology of the area.

During 1993 and 1994, four multiple-well monitoring sites containing a total of 18 individual wells were completed by mud rotary drilling in the study area—3 upstream (west) of the Helendale Fault and 1 downstream (east) (fig. 2). The monitoring sites consist of four to five wells with 2-inch diameter polyvinyl chloride (PVC) casings, except for one well with a 4.5-inch diameter casing. The well casings were installed at different depths in the same borehole at specific intervals, generally with 20 ft perforated intervals at or near the bottom of the well; a filter pack of Monterey #3 sand was placed around each screened interval. Each well was isolated from the others in the same borehole by low-permeability bentonite grout. The construction of these wells enables the collection of depth-specific water-level, water-quality, and aquifer-property data. Well-construction information for the 18 monitoring wells is provided in table 2.

A suite of geophysical logs was obtained after the boreholes were completed. The suite of logs include caliper, 64- and 16-inch normal resistivity, lateral resistivity, and natural gamma. For detailed well-construction diagrams, lithologic descriptions, and geophysical logs, the reader is referred to Huff and others (2002).

Table 1. Well-construction information and type of data collected for selected wells near Helendale, San Bernardino County, California, 1990–99

[U.S. Geological Survey (USGS) site identification number is the latitude, longitude, and sequence number of the site; State well No.: see well-numbering diagram in the table of contents; altitude of land surface in feet above sea level; original depth, top and bottom of perforations in feet below land surface; C-14, carbon 14; x, denotes that well is a multiple-well monitoring well; s, sample collected; —, no sample collected]

USGS identification No.	State well No.	Altitude of land surface	Original depth	Top of perforations	Bottom of perforations	Multiple-well site	Type of data collected				
							Water level[1] (1995)	Water quality	Isotopes	Tritium	C-14
344334117202701	7N/4W-6F5	2,450	99	89	99		—	s	s	—	—
344334117203001	7N/4W-6F6	2,450	20	10	20		—	s	s	—	—
344036117215201	7N/5W-23R1	2,725	740	700	740	x	—	—	s	s	s
344036117215202	7N/5W-23R2	2,725	510	490	510	x	—	s	s	—	s
344036117215203	7N/5W-23R3	2,725	306	295	315	x	—	s	s	s	s
344028117210601	7N/5W-24R5	2,505	550	510	550	x	—	s	s	s	s
344028117210602	7N/5W-24R6	2,505	265	265	285	x	—	s	s	s	s
344820117164901	8N/4W-3Q1	2,440	—	—	—		—	[2]s	s	—	—
344834117175401	8N/4W-4K1	2,470	—	—	—		—	[2]s	s	—	—
344834117175301	8N/4W-4K2	2,470	—	—	—		—	s	s	s	s
344817117180201	8N/4W-9B1	2,464	300	100	200		s	s	s	s	s
344733117173801	8N/4W-9R1	2,367	200	—	—			s	s	s	s
344816117163501	8N/4W-10A2	2,398	—	—	—		s	—	—	—	—
344754117164901	8N/4W-10G1	2,357	85.7	—	—		s	—	—	—	—
344727117171501	8N/4W-10P1	2,365	—	—	—		s	—	—	—	—
344728117165001	8N/4W-10Q1	2,355	62	14	59		s	—	—	—	—
344807117163001	8N/4W-11D6	2,375	—	—	—		—	[2]s	s	—	—
344818117151501	8N/4W-12C1	2,350	150	90	150		s	—	—	—	—
344728117145601	8N/4W-12Q1	2,329	49.1	—	—		[3]s	—	—	—	—
344726117145501	8N/4W-13B1	2,330	175	65	175		—	s	s	—	—
344638117162301	8N/4W-14N1	2,460	333	53 193	153 333		—	s	s	—	—
344714117172001	8N/4W-15C1	2,365	131	55	131		—	s	s	—	—
344712117164301	8N/4W-15H2	2,357	65	15	63		s	—	—	—	—
344701117173801	8N/4W-16J1	2,372	—	—	—		s	—	—	—	—
344659117181901	8N/4W-16L4	2,381	53.2	—	—		s	—	—	—	—
344702117184201	8N/4W-17H1	2,392.6	47	—	—		s	—	—	—	—
344645117190401	8N/4W-17Q3	2,400	72.5	—	—		s	—	—	—	—
344611117200801	8N/4W-19G1	2,458	316.4	295	315	x	s	s	s	s	s
344611117200802	8N/4W-19G2	2,458	239.4	220	240	x	s	s	s	s	s
344611117200803	8N/4W-19G3	2,458	170.6	150	170	x	s	s	s	s	s
344611117200804	8N/4W-19G4	2,458	101.1	80	100	x	s	s	s	s	s

Table 1. Well-construction information and type of data collected for selected wells near Helendale, San Bernardino County, California, 1990–99—Continued

USGS identification No.	State well No.	Altitude of land surface	Original depth	Top of perforations	Bottom of perforations	Multiple-well site	Type of data collected				
							Water level[1] (1995)	Water quality	Isotopes	Tritium	C-14
344628117190601	8N/4W-20B1	2,400	82	—	—		s	—	—	—	—
344625117193001	8N/4W-20D1	2,412.2	195	60	195		s	—	—	—	—
344634117194201	8N/4W-20D2	2,443.9	—	—	—		s	—	—	—	—
344612117193001	8N/4W-20E1	2,400.6	—	—	—		s	—	—	—	—
344613117194501	8N/4W-20E2	2,405.5	—	—	—		s	—	—	—	—
344549117192201	8N/4W-20P2	2,404.7	115	—	—		s	—	—	—	—
344546117190101	8N/4W-20Q7	2,397.3	452	440	460	x	s	s	s	s	s
344546117190102	8N/4W-20Q8	2,397.3	350.6	330	350	x	s	s	s	s	s
344546117190103	8N/4W-20Q9	2,397.3	270.8	250	270	x	s	s	s	—	—
344546117190104	8N/4W-20Q10	2,397.3	160.2	140	160	x	s	s	s	—	—
344546117190105	8N/4W-20Q11	2,397.3	51.9	30	50	x	s	s	s	—	—
344546117185901	8N/4W-20Q12	2,397.31	139.1	99.5	139.5		s	s	s	—	—
344631117182201	8N/4W-21C1	2,385	—	—	—		s	—	—	—	—
344624117181901	8N/4W-21C2	2,381	140	100	140		—	s	s	—	—
344609117182901	8N/4W-21M1	2,388.96	370.4	350	370	x	s	s	s	s	s
344609117182902	8N/4W-21M2	2,388.96	228.9	210	230	x	s	s	s	s	s
344609117182903	8N/4W-21M3	2,388.96	140.7	120	140	x	s	s	s	—	—
344609117182904	8N/4W-21M4	2,388.96	40.6	30	40	x	s	s	s	—	—
344544117154601	8N/4W-23Q1	2,489	253	153	253		—	s	s	—	—
344557117143701	8N/4W-24J2	2,478	360	—	—		—	[2]s	s	—	—
344524117193401	8N/4W-29E3	2,409.49	309.1	289	309	x	s	s	s	s	s
344524117193402	8N/4W-29E4	2,409.49	210.4	190	210	x	s	s	s	s	s
344524117193403	8N/4W-29E5	2,409.49	131.3	110	130	x	s	s	s	s	s
344524117193404	8N/4W-29E6	2,409.49	41.6	30	40	x	s	s	s	s	s
344401117194701	8N/4W-31R1	2,449	59	—	—		[3]s	—	—	—	—
344959117173101	9N/4W-34D1	2,483	620	—	—		[4]s	s	s	—	s
344933117173001	9N/4W-34M1	2,482	605	—	—		—	s	s	s	s

[1]Water-level measurement from the shallowest well at each multiple-well monitoring site was used to construct the water-table map (fig. 4).
[2]Sampled for selected anions only.
[3]March 1995 water-level measurement.
[4]April 1996 water-level measurement.

.

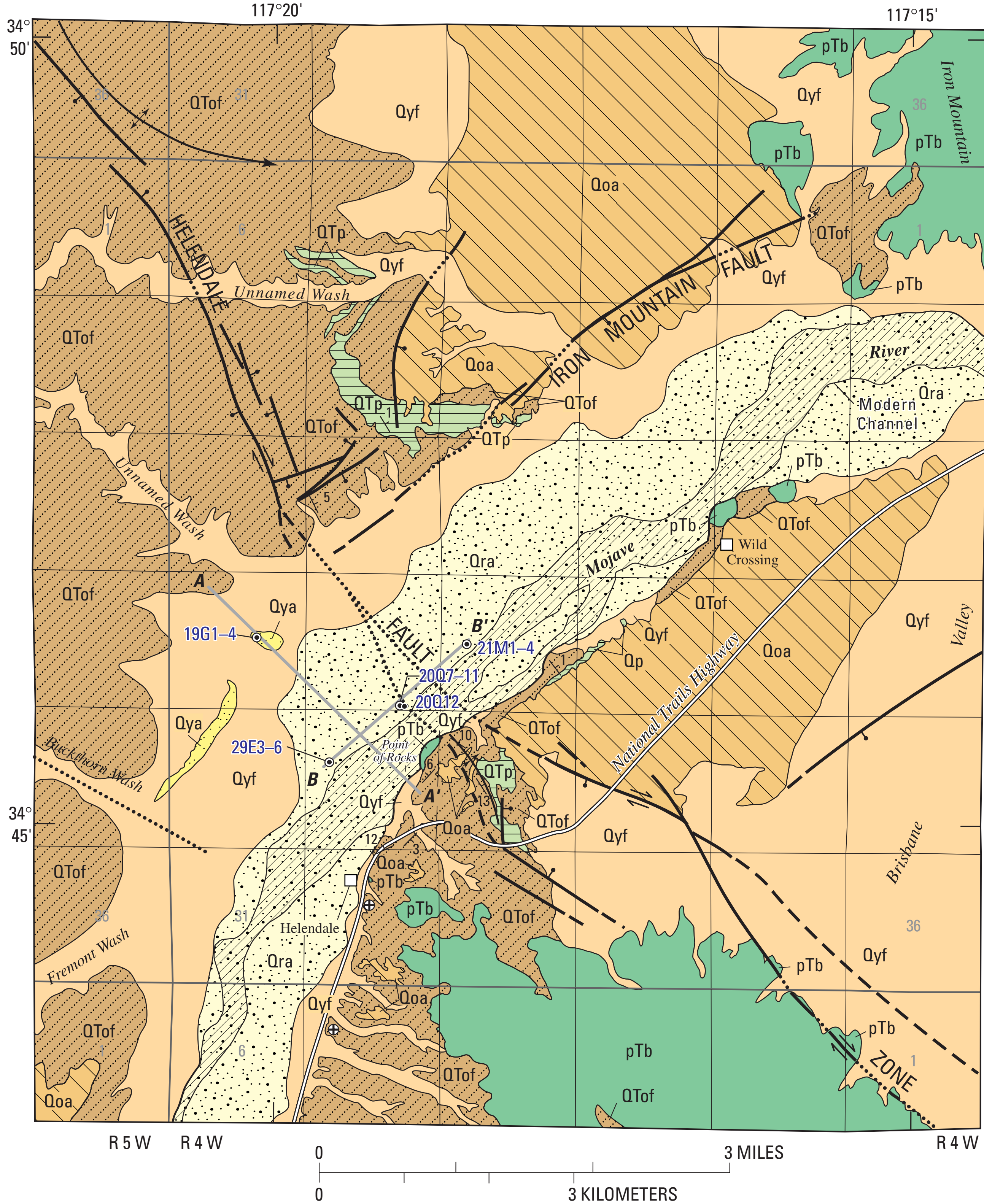


Figure 2. Surface geology, line of cross sections *A–A'* and *B–B'*, and location of the multiple-well monitoring sites near Helendale, San Bernardino County, California.

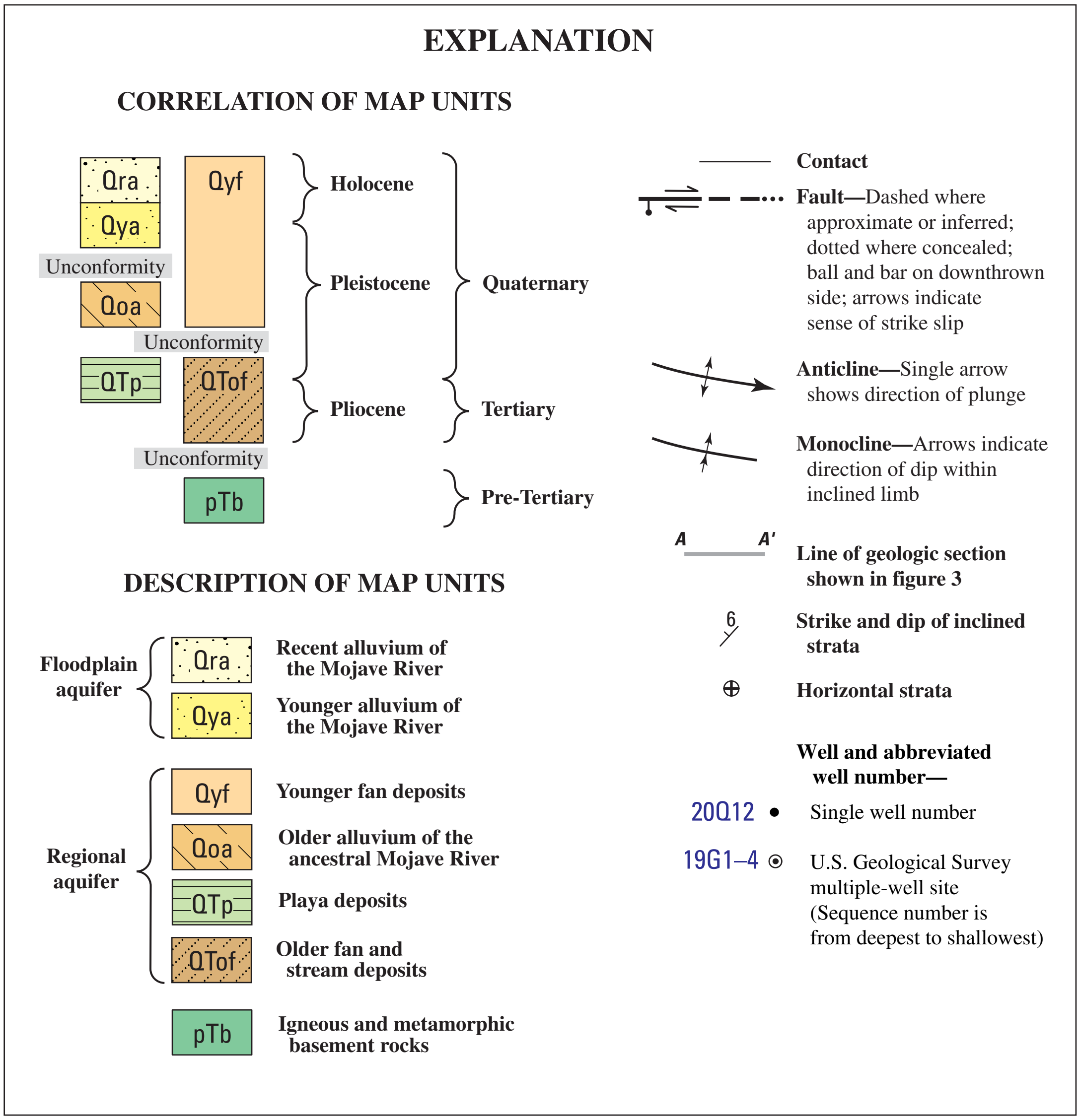


Figure 2.—Continued.

Table 2. Well-construction information for multiple-well monitoring sites near Helendale, San Bernardino County, California

[State well No.: See well-numbering diagram in the table of contents; altitude of land surface in feet above sea level; perforated interval and original depth in feet below land surface]

State well No.	Altitude of land surface	Aquifer or unit	Perforated interval	Original depth
8N/4W-19G1	2,458	Basement rocks (pTb)	295–315	315
8N/4W-19G2	2,458	Regional (QTof)	220–240	240
8N/4W-19G3	2,458	Floodplain (Qya)	150–170	171
8N/4W-19G4	2,458	Floodplain (Qya)	80–100	101
8N/4W-20Q7	2,397	Basement rocks (pTb)	440–460	460
8N/4W-20Q8	2,397	Basement rocks (pTb)	330–350	351
8N/4W-20Q9	2,397	Basement rocks (pTb)	250–270	271
8N/4W-20Q10	2,397	Floodplain (Qya)	140–160	160
8N/4W-20Q11	2,397	Floodplain (Qra)	30–50	52
8N/4W-20Q12[1]	2,397	Floodplain (Qya)	80–140	140
8N/4W-21M1	2,389	Basement rocks (pTb)	350–370	370
8N/4W-21M2	2,389	Regional (QTof)	210–230	230
8N/4W-21M3	2,389	Floodplain (Qya)	120–140	141
8N/4W-21M4	2,389	Floodplain (Qra)	30–40	41
8N/4W-29E3	2,409	Basement rocks (pTb)	289–309	309
8N/4W-29E4	2,409	Basement rocks (pTb)	190–210	210
8N/4W-29E5	2,409	Floodplain (Qya)	110–130	131
8N/4W-29E6	2,409	Floodplain (Qra)	30–40	42

[1]All wells are 2 inch in diameter, except 8N/4W-20Q12, which is 4.5 inches.

Water-Level Data

Ground-water levels were measured at the multiple-well completion sites and selected wells within the study area. Water levels were measured to an accuracy of 0.01 ft using a calibrated steel tape or a calibrated electric tape.

Water-Quality Data

Water-quality sampling was done by USGS personnel; all samples were collected, handled, and preserved following USGS field procedures (Marc Sylvester, U.S. Geological Survey, written commun., 1990). Purge logs, field measurements, and other information related to sample collection are on file at the USGS office in San Diego, California. Analyses of the major ions, nutrients, stable isotopes, carbon-14 (^{14}C), and tritium were done at USGS laboratories.

Tritium was measured by liquid scintillation (Thatcher and others, 1997) with electrolytic enrichment (Ostlund and Warner, 1962) in 1-liter unfiltered samples collected in glass containers. Sample bottles were filled from the bottom and allowed to overflow several times the bottle volume. The 2-sigma detection limit for tritium is 0.2 tritium units. The detection limit is a function of the statistics associated with the liquid scintillation counter. In general, the longer the counting time, the better the precision and the lower the detection limit.

Prior to 1994, ^{14}C samples were collected in a 96-liter nitrogen-filled stainless-steel vessel. The pH of an unfiltered sample water was adjusted to a pH greater than 11 using carbon-dioxide-free sodium hydroxide, and bicarbonate was precipitated as strontium carbonate by super saturating the sample with strontium chloride. The strontium carbonate precipitate was allowed to settle into a 1-liter polyethylene bottle at the bottom of the stainless-steel vessel. The 1-liter bottle was shipped to a laboratory where ^{14}C analyses were done by scintillation spectrophotometry (Thatcher and others, 1997). After 1994, the ^{14}C samples were filtered and collected in 1-liter glass bottles in the same manner as tritium, and then were analyzed for ^{14}C by accelerator mass spectrometry (Beukins, 1992).

GEOLOGIC SETTING

Geologic features near the intersection of the Mojave River and Helendale Fault were mapped during previous studies by Bowen (1954), Dibblee (1960a,b,c; 1967), California Department of Water Resources (1967), and Bortugno and Spittler (1986). To address geohydrologic questions raised during the present study, a new surficial geologic map of the study area was prepared (fig. 2). Data for the map were obtained, in part, by a field survey of the river bluffs and tributary ravines along the Mojave River between Helendale and Iron Mountain. Information for other parts of the map was obtained from reconnaissance field observations, inspection of aerial photographs, and evaluation of the cited geologic maps. Data obtained from the boreholes and from previous regional geophysical investigations were combined with the surficial geology to define the three-dimensional geologic framework of the Helendale area. Descriptions of the main geologic features in the study area, interpretations of their origin, and evaluations of how local landforms, stratigraphy, and geologic structure may affect ground-water flow are presented in the following sections.

Alluvial Topography of the Mojave River Valley

The study area is located within the alluvium-filled valley of the Mojave River near its intersection with the Helendale Fault (fig. 2). This segment of the river valley is 1.25 to 2.0 mi wide and is arcuate, trending north-northeast past Helendale to Point of Rocks, and from there heading northeast to Iron Mountain. The maximum topographic relief between the valley floor and nearby ridges is approximately 750 feet. Fremont Wash, Buckthorn Wash, and two other large unnamed washes (fig. 2) drain into the west side of the valley. Alluvial fans deposited at the mouths of these washes and neighboring smaller ravines coalesce to form a broad, gently sloping apron of sand and gravel (unit Qyf) along the northwest side of the valley (fig. 2). By contrast, a relatively narrow, discontinuous fringe of alluvial fans deposited by minor tributaries lines the southeast wall of the valley. The alluvial fans terminate down gradient at the nearly flat floor of the valley, which is 0.6 to 1.3 mi wide and contains Holocene alluvium (unit Qra) deposited in the channel and floodplain of the Mojave River (fig. 2). The floodplain consists of a low alluvial terrace that is 5 to 10 ft above the river channel. Older, late Pleistocene-age, river deposits (unit Qoa) are perched on the bluffs on either side of the river (fig. 2). An alluvial terrace elevated 130 to 220 ft above the valley floor caps these older river deposits. The high alluvial terrace is strongly dissected by erosion, particularly southwest of the Helendale Fault, where it rises to its greatest heights above the adjacent valley.

Stratigraphy

Seven stratigraphic units are exposed at the ground surface (fig. 2), and six are penetrated by boreholes in the study area (fig. 3): (1) pTb, basement complex of igneous and metamorphic rocks (pre-Tertiary), (2) QTof, older fan and stream deposits (Pliocene and Pleistocene), (3) QTp, playa deposits (Pliocene or early Pleistocene), (4) Qoa, older alluvium of the ancestral Mojave River (Pleistocene), (5) Qyf, younger fan deposits (Pleistocene and Holocene), (6) Qya, younger alluvium of the Mojave River (Pleistocene and Holocene), and (7) Qra, recent alluvium of the Mojave River (Holocene).

Igneous and Metamorphic Basement Rocks (pTb)

Hills and ridges of igneous and metamorphic rocks (unit pTb) locally protrude through a thick blanket of alluvial deposits that covers most of the study area (fig. 2). Basement ridges near the southern margin of the study area consist of silicic metavolcanic rocks of Jurassic age, including ash-flow tuff and tuff breccia, lava flows, and shallow intrusive bodies (Bowen, 1954; Dibblee, 1960b; Schermer, 1993). The northernmost of these outcrops forms Point of Rocks, a low headland of metarhyolite at the southeast edge of the Mojave River. Boreholes drilled in the Mojave River valley north and west of Point of Rocks penetrated similar metavolcanic rocks buried beneath about 175 to 275 ft of Quaternary alluvial deposits (figs. 2 and 3, well sites 8N/4W-19G1–4, -20Q7–11, -21M1–4, and -29E3–6). At Iron Mountain, near the northeast corner of the study area (fig. 2), granitic rocks of Late Jurassic or Cretaceous age intrude intensely deformed, schistose metavolcanic and metasedimentary rocks of Jurassic age (Bowen, 1954; Dibblee, 1960a,c; Boettcher and Walker, 1993). Granitic rocks also form two small hills near Wild Crossing.

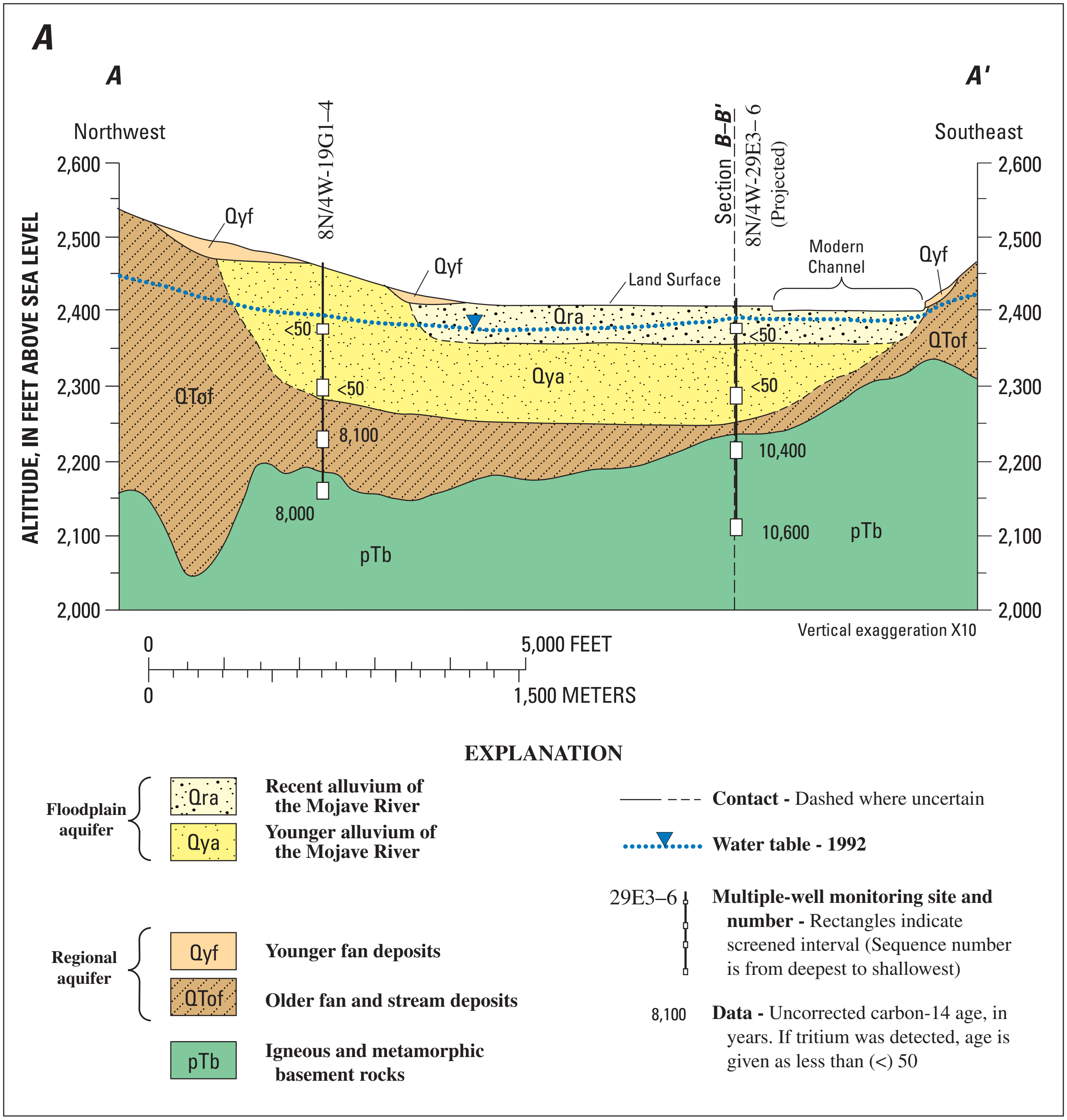


Figure 3. Geologic cross sections near Helendale, San Bernardino County, California, (*A*) cross section *A–A′*, and (*B*) cross section *B–B′*.

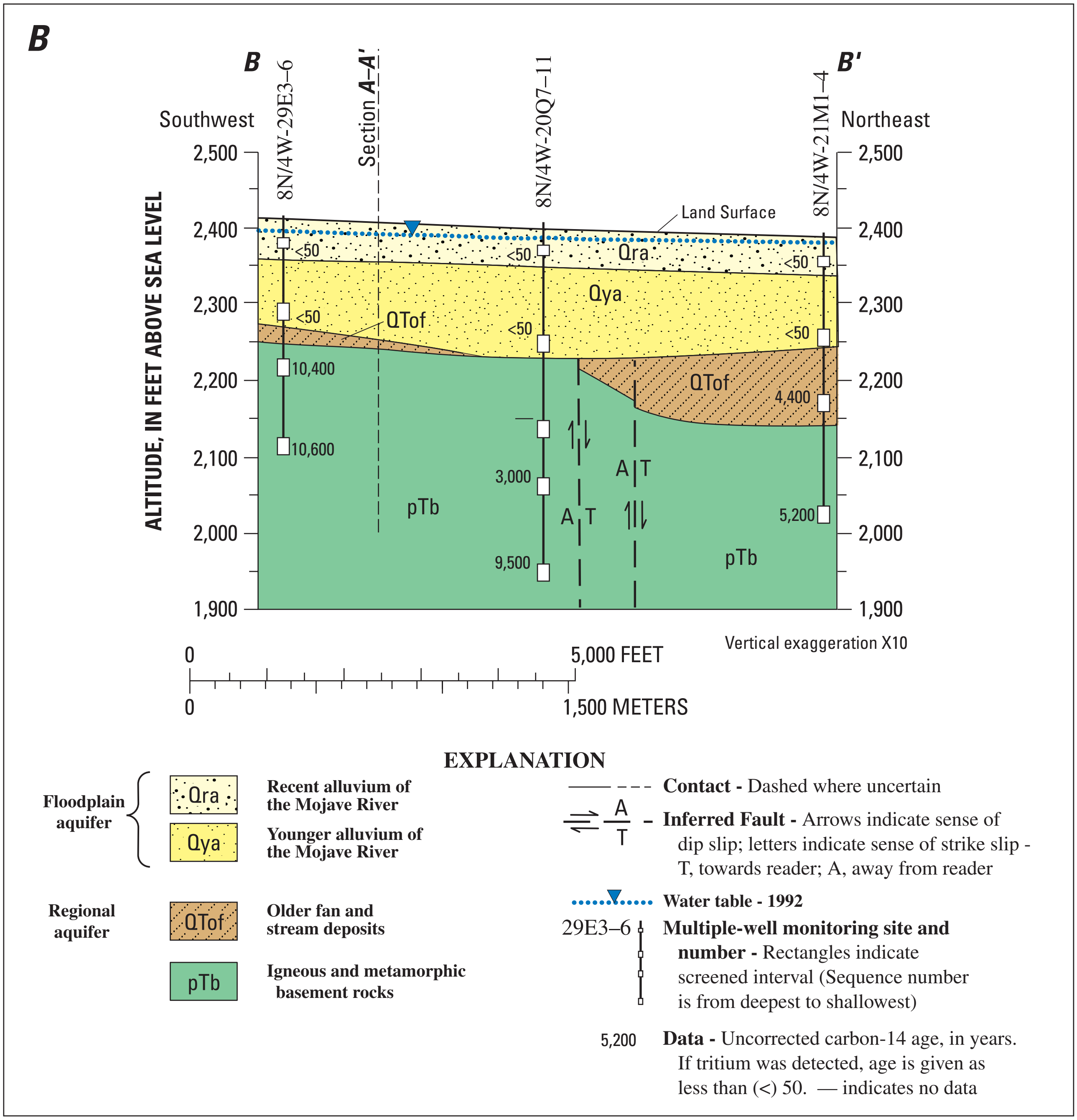


Figure 3—Continued.

Older Fan and Stream Deposits (QTof)

Alluvial-fan and braided-stream deposits of Pliocene and early Pleistocene age (unit QTof) overlie the pre-Tertiary basement rocks (figs. 2 and 3). These deposits mainly consist of unconsolidated to weakly indurated sand and pebble-cobble gravel. The deposits are hundreds of feet thick in the western part of the study area, but they thin and lap onto an irregular basement surface in the eastern part of the area. The deposits are gently folded, and in some areas, layers dip as steeply as 10 to 15 degrees. Deep erosion has destroyed all vestiges of the original depositional topography at the top of unit QTof. However, clast assemblages and sedimentary structures indicate that the deposits were laid down by a southward-flowing regional stream and by tributary alluvial fans (Cox and others, 1998; Cox and Hillhouse, 2000; Cox and others, 2003); therefore, the unit predates the origin of the present northeast-flowing surface drainage in the Helendale area.

The texture and detrital composition of the older fan and stream deposits vary laterally and vertically, reflecting diverse fluvial and alluvial-fan environments, derivation of rock debris from multiple local source areas, and varying degrees of weathering and diagenetic alteration. The deposits were derived from granitic, metamorphic, and volcanic rocks similar to those presently exposed in the upland areas of the southern and central Mojave Desert. Well-stratified sand and gravel deposited by a braided stream are exposed in road cuts of the National Trails Highway near Helendale, whereas poorly stratified silty sand and gravel of alluvial-fan origin crop out extensively in hills along the west side of the study area. Subsurface deposits penetrated by boreholes consist of a similarly diverse assemblage of sand, gravel, silt, and clay. A thick layer of reddish-brown clay 180 to 280 ft below the ground surface in borehole 8N/4W-19G (fig. 2) is absent from the boreholes along section line *B–B′*, located about 1.0 to 1.5 mi east and southeast of borehole 8N/4W-19G. This stratigraphic discontinuity may indicate that the clay was deposited in a lake or playa that did not extend eastward to the area of section *B–B′* or that a former eastern extension of the clay layer may have been uplifted and eroded before the younger alluvium of the Mojave River (unit Qya) was deposited. A thick succession of calcareous playa sediments (QTp) intercalated near the top of the older fan and stream deposits in the central and northern parts of the study area (fig. 2) is described separately in this report.

Regional gravity data suggest that the older fan and stream deposits, and possibly the underlying older units, fill deep depressions in the basement surface near the western and northern margins of the area mapped in figure 2. These depressions are part of a chain of north–south trending basins that extends southward for about 35 mi from Harper Lake to Victorville (Mabey, 1960; Biehler and others, 1988; Subsurface Surveys, 1990). The gravity data suggest that the basement surface is deeper than 3,000 ft at the centers of the basins, and therefore well below sea level (Subsurface Surveys, 1990). This implies that tectonic subsidence played a role in basin development. The basins possibly are remnants of a sinuous, southward-draining Miocene stream valley that was buried by alluvial deposits and then was deformed by northwest-trending faults and folds. Alternatively, the basins may consist of a series of structural depressions that subsided in response to east–west extension of the earth’s crust.

Playa Deposits (QTp)

A unit of playa deposits (QTp) as much as 70 ft thick crops out on either side of the Mojave River in the central part of the study area (fig. 2). This unit consists of weakly consolidated calcareous silt, clay, and fine sand interlayered with indurated beds of limestone, calcareous tufa, and sparse opalline chert. Fossilized plant stems are present in some of the limestone beds. The playa deposits interfinger with coarse-grained alluvial sand and gravel near the top of unit QTof. At one locality, on the southeast side of the Mojave River and approximately 2 mi northeast of Helendale, a discontinuous thin layer of volcanic ash overlies the playa deposits. The ash bed is 1 to 2 ft thick and is exposed in the river bluffs at about 2,525 ft above sea level. Based on a geochemical correlation, the ash apparently was deposited between about 0.9 and 1.2 million years ago (A. Sarna–Wojcicki, U.S. Geological Survey, written commun., 1998; Cox and others, 2003). This implies that the underlying playa deposits are early Pleistocene or older. They apparently accumulated in a small basin that was dammed on its southwest side by faulting or arching along the Helendale Fault (Cox and others, 2003).

Older Alluvium of the Ancestral Mojave River (Qoa)

Older alluvium of the ancestral Mojave River (unit Qoa) unconformably overlies the older fan and stream deposits and associated playa deposits (units QTof and QTp) on elevated benches that flank the valley of the modern Mojave River (fig. 2). Deposits as much as 80 ft thick underlie broad areas west of Brisbane Valley, west of Iron Mountain, and near the southwest corner of the study area. In addition, several small erosional remnants of the unit cap ridges south and east of Helendale. The older alluvium unit consists of essentially unweathered, loose to weakly consolidated sand and pebble-cobble gravel that accumulated in braided channels of the Pleistocene Mojave River. The upper half of the unit mainly consists of granitic debris eroded from the San Bernardino Mountains. The lower half is more heterogeneous in composition, containing granitic debris from the San Bernardino Mountains, mixed with detritus of granitic, volcanic, metavolcanic, and metasedimentary rocks derived from nearby sources in the southern Mojave Desert. Although the unit is deeply eroded, topographic summits commonly preserve remnants of a planar alluvial surface that developed on a broad, late Pleistocene floodplain of the ancestral Mojave River ("George surface" of Cox and Tinsley, 1999). In the study area, the old floodplain diverged significantly from the path of the modern Mojave River. For example, the extensive deposits of older alluvium located west of Iron Mountain represent a large distributary channel of the ancestral river that drained northward to Harper Lake (Cox and Tinsley, 1999; Cox and Hillhouse, 2000). The early river also developed alternate routes to Harper Lake on the east side of Iron Mountain.

Basal deposits of the older alluvium exposed in the river bluffs about l mi northeast of Point of Rocks overlie a thin layer of fine-grained volcanic ash. The chemical composition of the ash matches that of the PICO-40A ash near Ventura, California (about 100 mi west of study area), which was erupted between about 0.9 and 1.2 million years ago (A. Sarna–Wojcicki, U.S. Geological Survey, written commun., 1998). Thus, the deposits of the older alluvium unit probably began accumulating in the study area near the end of the early Pleistocene. Deposits from boreholes near Victorville, about 10 to 15 mi south of Helendale (fig. 1), indicate that deposition began somewhat earlier, during the Pliocene to early Pleistocene, in more southerly areas approaching the headwaters of the Mojave River (Cox and Hillhouse, 2000; Cox and others, 2003). The unit ceased accumulating between Victorville and Helendale about 60,000 to 70,000 years ago, when the Mojave River began incising its modern valley into the George surface (Cox and Hillhouse, 2000; Cox and others, 2003). The older alluvium generally is very porous and permeable; however, the unit has limited hydrologic significance because it lies above the water table throughout the study area.

Younger Fan Deposits (Qyf)

A widespread unit of locally derived younger alluvial-fan deposits (Qyf) flanks the Mojave River valley, extends up tributary ravines, and forms broad alluvial slopes in Brisbane Valley and west of Iron Mountain (fig. 2). These deposits include a belt of coalescing alluvial fans lying west of the Mojave River between Helendale and Iron Mountain. This tract is somewhat unusual; along most deeply incised segments of the Mojave River, periodic floods in the main river channel effectively curtail the growth of marginal alluvial fans. Within the study area, however, voluminous sedimentary detritus supplied by several large tributary ravines apparently has kept pace with river erosion. The main tributaries are Fremont Wash, Buckthorn Wash, and two unnamed washes farther north. The ephemeral streams in these washes drain a broad upland area extending northeastward from El Mirage Lake to the Helendale Fault (fig. 1). This watershed includes extensive hills of easily eroded, unconsolidated older fan and stream deposits (unit QTof) that probably are the main source of detritus within the young alluvial fans. The younger fan deposits mainly consist of sand and pebble–cobble gravel deposited by ephemeral streams and mudflows. They generally have silty, poorly sorted textures and consequently have low permeability. Deposits confined within large tributary drainages tend to be better sorted and probably are moderately permeable. Fan deposits confined within the Mojave River valley and tributary ravines likely range from latest Pleistocene to Holocene in age. However, the alluvial-fan deposits in Brisbane Valley locally intertongue with the older alluvium (Qoa) and, therefore, may be as old as early or middle Pleistocene.

Alluvium of the Mojave River (Qya and Qra)

The sedimentary fill of the Mojave River valley consists of unconsolidated sandy alluvium deposited during the late Pleistocene and Holocene. These sediments constitute the floodplain aquifer defined by Stamos and others (2001), and they are confined within a 350-foot-deep trough that formed when the river eroded into the older alluvium (Qoa) and older fan and stream deposits (QTof) during the late Pleistocene (Cox and others, 2003). Separate units of younger alluvium (Qya) and recent alluvium (Qra) are delineated in figures 2 and 3. Both units include abundant medium-grained to very coarse-grained arkosic sand, interlayered with lesser amounts of silt, fine sand, and pebble-cobble gravel.

Inspection of borehole cuttings and geophysical logs revealed that the alluvial deposits in both the Qya and Qra units are quite variable in texture and composition, comprising layers of poorly sorted silty sand and gravel, alternating with layers of moderately sorted, clean sand and gravel. The silty sediments consist of angular rock detritus derived from a diverse assortment of plutonic and metamorphic rocks. These sediments are similar in texture and composition to those in the younger fan deposits (Qyf), and they probably were deposited in much the same manner—by ephemeral floods and mudflows emitted from the mouths of nearby tributary ravines. The unit of older fan and stream deposits (QTof), which is abundant in the watershed of the tributaries in the study area, probably was the main source of the silty sand and gravel. In contrast, the interstratified layers of clean sand and gravel in units Qra and Qya consist of more conspicuously abraded, compositionally homogeneous granitic debris. This material apparently was mainly derived from distant mountain headwaters of the Mojave River in the Transverse Ranges. Major floods likely deposited these cleaner granitic sediments in the main river channel and on the adjacent floodplain. The large amounts of locally derived silty sediments intercalated within the valley fill may significantly reduce the average permeability of the alluvium along this stretch of the Mojave River, compared with more typical areas where the fill mainly consists of the cleaner, far-traveled river deposits.

The younger alluvium (unit Qya) is as much as 175 ft thick in the boreholes and forms the bulk of the alluvial fill beneath the Mojave River floodplain (fig. 3). The unit is largely concealed beneath recent alluvium of the Mojave River (Qra) and younger fan deposits (Qyf), but it crops out near the western margin of the river valley, north of Buckthorn Wash (figs. 2 and 3*A*). The age of the deposits probably range from late Pleistocene to Holocene. Deposition followed the incision of the Mojave River valley, which began about 60,000 to 70,000 years ago (Cox and Hillhouse, 2000; Cox and others, 2003). Deposition was completed before about 6,000 to 7,000 years ago, judging from radiocarbon ages obtained from alluvial terraces that are inset within the younger alluvium near Victorville (Rector and others, 1983; Rector, 1999) and east of Barstow (Reynolds and Reynolds, 1985, 1991; Densmore and others, 1997).

The recent alluvium (unit Qra) is about 50 ft thick in the study area, only partly filling a broad, 100-ft-deep trough that formed when the Mojave River eroded into the younger alluvium unit (fig. 3*A*). Surficial deposits of the recent alluvium form the modern channel and adjacent floodplain of the river. The unit was deposited during the middle to late Holocene, following an episode of river incision that evidently began prior to 6,000 to 7,000 years ago.

Geologic Structure

Various deformational structures, including faults, monoclinal flexures, and anticlinal folds, are present in the study area; several of these features are reported here for the first time. The structures are manifested by tilted or truncated topographic and stratigraphic surfaces observed in the field, and by scarps and other linear features visible on aerial photographs. The identification and interpretation of these structures contributed to a more complete understanding of local geologic history. Some of the structures also help explain the pattern of ground-water distribution and flow in the study area.

Helendale Fault

The Helendale Fault is the westernmost in a series of long, northwest-striking Quaternary-age faults that traverse the southern Mojave Desert (Dibblee, 1967; Bortugno, 1986; Bortugno and Spittler, 1986; Jennings, 1994). The northeast-flowing Mojave River intersects the Helendale Fault at nearly right angles within the area of this study (fig. 2). Here, the Helendale Fault comprises an irregular zone of discontinuous, overlapping fault strands with variable west–northwest to north–northwest trends, unlike neighboring areas to the southeast where there is a single, straight and continuous fault trace.

Linear depressions, low scarps, and lineaments visible on aerial photographs mark the individual strands within the fault zone. Four fault strands border the north side of the large basement ridge southeast of the Mojave River (fig. 2). These include two arcuate strands that diverge northwestward from the ridge, intersect one another, and finally terminate short of the Mojave River. About 1 mi to the south of these two fault strands, two shorter fault strands border the constricted northwest end of the basement ridge. These strands also seem to terminate before reaching the Mojave River; thus, as was previously concluded by Dibblee (1960a,b; 1967), the fault zone evidently does not extend across the Mojave River at the land surface. The fault zone reemerges northwest of the river, however, where two overlapping fault strands describe a broad arc concave to the southwest. Three accessory fault strands adjoin the southern part of this arc.

The faults southeast of the Mojave River die out northwestward into an apparently unfaulted, northeast-facing monoclinal flexure that is exposed directly east of Point of Rocks (fig. 2). The tilted strata in the monocline consist of an unconformable succession of units QTof, QTp, and Qoa. The beds strike northwest parallel to faults of the Helendale zone and dip northeastward as steeply as 10 to 15 degrees. Angular unconformities between the three units indicate that the monocline developed contemporaneously with sedimentation. The flexure probably extends northwestward beneath the alluvial fill of the Mojave River floodplain and presumably is underlain at depth by faulted basement rocks; therefore, the fault zone probably extends continuously across the Mojave River in the subsurface (fig. 3*B*). Thick masses of intensely fractured and brecciated metarhyolite that were encountered in outcrops near the north edge of Point of Rocks and also 220 to 460 ft beneath the ground surface in borehole 8N/4W-20Q (fig. 2) may have been produced by shearing or warping along the southwest margin of the fault zone. The structural relief across the monocline east of Point of Rocks indicates that its southwest limb has risen as much as 120 ft relative to the northeast limb, which may represent the net vertical displacement along this segment of the fault zone since the latest Pliocene or early Pleistocene (Cox and Hillhouse, 2000; Cox and others, 2003).

Northwest-trending faults of the southern Mojave Desert typically show evidence of right-lateral strike-slip displacement, which is consistent with the northwestward drift of western California along the nearby San Andreas Fault (fig. 1) (Dibblee, 1961; Dokka and Travis, 1990). However, the discontinuous pattern of faulting and warping observed in the study area, and supplementary evidence from neighboring areas, suggest that the net lateral displacement of the Helendale Fault is minimal near the Mojave River. Previous investigations inferred that the cumulative lateral slip is no greater than about 0.6 to 1.2 mi at two sites southeast of the study area (Miller, 1977, 1981; Miller and Morton, 1980). During the current study, field inspections of areas directly southeast of the Mojave River revealed that the southeastern margin of unit Qoa is separated right-laterally about 1 mi across one strand of the fault (fig. 2). However, as this strand apparently terminates abruptly before reaching the Mojave River, the lateral separation probably was not produced by lateral displacement. It more likely resulted from minor vertical displacement that dropped unit Qyf down against unit Qoa. Evidence of possible strike-slip displacement is found where this fault is intersected obliquely by a neighboring, more northerly trending fault (fig. 2). If both faults are steeply dipping, then the latter may have displaced the former about 500 ft in a right-lateral sense.

The scarps and lineaments associated with the strands of the Helendale Fault in the study area cut units Qoa, Qyf, and older deposits, which imply that faulting occurred during the Quaternary period. Most of the displacement evidently accumulated during the Pleistocene epoch. This conclusion is supported by the degraded condition of the fault scarps, which suggests that the most recent movements occurred during the late Pleistocene. There is no conspicuous evidence of Holocene movements. Northwest-trending scarps or other signs of ground-surface rupture are absent from the Holocene and latest Pleistocene-age alluvial deposits of units Qyf, Qya, and Qra that blanket the floor and margins of the Mojave River valley. Furthermore, hydrologic data suggest that the Helendale Fault zone does not affect the flow of ground water in the subsurface deposits of units Qra and Qya that form the floodplain aquifer of the Mojave River (Hardt, 1971; Stamos and Predmore, 1995; Stamos and others, 2001).

In summary, results of the geologic mapping survey and of the borehole drilling done during this study suggest that displacement on the Helendale Fault within the study area, for the most part, predates the alluvial fill of the Mojave River valley and therefore should have little, if any, affect on the flow of ground water in the floodplain aquifer. However, movements along the fault zone have affected pre-Tertiary basement rocks (unit pTb) and have disrupted the overlying units of older fan and stream deposits (QTof), playa deposits (QTp), older alluvium of the ancestral Mojave River (Qoa), and some parts of the younger fan deposits (Qyf). The resulting deformational structures may affect the flow of ground water in the basement rocks and in the overlying regional aquifer.

Other Faults

Field observations and an analysis of aerial photographs disclosed several northeast-trending faults in the region east of the Helendale Fault (fig. 2). These include a 4-mile-long zone of overlapping faults at the north edge of the Mojave River valley (referred to as the "Iron Mountain fault" in Stamos and others, 2001) and a 2-mile-long fault in Brisbane Valley. Several shorter northeast-trending faults flank the southwest end of the Iron Mountain Fault. Geomorphic and stratigraphic evidence indicate that the southeast sides of most of the northeast-trending faults have dropped downward relative to the northwest sides. Strata near the middle of the Iron Mountain Fault are dropped about 10 ft on the south side of the zone; the other northeast-trending faults probably have similarly small net displacements.

The northeast-trending faults cut the younger fan deposits (Qyf), which implies that these faults moved as recently as the late Pleistocene or the Holocene. The scarps in Brisbane Valley are strongly eroded, which suggests the most recent faulting in that area may have occurred during the late Pleistocene. However, lineaments at the southwest end of the Iron Mountain Fault cut deposits that appear to be Holocene in age. The Iron Mountain Fault may be partly responsible for a ground-water barrier that was previously deduced from a steep northward inclination of the water table northwest of the Mojave River (Stamos and Predmore, 1995).

A previously unrecognized northwest-trending fault may underlie the axis of Buckthorn Wash, which has eroded into deposits of older fan and stream deposits (QTof) in the southwestern part of the study area (fig. 2). A fault is proposed to explain the linear configuration of this narrow tributary valley, which extends northwestward about 10 mi from its confluence with the Mojave River. The proposed fault conceivably continues southeastward beneath the Mojave River, but there is no obvious geomorphic or structural evidence indicating a further extension east of the river. The age of the fault is uncertain. By analogy with nearby parallel strands of the Helendale Fault, it presumably was most active during the Pleistocene.

Folds

Two northwest-trending fold structures are associated with the Helendale Fault in the study area (fig. 2). One of these is the northeast-facing monoclinal flexure southeast of the Mojave River that was previously described with the Helendale Fault. The other is an anticline within unit QTof northwest of the river. The anticline lies near the northwest corner of the area shown in figure 2 and was originally mapped by Bowen (1954), and subsequently by Dibblee (1960a, 1967). It consists of a low oval dome about 4 to 5 mi long that plunges very gently to the northwest and southeast. The crest of the dome stands about 200 to 400 ft above the adjacent land surface to the southwest and northeast, respectively. Alluvial strata exposed on its flanks dip very gently, about 5 degrees or less (Dibblee, 1960a, 1967). Overlapping strands of the Helendale Fault cut the dome high on its southwest flank. Much of the dome trends northwest parallel to the fault zone, but its southeast end veers to the east. Other less prominent anticlinal folds may coincide with long northwest-trending ridges on either side of Buckthorn Wash, as was previously suggested by Bowen (1954).

The age of the anticlinal folding can be estimated from stratigraphic relations. The dome northwest of the Mojave River postdates the deposition of unit QTof and predates deposition of unit Qyf. Thus, it probably developed chiefly during the Pleistocene, contemporaneously with the nearby monoclinal flexure and the overlapping strands of the Helendale Fault. The folds and faults mainly developed where a thick blanket of ductile alluvial deposits covers brittle basement rocks. A more continuous, linear zone of faulting—comparable to segments of the Helendale Fault southeast of the study area—presumably cuts the basement rocks in the deep subsurface. Faulting evidently propagated irregularly upward through the thick alluvial cover to produce the complex pattern of folds and faults observed at the land surface.

Geologic History

Geologic evidence from this and previous investigations shows how a sequence of late Cenozoic depositional and tectonic events produced the Mojave River ground-water basin. The Mojave Desert apparently drained to the Pacific Ocean about 18 to 10 million years ago, as indicated by southward-flowing paleocurrents in the Miocene stream deposits near Cajon Pass (fig. 1) (Woodburne and Golz, 1972; Foster, 1980; Meisling and Weldon, 1989). After about 10 million years ago, north–south directed tectonic compression progressively buckled the crust of the Mojave Desert and the surrounding areas (Bartley and others, 1990), resulting in east–west-trending ridges and basins that altered regional patterns of drainage and sedimentation (Cox and others, 2003).

During the Pliocene, about 5 to 2 million years ago, streams flowing southward across the Mojave Desert terminated in an oblong east–west-trending sedimentary basin lying between Victorville and Cajon Pass (fig. 1) (Meisling and Weldon, 1989; Weldon and others, 1993). The axis of the basin passed through the area where the city of Hesperia is now located, and extended eastward beyond the Helendale Fault (fig. 1). As the basin filled with sediments, streams on its northern flank aggraded their valleys; thus, a southward-flowing stream and tributary alluvial fans deposited the unit of older fan and stream deposits (QTof) in the study area (Cox and others, 2003). This stratigraphic unit now constitutes much of the regional aquifer (described in the following section) of the Mojave River ground-water basin. Also during this period, basement rocks and overlying Cenozoic sediments in the southern Mojave Desert were gently folded above a horizontal fault zone, or décollement, lying 5 to 8 mi beneath the land surface. This process generated a regional arch trending west–northwest for about 150 mi across the southern Mojave Desert (Howard and Miller, 1992; Howard and Cox, 2001; Cox and others, 2003). The western part of the arch bounded the northern side of the sedimentary basin; its crest lay about 4 mi north of Adelanto (fig. 1).

During the late Pliocene and early Pleistocene, about 2.0 to 0.78 million years ago, the northern San Bernardino Mountains were warped and faulted up along the southern Mojave Desert, and the San Andreas Fault shifted high peaks of the central San Gabriel Mountains to a position directly west of the San Bernardino Mountains (fig. 1) (Meisling and Weldon, 1989). These tectonic movements produced a lofty mountain belt that shed increased amounts of water and sediment northward into the adjacent basin at the southern edge of the Mojave Desert. The ancestral Mojave River transported much of the rock detritus that was eroded from the San Bernardino Mountains (Cox and others, 2003). The regional arch in the southern Mojave Desert continued rising and became a significant drainage divide during this period. Detritus transported northward by the ancestral Mojave River and other streams was therefore barred from areas north of the arch, including the study area of this report. Also during this period, local folding and faulting along or near the Helendale Fault created a closed depression in the study area that was filled with the fine-grained playa sediments of unit QTp (Cox and Hillhouse, 2000; Cox and others, 2003).

The basin near Hesperia had completely filled with alluvium by the middle Pleistocene, about 0.5 million years ago. This occurred when the alluvium built up to a low point on the crest of the regional arch located due north of Adelanto. Thereafter, the ancestral Mojave River rapidly advanced northward beyond the arch and deposited sand and gravel (unit Qoa) in the study area (Cox and Hillhouse, 2000; Cox and others, 2003). Throughout the remainder of the Pleistocene, the terminus of the Mojave River alternated between Harper Lake and basins east of Barstow.

The transition from the ancestral to the modern Mojave River occurred during the late Pleistocene, about 60,000 to 70,000 years ago, when the river began incising its present shallow canyon between the San Bernardino Mountains and Barstow (fig. 1) (Cox and Hillhouse, 2000; Cox and others, 2003). Once incision began, the river was locked into its present northeastward course south of Iron Mountain, abandoning the alternate northward route west of Iron Mountain. Downcutting probably was induced by the broad uplift of the southern Mojave Desert (Bowen, 1954) that occurred in response to renewed north–south tectonic compression. This inferred late Pleistocene pulse of regional compression also may account for the latest growth of the monoclinal flexure east of Point of Rocks (fig. 2), which lifted the top of unit Qoa about 30 ft on the southwest side of the Helendale Fault.

The Mojave River initially cut down about 350 ft where it crosses the Helendale Fault. However, the river and local tributaries filled about half of the depth of this early valley with sand and gravel of the younger alluvium (Qya) by the early Holocene, before about 6,000 to 7,000 years ago. By cutting a deep trough into the slightly permeable sediments of the older fan and stream deposits (QTof) and then partly filling the trough with more permeable sand and gravel, favorable conditions were established for containment of ground-water flow within the floodplain aquifer (described in the following section). The permeability of the floodplain aquifer may be lower than expected in some areas of the study area, however, because the large tributary ravines along the west side of the river deposited abundant layers of poorly sorted silty sand and gravel that are interstratified among the well sorted, more permeable river deposits.

The Mojave River completed a second cycle of cutting and filling after about 6,000 to 7,000 years ago. During this cycle, the river incised a channel about 100 ft deep within the younger alluvium (Qya), then filled this channel about halfway with coarse sand and gravel of the recent alluvium (Qra). These young river deposits constitute the most permeable strata of the floodplain aquifer.

GEOHYDROLOGY

The unconsolidated alluvial sands and gravels of Pliocene and Quaternary age form two aquifers within the Mojave River ground-water basin—a floodplain aquifer that is composed of the recent and younger alluvium (Qra and Qya, respectively) of the Mojave River river deposits, and a regional aquifer underlying and surrounding the floodplain aquifer that is composed of the younger fan deposits (Qyf), older alluvium of the ancestral Mojave River (Qoa), older fan and stream deposits (QTof), and playa deposits (QTp) (figs. 2 and 3). Nonwater-bearing metamorphic and granitic rocks (pTb) that underlie the alluvial deposits of the basin crop out in the surrounding hills and mountains, forming the base of the ground-water system. In contrast to the overlying alluvial deposits, the consolidated rocks are nonporous and yield only small amounts of water to wells. Results of test drilling show that metamorphosed basement rocks commonly are highly weathered and fractured. These rocks were distinguished from the overlying alluvial deposits by examination of the borehole cuttings and the high resistivity on electric logs.

Floodplain Aquifer

The young, permeable alluvial deposits beneath and adjacent to the modern channel and floodplain of the Mojave River constitute the floodplain aquifer. Results of test drilling during the installation of the multiple-well monitoring sites in the study area indicate that the floodplain aquifer comprises two stratigraphic units deposited by the Mojave River: recent alluvium of Holocene age (Qra) and younger alluvium of Holocene to Pleistocene age (Qya) (fig. 3).The recent river alluvium is thin, typically less than 50 ft, and is confined to the shallow canyon of the Mojave River. Deposits exposed at land surface consist of clean, coarse arkosic sand. The younger alluvium underlies the recent alluvium and extends to depths of about 100 to 150 ft. Both units were identified by the high resistivities on borehole electric logs and by borehole cuttings, which include clean, coarse arkosic sand. At the westernmost monitoring-well site, 8N/4W-19G1–4 (figs. 2 and *3A*), the younger alluvium extends up to about 2,460 ft above sea level, or roughly 50 ft higher than the active river channel. The younger alluvium apparently has been strongly eroded by recent downcutting of the river.

The floodplain aquifer is more productive than the regional aquifer, yielding most of the water pumped from the basin. Wells drilled in the river deposits typically yield between 100 and 2,000 gal/min (Hardt, 1971). These deposits receive most, if not all, of the recharge from surface-water flows. The floodplain aquifer near Helendale is recharged primarily by the infiltration of winter stormflows from the Mojave River. In recent years, the discharge of treated municipal wastewater by the Victor Valley Wastewater Reclamation Authority (fig. 1) has maintained perennial flow in some areas of the Mojave River upstream from the study area and, as a result, has increased the amount of recharge going into the floodplain aquifer in the Transition zone. During the summer and periods when the river is not flowing, water levels in the floodplain aquifer decline mainly as a result of pumping and transpiration by riparian vegetation. Water levels recover in the winter when the floodplain aquifer is recharged by stormflow in the Mojave River.

Regional Aquifer

Within the study area, the floodplain aquifer is surrounded and underlain by unconsolidated alluvium of the regional aquifer (Qyf, Qoa, QTp, and QTof). The regional aquifer is composed of younger alluvial fan deposits of Holocene to Pleistocene age (Qyf), older alluvium of the ancestral Mojave River of Pleistocene age (Qoa), and older fan and stream deposits of Pleistocene to Pliocene age (QTof) (fig. 2). Unit QTof is the most important of these deposits because it is thick and extends well below the water table, whereas the other units are much thinner and mainly lie above the water table in the study area (fig. 3*A*). The test drilling results, combined with the exposures on the margins of the river valley, indicate that deposits of unit QTof are as much as 350 ft thick in the study area (fig. 3*A*). However, similar alluvial deposits are more than 1,000 ft thick in other parts of the Mojave River ground-water basin (Stamos and others, 2001).

The younger fan deposits (Qyf) consist of sand and gravel from the older fan and stream deposits that were eroded and redeposited by tributary streams along the margins of the Mojave River. These deposits are poorly to moderately sorted and slightly weathered; they are less permeable than the recent alluvium (Qra) and younger alluvium (Qya) of the floodplain aquifer, but more permeable than the older fan and stream deposits (QTof). In many areas along the Mojave River, including the Helendale area, the recent and younger alluvium of the floodplain aquifer are separated at the ground surface from neighboring older alluvial deposits of the regional aquifer by wedge-shaped bodies of younger fan deposits (Qyf) (figs. 2 and 3*A*). Within the study area, the younger fan deposits are above the water table and are unsaturated. The younger fan deposits were distinguished from the younger alluvium by lower electrical resistivity on the borehole electric logs and by the texture and composition of the borehole cuttings. The older alluvium (Qoa) consists of sandy river deposits that are about 25 to 80 ft thick; the deposits are similar to the recent and younger alluvium of the Mojave River, but are slightly more consolidated. The older fan deposits (QTof) contain more interstitial silt and clay, are more consolidated than the deposits of the floodplain aquifer, and are also distinguished by their low resistivity. The playa deposits (QTp) interfinger with the alluvial sediments of the older fan deposits (QTof). The permeability of the playa sediments is controlled by fine-grained textures and abundant cemented layers. The QTp unit probably is not an important aquitard within the regional aquifer because it has a limited areal extent, and it is largely above the water table in the study area.

The regional aquifer is recharged by infiltration of stormflow in ephemeral washes along the southern boundary of the Mojave River ground-water basin (Izbicki and others, 1995). In the Helendale area, infiltration of runoff from local desert mountains also may be an important source of recharge. In comparison to the floodplain aquifer, recharge to the regional aquifer is small. On the basis of ^{14}C data from water sampled from the regional aquifer near Victorville, Izbicki and others (1995) determined that water in the regional aquifer was recharged as early as 20,000 years ago, during climatic and hydrologic regimes that were different than those of the present-day Mojave Desert. Although the regional aquifer contains a substantial amount of ground water in storage, the low permeability and fine-grained texture of the sediments in this aquifer results in well yields lower than those of the floodplain aquifer, and the water generally is of poor quality (high dissolved-solids concentrations) in most areas of the Mojave River Basin.

Ground-Water Movement near the Helendale Fault

Water levels measured in 26 wells were used to construct the water-table map shown in figure 4. Water levels from the shallowest wells at the multiple-well monitoring sites were used because they are the best representation of the water table. All but three of the water levels were collected in July 1995. The water-level measurements from wells 8N/4W-31R1 and 8N/4W-12Q1 were collected in March 1995 to determine the direction of ground-water flow upgradient and downgradient of the Helendale Fault, respectively. Water levels also were collected at well 9N/4W-34D1 in April 1996 to determine the water-level altitude in the northern part of the study area. Ten of the wells measured in July 1995 are located upgradient (west) of the Helendale Fault and 16 of them are located downgradient (east) of the fault. Depth to water in the wells ranged from less than 5 ft below land surface in wells completed in the floodplain aquifer near the Mojave River to almost 200 ft below land surface in wells completed in the regional aquifer on the bluffs overlooking the river.

The regional pattern of ground-water movement in the Mojave River Basin is affected by right-lateral, strike-slip faults that trend predominately northwest to southeast and act as barriers to ground-water flow (Stamos and Predmore, 1995). In the area near the Helendale Fault, the movement of ground water in the floodplain aquifer is from the southwest to the northeast—in the same direction as the intermittent surface-water flows of the Mojave River. The study area contains several previously unmapped faults that may restrict subsurface flow (fig. 4). On the basis of water-level data from this and previous studies (Hardt, 1971; Stamos and Predmore, 1995), the Helendale Fault was not considered to be a barrier to ground-water flow in the floodplain aquifer. However, water-level data collected from wells at the multiple-well monitoring sites indicate that the fault does restrict flow in the regional aquifer and therefore resulted in upward flow of ground water in the past. The historical record describes many places along the Mojave River, including the study area, that had a shallow water table or perennially flowing surface water where active faults acted as barriers to ground-water flow. Evidence of flowing surface water at the Helendale Fault was reported in the 1800s by early explorers and trappers who established a watering and resting spot at Point of Rocks (fig. 4) (Lines, 1996). Samples of deuterium (a stable isotope of hydrogen) taken from the multiple-well monitoring sites upgradient of the Helendale Fault indicate that the natural (predevelopment) gradient of vertical ground-water flow was upward (discussed later in the “Isotopic Composition of Water from Wells” section), which implies that ground water discharged to the river before ground-water pumping started. This conclusion is also supported by the ^{14}C data (discussed later in the “Tritium and Carbon-14” section), which indicate that water in the floodplain aquifer at well 8N/4W-19G3 (fig. 2) originated as discharge from the regional aquifer. In comparison to the amount of recharge that the floodplain aquifer receives from the Mojave River, the amount of seepage from the regional aquifer during predevelopment conditions likely was small.

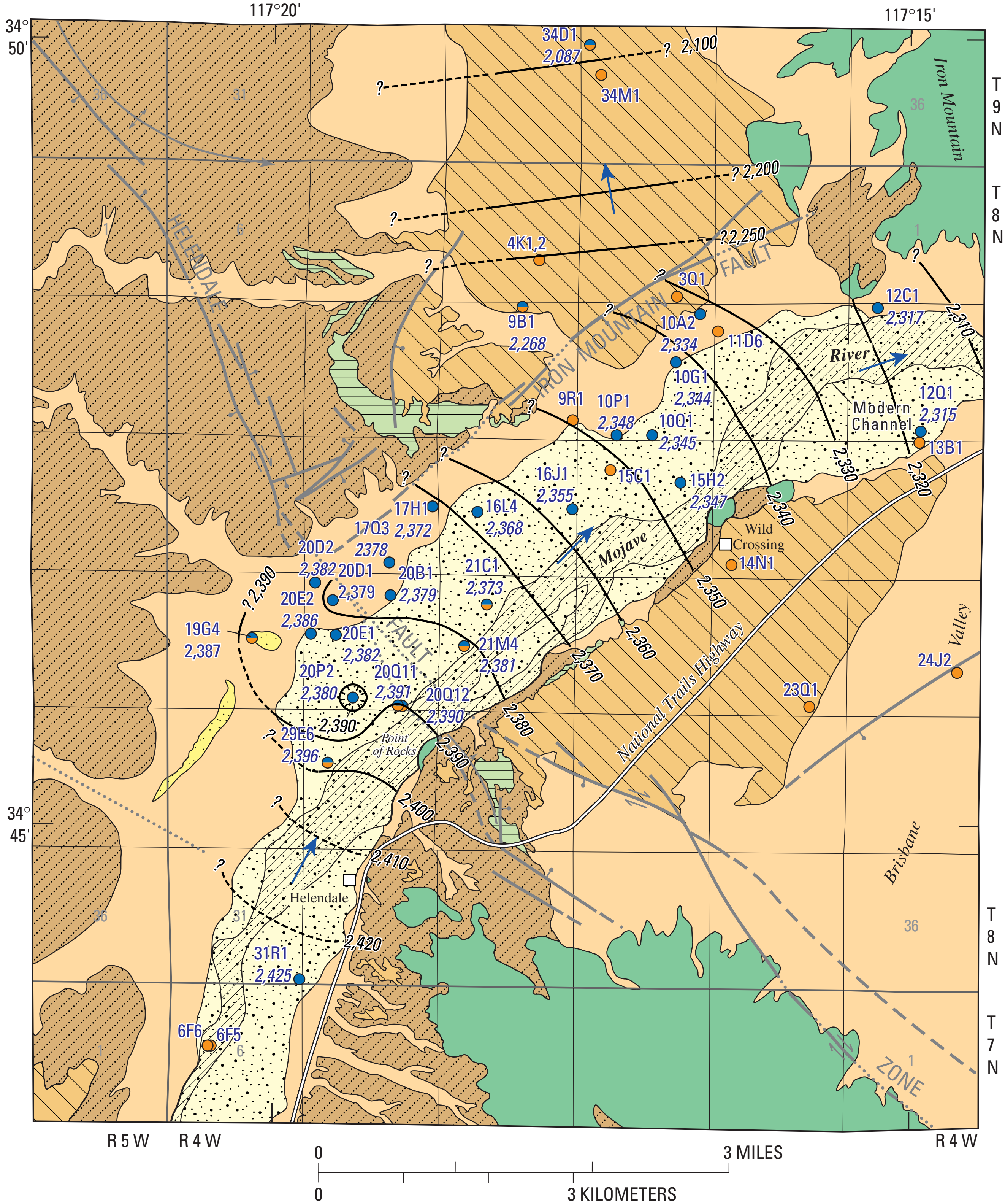


Figure 4. Water-level data and water table near Helendale, San Bernardino County, California, 1995.

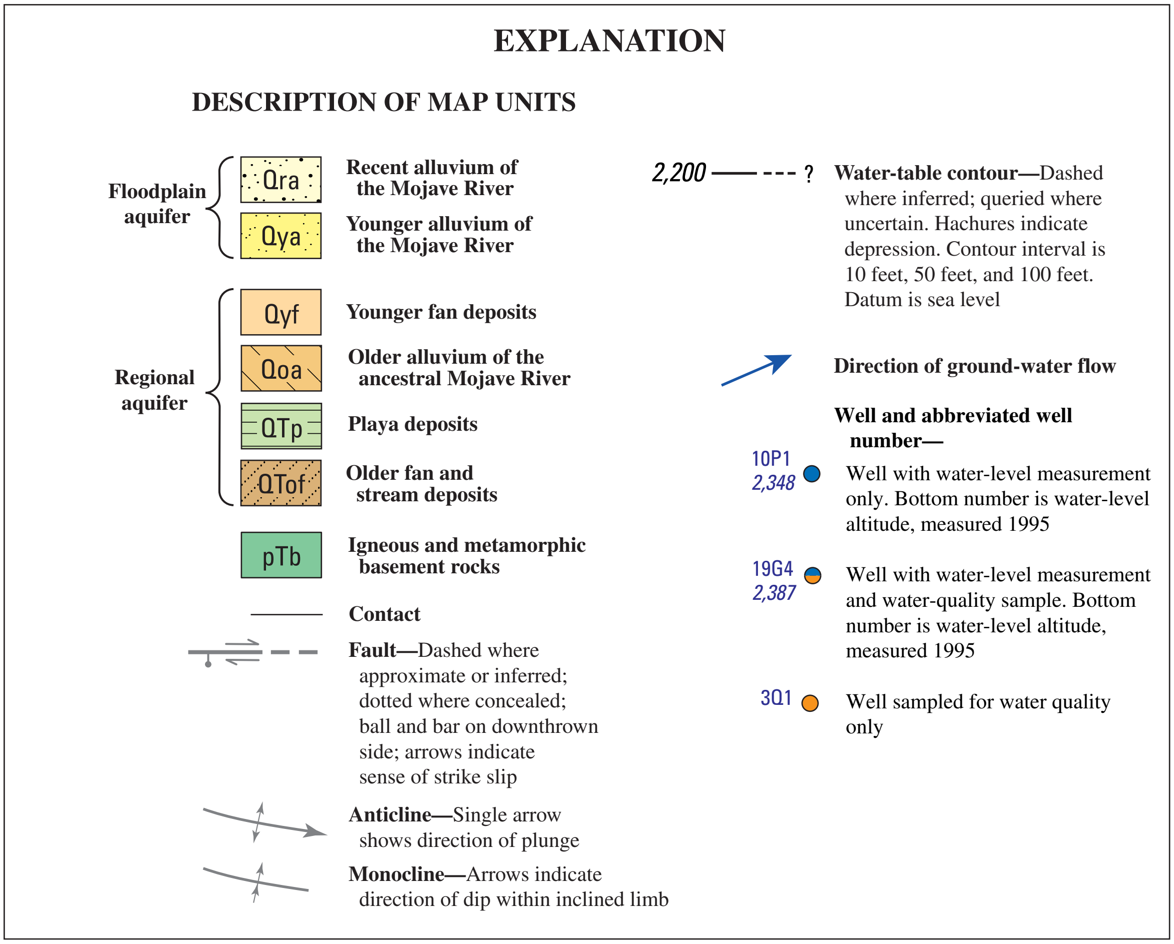


Figure 4.—Continued.

Water-level data measured during this study at two of the multiple-well monitoring sites (8N/4W-19G1–4 and 8N/4W-29E3–6) indicate that hydraulic heads are now higher in the floodplain aquifer than in the underlying regional aquifer and basement rocks upgradient from the Helendale Fault (fig. 5). The hydraulic head data imply that the gradient is now downward, from the floodplain aquifer to the regional aquifer, and that there is now the potential for water to move downward through the floodplain aquifer into the regional aquifer. This reversal in the vertical gradient since predevelopment conditions suggests that water levels have been affected, at least in part, by ground-water pumping for the community of Helendale (fig. 4). In a 2-year period (1993 and 1994) pumping in the study area averaged about 6,200 acre-ft/yr—95 percent of which was from wells that were located upgradient of the Helendale Fault (Valerie Wiegenstein, Mojave Water Agency, written commun., 1999).

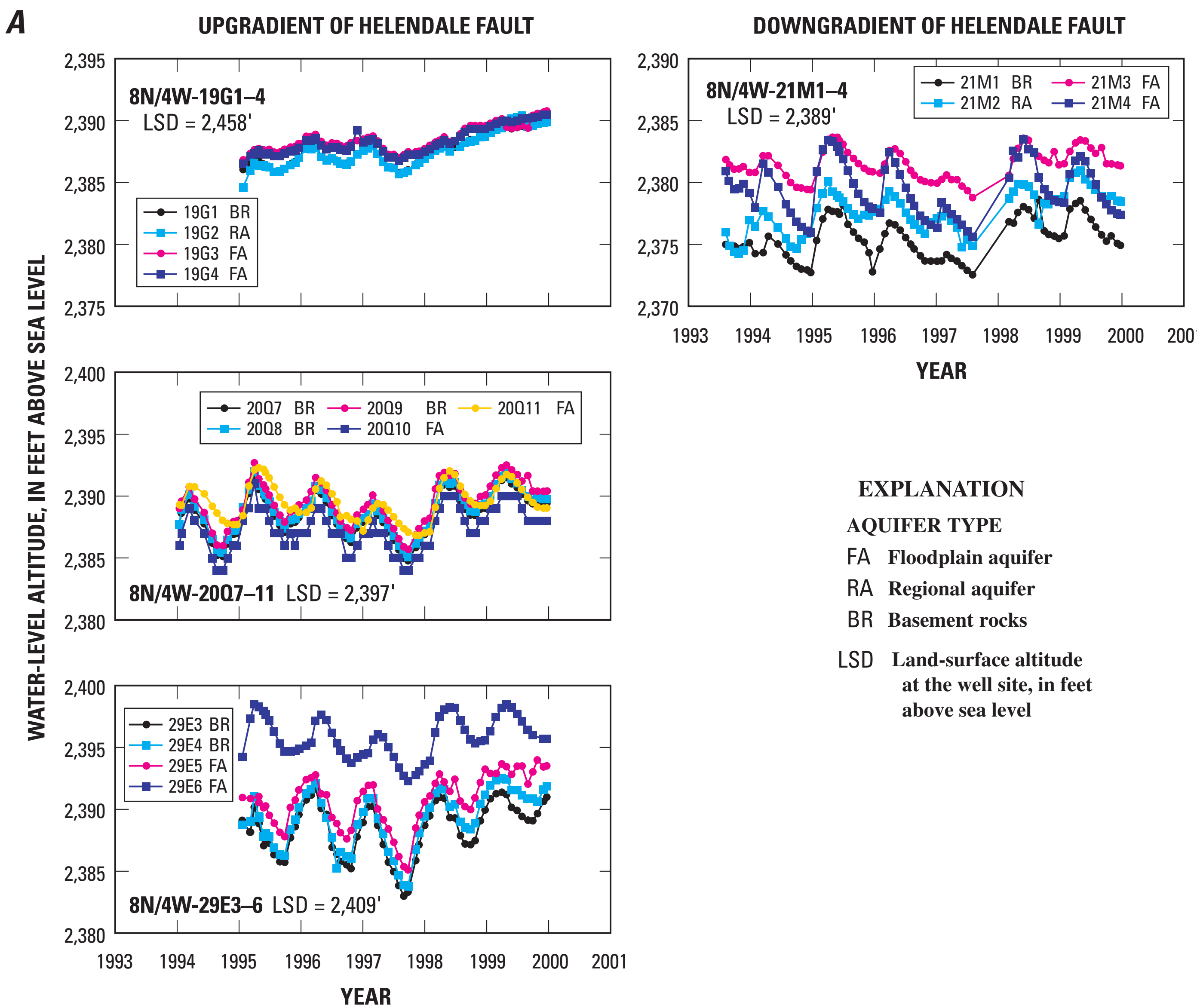


Figure 5. Water levels in wells at (*A*) multiple-well monitoring sites (1993–2001), and (*B*) selected existing wells, (1990–2001), near Helendale, San Bernardino County, California.

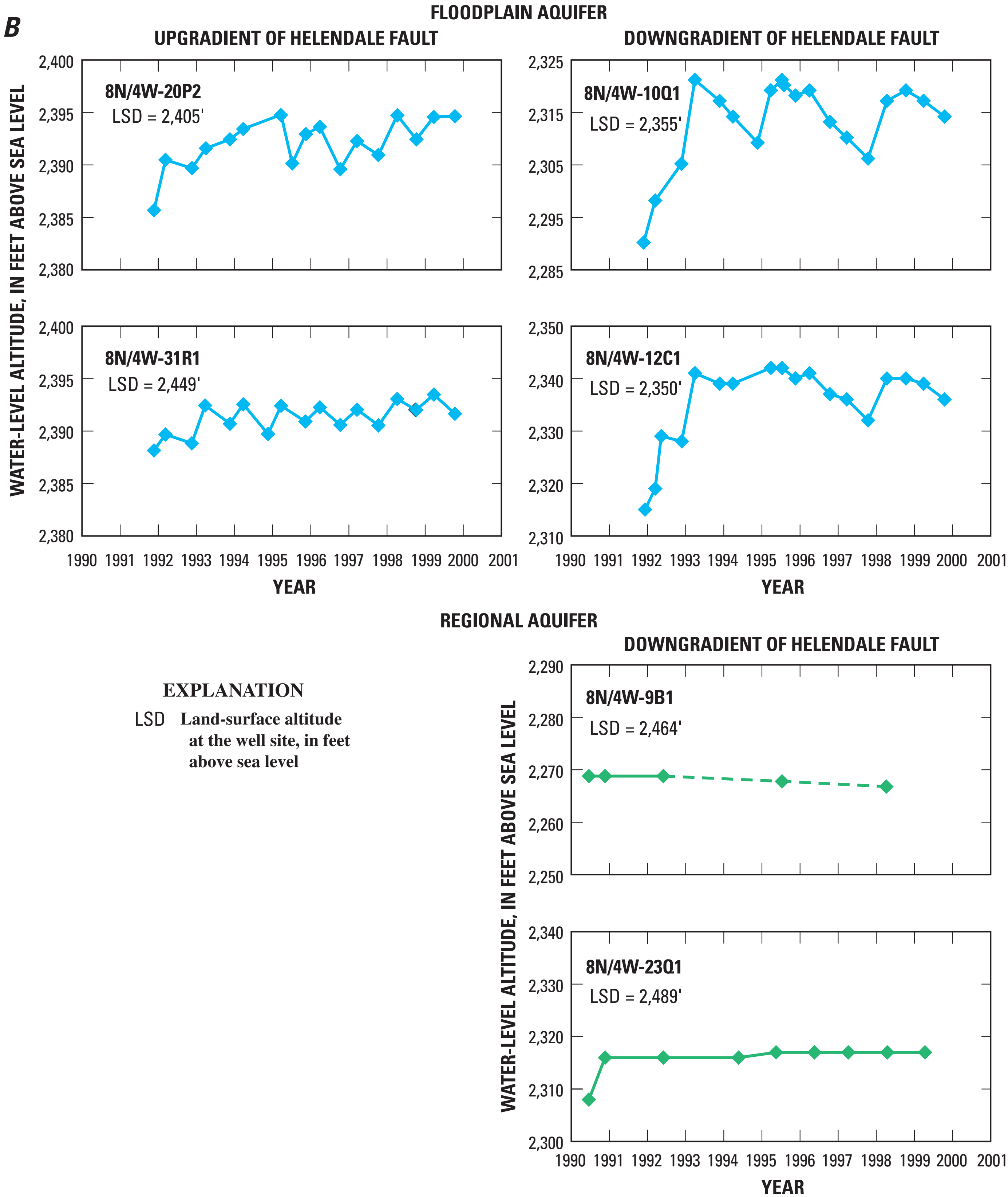


Figure 5.—Continued.

At multiple-well monitoring site 8N/4W-29E3–6 (figs. 2 and 5), there are significant differences in water levels between the upper (Qra) and lower (Qya) units of the floodplain aquifer. These differences suggest that water levels upgradient of the Helendale Fault are affected by recharge from the Victor Valley Wastewater Reclamation Authority (fig. 1). As discussed in the “Description of Study Area” section, the discharge of treated municipal wastewater by the Victor Valley Wastewater Reclamation Authority has maintained perennial flow in the Mojave River upstream from the study area since 1981.

Ground water flows across the Helendale Fault, which is the boundary between the Transition zone and the Centro subareas, through the floodplain aquifer and continues downstream toward Barstow and northward to Harper Lake (figs. 1 and 4). Flow across the Helendale Fault was estimated for several time periods using the ground-water flow model of the Mojave River ground-water basin, which spanned 69 years (Stamos and others, 2001). Flow across the fault was about 2,444 acre-ft/yr in 1930 and 720 acre-ft/yr in 1994; the average annual flow was 1,566 acre-ft for 1931–90. Water levels from the multiple-well monitoring site 8N/4W-21M1–4 indicate that ground water moves downward from the floodplain aquifer to the regional aquifer downgradient of the Helendale Fault (fig. 5). Unlike the upgradient side of the fault, the historical movement of water has been from the floodplain aquifer to the regional aquifer and underlying rocks, and therefore no reversal of gradient has taken place. Further evidence of downward ground-water movement is supported by the deuterium data from these wells, which is discussed later in the “Oxygen-18 and Deuterium” section of this report.

Water-level contours for the area between the Helendale Fault and Iron Mountain (fig. 4) indicate that some ground water flows northward from the floodplain to the regional aquifer. The existence of faults in this area may account for the steep water-level gradients shown in figure 4. Further evidence of this faulting can be seen by a precipitous drop in water levels (160 ft) between wells 9N/4W-34D1 and 9N/4W-34M1 (fig. 4) measured in 2000, which are about 0.5 mi apart in (Smith and others, 2003).

The recharge from large stormflows in the Mojave River affects water levels in the floodplain aquifer on both sides of the Helendale Fault but has little effect in the regional aquifer. During water year 1993 (October 1992 to September 1993), recharge to the floodplain aquifer between the Lower Narrows and Barstow (fig. 1) was about 190,000 acre-ft, about 487 percent of average for that reach during water years 1931–94 (Lines, 1996). Water levels near the Helendale Fault illustrate how quickly the stormflow from the winter of 1992–93 recharged the floodplain aquifer and how that recharge has continued to affect water levels for many years after it occurred, especially downgradient from the fault where depth to water is generally greater. Wells 8N/4W-10Q1 and 8N/4W-12C1 show increases in water levels of more than 20 ft immediately after the winter of 1992–93, and water levels had not declined to pre-1992–93 levels by 2000 (fig. 5*B*). Other stormflows may have helped maintain the water levels in these wells since the winter of 1992–93; however, with the exception of two smaller stormflows that reached the USGS gaging station on the Mojave River at Barstow in 1995 and 1998, streamflow records at the Lower Narrows (fig. 1) show a decline in streamflow between the winter of 1992–93 and the end of 2000 (Julia A. Huff, U.S. Geological Survey, written commun., 2003).

Aquifer Tests

Hydraulic conductivity, transmissivity, and storage coefficient values for the floodplain aquifer, regional aquifer, and basement rocks were estimated from aquifer-test data collected in June and July 1995. Interpretations of the hydraulic properties from a multiple-well aquifer test (pumping test) and single-well aquifer tests (slug tests) conducted at the multiple-well monitoring sites are summarized in table 3. The data from all the aquifer tests are on file at the USGS office in San Diego, California. Because of the disparity between the slug-test results and estimates of aquifer properties from previously published work (Hardt, 1971; Stamos and others, 2001), the aquifer properties estimated from the slug tests should be used only to compare the relative hydraulic conductivities and transmissivities of the wells within the study area.

Table 3. Hydraulic properties of water-bearing materials estimated from aquifer tests near Helendale, San Bernardino County, California

[State well No.: See well-numbering diagram in the table of contents; ft/d, foot per day; ft^2/d, foot squared per day; —, no data; <, actual value is less than value shown]

State well No.	Aquifer or unit	Hydraulic conductivity (ft/d)	Transmissivity[1] (ft^2/d)	Storage coefficient
8N/4W-19G1	Basement rocks (pTb)	7	137	3×10^{-2}
8N/4W-19G2	Regional (QTof)	—	[3]<1	—
8N/4W-19G3	Floodplain (Qya)	23	465	2×10^{-3}
8N/4W-19G4	Floodplain (Qya)	20	378	([2])
8N/4W-20Q7	Basement rocks (pTb)	<1	<1	([2])
8N/4W-20Q8	Basement rocks (pTb)	2	40	([2])
8N/4W-20Q9	Basement rocks (pTb)	<1	10	([2])
8N/4W-20Q10	Floodplain (Qya)	4	77	([2])
8N/4W-20Q10	Floodplain (Qya)	[4]9	[4]180	[4]7×10^{-4}
8N/4W-20Q11	Floodplain (Qra)	9	184	1.3×10^{-1}
8N/4W-21M1	Basement rocks (pTb)	3	58	([2])
8N/4W-21M2	Regional (QTof)	<1	2	([2])
8N/4W-21M3	Floodplain (Qya)	3	68	2×10^{-2}
8N/4W-21M4	Floodplain (Qra)	13	128	([2])
8N/4W-29E3	Basement rocks (pTb)	9	176	([2])
8N/4W-29E4	Basement rocks (pTb)	<1	6	([2])
8N/4W-29E5	Floodplain (Qya)	—	—	—
8N/4W-29E6	Floodplain (Qra)	11	113	9×10^{-4}

[1]Transmissivities were estimated from single-well aquifer tests (slug tests) using type curve solutions from Cooper and others (1967), unless otherwise noted.

[2]Storage coefficient is equal to the specific storage (10^{-6}) multiplied by the screened interval of the well (see table 2).

[3]This zone does not respond rapidly enough to calculate hydraulic values; a transmissivity of <1 ft^2/d can be assumed.

[4] Hydrologic properties estimated from multple-well aquifer test (pumping well 8N/4W-20Q12) using Hantush (1960).

A multiple-well aquifer test (pumping test) was done at well 8N/4W-20Q12 on June 6, 1995, for 6 hours and 42 minutes at 30 gal/min. The water-level responses to pumping were measured in the 2-inch monitoring wells 8N/4W-20Q7–11, located 63 ft away (figs. 4 and 6). Well 8N/4W-20Q12 is a 4.5-inch diameter well that is screened from 99 to 139 ft below land surface in the younger alluvial deposits (Qya) of the floodplain aquifer (tables 1 and 3). The data from the pumping test were analyzed using the method developed by Hantush (1960).

Water levels declined in wells 8N/4W-20Q10 and 8N/4W-20Q11 at the multiple-well monitoring site in response to the pumping test (fig. 6). Well 8N/4W-20Q10 is perforated in the younger alluvium (Qya) of the floodplain aquifer—the same as the pumping well—and had a water-level decline of about 10 ft during the test. Well 8N/4W-20Q11 is perforated in the recent alluvium (Qra) of the floodplain aquifer and had about a 0.5 ft water-level decline. Interestingly, wells 8N/4W-20Q7–9, located in the fractured basement rocks, actually had water-level increases between about 0.5 ft and almost 2 ft. This could be the result from 'unloading' in the overlying floodplain aquifer as water was being removed during the test. Additional long-term pumping tests and water-level monitoring are needed to explain the water-level increases more definitively.

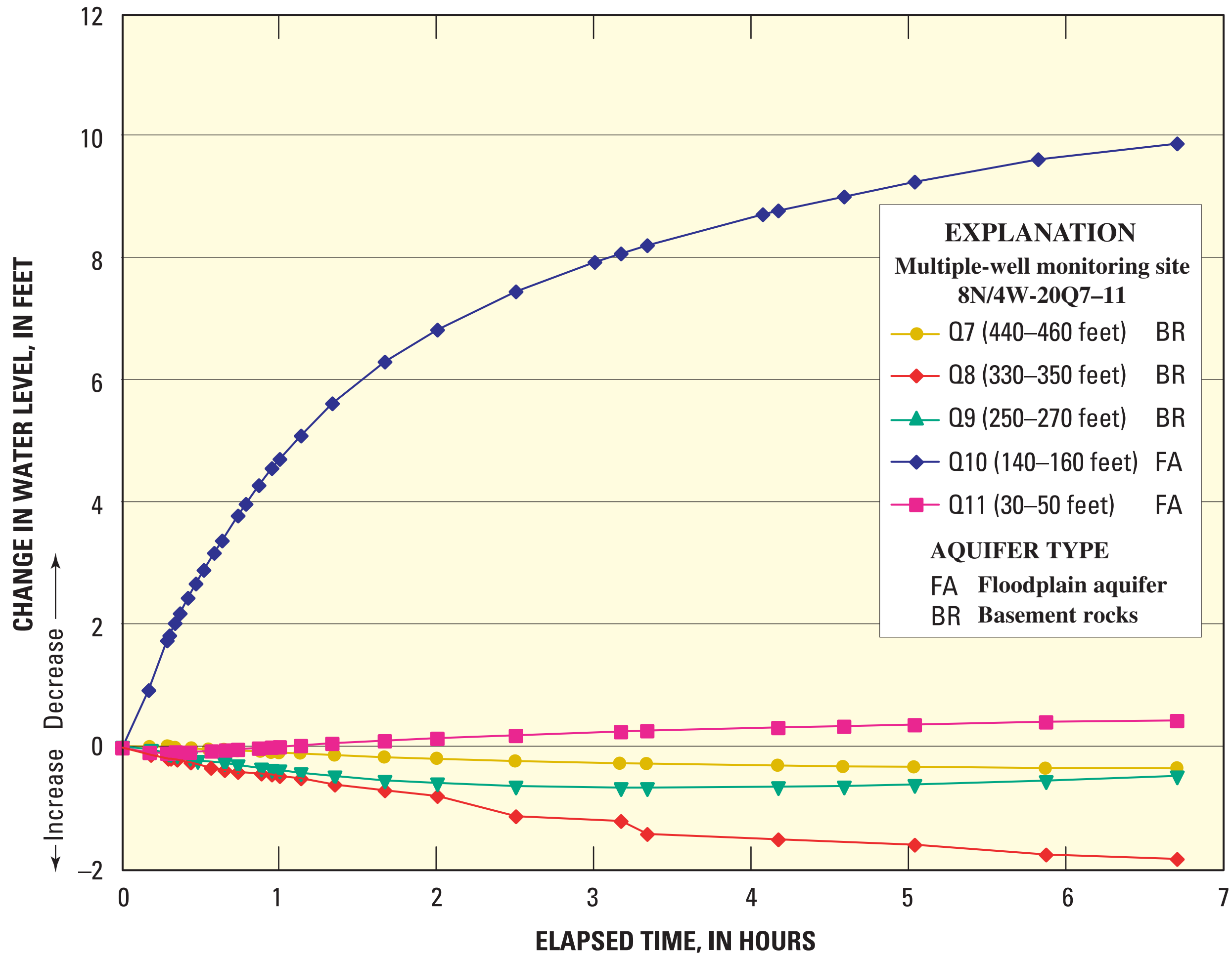


Figure 6. Changes in water levels at observation wells 8N/4W-20Q7–11, June 6, 1995, located 63 feet from pumping well 8N/4W-20Q12 near Helendale, San Bernardino County, California.

The hydraulic conductivity, transmissivity, and storage coefficient values for the floodplain aquifer calculated from the pumping test at well 8N/4W-20Q10 were about 9 ft/d, 180 ft^2/d, and 7×10^{-4}, respectively (table 3). The value of 9 ft/d for hydraulic conductivity is similar to the values for clean sand reported by Freeze and Cherry (1979) but is significantly less than the hydraulic conductivity value of about 240 ft/d estimated from aquifer-test data collected in the floodplain aquifer near Adelanto, about 10 mi south the study area (Steven Crawford, U.S. Geological Survey, written commun., 1995). However, the hydraulic conductivity value from the pumping test at well 8N/4W-20Q10 is consistent with the poorly sorted texture of the younger alluvium (Qya) in the study area, and is expected to be lower than the hydraulic conductivity values from areas upstream where coarser sediments are present. Similarly, the transmissivity value of 180 ft^2/d from the pumping test is much lower than the transmissivity values from the calibrated ground-water flow model (Stamos and others, 2001). Simulated transmissivity values from Stamos and others (2001) were between 1,000 to 20,000 ft^2/d. The storage coefficient from the pumping test and the calibrated flow model are essentially the same.

Single-well aquifer tests (slug tests) were used primarily to compare the relative hydraulic conductivities and transmissivities of the wells within the study area. These data helped confirm that coarse-grained, unconsolidated deposits encountered at depth near wells 8N/4W-19G3 and 19G4 are part of the floodplain aquifer (fig. 3). Slug tests measure aquifer response to the addition, or removal, of a slug of known volume. The slug used in this study was a 52-inch-long, 1-inch-diameter polyvinyl chloride pipe filled with sand and capped on both ends. Typical water-level displacements produced by the slug were between 1 and 2 ft—actual water-level displacement depends on how fast the slug is inserted or withdrawn from the water column within the well. Changes in water-level in response to the addition or removal of the slug were measured with a 10-pounds per square inch pressure transducer and recorded on a data logger. Computations of transmissivity were analyzed in the same manner as the pumping-test data using the method developed by Cooper and others (1967). The method of Cooper and others (1967) assumes that the aquifer is confined, homogeneous, and isotropic, and is of uniform thickness, and that flow is horizontal and radially symmetric. It further assumes that the aquifer is screened throughout its entire thickness. The values in table 3 were obtained by assuming that the aquifer thickness is equal to the length of the screened interval of the monitoring well and that the response is influenced over entire screened interval. These assumptions may account for some of the variability in the values from the slug tests. As pointed out by Cooper and others (1967), estimates of storage coefficient (S) from slug-test data are problematic because the determined value of S is extremely sensitive to the choice of the matching type curve.

Transmissivity values estimated from the slug tests for wells completed in the floodplain aquifer ranged from about 68 to 595 ft^2/d (table 3). The hydraulic conductivity values, which were derived by dividing the transmissivity values by the length of the perforated interval at each well, ranged from about 3 to 30 ft/d. Both the lowest and highest values of hydraulic conductivity in the floodplain aquifer were from wells completed in the younger alluvium (Qya) of the Mojave River. Low hydraulic conductivity values from these sediments are consistent with their poorly sorted texture, which was determined from the lithologic cuttings from the borehole. The higher hydraulic conductivity values suggests that sorting varies in the younger alluvium and that well-sorted zones have significant ability to transmit water. These values are an order of magnitude lower than those estimated from a pumping test done at a well in the floodplain aquifer near Adelanto and from the simulated transmissivity values used by Stamos and others (2001).

The value of transmissivity from well 8N/4W-21M2, completed in the older fan and stream deposits (QTof) of the regional aquifer, is about 13 ft^2/d (table 3); the corresponding value of hydraulic conductivity is less than 1 ft/d. This value of hydraulic conductivity is similar to values for silty sand reported by Freeze and Cherry (1979). However, similar to the results for the floodplain aquifer, the transmissivity values are about two orders of magnitude lower than the simulated transmissivity values used by Stamos and others (2001).

Compared with the hydraulic conductivity values from the pumping test and from the ground-water flow model (Stamos and others, 2001), the estimated values of hydraulic conductivity from the slug tests probably represent the lower range of values for the floodplain aquifer. This could be attributed, at least in part, to the poorly sorted nature of the sediments. The average permeability of the aquifer may be anomalously low in the study area because the large tributary ravines along the west side of the river supplied copious amounts of poorly sorted silty sand and gravel that are interstratified amongst the cleaner, more permeable river deposits. The assumed thickness of the aquifer material also contributes to the low values of hydraulic conductivity. It was assumed that the interval for which a slug tests was being performed—10 or 20 ft in the wells in this study—is representative of the entire aquifer. In some parts of the study area, the aquifers are considerably thicker, especially the regional aquifer. The lower values from the slug tests can also be attributed to localized but significant differences in the hydraulic properties of the aquifer material around a well, or to the localized affects that the drilling of a well may have on the sediments adjacent to the well.

Hydraulic conductivity values for seven wells completed in the underlying basement rocks ranged from less than 1 to 9 ft/d. These are similar to values for fractured igneous and metamorphic rocks reported by Freeze and Cherry (1979). The extent of fracturing of the rocks, which was observed during test drilling near the Helendale Fault, is consistent with the condition of the basement rock exposed southeast of the river at Point of Rocks (fig. 4) and may be related to deformation along the Helendale Fault.

GROUND-WATER QUALITY

Ground-water chemistry data were used to evaluate the water in the study area for compliance with the U.S. Environmental Protection Agency's maximum and secondary maximum contaminant levels. Sixty-seven ground-water samples were analyzed for major ions, nutrients, and stable isotopes of oxygen and hydrogen from 34 wells (table 1). A subset of these wells was sampled for tritium, a naturally occurring radioactive isotope of hydrogen, and ^{14}C, a naturally occurring radioactive isotope of carbon. Samples collected from selected wells between 1994 and 1997 were supplemented with data from an ongoing USGS regional monitoring network between 1990 and 2000. Some wells were sampled several times during this period; for the purposes of this discussion, results from wells having multiple analyses were averaged and the average value was used to compute the 25th quartile, median and 75th quartile values discussed in the following section. For the wells with multiple analyses, "maximum" and "minimum" values are the highest and lowest values sampled. See "Data Collection Techniques" section to download a file containing the site identification numbers for these wells. Complete analyses for all the samples can be retrieved from the USGS National database: http://waterdata.usgs.gov/ca/nwis/.

Chemical Composition of Water from Wells

Dissolved-solids concentrations in water from 14 wells sampled in the floodplain aquifer between May 1990 and November 1999 ranged from 339 to 2,330 milligrams per liter (mg/L) with a median concentration of 825 mg/L (fig. 7). Water from 11 wells exceeded the U.S. Environmental Protection Agency (USEPA) Secondary Maximum Contaminant Level (SMCL) of 500 mg/L (U.S. Environmental Protection Agency, 2002). The highest dissolved-solids concentration was in water from well 8N/4W-19G4. This well is screened near the water table and underlies agricultural fields irrigated with treated municipal wastewater from the community of Helendale. Water from this well had a nitrate concentration of 4.5 mg/L (NO_2+NO_3 was analyzed, but because NO_2 concentrations were low, NO_2+NO_3 was assumed to be in the form of NO_3, as nitrogen for all samples), the second highest nitrate concentration in water sampled from wells in the floodplain aquifer. The highest nitrate concentration was 15 mg/L (fig. 7) in water from well 8N/4W-13B1. This concentration exceeded the USEPA Maximum Contaminant Level (MCL) for nitrate of 10 mg/L (U.S. Environmental Protection Agency, 2002).

Arsenic concentrations in water from 14 wells in the floodplain aquifer ranged from less than the detection limit of 2 to 34 micrograms per liter (µg/L) with a median concentration of 6 µg/L (fig. 7). In 2006, the USEPA MCL for arsenic will be 10 µg/L. Water from six of the wells exceeded the USEPA 2006 MCL for arsenic (U.S. Environmental Protection Agency, 2002).

Dissolved-solids concentrations in water from nine wells sampled in the regional aquifer ranged from 479 to 946 mg/L with a median concentration of 666 mg/L. With the exception of well 8N/4W-21M2, at least one sample of water from all wells in the regional aquifer exceeded the USEPA SMCL for dissolved solids; however, the median dissolved-solids concentration of water from wells in the regional aquifer was lower than the median concentration of water from wells in the floodplain aquifer (fig. 7). The higher median concentration in the floodplain aquifer may occur, in part, because irrigated fields (and subsequent irrigation returns with high dissolved-solids concentrations) generally are located near the Mojave River, which overlies the floodplain aquifer. The highest nitrate concentration from the regional aquifer, 5.3 mg/L, was from well 8N/4W-9R1, located near the floodplain aquifer. Nitrogen concentrations in water from other wells in the regional aquifer did not exceed 1.4 mg/L and typically were less than 0.6 mg/L.

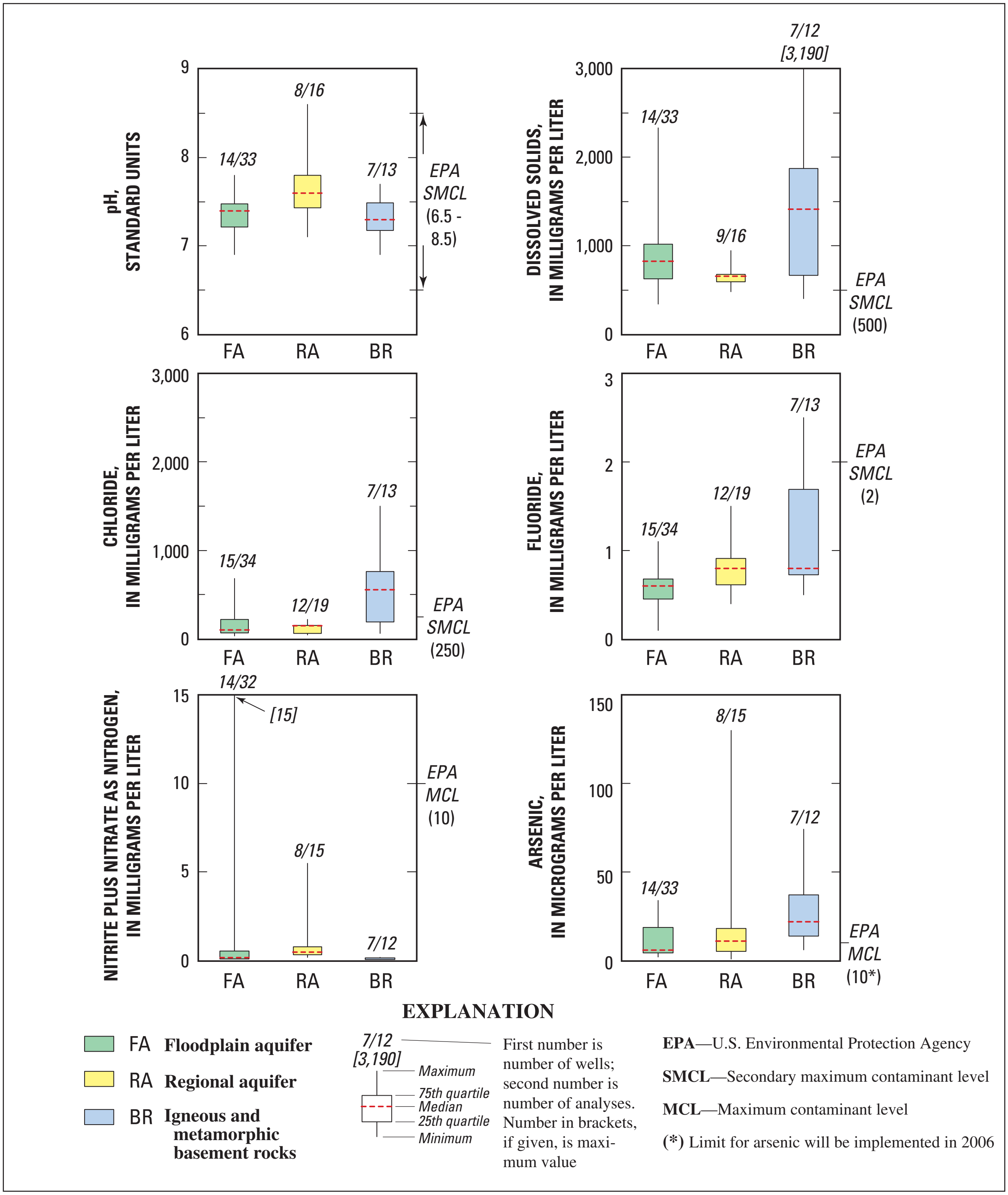


Figure 7. Concentrations of selected chemical constituents and chemical characteristics of water in the floodplain aquifer, regional aquifer, and underlying basement rocks near Helendale, San Bernardino County, California, 1990–2000.

Arsenic concentrations in water from eight wells in the regional aquifer ranged from less than the detection limit of 2 to 130 μg/L with a median concentration of 11μg/L. Water samples from five of the wells exceeded the USEPA MCL for arsenic. The median pH of water from the regional aquifer was higher than that of water from the floodplain aquifer (fig. 7) and as high as 8.6 in water from well 9N/4W-34D1. Increases in pH in the regional aquifer have been attributed to slow geochemical reactions such as silicate weathering (Izbicki and others, 1995). No water sample in the regional or floodplain aquifer exceeded the USEPA SMCL of 2 mg/L for fluoride (U.S. Environmental Protection Agency, 2002).

Dissolved-solids concentrations in water from seven wells completed in the basement rocks that underlie the floodplain and regional aquifers ranged from 400 to 3,190 mg/L with a median concentration of 1,410 mg/L. Water from all but one well sampled exceeded the USEPA SMCL for dissolved solids. Dissolved-solids concentrations were lowest in water from well 8N/4W-21M1, completed in basement rocks downgradient from the Helendale Fault. The stable isotopes of oxygen and hydrogen, discussed in the next section, show that the water from this well initially was recharged to the overlying floodplain and regional aquifers by infiltration of stormflow in the Mojave River and then flowed into the deeper deposits. Nitrate concentrations were low in the water samples from the basement rocks, typically less than 0.2 mg/L. With the exception of two wells (8N/4W-20Q7 and 8N/4W-29E3), water from the basement rocks exceeded the USEPA SMCL for arsenic of 10 μg/L. Water from most wells also contained high concentrations of chloride, sodium, calcium, sulfate, fluoride, and many other constituents. The high concentrations of the dissolved constituents are probably naturally occurring.

Isotopic Composition of Water from Wells

Samples collected from 34 of the wells in the study area between May 1993 and October 1997 were analyzed for the stable isotopes of oxygen (oxygen-18) and hydrogen (deuterium) to determine the source of water to wells and to evaluate the movement of water between aquifers. Stable-isotope data collected from five wells located about 3 mi upstream of the study area were used to supplement the data collected for this study. Selected samples were analyzed for the radioactive isotopes of hydrogen (tritium) and carbon (carbon-14) to determine the age, or time since recharge, of the ground water.

Oxygen-18 and Deuterium

Oxygen-18 and deuterium are naturally occurring isotopes of oxygen and hydrogen. Oxygen-18 and deuterium abundances are expressed as ratios in delta notation (δ) as a per mil (parts per thousand) difference relative to the standard Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1978). By convention, the value of VSMOW is 0 per mil.

Most of the world's precipitation originates from the evaporation of seawater, and the delta oxygen-18 ($\delta^{18}O$) and delta deuterium (δD) composition of precipitation throughout the world is linearly correlated and distributed along a line known as the Global Meteoric Water Line (fig. 8) (Craig, 1961). The $\delta^{18}O$ and δD composition of precipitation relative to the global meteoric water line and relative to the isotopic composition of water from other sources, provides evidence of the source of the water. For example, water from a given air mass that condensed at higher altitudes and cooler temperatures has more of the lighter isotopes of oxygen and hydrogen and plots at a different position along the meteoric water line than water that condensed from the same air mass at lower altitudes and warmer temperatures. Conversely, evaporation preferentially removes the lighter isotopes, and water that has been partly evaporated plots to the right of the meteoric water line along a line known as the evaporative trend line (fig. 8) (Gat and Gonfiantini, 1981). In some areas, the processes that occur during condensation, precipitation, or prior to ground-water recharge may create a slightly different distribution of $\delta^{18}O$ and δD data along a local meteoric water line. Information about the source and evaporative history of water can be used to evaluate the movement of water between aquifers. Because ground water moves slowly, isotopic data often preserve a record of ground-water recharge and movement under predevelopment conditions. This is especially useful in areas where traditional hydrologic data, such as water levels, have been altered by pumping, changes in recharge and discharge, or other changes that have occurred as a result of human activities.

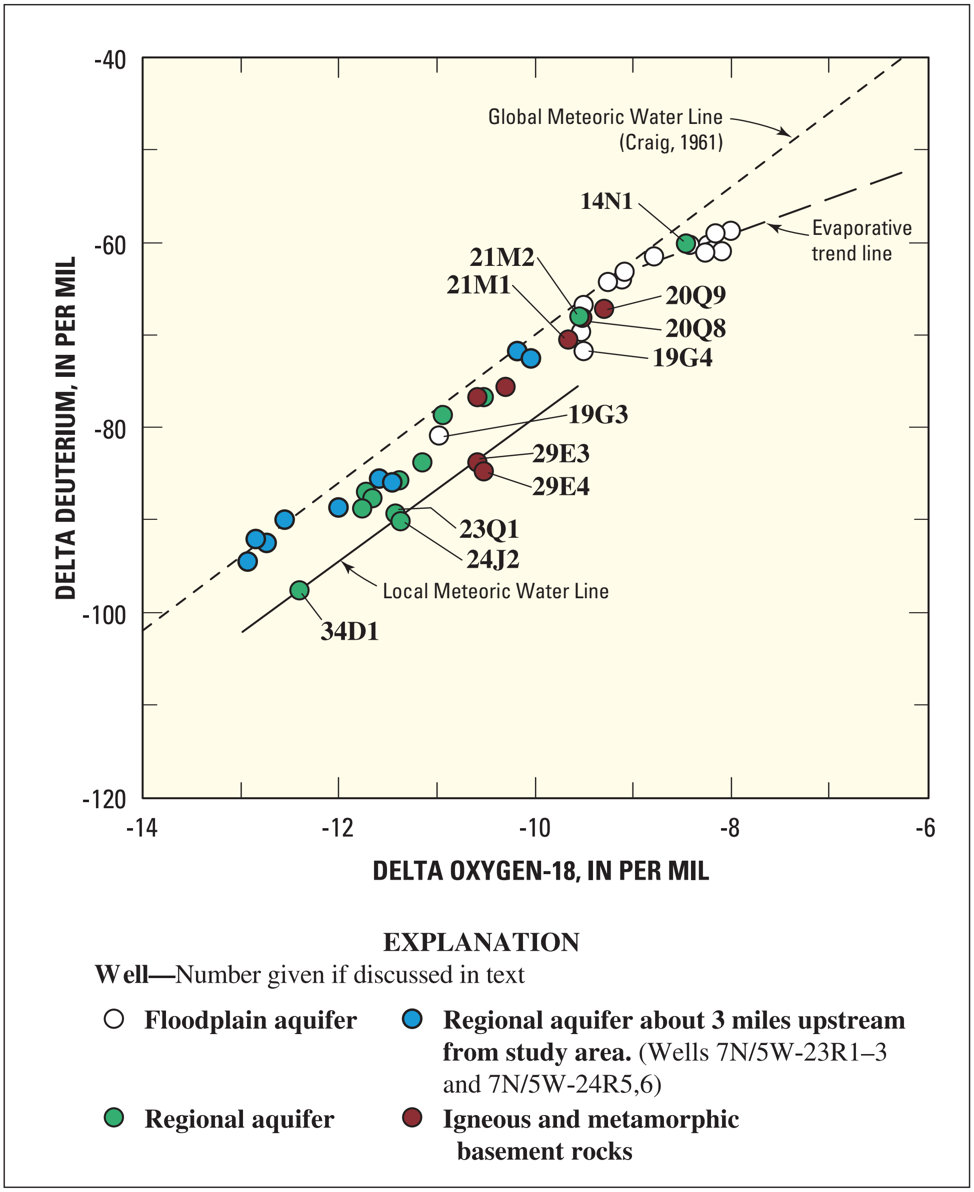


Figure 8. Delta oxygen-18 and delta deuterium from wells in the floodplain aquifer, regional aquifer, and underlying basement rocks near Helendale, San Bernardino County, California, 1994–97.

Under predevelopment conditions, the floodplain aquifer near Helendale mainly was recharged by infiltration of winter stormflows from the Mojave River. Izbicki and others (1995) showed that winter stormflow in the Mojave River was the result of precipitation at low altitudes near Cajon Pass (fig. 1) which funnels storms passing northward across the San Gabriel and San Bernardino Mountains. Cool, moist air masses associated with winter storms enter the Mojave Desert through Cajon Pass and precipitate without orographic uplift and subsequent cooling over the higher elevations of the surrounding mountains. As a result, precipitation that falls near Cajon Pass has δD values that are as much as 20 per mil heavier than precipitation that falls in the surrounding mountains (Izbicki and others, 2002). The resulting isotopic composition of the recharge and subsequent ground water has been identified by Freidman and others (1992), Gleason and others (1994), Izbicki and others (1995), and Williams and Rodini (1997) as far as Afton Canyon, almost 100 mi downstream from the headwaters of the Mojave River.

The water sampled from 15 wells in the floodplain aquifer had $\delta^{18}O$ compositions that ranged from –8.0 to –11.0 per mil (fig. 8), with a median value of –8.8 per mil. The δD composition ranged from –59 to –82 per mil, with a median value of –61.6 per mil. These values are consistent with the $\delta^{18}O$ and δD composition of water from wells in the floodplain aquifer upstream from Helendale (Izbicki and others, 1995) and the δD composition of water from wells along the Mojave River (Freidman and others, 1992; Gleason and others, 1994). The heaviest (least negative) $\delta^{18}O$ and δD values plot along an evaporative trend line (fig. 8) and are from wells having higher dissolved-solids concentrations. The lightest (most negative) $\delta^{18}O$ and δD values in the floodplain aquifer were in water from wells 8N/4W-19G3 and 8N/4W-19G4, which are near the contact of the regional aquifer (fig. 3*A*). Water from these wells was not recharged by infiltration of surface flow in the Mojave River but was discharged upward from the regional aquifer to the floodplain aquifer upstream from the Helendale Fault. As discussed earlier in the "Ground-Water Movement near the Helendale Fault" section, discharge from the regional aquifer to the floodplain aquifer upgradient of the Helendale Fault is not apparent on the basis of present-day water-level data. Water from well 8N/4W-19G4 has high dissolved solids and plots to the right of the meteoric water line as a result of evaporation.

Under predevelopment conditions, the regional aquifer was recharged largely by infiltration of surface flow from small streams near the front of the San Gabriel and San Bernardino Mountains. These streams flow intermittently as a result of runoff from winter storms and snowmelt. Due to orographic uplift and subsequent cooling, the $\delta^{18}O$ and δD composition of precipitation and resulting runoff from small streams is lighter (more negative) than the composition of precipitation that falls near Cajon Pass (Izbicki and others, 2002).

The water from 12 wells sampled in the regional aquifer had $\delta^{18}O$ compositions that ranged from –8.5 to –12.4 per mil, with a median value of –11.4 per mil (fig. 8). The δD composition ranged from –60 to –98 per mil, with a median value of –86 per mil. These values are consistent with the $\delta^{18}O$ and δD composition of water from wells in the regional aquifer located about 3 mi upstream of the study area (shown in blue in figure 8)—except that the wells in the study area plot farther to the right of the global meteoric water line than water from the upstream wells.

The heaviest $\delta^{18}O$ and δD values in the regional aquifer were in water from well 8N/4W-14N1. Water from this well had an isotopic (and chemical) composition similar to water from wells in the floodplain aquifer. This well is located in the regional aquifer downgradient from the Helendale Fault. Water from well 8N/4W-21M2, also completed in the regional aquifer downgradient from the Helendale Fault, was similarly affected, although to a lesser extent. Present-day water-level data collected from multiple-well monitoring site 8N/4W-21M1–4 are consistent with the $\delta^{18}O$ and δD data that show a downward hydraulic gradient in this area, indicating ground-water flow from the floodplain to the regional aquifer.

$\delta^{18}O$ and δD data do not indicate significant movement of water from the floodplain aquifer toward Harper Lake (dry) west of Iron Mountain. This suggests that the fault in that area (Iron Mountain Fault) (fig. 2) is an effective barrier to ground-water flow. The isotopic data are consistent with the results from the regional ground-water flow model (Stamos and others, 2001) which simulated this fault as a barrier to ground-water flow.

There is only one well (8N/4W-19G2) completed in the regional aquifer upgradient of the Helendale Fault in the study area (fig. 3*A*). Data from wells at two multiple-well monitoring sites (7N/5W-23R1–3 and 7N/5W-24R5 and 24R6) located about 3 mi upstream of the study area were used to supplement $\delta^{18}O$ and δD data near the Helendale Fault and to provide information on the isotopic composition of water from the regional aquifer upgradient from the study area. The $\delta^{18}O$ and δD composition of water from the upstream wells was similar to the composition of water from most of the wells in the study area—except that the wells located upstream plot closer to the meteoric water line. In contrast, water from three wells in the regional aquifer downgradient from the Helendale Fault (9N/4W-34D1, 8N/4W-23Q1 and 8N/4W-24J2) (fig. 4) plot farther to the right of the meteoric water line than water from wells elsewhere in the study area. Along with water from some wells in the underlying basement rocks, the data from these three wells define a local meteoric water line parallel to, and below, the global meteoric water line (fig. 8). The isotopic composition of water from these three wells is similar to the composition of water from wells in the Mojave Desert to the east of the study area that were recharged by infiltration of runoff from the local mountains. Because of the location of these wells, it is possible that they had not been recharged by infiltration of water near the front of the San Gabriel and San Bernardino Mountains but instead had been recharged by infiltration of runoff from local mountains. The shift in the meteoric water line probably is due to partial evaporation prior to recharge in the dry desert climate.

The water from seven wells sampled in the basement rocks that underlie the floodplain and regional aquifer in the study area had $\delta^{18}O$ compositions that ranged from –9.3 to –10.6 per mil, with a median value of –10.3 per mil (fig. 8). The δD composition ranged from –67 to –85 per mil, with a median value of –76 per mil. These values are between the composition of the water in the floodplain and regional aquifers. The heaviest values were in water from wells 8N/4W-20Q8 and 20Q9, which are upgradient of the Helendale Fault, and 8N/4W-21M1, which is downgradient from the fault; the water from these wells is similar in composition to the water from the wells in the floodplain aquifer. The presence of heavy δD values in the regional aquifer supports the conclusions drawn from the water-level data, which show a downward gradient of ground water from the floodplain to the regional aquifer in this area. The lightest values were in water from wells 8N/4W-29E3 and 29E4 upgradient of the Helendale Fault. The data for these wells plot along the local meteoric water line and are similar in composition to water from wells 9N/4W-34D1, 8N/4W-23Q1, and 8N/4W-24J1 in the regional aquifer. As previously discussed, this water may have been recharged as infiltration of runoff from the local mountains. Carbon-14 data, presented in the next section, show that water from these wells is very old and that recharge from this local source may no longer occur under present-day climatic conditions.

Tritium and Carbon-14

Tritium is a naturally occurring radioactive isotope of hydrogen having a half-life of 12.4 years. The concentration of tritium is measured in tritium units (TU); each tritium unit equals one atom of tritium in 10^{18} atoms of hydrogen. Approximately 800 kilograms of tritium was released as a result of the atmospheric testing of nuclear weapons between 1952 and 1962 (Michel, 1976). As a result, tritium concentrations in precipitation and ground-water recharge increased during that time. Because tritium is part of the water molecule, tritium concentrations are not affected significantly by chemical reactions other than radioactive decay. Therefore, tritium is an excellent tracer of the movement and relative age of water on timescales ranging from recent to about 50 years before present (post 1952). In this report, ground water that has measurable tritium is interpreted as water recharged after 1952.

Tritium concentrations in water from 16 wells ranged from 6.2 TU to less than the detection limit of 0.2 TU. All the wells sampled in the floodplain aquifer had measurable tritium and therefore at least some water from these wells is believed to have been recharged after 1952. Water samples containing tritium were used in conjuction with the samples from the aquifer materials obtained while drilling the multiple-well monitoring sites to confirm the depth and lateral extent of the floodplain aquifer (fig. 3). Water from only one well (8N/4W-9R1) in the regional aquifer had measurable tritium (0.9 TU). Because this well is near the floodplain aquifer (fig. 4), the relatively low tritium concentration may be due to the movement of a small amount of water from the floodplain aquifer owing to pumping. Water from most of the wells in the regional aquifer and the underlying basement rocks did not contain tritium and therefore was recharged prior to 1952.

Carbon-14 (^{14}C) is a naturally occurring radioactive isotope of carbon that has a half-life of about 5,730 years (Mook, 1980). ^{14}C data are expressed as percent modern carbon (pmc) by comparing ^{14}C activities to the specific activity of National Bureau of Standards oxalic acid: 12.88 disintegrations per minute per gram of carbon in the year 1950 equals 100 percent modern carbon. ^{14}C was produced, as was tritium, by the atmospheric testing of nuclear weapons (Mook, 1980). As a result, ^{14}C activities may exceed 100 pmc in areas where ground water contains tritium. ^{14}C activities are used to determine the age of a ground-water sample on timescales ranging from recent to more than 20,000 years before present. Because ^{14}C is not part of the water molecule, its activity in water is affected by chemical reactions that may remove carbon from solution or add carbon to solution. In addition, ^{14}C activities are affected by the mixing of younger water that has high ^{14}C activity with older water that has low ^{14}C activity. ^{14}C ages presented in this paper do not account for changes in ^{14}C activity resulting from chemical reactions or mixing and therefore are considered uncorrected ages. In general, uncorrected ^{14}C ages are older than the actual age of the associated water. Izbicki and others (1995) estimated that uncorrected ^{14}C ages were as much as 30 percent older than actual ages for ground water in the regional aquifer near Victorville, upstream of the study area. The uncorrected ^{14}C ages for ground water from the regional aquifer and the underlying basement rocks at the multiple-well monitoring sites are shown in figure 3. In general, uncorrected ^{14}C ages increase with depth and are younger near and downgradient from the Helendale Fault.

The ^{14}C activity in water from 17 wells ranged from 117 to 12 pmc (fig. 9). In general, ^{14}C activities were higher in water from wells in the floodplain aquifer and lower in water from wells in the regional aquifer and underlying basement rocks (fig. 9). There are exceptions to this general rule; ^{14}C activities may be lower in areas where water has moved between aquifers or is a mixture of water from different sources. For example, water from well 8N/4W-19G3 has a comparatively low ^{14}C activity for the floodplain aquifer—$\delta^{18}O$ and δD data indicate that water from this well originated as discharge from the regional aquifer upgradient of the Helendale Fault. In contrast, water from well 8N/4W-9R1 has a comparatively high ^{14}C activity for water from wells in the regional aquifer—tritium data indicate that water in this well contains some recently recharged water from the floodplain aquifer. Similarly, water from two wells in the underlying basement rocks, 8N/4W-20Q8 (upgradient of the Helendale Fault) and 8N/4W-21M1 (downgradient from the fault), and one well in the regional aquifer, 8N/4W-21M2 (also downgradient from the fault), have comparatively high ^{14}C activities. The $\delta^{18}O$ and δD data for these three wells indicate that they contain water from the floodplain aquifer.

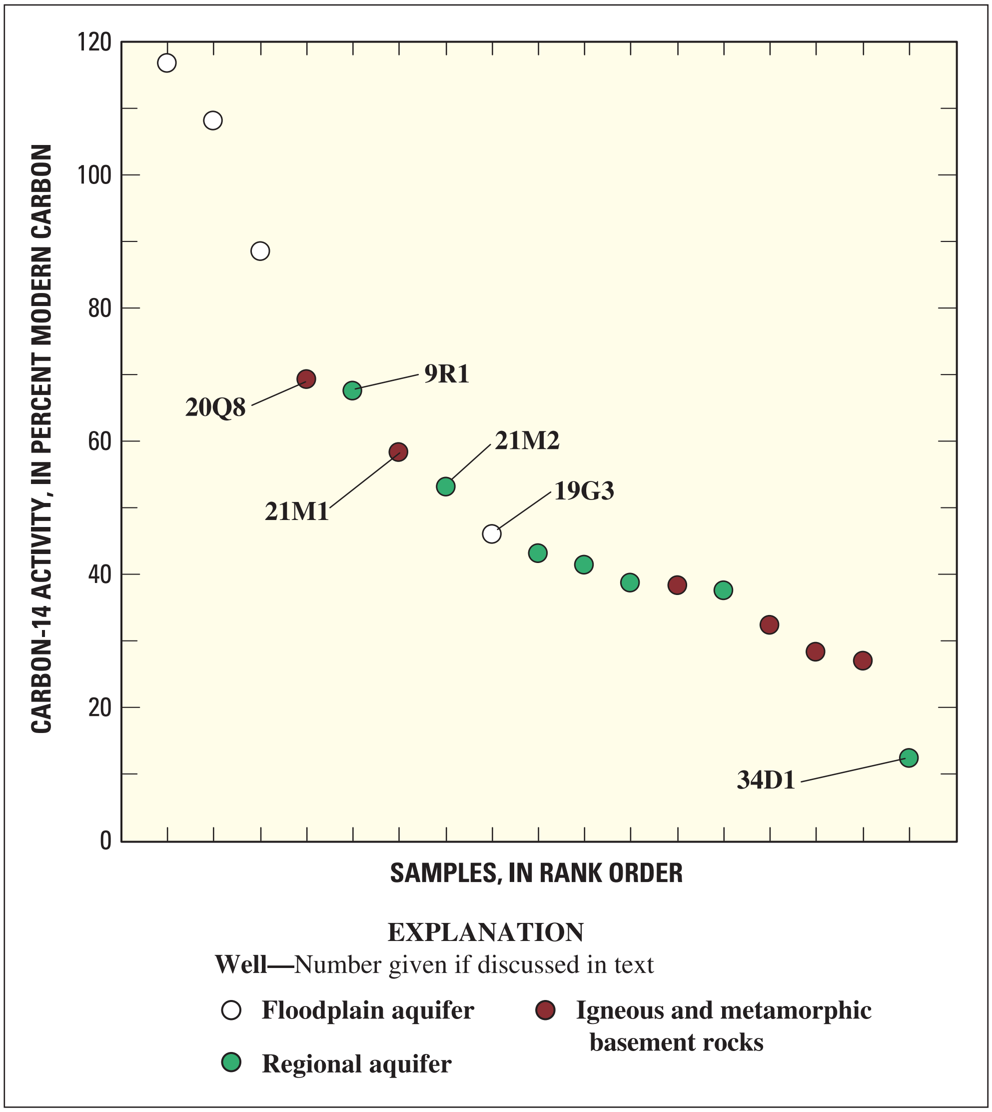


Figure 9. Carbon-14 activity of water from wells in the floodplain aquifer, regional aquifer, and underlying basement rocks near Helendale, San Bernardino County, California, 1994–97.

When the water from wells of mixed sources is excluded, the ^{14}C activity of water from wells in the floodplain aquifer, regional aquifer, and the underlying basement rocks ranged from 117 to 88 pmc, 43 to 12 pmc, and 38 to 27 pmc, respectively. These ^{14}C activities correspond to uncorrected ground-water ages which range from recent for the floodplain aquifer, from 6,980 to 17,500 years before present for the regional aquifer, and from 8,000 to 10,800 years before present for the underlying basement rocks. The great age of the water in the regional aquifer reflects the long flow paths and times of travel from the recharge areas near the front of the San Gabriel and San Bernardino Mountains. However, the $\delta^{18}O$ and δD data from well 9N/4W-34D1, which had the lowest ^{14}C activity and presumably the oldest ground water, indicate that this well was not recharged by infiltration from intermittent streams near the front of the San Gabriel and San Bernardino Mountains, but rather by infiltration of runoff from the local mountains near and within the study area. Because presumed flow paths from the local recharge areas are short, the age of this water suggests that recharge from any local sources is small and may not be occurring under present-day climatic conditions. This is consistent with the distribution of mountain-front recharge used in the ground-water flow model of the Mojave River ground-water basin by Stamos and others (2001), which did not simulate any local recharge in this area.

SUMMARY

The Mojave River Basin is located in the western part of the Mojave Desert in southern California. The proximity to the Los Angeles area has led to a rapid growth in population and, consequently, to an increase in the demand for water. The Mojave River, the primary source of surface water for the region, normally is dry—except during periods of flow after intense storms; therefore, the region relies almost entirely on ground water to meet its agricultural and municipal needs. The area around the Helendale Fault is of particular hydrogeologic interest because of its importance as a boundary between two water-management subareas of the Mojave Water Agency. The Helendale Fault is the boundary between the upper Mojave River Basin (Oeste, Alto, and Este subareas) and the lower Mojave River Basin (Centro and Baja subareas); specifically, it is the boundary of the Transition zone of the Alto and the Centro subareas. The purpose of this study was to map the surficial geology of the area near the Helendale Fault, to define the vertical and horizontal extent of the aquifers in this area, and to determine what effects the Helendale Fault has on ground-water flow and water quality. Selected wells in the study area were sampled and analyzed to determine the concentration of dissolved constituents and to approximate the age and source(s) of recharge of the water in the alluvial aquifers and underlying basement rocks.

Data from four multiple-well monitoring sites installed as part of this study were used to help determine the extent of the floodplain aquifer, the regional aquifer, and the underlying basement rocks. The insights gained by the detailed mapping of the surficial geology, stratigraphy, and effects of the Helendale Fault and other faults and folds were used in conjuction with borehole data from the multiple-well monitoring sites to reveal information about the extent of the individual aquifers and underlying basement rocks. The younger fan deposits, older alluvium of the ancestral Mojave River, older fan and stream deposits, and playa deposits constitute the regional aquifer, which underlies and surrounds the recent and younger alluvium of the floodplain aquifer. Aquifer-test data show that hydraulic conductivity and transmissivity values from the floodplain aquifer are one to two orders of magnitude higher than those for the regional aquifer.

The detailed surficial geologic mapping and the water-level measurements indicate that the Helendale Fault impedes the flow of ground water in the deeper regional aquifer, but not in the overlying floodplain aquifer. Other faults mapped in the area impede the flow of ground water in both aquifers. The historical record contains evidence of upward flow of water on the upgradient side of the Helendale Fault, but data from this study indicate that water levels in the floodplain aquifer are higher than those in the underlying regional aquifer and basement rocks. Water-level and isotopic data, primarily sampled from the multiple-well monitoring sites installed as part of this study, indicate that pumping upstream of the Helendale Fault has reversed the vertical gradient of ground-water flow since predevelopment conditions, and the potential now exists for water to flow downward from the floodplain aquifer to the regional aquifer.

Dissolved-solids concentrations in water from 14 wells sampled in floodplain aquifer ranged from 339 to 2,330 mg/L with a median concentration of 825 mg/L. Water from 11 wells exceeded the USEPA SMCL of 500 mg/L. Dissolved-solids concentrations of water from nine wells sampled in the regional aquifer ranged from 479 to 946 mg/L with a median concentration of 666 mg/L. With the exception of water from one well, at least one sample of water from all wells in the regional aquifer exceeded the USEPA SMCL for dissolved solids. Arsenic concentrations in water from 14 wells in the floodplain aquifer ranged from less than the detection limit of 2 to 34 μg/L with a median concentration of 6 μg/L. Water from six wells exceeded the USEPA MCL for arsenic of 10 μg/L. Arsenic concentrations in water from nine wells in the regional aquifer ranged from less than the detection limit of 2 to 130 μg/L with a median concentration of 11 μg/L. Water from six of these wells exceeded the USEPA MCL for arsenic. Dissolved-solids concentrations of water from seven wells completed in the basement rocks that underlie the floodplain and regional aquifers ranged from 400 to 3,190 mg/L with a median concentration of 1,410 mg/L. Water from all but one well exceeded the USEPA SMCL for dissolved solids. With the exception of two wells, water from the basement rocks exceeded the USEPA SMCL for arsenic of 10 μg/L. The high concentrations of arsenic and other constituents probably are naturally occurring.

Stable isotopes of oxygen and hydrogen indicate that under predevelopment conditions, the floodplain aquifer near Helendale was recharged by infiltration of winter stormflows from the Mojave River and that the regional aquifer was recharged by the infiltration of surface flow from small streams near the front of the San Gabriel and San Bernardino Mountains, locally supplemented by infiltration of runoff from local mountains. Tritium, the radioactive isotope of hydrogen, was present in every well tested in the floodplain aquifer, indicating that at least some of the water was recharged after 1952. Water from most wells in the regional aquifer and underlying basement rocks did not contain tritium and thus was recharged prior to 1952. Carbon-14, a naturally occurring radioactive isotope of carbon, was used to estimate the relative age of the water from wells in the regional aquifer and the underlying basement rocks. In general, uncorrected carbon-14 activities increase with depth and are relatively younger near and downgradient of the Helendale Fault. The uncorrected carbon-14 activities correspond to uncorrected ground-water ages which range from recent for the floodplain aquifer, from 6,980 to 17,500 years before present for the regional aquifer, and from 8,000 to 10,800 years before present for the underlying basement rocks. The great age of the water in the regional aquifer reflects the long flow paths and times of travel from the recharge areas near the front of the San Gabriel and San Bernardino Mountains. It is also possible that a small amount of recharge may have occurred from streams draining local mountains near and within the study area during past climatic and hydrologic conditions that were different than those of the present-day Mojave Desert.

REFERENCES CITED

Bartley, J.M., Glazner, A.F., and Schermer, E.R., 1990, North–south contraction of the Mojave block and strike-slip tectonics in southern California: Science, v. 248, p. 1398–1401.

Beukins, R.P., 1992, Radiometric accelerator mass spectrometry: Background, precision, and accuracy, *in* Taylor, R.E., A. Long, and R.S., Kra, eds., Radiocarbon after four decades: Springer-Verlag, New York, p. 230–239.

Biehler, Shawn, Tang, R.W., Ponce, D.A., and Oliver, H.W., compilers, 1988, Bouguer gravity map of the San Bernardino quadrangle, California: California Division of Mines and Geology Regional Geologic Map Series, map no. 3B, scale 1:250,000.

Boettcher, S.S., and Walker, J.D., 1993, Geologic evolution of Iron Mountain, central Mojave Desert, California: Tectonics, v. 12, p. 372–386.

Bortugno, E.J., compiler, 1986, Map showing recency of faulting, San Bernardino quadrangle, California: California Division of Mines and Geology, Regional Geologic Map Series, map no. 3A (geology), sheet 5 of 5, scale 1:250,000.

Bortugno, E.J., and Spittler, T.E., compilers, 1986, Geologic map of the San Bernardino quadrangle, California: California Division of Mines and Geology, Regional Geologic Map Series, map no. 3A (geology), sheet 1 of 5, scale 1:250,000.

Bowen, O.E., Jr., 1954, Geology and mineral deposits of the Barstow quadrangle, San Bernardino County, California: California Division of Mines, Bulletin 165, 185 p.

California Department of Water Resources, 1967, Mojave River ground water basins investigation: Bulletin 84, 151 p.

Cooper, H.H., Jr., Bredehoeft, J.D., and Papadopolous, I.S., 1967, Response of a finite diameter well to an instantaneous charge of water: Water Resources Research, v. 3, no. 1, p. 263–269.

Cox, B.F., and Hillhouse, J.W., 2000, Pliocene and Pleistocene evolution of the Mojave River, and associated tectonic evolution of the Transverse Ranges and Mojave Desert, based on borehole stratigraphy studies near Victorville, California: U.S. Geological Survey Open-File Report 00-147, 66 p.

Cox, B.F., Hillhouse, J.W., and Owen, L.A., 2003, Pliocene and Pleistocene evolution of the Mojave River, and associated tectonic development of the Transverse Ranges and Mojave Desert, based on borehole stratigraphy studies and mapping of landforms and sediments near Victorville, California, *in* Enzel, Y, Wells, S.G., and Lancaster, N., eds., Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts, Geological Society of America Special Paper 368, p. 1–42.

Cox, B.F., Hillhouse, J.W., Sarna–Wojcicki, A.M., and Tinsley, J.C., III, 1998, Pliocene–Pleistocene depositional history along the Mojave River north of Cajon Pass, California–Regional tilting and drainage reversal during uplift of the central Transverse Ranges: Geological Society of America, Abstracts with Programs, v. 30, no. 5.

Cox, B.F., and Tinsley, J.C., III, 1999, Origin of the late Pliocene and Pleistocene Mojave River between Cajon Pass and Barstow, California, *in* Reynolds, R.E., and Reynolds, Jennifer, Tracks along the Mojave: A field guide from Cajon Pass to the Calico Mountains and Coyote Lake: San Bernardino County Museum Association Quarterly, v. 46, no. 3, p. 49–54.

Craig H., 1961, Isotopic variations in meteoric waters: Science 133, 1702–1703.

Densmore, J.N., Cox, B.F., and Crawford, S.M., 1997, Geohydrology and water quality of Marine Corps Logistics Base, Nebo and Yermo Annexes, near Barstow, California: U.S. Geological Survey Water-Resources Investigations Report 96-4301, 116 p.

Dibblee, T.W., Jr., 1960a, Geologic map of the Hawes quadrangle, San Bernardino County, California: U.S. Geological Survey Mineral Investigations Field Studies Map MF-226, scale 1:62,500.

______1960b, Preliminary geologic map of the Victorville quadrangle, California: U.S. Geological Survey Mineral Investigations Field Studies Map MF-229, scale 1:62,500.

______1960c, Geologic map of the Barstow quadrangle, San Bernardino County, California: U.S. Geological Survey Mineral Investigations Field Studies Map MF-233, scale 1:62,500.

______1961, Evidence of strike-slip faulting along northwest-trending faults in the Mojave Desert: U.S. Geological Survey Professional Paper 424-B, p. B197–B199.

______1967, Areal geology of the western Mojave Desert, California: U.S. Geological Survey Professional Paper 522, 153 p., map scale 1:125,000.

Dokka, R.K., and Travis, C.J., 1990, Late Cenozoic strike-slip faulting in the Mojave Desert, California: Tectonics, v. 9, no. 2, p. 311–340.

Foster, J. H., 1980, Late Cenezoic tectonic evolution of Cajon Valley, southern California [Ph.D. dissertation]: Riverside, University of California, 243 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Freidman, Irvine, Smith, G.I., Gleason, J.D., Warden, A., and Harris, J.M., 1992, Stable isotope composition of waters in southeastern California 1. Modern precipitation: Journal of Geophysical Research, v. 97, p. 5795–5812.

Gat, J.R., and Gonfiantini, R., 1981, Stable isotope hydrology, deuterium and oxygen-18 in the water cycle: International Atomic Energy Agency, Technical Reports Series No. 210, 339 p.

Gleason, J.D., Veronda, Guida., Smith, G.I., and Friedman, Irving, 1994, Deuterium content of water from wells and perennial springs, southeastern California: U.S. Geological Survey Hydrologic Investigations Atlas HA-727, 1 map.

Gonfiantini, R., 1978, Standards for stable isotope measurements in natural compounds: Nature, v. 271, p. 534–536.

Hantush, M.S., 1960, Modification of the theory of leaky aquifers, Journal of Geophysics Research, v. 65, p. 3713–3725.

Hardt, W.F., 1971, Hydrologic analysis of Mojave River basin, California, using electric analog model: U.S. Geological Survey Open-File Report, 84 p.

Howard, K.A., and Cox, B.F., 2001, Geologic strain partitioning in the eastern California shear zone: riding crustal waves in the Mojave Desert: Geological Society of America Abstracts with Programs, v. 33, no. 3, p. 73–74.

Howard, K.A., and Miller, D.M., 1992, Late Cenozoic faulting at the boundary between the Mojave and Sonoran blocks: Bristol Lake area, California, *in* Richard, S.M., ed., Deformation associated with the Neogene Eastern California Shear Zone, southwestern Arizona and southeastern California: Redlands, California, San Bernardino County Museum Special Publication, p. 37–47.

Huff, J.A., Clark, D.A., and Martin, Peter, 2002, Lithologic and ground-water data for monitoring sites in the Mojave Water Agency Management area, San Bernardino County, California, 1992-98: U.S. Geological Survey Open-File Report 02-354, 415 p.

Izbicki, J.A., Martin, Peter, and Michel, R.L., 1995, Source, movement, and age of groundwater in the upper part of the Mojave River Basin, California, USA, *in* Adar, E.M., and Leibundgut, Christian, eds., Application of tracers in arid zone hydrology: International Association of Hydrological Sciences, no. 232, p. 43–56.

Izbicki, J.A., Radyk, J., and Michel, R.L., 2002, Movement of water through the thick unsaturated zone underlying Oro Grande and Sheep Creek Washes in the western Mojave Desert, USA: Hydrogeology Journal, v. 10, p. 409–427.

Jennings, C.W., compiler, 1994, Fault activity map of California and adjacent areas, with locations and ages of recent volcanic eruptions: California Division of Mines and Geology, Geologic Data Map no. 6, scale 1:750,000.

Lines, G.C., 1996, Ground-water and surface-water relations along the Mojave River, Southern California: U.S. Geological Survey Water-Resources Investigations Report 95-4189, 43 p.

Mabey, D.R., 1960, Gravity survey of the western Mojave Desert, California: U.S. Geological Survey Professional Paper 316-D, p. 51–73.

Matti, J.C., and Morton, D.M., 1993, Paleogeographic evolution of the San Andreas Fault in southern California: A reconstruction based on a new cross-fault correlation, *in* Powell, R.E., Weldon, R.J., II, and Matti, J.C., eds., The San Andreas Fault System: Displacement, Palinspastic Reconstruction, and Geologic Evolution: Boulder, Colorado, Geological Society of America Memoir 178, p. 107–159.

Meisling, K.E., and Weldon, R.J., 1989, Late Cenozoic tectonics of the northwestern San Bernardino Mountains, southern California: Geological Society of America Bulletin, v. 101, p. 106–128.

Mendez, G.O., and Christensen, A.H., 1997, Regional water table (1996) and water-level changes in the Mojave River, the Morongo, and the Fort Irwin ground-water basins, San Bernardino County, California: U.S. Geological Survey Water-Resources Investigations Report 97-4160, 34 p., 1 pl.

Michel, R.L., 1976, Tritium inventories of the worlds oceans and their implications: Nature, v. 263, p. 103-106.

Miller, E.L., 1977, Geology of the Victorville region, California [Ph.D. dissertation]: Houston, Texas, Rice University, 226 p.

______1981, Geology of the Victorville region, California: Geological Society of America Bulletin, Part II, v. 92, p. 554–608.

Miller, F.K., and Morton, D.M., 1980, Potassium-argon geochronology of the eastern Transverse Ranges and southern Mojave Desert, southern California: U.S. Geological Survey Professional Paper 1152, 30 p.

Mojave Water Agency, 1996, Second annual report of the Mojave Basin area watermaster: Apple Valley, California, 133 p.

Mook, W.G., 1980, Carbon-14 in hydrogeological studies, *in:* Fritz, P., and Fontes, J.C. (eds.), Handbook of environmental isotope geochemistry, volume 1 The terrestrial environment: New York, Elsevier Scientific Publishing Company, p. 49–74.

Ostlund, H.G., and Warner, E., 1962, Electrolytic enrichment of tritium and deuterium for natural tritium measurements. Tritium in the physical and biological sciences: Vienna, Austria, International Atomic Energy Agency, vol. 1, p. 96–104.

Rector, C.H., Swenson, J.D., and Wilke, P.J., 1983, Archaeological studies at Oro Grande, Mojave Desert, California: Redlands, California, San Bernardino County Museum Association, 181 p.

Rector, Carol, 1999, Human and animal trackway at Oro Grande, *in* Reynolds, R.E., ed., Fossil footprints: Redlands, California, San Bernardino County Museum Association, 1999 Desert Research Symposium, Abstracts from proceedings, p. 53–55.

Reynolds, R.E., and Reynolds, R.L., 1985, Late Pleistocene faunas from Daggett and Yermo, San Bernardino County, California, *in* Reynolds, R.E., compiler, geologic investigations along Interstate 15, Cajon Pass to Manix Lake, California: San Bernardino County Museum, p. 175–191.

______1991, Structural implications of late Pleistocene faunas from the Mojave River Valley, California, *in* Woodburne, M.O., Reynolds, R.E., and Whistler, D.P., eds., Inland southern California: The last 70 million years: San Bernardino County Museum Association Quarterly, v. 38, nos. 3 and 4, p. 100–105.

Schermer, E.R., 1993, Mesozoic structural evolution of the west-central Mojave Desert, *in* Dunn, G., and McDougall, K., eds., Mesozoic paleogeography of the western United States-II: Pacific Section SEPM, book 71, p. 307–322.

Smith, G.A., 2003, Regional water table (2000) and ground-water-level changes in the Mojave River and the Morongo ground-water basins, southwestern Mojave Desert, California: U.S. Geological Survey Water-Resources Investigations Report 02-4277, 37 p.

Smith, G.A., and Pimentel, M.I., 2000, Regional water table (1998) and ground-water-level changes in the Mojave River and the Morongo ground-water basins, San Bernardino County, California: U.S. Geological Survey Water-Resources Investigations Report 00-4090, 107 p.

Stamos, C.L., Martin, Peter, Nishikawa, Tracy, and Cox, B.F., 2001, Simulation of ground-water flow in the Mojave River ground-water basin, California: U.S. Geological Survey Water-Resources Investigations Report 01-4002, 129 p.

Stamos, C.L., and Predmore, S.K., 1995, Data and water-table map of the Mojave River ground-water basin, San Bernardino County, California, November 1992: U.S. Geological Survey Water-Resources Investigations Report 95-4148, scale 1:125,000.

Subsurface Surveys, Inc., 1990, Inventory of ground water stored in the Mojave River basins: unpublished report, prepared for Mojave Water Agency, Apple Valley, California, 47 p.

Thatcher, L.L., Janzer, V.J., and Edwards, K.W., 1977, Methods for determination of radioactive substances in water and fluvial sediments: Techniques of Water-Resources Investigations of the U.S. Geological Survey, chap. A-5, 95 p.

U.S. Environmental Protection Agency, 2002, 2002 Edition of the drinking water standards and health advisories: EPA 822-R-02-038, Office of Water, U.S., Environmental Protection Agency, Washington, DC, accessed December 3, 2002 at URL http://epa.gov/waterscience/drinking/standards/.

Walker, C.J., 1986, Back door to California--the story of the Mojave River Trail: Barstow, California, Mojave River Valley Museum Association, 337 p.

Weldon, R.J., II, Meisling, K.E., and Alexander, J., 1993, A speculative history of the San Andreas fault in the central Transverse Ranges, California, in Powell, R.E., Weldon, R.J., II, and Matti, J.C., eds., The San Andreas Fault System: Displacement, Palinspastic Reconstruction, and Geologic Evolution: Boulder, Colorado, Geological Society of America Memoir 178, p. 161–198.

Williams, A.E., and Rodini, D.P., 1997, Regional isotope effects and application to hydrologic investigations in southwestern California: Water Resources Research, v. 33, p. 1721–1729.

Woodburne M.O., and Golz, D.J., 1972, Stratigraphy of the Punchbowl Formation, Cajon Valley, southern California: University of California Publications in Geological Sciences, v. 92, 73 p.