

Hydrogeology and Geochemistry of Acid Mine Drainage
in Ground Water in the Vicinity of Penn Mine and
Camanche Reservoir, Calaveras County, California:
Second-Year Summary, 1992-93



U.S. GEOLOGICAL SURVEY
Water Resources Investigations
Report 96-4257



Prepared in cooperation with the
CALIFORNIA STATE WATER RESOURCES CONTROL BOARD
and the EAST BAY MUNICIPAL UTILITY DISTRICT

Photograph on cover is the smelting works of the Penn Mining Company at Campo Seco, California.

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Aubrey, L.E., 1908, The Copper Resources of California: Bulletin 50, California State Mining Bureau; courtesy of California Department of Conservation, Division of Mines and Geology

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Sacramento, California
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CONVERSION FACTORS, WATER-QUALITY INFORMATION, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
acre	0.4047	hectare
acre	4,047	square meter
cubic foot per day (ft ³ /d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft ² /d)	0.0929	meter squared per day
gallon per day (gal/d)	0.004546	cubic meter per day
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
square foot (ft ²)	0.09290	square meter

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

$$^{\circ}\text{F}=1.8(^{\circ}\text{C})+32.$$

WATER-QUALITY INFORMATION

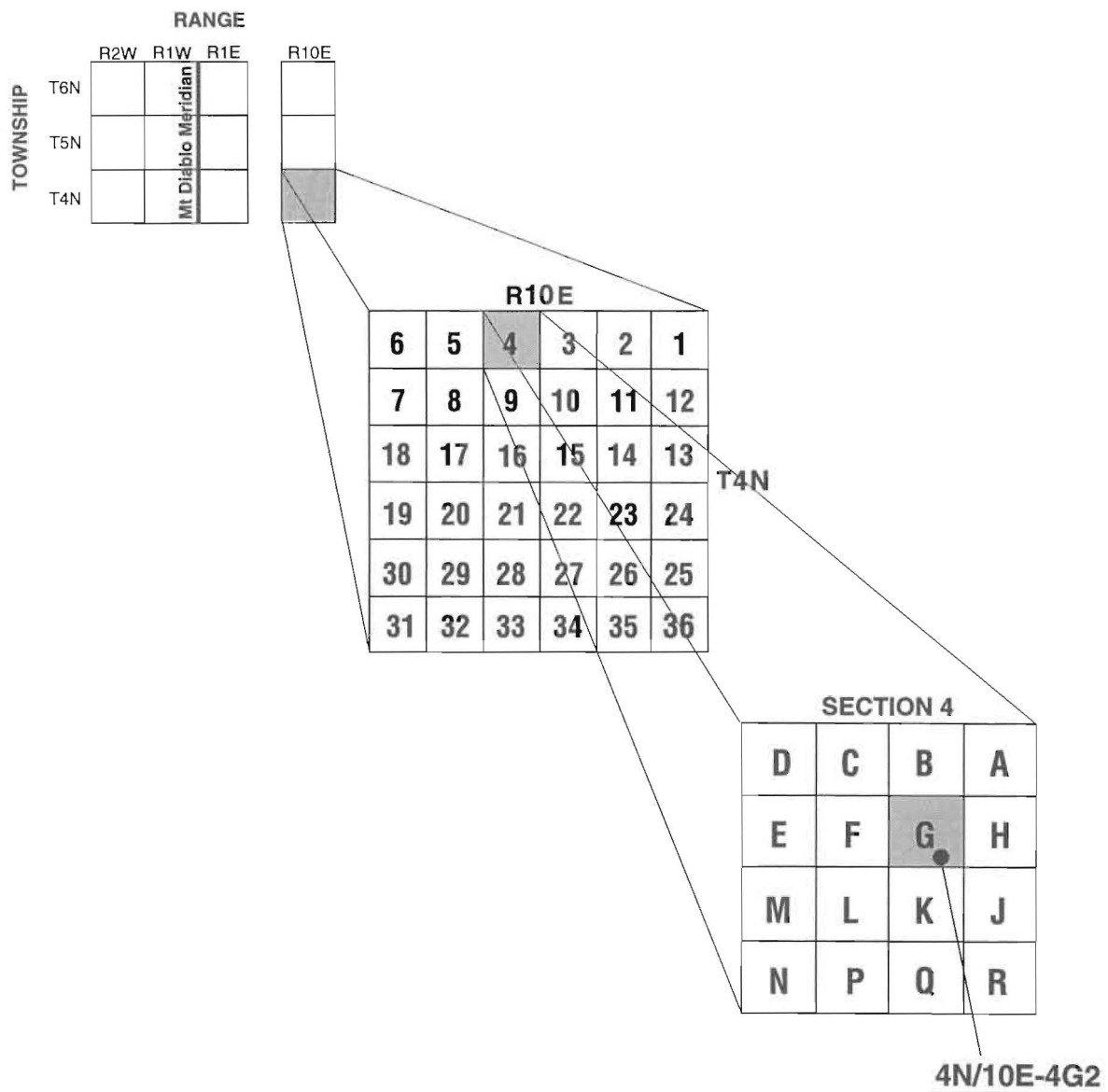
Chemical concentrations in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the mass of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For dissolved solids concentrations less than about 7,000 mg/L, milligrams per liter is equivalent to "parts per million," and micrograms per liter is equivalent to "parts per billion."

VERTICAL DATUM

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

Well-Numbering 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 Mount Diablo base line and meridian (M). Well numbers consist of 15 characters and follow the format 004N010E04G002M. In this report, well numbers are abbreviated and written 4N/10E-4G2. Wells in the same township and range are referred to only by their section designation, 4G2. The following diagram shows how the number for well 4N/10E-4G2 is derived.



Hydrogeology and Geochemistry of Acid Mine Drainage in Ground Water in the Vicinity of Penn Mine and Camanche Reservoir, Calaveras County, California: Second-Year Summary, 1992-93

By Scott N. Hamlin *and* Charles N. Alpers

Abstract

Acid drainage from the Penn Mine in Calaveras County, California, has produced a plume of contamination in ground water between Mine Run Dam and Camanche Reservoir. Historically, contaminated surface runoff from the mine flowed directly into the Mokelumne River; after the construction of Camanche Dam in 1963, the surface runoff flowed into Camanche Reservoir. Interaction of surface water with sulfide-bearing waste rock and mill tailings has produced acidic surface water with pH values between 2.3 and 2.8 and high concentrations of sulfate and metals including aluminum, cadmium, copper, iron, and zinc. Diversions and unlined impoundments were constructed in 1978 to prevent or reduce surface runoff from the mine site. Some of the impounded mine drainage infiltrates to the ground water through fractures in bedrock and flows toward Camanche Reservoir. The lowermost impoundment was treated with lime for several months during 1993 to raise pH and to immobilize contaminants, but the impoundment has since been allowed to resume its untreated condition.

This report summarizes the findings from the first 2 years of study by the U.S. Geological Survey of contaminated ground water at the Penn Mine. The distribution and flow of ground water at the Penn Mine is controlled by geologic features and hydraulic properties. Geologic controls include fractures in bedrock, faults, and the contact between the principal rock types in the area. Most flow occurs through fractures in a metavolcanic unit

along its contact with an underlying metasedimentary (slate) unit. The median hydraulic conductivity is about 10 times higher in the metavolcanic unit (0.1 foot per day) than in the slate unit (about 0.01 foot per day). Most flow occurs in the fractured metavolcanic rocks; hydraulic conductivity in this unit is as high as 50 feet per day. The general hydraulic gradient in ground water in the area between Mine Run Dam and Camanche Reservoir is westward toward Camanche Reservoir.

Field data show a close relation between water quality in Mine Run Reservoir and water quality in downgradient wells in an area covered by slag. Specific conductance at all wells increased between April and December 1992. During the same period, some wells showed a decrease in pH and an increase in dissolved metals concentration, reflecting a higher proportion of acid drainage in the ground water. Heavy stable isotopes of hydrogen and oxygen are enriched in the impounded surface water, as well as in the ground water downgradient from the impoundments. These stable isotope data indicate that the partially evaporated water in the impoundments is the most likely source of contamination to the fractured-rock aquifer in the slag area between Mine Run Dam and Camanche Reservoir.

Water from the underground mine workings is chemically distinct from ground water in the slag area. Exsolved-gas compositions in water from the flooded mine workings indicate somewhat reducing conditions. Ratios of dissolved concentrations

of zinc to copper and of zinc to cadmium are anomalously high in the underground mine water in comparison with such ratios for ground water in the slag area. These data suggest preferential scavenging of copper and cadmium, relative to zinc, by hydrogen sulfide produced by sulfate reduction in the mine workings. Variations in stable isotopes of sulfur and oxygen in dissolved sulfate are consistent with this interpretation.

Discharge toward Camanche Reservoir within the acidic ground-water plume at the base of Mine Run Dam is estimated to be about 40 cubic feet (300 gallons) per day, using an average hydraulic gradient of 0.07 and a geometric mean value for hydraulic conductivity of 0.1 foot per day based on a total of five measurements from three wells in this immediate area. The actual rates of ground-water discharge in the contaminant plume vary with plume width, hydraulic gradient, and hydraulic properties of the fractured-rock aquifer. The hydraulic gradient varies with seasonal changes in recharge and in the water level of Camanche Reservoir. For the flow rate of 40 cubic feet per day, the corresponding loadings of dissolved metals flowing toward Camanche Reservoir were estimated to be 17 grams of copper per day, 250 grams of zinc per day, and 2.7 grams of cadmium per day.

INTRODUCTION

Background

The Penn Mine is an abandoned copper-zinc mine in the Foothill copper-zinc belt in northwestern Calaveras County, California (Peterson, 1985) (fig. 1). The mine property encompasses about 140 acres (Finlayson and Rectenwald, 1978) in the drainage basin of Mine Run, an intermittent tributary to Camanche Reservoir. Mining activity at Penn Mine was active from the early 1860's to the late 1950's (Clark and Lydon, 1962). The area has 20 or more shafts,

several adits, and numerous open pits and cuts; two smelters and several mills operated at the site (Clark and Lydon, 1962). About 10.5 mi of underground workings were excavated to a depth of 3,300 ft (Heyl and others, 1948). Several acres of mill tailings and unmilled waste rock are exposed on the surface (Bond, 1988). Slag from the smelters was dumped in a 1,500-ft-long area immediately adjacent to the former channel of the Mokelumne River (Finlayson and Rectenwald, 1978). The history of the Penn Mine was presented in more detail in a report by Hamlin and Alpers (1995).

Historically, contaminated surface runoff from the Penn Mine flowed directly into the Mokelumne River. Completion of Pardee Dam, about 3 mi upstream from the mine, in 1929 decreased the streamflow available for diluting the contaminated runoff. Completion of Camanche Dam, about 9 mi downstream from the mine, in 1963 flooded part of the Mokelumne River basin to approximately 0.5 mi upstream of Penn Mine. The altitude of the spillway of Camanche Dam is 236 ft above sea level, whereas the top surface of the slag pile is about 220 ft above sea level. The slag pile along the former Mokelumne River channel is about 20 ft thick; consequently, the slag is partially or totally flooded when the reservoir pool is higher than about 200 ft above sea level (Finlayson and Rectenwald, 1978).

In response to incidents of fish mortality, several diversion channels were constructed in 1978 at the Penn Mine site to divert relatively unpolluted surface runoff around the Hinckley Run and Mine Run drainages (California Regional Water Quality Control Board—Central Valley Region, written commun., 1978, 1979). Hinckley Run drains from the northeast into Mine Run Reservoir and contains impoundments HR1, HR2, and HR3 (fig. 2). Mine Run drains from the southeast into Mine Run Reservoir and contains impoundments MR1, MR2, and MR3 (fig. 2). These seven impoundments (Mine Run Reservoir, HR1-3, and MR1-3) were constructed in 1978 to capture contaminated runoff from the Penn Mine site, replacing two or more previously existing impoundments. The Mine Run Dam was constructed from nonreactive earth materials with a clay core. The remaining dams or

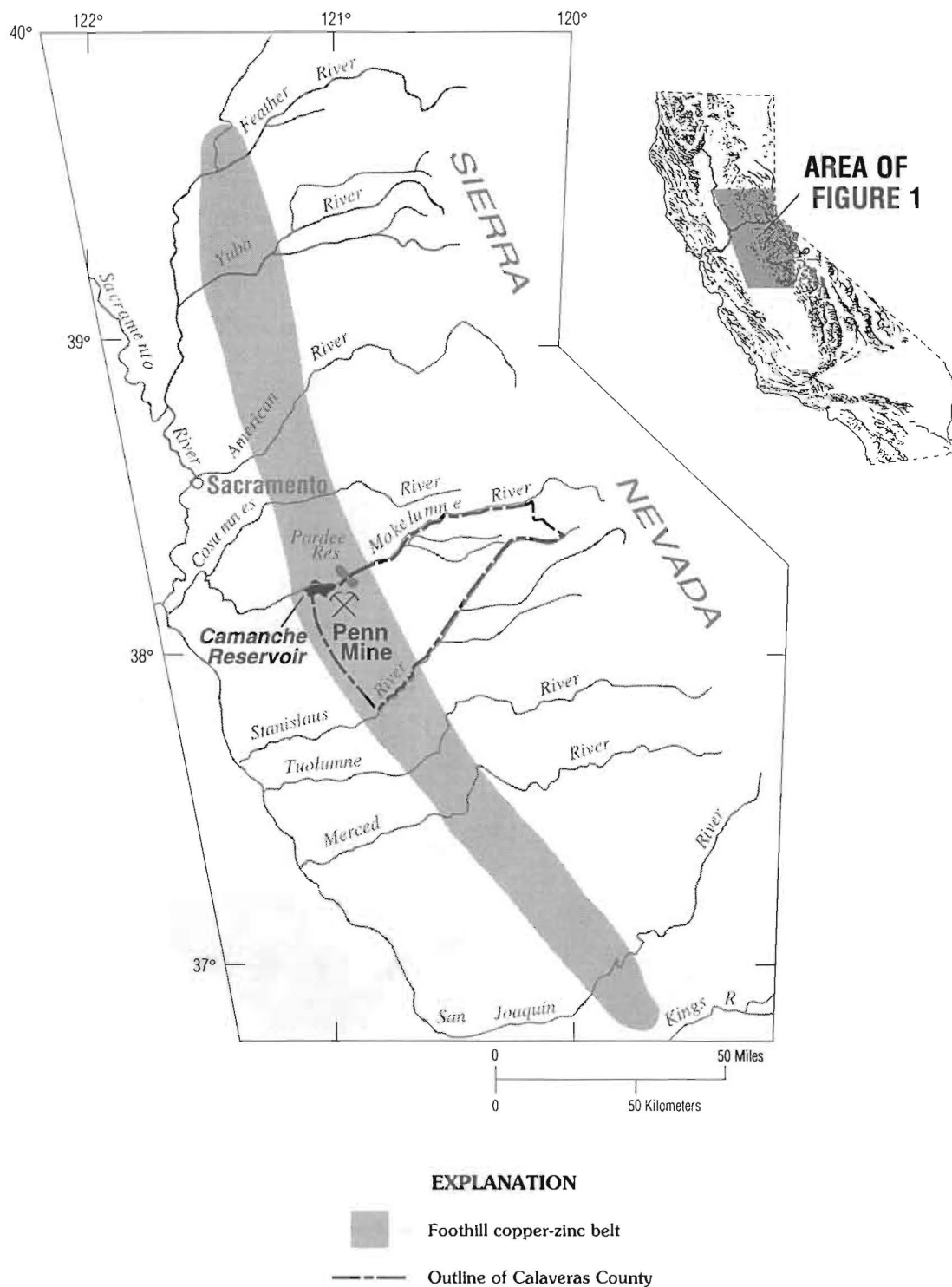


Figure 1. Location of Penn Mine and Camanche Reservoir in the Foothill copper-zinc belt of California (after Peterson, 1985).

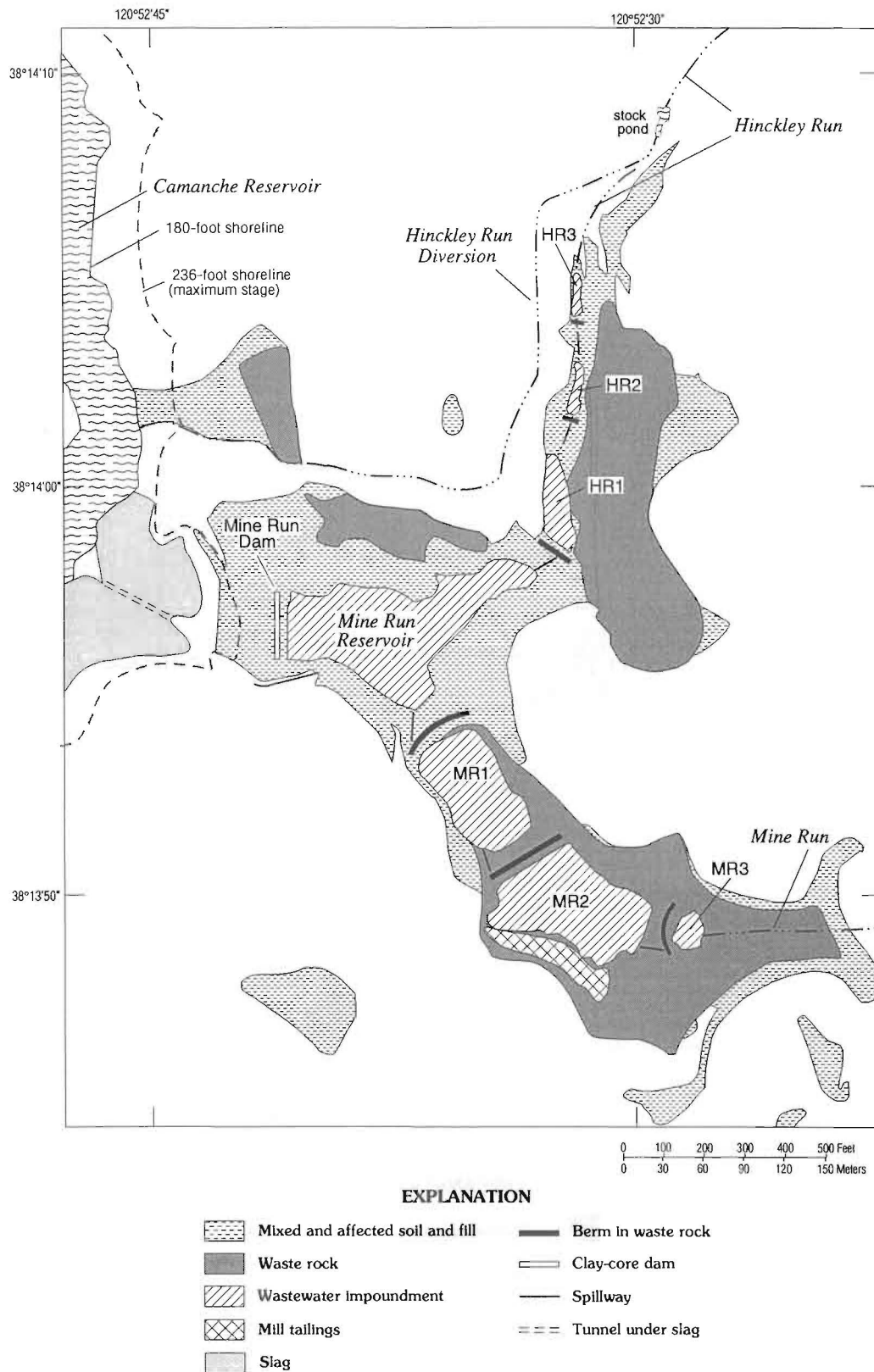


Figure 2. Penn Mine site and location of unlined wastewater impoundments, Calaveras County, California (modified from Davy Environmental, 1993).

dikes were constructed from available sulfide-bearing waste rock, mill tailings, and soil; the impoundments were not lined, with the exception of an ineffective plastic liner in pond MR1.

Construction of the unlined impoundments did not eliminate releases of surface runoff to Camanche Reservoir. Releases of surface water from Mine Run Reservoir to Camanche Reservoir occurred during wet periods in 1979 through 1984 and in 1986 (Bond, 1988). A relatively small amount of surface water discharged during February and March 1993 after Mine Run Reservoir was treated with hydrated lime [$\text{Ca}(\text{OH})_2$] to attain a pH value of greater than 7.0 (Richard Sykes, East Bay Municipal Utility District, oral commun., 1993). Recirculation of water from lower to upper ponds to reduce the volume of acid water enhanced the evaporation of contaminated waters and increased the contact time of acid drainage with the reactive waste rock and tailings (Bond, 1988). Because the impoundments are not lined, acid water can infiltrate to the ground water contained within the underlying fractured-rock aquifer. Characterization of the resultant acid ground-water plume downgradient from Mine Run Dam will facilitate management and remediation of the contamination. This study was done by the U.S. Geological Survey (USGS) in cooperation with the California Regional Water Quality Control Board—Central Valley Region (herein referred to as the Regional Board) and the East Bay Municipal Utility District (herein referred to as the Utility District).

Purpose and Scope

The ground-water investigation by the USGS in the Penn Mine area began in October 1991 and has the overall goal of characterizing the distribution of metals, sulfate, and acidity in ground water flowing through a fractured-rock aquifer. This report summarizes the findings from the first 2 years of study. In a previous report, Hamlin and Alpers (1995) presented initial findings from the first year of study. The specific objectives of the investigation are to evaluate (1) the quantity and quality of ground water flowing from the Penn Mine area toward Camanche Reservoir;

(2) ground-water transport of metals, sulfate, and acidity between Mine Run and Camanche Reservoirs; and (3) the hydrologic interactions between the flooded mine workings and other ground water and surface water in the Penn Mine area. Accomplishment of these objectives will facilitate the development of effective pollution-abatement measures (such as those described by Golder Associates, Inc., 1996) for the site.

Hamlin and Alpers (1995) described ground water in the Mine Run drainage basin between Mine Run Dam and Camanche Reservoir on the basis of data from eight boreholes drilled in 1991. This report includes data from 12 additional boreholes drilled in 1992 (eight boreholes in the vicinity of Mine Run Dam and four boreholes in the vicinity of shafts 3 and 4 in the area adjacent to pond HR2; fig. 2). Geologic, hydrologic, and water-quality data were collected during 1991-93 from the 20 USGS boreholes and 2 boreholes constructed by the Utility District and its contractors (Brown and Caldwell Consultants, written commun., 1991)¹. These data were used to describe geologic structure, ground-water movement, and the distribution of acid mine drainage in the ground-water system.

Acknowledgments

The authors acknowledge several USGS colleagues for assistance with this study. Paul A. Hsieh (Menlo Park, Calif.) assisted with the design, procurement, and installation of downhole inflatable packers. Frederick L. Paillet (Denver, Colo.) supervised field measurements and data analysis of borehole geophysics, including conventional logs (caliper, gamma, etc.), acoustic-televiwer logs, and heat-pulse flowmeter tests; assistance from Roger H. Morin and Richard E. Hodges on these tasks also is appreciated. Gas analyses were done by William C. Evans (Menlo Park, Calif.) Stable isotopes of oxygen and sulfur in dissolved sulfate were analyzed under the supervision of Robert O. Rye (Denver, Colo.). Interpretation of the hydrogeology benefitted from discussions with Clark Londquist (Sacramento, Calif.) and Anthony Buono (San Diego, Calif.). Interpretation of geochemical correlations was improved by discussions with Terry Rees (San Diego, Calif.).

¹Available from East Bay Municipal Utility District

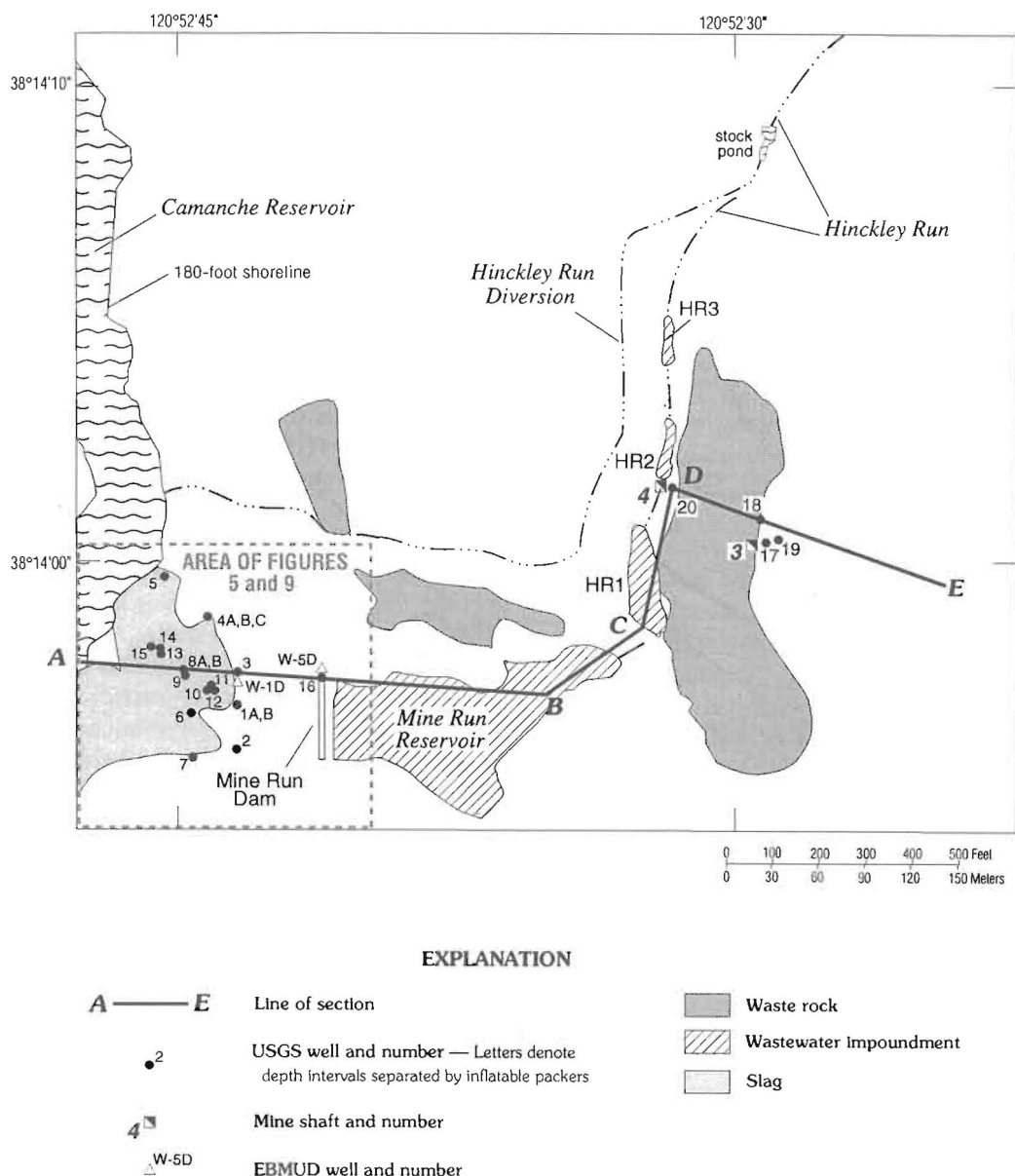


Figure 3. Location of monitoring wells and conceptual hydrogeologic section line, Calaveras County, California.

METHODS

Drilling and Well Construction

The USGS completed 20 boreholes for ground-water monitoring during 1991 and 1992 (fig. 3). Boreholes GS-1 through GS-8 were drilled in November 1991 (Hamlin and Alpers, 1995) and GS-9 through GS-20 were drilled in November

1992. All of these boreholes were drilled using the rotary air-circulation method. During drilling, compressed air was sufficient to keep the holes open; the addition of water during drilling was not necessary. Drill cuttings were monitored continuously, and samples were collected every 5 to 10 ft. Drill logs and details of well construction for wells GS-1 through GS-20 are summarized in appendix 1.

In the area between Mine Run Dam and Camanche Reservoir, two shallow (20-25 ft) boreholes (GS-9 and -10) intersected unconsolidated material consisting primarily of slag and weathered metavolcanic rock. These holes did not intersect the ground-water table at the time of drilling. Eight of the 12 boreholes drilled in 1992 were completed primarily in the metavolcanic unit. Boreholes GS-11, -13, and -14 were drilled in the metavolcanic unit in the slag-pile area between Mine Run Dam and Camanche Reservoir. The remaining five boreholes in the metavolcanic unit were located as follows: one borehole (GS-16) was drilled on the north abutment of Mine Run Dam, three boreholes (GS-17, -18, and -19) intersect inclined shaft 3 and adjacent mine workings, and one borehole (GS-20) intersects inclined shaft 4. Two boreholes (GS-12 and -15) were completed in the slate unit beneath the slag pile. Total depths of the boreholes completed during 1992 ranged from 20 ft in well GS-9 to 260 ft in well GS-18.

At drilling sites GS-9 through GS-20, a 13.75-inch-diameter rotary bit was used to drill through the overburden (alluvium, slag, and (or) waste rock) to a depth of about 6 ft, and 10-inch-diameter steel surface casing was set and sealed with a mix of bentonite and cement. For wells GS-9 and -10, which were constructed to monitor hydrologic conditions in the slag, perforated 6-inch-diameter casing was installed to the total depth of the well.

For wells GS-11, -13, -14, and -16, constructed to monitor hydrologic conditions in the metavolcanic unit (see "Hydrogeology" section of this report), an 8.75-inch-diameter hole was drilled below the bottom of the 10-inch-diameter surface casing into the metavolcanic rocks to a depth of 10 to 60 ft, generally above the contact between the metavolcanic and slate units. A 6-inch-diameter polyvinyl chloride (PVC) casing was set in the 8.75-inch-diameter hole, from land surface to 10 to 60 ft below land surface. The bottom 5 ft of annular space between the PVC casing and hole wall was filled with 0.375-inch bentonite pellets followed by hydrated mortar mix. In holes with more than 20 ft of PVC casing, non-sulfide-bearing drill cuttings were used for part of the back fill of the annular space and the upper 3 to 5 ft were then filled with hydrated mortar mix. A 5.65-inch-diameter air hammer bit was used to drill below the 6-in. casing to the metavolcanic-slate contact. The

borehole was left open from below the PVC casing to the bottom of the hole.

For wells GS-12, and -15, constructed to monitor the hydrologic conditions in the slate unit underlying the metavolcanic rocks in the slag area, an 8.75-inch-diameter hole was drilled to the metavolcanic-slate contact and 6-inch-diameter PVC casing was set to this depth in the same manner as described above. Below the 6-inch-diameter casing, a 5.65-inch-diameter air-hammer bit was used to drill 50 ft into the underlying slate unit. This part of the well was left as open borehole.

The wells constructed to monitor hydrologic conditions in the underground mine workings (GS-17, -18, -19, and -20) were constructed in a manner similar to that of the other wells constructed in metavolcanic rocks (GS-11, -13, -14, and -16), with the exception that that slate contact was not reached in the area of the mine workings. Instead, the drilling stopped when the mine workings were intersected. Of the four wells that penetrate the mine workings, GS-18 is the only one that intersects several feet of open mine workings; the other boreholes intersect shaft 3 (GS-17 and -19) or shaft 4 (GS-20), which apparently were backfilled with waste rock in 1978.

In addition to the wells constructed by the USGS for this study, several wells were drilled in 1989 and 1990 by the Utility District and its consultants (Brown and Caldwell Consultants, written commun., 1991)¹. Of these wells, W-1D and W-5D were sampled by USGS as part of the present study. Lithologic logs and details of well construction for wells W-1D and W-5D were provided by Brown and Caldwell Consultants, written commun., (1991)¹.

Segments of three boreholes drilled in 1991 were isolated for additional testing to distinguish flow and chemical characteristics of individual fracture zones. Four inflatable packers were installed for the duration of the study in three of the fractured-rock monitoring wells. Once inflated, the packers virtually eliminate vertical ground-water flow and mixing. Additional details on the construction of the packers were reported by Hamlin and Alpers (1995). Single packers were installed at sites GS-1 and GS-8. Upper intervals were designated as "A" and lower intervals as "B". The packer at site GS-1, set at a depth of 80 ft

¹Available from East Bay Municipal Utility District

below land surface, separates the upper well (GS-1A) from the lower well (GS-1B). The upper well monitors the metavolcanic unit and the metavolcanic-slate contact at a depth of 70 ft below land surface. The lower well monitors the slate unit exclusively. The packer at site GS-8 was set at a depth of 76 ft below land surface. Well GS-8A (upper interval) monitors the metavolcanic unit and the metavolcanic-slate contact; GS-8B (lower interval) monitors the slate unit. Two packers (a "straddle" assembly) were installed at site GS-4 at depths of 55 and 80 ft below land surface. The wells are designated (from shallow to deep) GS-4A, -4B, and -4C. GS-4A and -4B monitor ground water intervals in the metavolcanic unit. GS-4C monitors the metavolcanic-slate contact and the slate unit.

Geophysical Logging, Flowmeter Tests, and Water-Level Measurements

The open boreholes were logged by standard geophysical methods and by an acoustic televiewer and a heat-pulse flowmeter during December 1992. The downhole geophysical data were collected and processed by a USGS crew from Denver, Colorado, under the direction of Frederick L. Paillet. The standard geophysical logs included natural gamma, fluid temperature, single-point resistivity, fluid resistivity, short-normal resistivity (16-inch separation), long-normal resistivity (64-inch separation), and caliper. The gamma log was used to differentiate slate and metavolcanic rock units, the principal rock types encountered. The relatively high radioisotope (potassium and uranium) content of the slate gives it a distinctively high gamma response. Geophysical logs for wells GS-10, -11, -12, -13, -14, -15, -16, and -18 are provided in appendix 2. Caliper logs were the only standard geophysical data collected for wells GS-10, -12, and -18.

The acoustic televiewer uses high-frequency acoustic energy to produce a 360-degree representation of the borehole surface. It yields high-resolution information about the location, character, and orientation of fractures and other openings. The thickness or aperture of individual fractures also can be estimated from this log. The acoustic televiewer is not subject to the problems of optical clarity and distortion common to video-camera logs (Paillet and Kapucu, 1989). Acoustic televiewer images for wells GS-11, -12, -16, and -18 are included in appendix 2.

Downhole heat-pulse flowmeter tests were used to determine the magnitude and direction of flow at different depth intervals in boreholes under both static and injection conditions. The flowmeter was composed of a thermistor above and below a filament that puts out a tiny heat pulse when triggered (Hess, 1986; Paillet and others, 1987). Detection of the heat pulse by the upper or lower thermistor determines whether flow is upward or downward. The velocity of flow in the borehole is proportional to the time it takes the pulse to reach one of the thermistors. Measurement of low flow rates in the borehole is facilitated by use of an inflatable bladder, which directs all vertical flow through the meter. Low flow rates are thus amplified in proportion to the reduced cross-sectional area produced when the bladder is inflated. The lower limit of detection for this method is about 0.02 gal/min when measured in a 6-inch well (Hess, 1986). Flowmeter tests were done in wells GS-10, -11, and -16 (appendix 3).

Water-level data were collected on a monthly basis at each of the 20 USGS monitoring well sites (GS-1 through -20) when accessible. Inflatable packers were installed at sites GS-1, -4, and -8 to isolate fracture zones of interest. The remaining boreholes represent average water-level conditions over the entire length of open boreholes. Static-water-level data were collected with an electric sounder. Automated water-level recorders were installed at sites GS-1, -4, -6, and -8. Shaft encoders, in conjunction with float-counterweight mechanisms, were used at wells GS-1A, -1B, -4B, -4C, -6, -8A, and -8B. Because of space limitations, a pressure transducer was used to monitor water levels in well GS-4A. Water-level data were stored on an hourly basis with datalogger units at each of the four instrumented sites (Hamlin and Alpers, 1995).

Water-level measurements could not be obtained in wells GS-1 through -15 from early Summer 1993 until December 1993. During this period, the water level in Camanche Reservoir rose above the 220-foot level, inundating the slag area. The wells were sealed prior to submergence to prevent interchange between the reservoir and contaminated ground water. In most cases, threaded fittings with plastic screw caps were glued directly to the well casing. At sites where this was not possible, a rubber sleeve and plastic cap were attached to the top of the 10-inch steel pipe that provides the surface seal for these wells. This

required removal of the water-level recorders and associated equipment at sites GS-1, -4, -6, and -8. One of these recorders was installed at well GS-18 to monitor water-level changes in the mine workings near shaft 3.

Water-Quality Sampling

Wells at sites GS-1 through -8 were sampled during the periods January 26-February 1, 1992, and April 13-18, 1992 (Hamlin and Alpers, 1995); selected wells at sites GS-1 to -20 were sampled during December 10-22, 1992. Specific conductance, pH, temperature, dissolved oxygen, and oxidation-reduction (redox) potential (Eh) were measured in the field during pumping using a flow-through chamber to prevent aeration of the ground water. A platinum electrode was used in the flow chamber to measure the redox potential (in millivolts) of the ground water. Millivolt values were converted to Eh using the method described by Makita and Fujii (1992). After these properties had stabilized in the flow-through cell, samples were collected and processed using standard methods adopted by the USGS (Wood, 1976). At many wells, fewer than three "casing volumes" were purged because of slow recovery of water levels and low sustainable pumping rates.

Samples for anion and cation analysis were filtered through a 0.10- μ m cellulose nitrate membrane (142 mm in diameter) and a plate filter assembly. Filtered samples for cation analysis were acidified with nitric acid to a pH of about 1. All samples, except those collected for analysis of isotopes in dissolved sulfate, were submitted to the USGS National Water Quality Laboratory (NWQL) for analysis. Sulfur and oxygen isotopes in dissolved sulfate were determined by the USGS stable-isotope laboratory in Denver, Colorado, using methods described by Wasserman and others (1992).

Stable isotopes of hydrogen and oxygen were determined by the USGS NWQL using raw samples (not filtered or acidified) collected in glass bottles that were predried in an oven at 110°C. The most abundant isotopes that compose the water molecule are oxygen-16 (^{16}O), oxygen-18 (^{18}O), hydrogen (^1H or H), and hydrogen-2 (^2H ; also known as deuterium, D). The heavy isotopes ^{18}O and ^2H exist naturally in water molecules in global

average proportions of about 0.2 percent of total oxygen and 0.07 percent of total hydrogen.

Ratios of the heavy to light isotopes, R , are expressed in delta units (δ), which are parts per thousand (per mil, ‰) differences relative to an arbitrary standard known as standard mean ocean water (V-SMOW)

$$\delta (\text{‰}) = [(R - R_{\text{std}}) / R_{\text{std}}] \times 1,000, \quad (1)$$

where R and R_{std} are the isotope ratios (D/H or $^{18}\text{O}/^{16}\text{O}$) of the sample and standard, respectively. Relative concentrations of ^2H and ^{18}O , expressed as δD and $\delta^{18}\text{O}$, generally correlate in a linear fashion. Graphic representation of this relation for global precipitation data produces a straight line known as the global meteoric water line (Craig and others, 1963), defined by

$$\delta\text{D} = 8\delta^{18}\text{O} + 10. \quad (2)$$

Aqueous sulfate was precipitated as barium sulfate from filtered, unacidified samples by addition of a solution containing 1 M (molar) barium chloride. The barium sulfate precipitate was filtered, dried, and analyzed for sulfur and oxygen isotope ratios. Sulfur isotope variations are most commonly reported with regard to stable isotopes sulfur-34 (^{34}S) and sulfur-32 (^{32}S), which compose approximately 4.21 and 95.02 percent, respectively, of the natural abundance. The ratio $^{34}\text{S}/^{32}\text{S}$ relative to the standard Canyon Diablo Troilite (CDT), an iron sulfide from a meteorite, is expressed as $\delta^{34}\text{S}$ using the same notation as for δD and $\delta^{18}\text{O}$.

Exsolved gas was collected from well GS-18 in an inverted 60-mL glass bottle submerged in sample water at the discharge outlet of the flow chamber. When filled, the bottle was closed with a polyseal cap while submerged. Gas samples were analyzed by gas chromatography at the USGS laboratory in Menlo Park, California, using standard methods.

Although every effort was made to isolate zones within well bores using inflatable packers, the following concerns about water samples were recognized. Zones of low permeability in wells in which packers are installed can produce samples not representative of ambient ground-water quality because of extremely low recharge rates. Deep intervals

in wells can reflect contamination from water that cascaded downward from fractures in the overlying metavolcanic rocks prior to installation of the packers. Conversely, samples collected from the upper intervals of open boreholes might have contained water derived from the underlying slate unit.

HYDROGEOLOGY

The study area is in the western metamorphic belt of the Sierra Nevada (Clark, 1964). Marine sedimentary and volcanic rocks (see fig. 4) were deposited during the Jurassic period and then buried and metamorphosed during the Cretaceous period (Schweickert, 1981). Rocks in the vicinity include the Gopher Ridge volcanics of Jurassic age, a metavolcanic complex composed of one intrusive and five extrusive units, and the metasedimentary Salt Spring Slate, also of Jurassic age (Peterson, 1985). Metavolcanic rocks in the area have weak to intense bedding, schistosity, and cleavage that trend N. 30° W. to N. and dip steeply to the northeast or east (Peterson, 1985; Martin, 1988). Geology and mineralogy of the area were described in greater detail by Hamlin and Alpers (1995).

Massive-sulfide ore bodies are associated with the intrusive metavolcanic unit and consist primarily of pyrite (FeS_2), chalcopyrite (CuFeS_2), and sphalerite $[(\text{Zn}, \text{Fe}, \text{Cd})\text{S}]$ (Peterson, 1985; Martin, 1988). The following minerals have been identified in samples from waste-rock and tailings piles by optical examination and x-ray diffraction methods: bornite (Cu_5FeS_4), chalcopyrite, pyrite, sphalerite, galena (PbS), brochantite $[\text{Cu}_4(\text{SO}_4)(\text{OH})_6]$, covellite (CuS), halotrichite-pickeringite $[(\text{Fe}^{\text{II}}, \text{Mg})\text{Al}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}]$, and copiapite $[\text{Fe}^{\text{II}}\text{Fe}^{\text{III}}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}]$.

Geologic features controlling the movement and distribution of ground water at the Penn Mine include fractures in the bedrock, fault planes, and the contact between the major rock types in the area. Bedrock fractures that transmit ground water are chiefly near the base of the metavolcanic rock unit. The metavolcanic-slate contact, associated with the Campo Seco Fault in the western part of the study area (fig. 4), dips about 20° NE. and was encountered in boreholes at depths between 45 and 183 ft below land surface (see appendix 1; Hamlin and Alpers, 1995). The underlying slate unit has been identified as the Salt Spring Slate by Peterson

(1985) and is significantly less permeable than the overlying metavolcanic rocks. The relatively impermeable slate is likely to form a barrier to downward movement of ground water from the metavolcanic unit, causing the contact zone to act as a conduit that transmits ground water along its strike, which is generally N. 20° W.

A conceptual hydrogeologic section (fig. 4) oriented roughly east-west (fig. 3) was constructed using lithologic and topographic data from Heyl and others (1948), Davy Environmental (1993), and this study. Information on the location of the underground mine workings was taken from Heyl and others (1948). Section A-B-C-D-E (fig. 4) shows geologic features between the mine workings and slag area, as well as potential ground-water flow paths, such as along the Campo Seco Fault. Contours of the altitude of the contact between metavolcanic rocks and slate in the slag area are shown in figure 5. The disrupted area in the vicinity of well GS-7 may be explained by folding and (or) fault displacement (dotted lines in fig. 5). During drilling of well GS-7 (fig. 3), cuttings alternated between slate and metavolcanic rock, and the hole continually caved in, indicating the possible presence of a highly fractured or folded zone. In general, faults impede ground-water flow perpendicular to the fault surface and enhance flow along the fault surface. Northeast-trending faults in outcrops adjacent to the slag pile were mapped by Hunerlach and Alpers (1994). Davy Environmental (1993) also reported northeast-trending faults in other areas of the Penn Mine. On the basis of the sparse altitude data, the contact zone is interpreted as an anticlinal fold. Additional data defining the contact from new boreholes and (or) from geophysical surveys would help characterize the nature of structural deformation in this area.

Identification of Fracture Zones

The downhole acoustic televiewer records correlate well with the caliper logs. Fracture zones shown on televiewer images tend to be associated with large-diameter segments of the caliper logs. Graphical reproductions of the televiewer images for selected wells show the location and orientation of primary fractures in the boreholes (appendix 2). Well GS-16 (total depth 183 ft), located at the north abutment of Mine Run Dam, showed many large fractures (fig. 6); the most extensive fractures were between 73 and 85 ft below land surface.

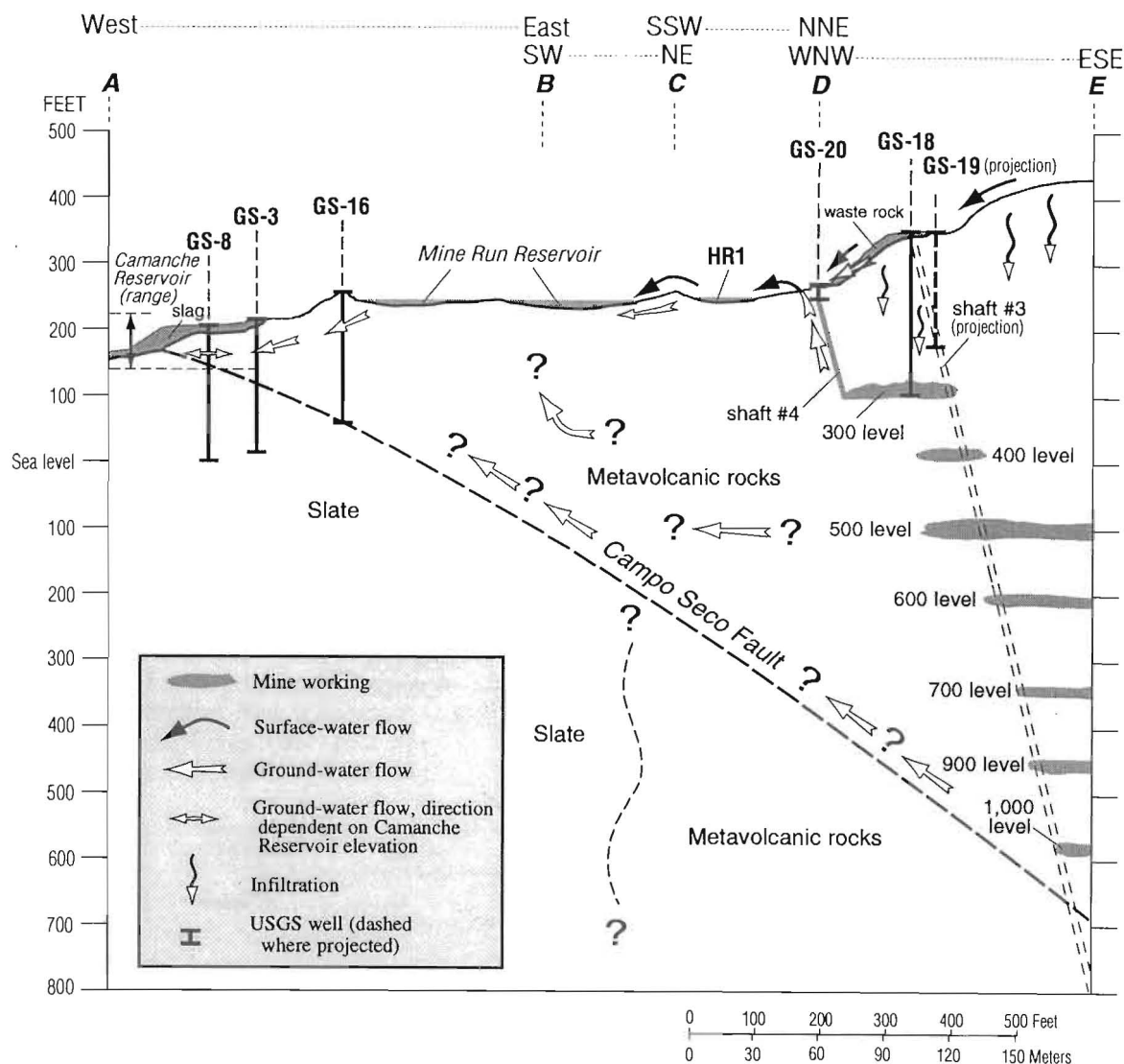


Figure 4. Conceptual hydrogeologic section A-B-C-D-E constructed using data from Camanche Reservoir; wells GS-3, -8, -16, -18, -19, and -20; and Mine Run Reservoir.

The flowmeter tests were run in static and injection modes for selected wells. Results of these tests are included in appendix 3. The flowmeter was lowered into the well in static mode, and readings were taken at several depths. Static tests were completed in boreholes GS-11, -12, and -16. Only well GS-16 yielded conclusive results in the static mode (fig. 6): The data showed downflow of approximately 0.05 gal/min between 80 and 115 ft below land surface and upflow rates of 0.04 to 0.07 gal/min between 20 and 70 ft below land surface. These static flow data indicate that the zone of highest conductance in well GS-16 is near the 80-foot depth.

In injection mode, well GS-16 showed changes in flow at four depth intervals (fig. 6), the most significant of which was at about 80 ft. An injection rate of 3.1 gal/min was used for flow measurements at depths of 60 ft and greater. For depths less than 60 ft, the injection rate was reduced to 2.0 gal/min to improve the accuracy of the measurements (appendix 3). Apparent downflow rates of 1.7 to 2.2 gal/min were recorded between depths of 15 and 50 ft below land surface; normalized to an injection rate of 3.1 gal/min, the downflow rate was constant within the uncertainty of the measurements between depths of 15 ft and 75 ft (fig. 6; appendix 3). It is interpreted that no

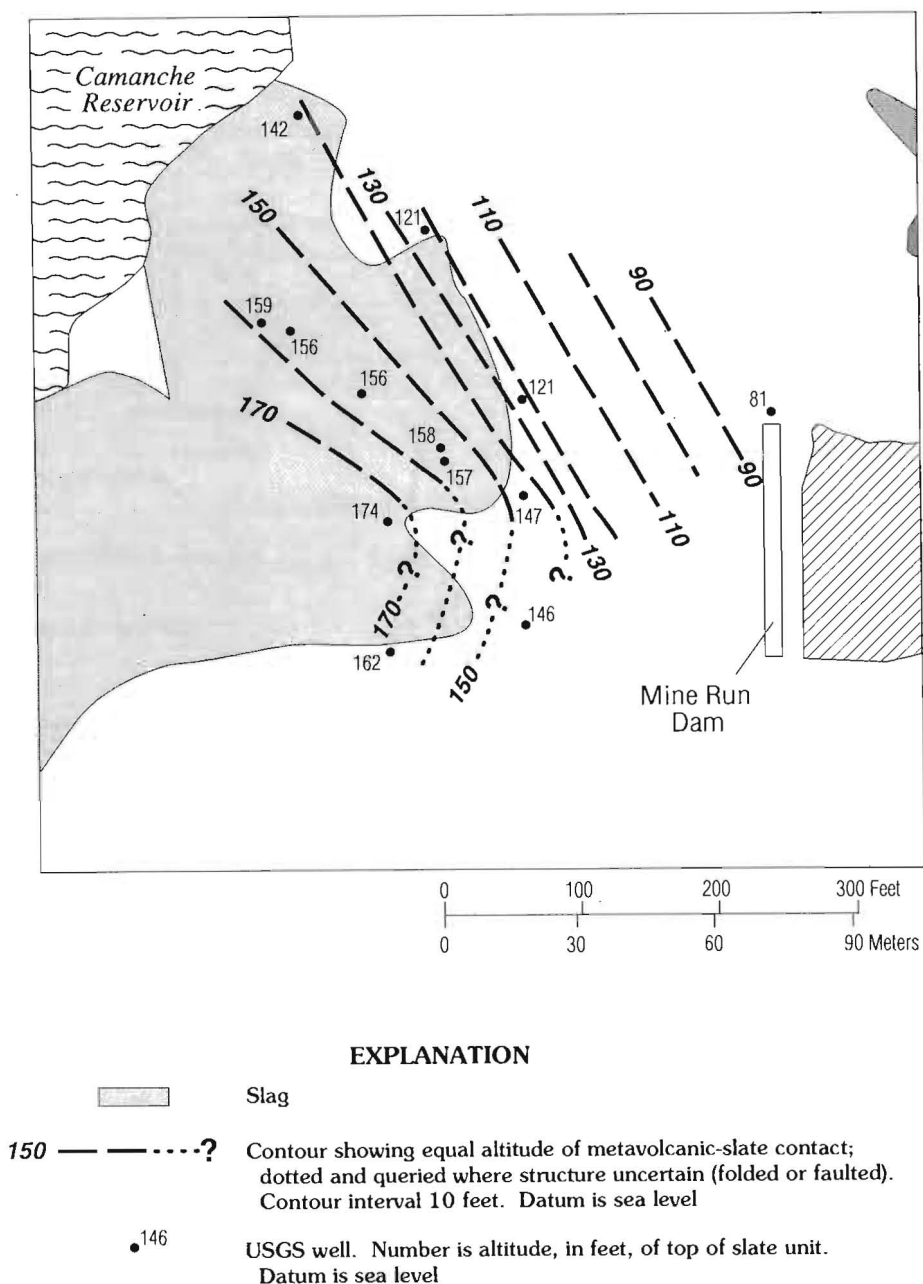


Figure 5. Subsurface altitude of the metavolcanic-slate contact, Camanche Reservoir, Calaveras County, California.

hydraulically significant fractures were present in this interval. A dramatic decrease of the downflow rate, from 3.0 to 0.20 gal/min, was recorded between 75 and 85 ft below land surface, (fig. 6). The static and injection test data for well GS-16 indicate that the most hydraulically active fracture zone is at a depth of about 80 ft below land surface and that less active fracture zones occur at depths of about 112 ft, 120 ft, and 160 ft below land surface.

Hydraulic Characteristics of Fractured Bedrock

Hydraulic characteristics of fractured bedrock were estimated for wells GS-1 through -8 by Hamlin and Alpers (1995). Values of hydraulic conductivity (K) and transmissivity (T) were estimated through (1) analysis of recovery data using the Cooper-Jacob straight-line method

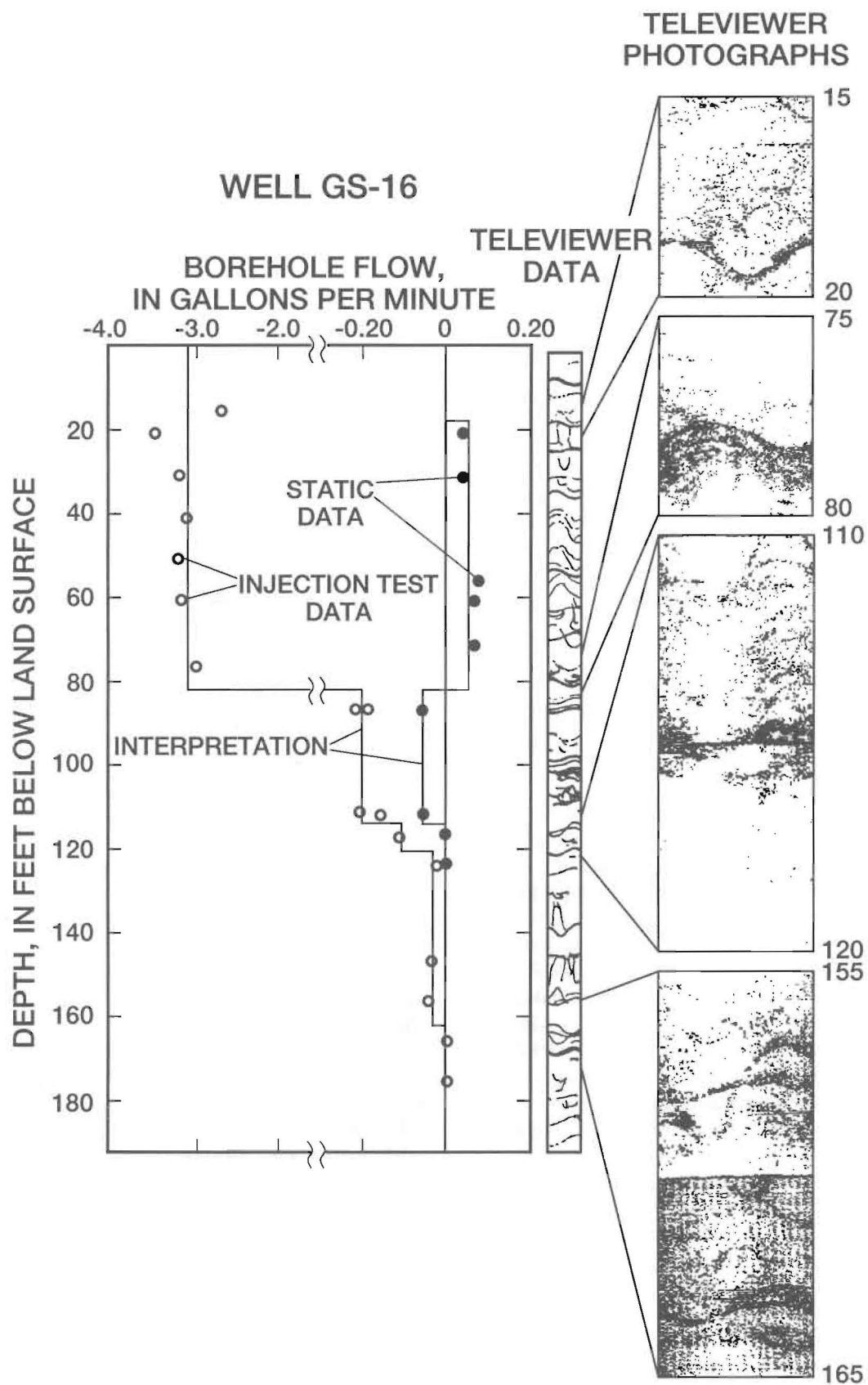


Figure 6. Flowmeter data and acoustic televiewer logs for well GS-16.

(Driscoll, 1986) and (2) analysis of specific capacity data (Huntley and others, 1992). Specific depth intervals were tested in boreholes GS-1, GS-4, and GS-8 using inflatable packers to isolate selected zones.

Using the Cooper-Jacob method, the highest calculated value for K was 57 ft/d at well GS-5, which penetrates both metavolcanic rocks and slate, as do other wells. Flowmeter tests indicate that the most hydraulically active fractures are in the metavolcanic unit primarily near the contact with the underlying slate unit. Therefore, higher K values are attributed to metavolcanic rocks, and the largest volume of ground-water flow is expected to be in a zone along or adjacent to the contact between the metavolcanic and slate units. The lowest K value was 0.008 ft/d at well GS-1B, which is open only to the slate unit.

Values for T and K calculated from specific capacity measured in April 1992 were generally within one order of magnitude of values estimated using the Cooper-Jacob straight-line method (Hamlin and Alpers, 1995). The Huntley-Nommensen-Steffey specific-capacity method consistently yielded lower values for T and K . The median value of K for the metavolcanic unit, for both methods, was about 10 to 50 times higher than that for the slate unit (Hamlin and Alpers, 1995). The median value of K for both methods was 0.1 ft/d in the metavolcanic unit. The median value of K for the slate unit ranged from 0.002 ft/d (Huntley-Nommensen-Steffey method) to 0.01 ft/d (Cooper-Jacob method).

Observations made during construction of boreholes in November 1992 indicated high values of K at some sites. Intervals in wells GS-13, -14, and -15 near the slate-metavolcanic contact yielded large volumes of ground water during drilling, probably from fractures in the metavolcanic rocks. Buildup of hydraulic pressure during airlift purging of well GS-14 caused water to flow from well GS-13, about 10 ft away, indicating a good hydraulic connection. The same fracture system provides a conduit for contaminated ground water, as discussed in the "Water Quality" section of this report.

Water Levels

Ground-water levels for USGS wells at the Penn Mine from September 1992 to November 1993 are given in appendix 4. Ground-water levels

for wells GS-1 through -8 for December 1991 through August 1992 were presented by Hamlin and Alpers (1995).

Changes in water level for wells GS-1A, -1B, -3, -8A, -16, -18, -19, and -20 for various periods during 1992-93 are shown in figure 7. Water levels in wells are highest in the eastern part of the study area and lowest near Camanche Reservoir. Water levels in wells GS-4A, -5, -8A, and -14 (appendix 4) were nearly identical to the water level in Camanche Reservoir (180-185 ft above sea level) during the period September 1992 through January 1993 (well GS-8A shown in fig. 7A). This indication of good hydraulic connection is corroborated by high hydraulic conductivity in fractures in wells GS-5 and -8A (fig. 3) (Hamlin and Alpers, 1995). Well GS-5 is closest to Camanche Reservoir at the northwest end of the slag pile, and well GS-8A is about midway between Mine Run Dam and Camanche Reservoir (180-foot shoreline; fig. 3).

The water level in well GS-16 closely correlated with the water level in Mine Run Reservoir (fig. 7A). This well is on the north abutment of Mine Run Dam (fig. 3). Water levels in well GS-16 were within about 2 ft of those in Mine Run Reservoir during the period of October 1992 to January 1993, when Mine Run Reservoir levels were at or below about 245 ft above sea level. When Mine Run Reservoir levels rose above 255 ft after March 1993, water levels in GS-16 tracked at about 3 to 4 ft below those of Mine Run Reservoir. Water-level data (appendix 4) and geochemical data (discussed in the "Water Quality" section) indicate a strong hydraulic connection between well GS-16 and Mine Run Reservoir through fractures in the metavolcanic rocks.

Water-levels for wells GS-18 through -20 in the vicinity of shafts 3 and 4 are shown in figure 7B. These wells are in the Hinckley Run drainage, with land-surface altitudes of about 280 ft (GS-20) and 362 ft (GS-18 and -19) above sea level. Shafts 3 and 4 are inclined mine workings that plunge 70° to 80° northeast (Heyl and others, 1948). These shafts intersect production stopes and haulage tunnels at different levels (fig. 4) and have been filled with mine waste and soil near the surface. Well GS-18 intersects the "300 level" of the mine workings adjacent to shaft 3 at a depth of about 250 ft; well GS-19 intersects shaft 3 at a depth of about 140 ft, an area of the shaft that had been filled with mine waste in 1978. Well GS-20 penetrates shaft 4 at a depth of about 11 ft. The water levels in wells

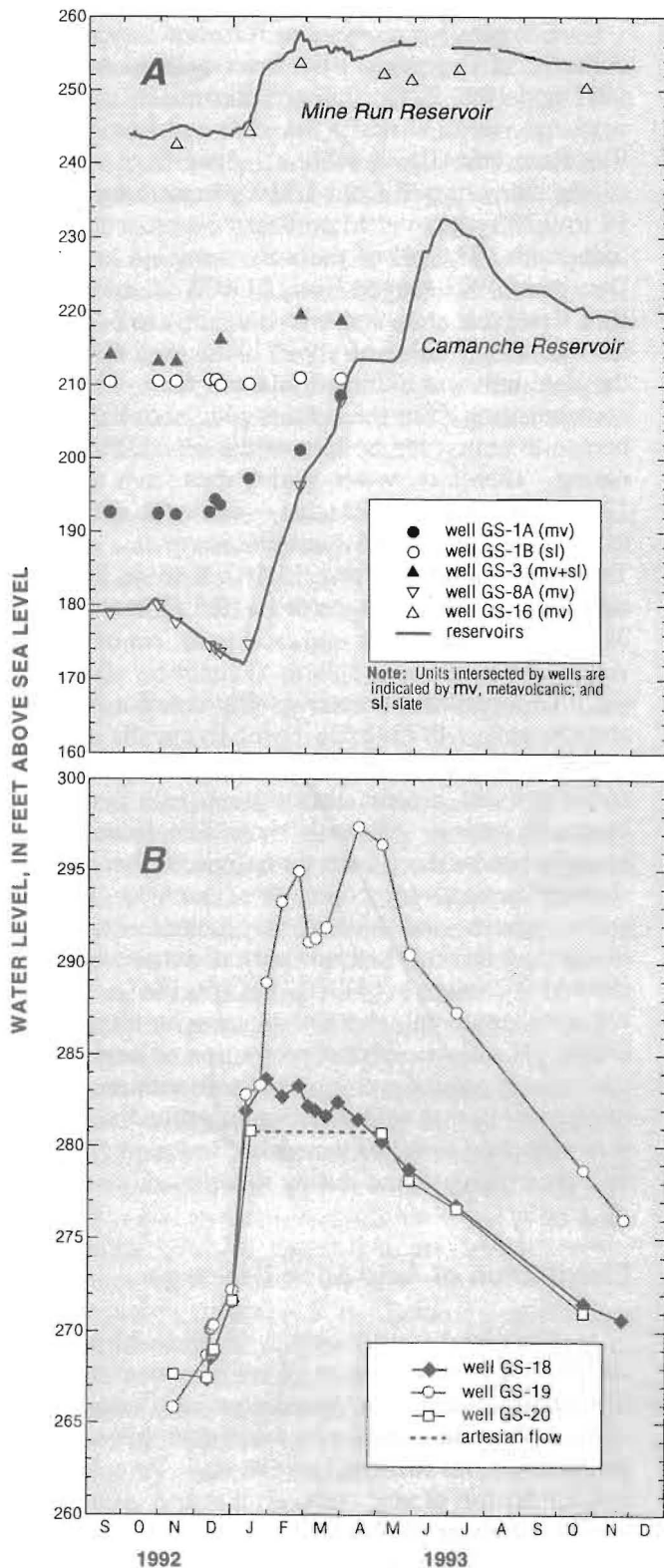


Figure 7. Water levels in Camanche and Mine Run Reservoirs, and in selected adjacent wells at Penn Mine, September 1992–November 1993 (A); and in wells GS-18, -19, and -20 at Penn Mine, November 1992–November 1993 (B), Calaveras County, California.

GS-18 and -20 were nearly identical, except during pumping, indicating hydraulic connection between shafts 3 and 4 through the underground mine workings, as reported by Heyl and others (1948). The water level in well GS-18 rose above the altitude of well GS-20, causing artesian flow from well GS-20 during the period January to May 1993. The differences in the water levels in well GS-19 relative to wells GS-18 and -20 probably reflect reduced hydraulic conductance caused by the presence of mine waste in shaft 3. During the period of artesian discharge from well GS-20 (fig. 7B), numerous seeps were observed in the bedrock in the vicinity of shaft 4. The flow rates measured from these seeps and well GS-20 were positively correlated with water levels in well GS-18 (fig. 8). Increasing flow from well GS-20 and adjacent seeps corresponded with rising water levels in well GS-18, which reflected rising ground-water levels in the mine workings.

The overall hydraulic gradient from Mine Run Dam is westward toward Camanche Reservoir (see fig. 4). However, the hydraulic gradient can vary considerably with changes in the level of Camanche Reservoir and to a lesser extent with the level of Mine Run Reservoir. Furthermore, the direction of the hydraulic gradient between ground water in the slag area and Camanche Reservoir is controlled by the level in Camanche Reservoir.

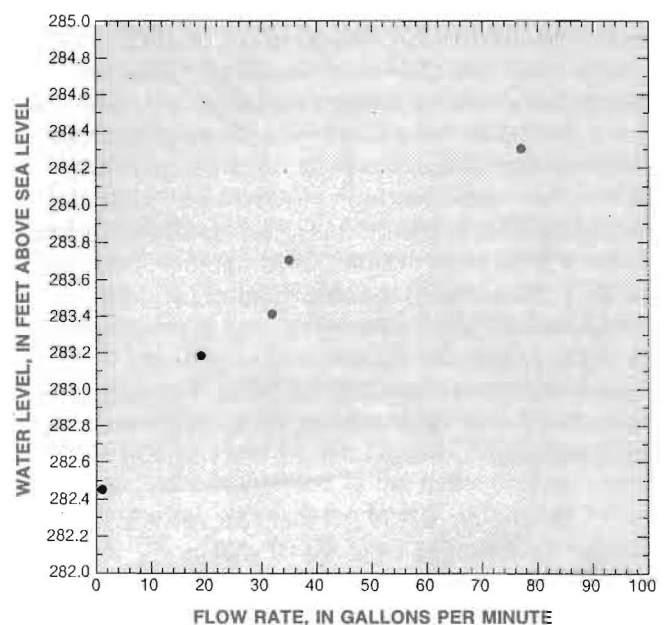


Figure 8. Relation between flow rate from seeps at well GS-20 (shaft no. 4) and water level in well GS-18 (300-foot level, near shaft no. 3) at Penn Mine, Calaveras County, California.

When Camanche Reservoir levels are low, as in the period from September 1992 through January 1993, gradients clearly are toward Camanche Reservoir. When the level of Camanche Reservoir is above about 220 feet, as in the period from May to October 1993 when the slag area was inundated, the gradients likely are reversed. The correlation of ground-water levels in the slag area with the level of Camanche Reservoir indicates that there is good hydraulic connection between the two, probably through fractures in the metavolcanic rocks.

WATER QUALITY

Results of Sampling

Water-quality data for April and December 1992 and January and July 1993 are summarized in table 1. The USGS wells were sampled in April and December 1992; Mine Run Reservoir and two Utility District wells were sampled in December 1992. A seep and one artesian well were sampled in January 1993, and another seep was sampled in July 1993. Summarized in table 2 are exsolved-gas data for well GS-18, which penetrates the mine workings near shaft 3 (fig. 3).

As part of the quality-control program, field equipment blanks were run through the sampling process, including filtration and preservation, in April and December 1992. The concentrations of most constituents determined in the field equipment blanks were less than detection limits. Calcium, magnesium, sulfate, silica, aluminum, iron, and zinc were present at concentrations near their detection limits in one of the two field blank samples and below their detection limits in the other; chloride was present at concentrations near its detection limit in both field blanks (table 1). Properties measured in the field included specific conductance, pH, temperature, dissolved oxygen, and redox potential. A depth profile for dissolved oxygen and temperature was compiled for Mine Run Reservoir at 1- and 6-foot depths using a 3-L (liter) van Dorn grab sampler.

During April 1992, values for specific conductance ranged from 1,810 $\mu\text{S}/\text{cm}$ (microsiemens per centimeter) at well GS-2 to 18,000 $\mu\text{S}/\text{cm}$ at well GS-6. The pH of sampled water ranged from 3.7 at well GS-8A to 7.8 at well GS-2. Water temperatures ranged from 17.5°C at well GS-5 to 19.5°C at well GS-3 (table 1).

Samples for analysis of water quality were collected in December 1992 from wells installed in 1991 and 1992 in the slag area and the mine workings (areas of shafts 3 and 4) and from Mine Run Reservoir (fig. 3; table 1). Specific conductance ranged from 1,710 $\mu\text{S}/\text{cm}$ at well GS-19 to 9,300 $\mu\text{S}/\text{cm}$ at Mine Run Reservoir at the 6-foot depth. The pH of the water sampled in December 1992 ranged from 2.8 (GS-20 and Mine Run Reservoir at 1- and 6-foot depths) to 6.2 at GS-4B. A pH value of about 11 for well GS-12 in the slate unit was assumed to result from contamination from the cement plug above the bentonite seal at the bottom of the 6-inch PVC casing. Therefore, water-quality data from well GS-12 were not included in table 1 and were not used to evaluate the ground-water chemistry. Temperatures ranged from 13.5°C in Mine Run Reservoir at the 6-foot depth to 19.5°C in wells GS-3 and -18 (table 1).

Comparison of water-quality data for April and December 1992 (table 1) for five wells sampled on both occasions indicates transient behavior consistent with a contaminant plume in a dynamic hydraulic setting. All wells showed increases in specific conductance with time; four of five wells showed increases in copper, zinc, cadmium, iron, and aluminum, and three of five showed increases in sulfate. During the same period, some wells showed decreases in pH. Rising specific conductance, metal, and sulfate concentration and falling pH reflect a higher proportion of acid drainage in ground water, consistent with the interpretation that acid drainage in ground water was migrating toward Camanche Reservoir (fig. 4) in a prograding plume during this period.

Distribution of Acid Mine Drainage

Dissolved constituents at the Penn Mine site are derived from oxidation of sulfide minerals and from dissolution of associated aluminosilicate and oxide-hydroxide minerals in waste-rock piles exposed at several locations on the site. Percolation and infiltration of acid mine drainage to ground water will lower pH and raise concentrations of metals and sulfate in the ground water. Another possible source of these constituents could be the dissolution of soluble sulfate minerals in bedrock intersected by the underground mine workings. The generation of acid mine drainage was discussed in greater detail by Hamlin and Alpers (1995).

Table 1. Chemical data for water samples from Mine Run Reservoir, wells, and two seeps at the Penn Mine, Calaveras County, California

[State well number: All wells are in 4N/10E, township and range. MRR, Mine Run Reservoir; MRD, Mine Run Dam. °C, degrees Celsius; ft, foot; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; µg/L, microgram per liter (divided by 1,000 = milligrams per liter); <, actual value is less than value shown; δD, delta deuterium; δ¹⁸O, delta 18-oxygen; δ³⁴S, delta 34-sulfur; --, no data]

Well or sample site	State well No.	Date	Depth of well, total (ft)	Specific conductance (µS/cm)	pH water whole field (standard units)	Eh, Redox potential (mV)	Temperature, water (°C)	Oxygen dissolved (mg/L)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)
GS-1A	4G1A	4-17-92	80	4,950	5.1	460	18.0	--	480	350	280
		12-15-92	80	4,980	4.6	499	18.5	0.2	470	400	270
GS-1B	4G1B	4-18-92	200	5,980	7.2	263	18.5	--	480	260	810
GS-2	4G2	4-14-92	200	1,810	7.8	319	18.5	.9	72	34	320
GS-3	4G3	4-15-92	200	4,600	4.8	451	19.5	1.7	440	550	57
		12-19-92	200	5,660	5.1	446	19.5	.2	510	690	100
GS-4A	4G4A	4-16-92	55	2,430	5.7	387	18.5	--	210	260	29
		4-16-92	55	2,430	5.7	387	18.5	--	200	240	31
GS-4B	4G4B	4-16-92	80	3,120	6.6	400	19.0	--	360	250	83
		12-15-92	80	3,360	6.2	428	16.5	2.0	390	310	63
GS-4C	4G4C	4-18-92	200	4,380	7.3	293	19.0	--	380	270	360
GS-5	4G5	4-13-92	201.5	3,430	5.4	438	17.5	.5	360	320	49
		12-18-92	201.5	4,300	4.6	467	18.0	.5	430	380	62
GS-6	4G6	4-15-92	401	18,000	4.2	484	18.5	.5	560	290	3,200
		4-15-92	401	18,000	4.1	484	18.5	--	600	270	3,100
GS-7	4G7	4-14-92	202	2,390	4.9	565	18.5	1.0	300	170	28
GS-8A	4G8A	4-14-92	76	5,660	3.7	500	18.5	.2	480	580	60
		12-04-92	76	6,230	3.8	432	18.0	.2	440	620	64
GS-8B	4G8B	4-17-92	200	6,200	4.3	420	18.5	--	460	460	390
GS-11	4G11	12-13-92	61	3,940	3.9	453	19.0	1.0	400	300	64
GS-14	4G14	12-14-92	66	6,750	3.6	--	18.0	.3	490	710	67
GS-15	4G15	12-19-92	120	6,380	3.5	536	18.0	.1	480	690	110
GS-16	4G16	12-16-92	183	6,380	3.5	536	18.0	--	460	940	72
GS-18	4G18	12-16-92	260	4,480	3.8	422	19.5	.2	460	150	67
GS-19	4G19	12-16-92	162	1,710	3.1	664	18.5	6.1	30	120	11
GS-20 GS-20 ¹	4G20	12-16-92	23	5,790	2.8	604	18.0	--	380	240	46
		1-28-93	23	3,850	4.2	--	--	--	540	130	54
GS-20-Seep		1-28-93	23	3,880	4.2	--	--	--	500	130	54
MRR-A ²		12-22-92	--	8,000	2.8	686	14.0	4.7	430	810	73
MRR-A ³		12-22-92	--	8,000	2.8	--	14.0	4.7	280	450	45
MRR-B ²		12-22-92	--	9,300	2.8	728	13.5	3.9	--	--	--
MRD-Seep		7-07-93	--	4,000	3.7	--	30.0	--	510	270	43
W-1D		12-19-92	48	6,450	3.5	594	20.5	2.1	490	720	57
W-5D		12-22-92	49	8,080	3.6	508	17.0	0.5	450	920	71
Field blanks		4-21-92	--	--	--	--	--	--	0.07	0.03	<0.20
		12-22-92	--	--	--	--	--	--	<0.02	<0.01	<0.20

See footnotes at end of table.

Table 1. Chemical data for water samples from Mine Run Reservoir, wells, and two seeps at the Penn Mine, Calaveras County California—*Continued*

Well or sample site	Date	Potassium, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Silica, dissolved (mg/L)	Solids, residue at 180 °C, dissolved (mg/L)	Aluminum, dissolved (µg/L)	Cadmium, dissolved (µg/L)
GS-1A	4-17-92	11	3,500	97	1.5	.88	42	5,580	3,800	2,100
	12-15-92	10	3,700	78	1.3	.39	47	5,540	10,000	2,300
GS-1B	4-18-92	18	3,000	570	.90	4.5	13	6,090	30	440
GS-2	4-14-92	5.5	450	240	.20	1.6	16	3,750	<10	<10
GS-3	4-15-92	3.9	3,700	21	.30	.10	59	5,290	4,800	2,600
	12-19-92	5.8	4,400	36	.40	.15	72	6,590	3,800	3,700
GS-4A	4-16-92	2.7	1,400	8.1	<.10	.26	42	2,320	40	1,100
	4-16-92	2.7	1,500	9.2	.10	.27	42	2,340	50	1,000
GS-4B	4-16-92	2.8	2,100	54	.20	1.3	32	3,190	20	530
	12-15-92	2.7	2,300	26	.20	.24	37	3,510	60	900
GS-4C	4-18-92	7.6	2,200	320	.30	1.3	22	3,870	30	520
GS-5	4-13-92	6.4	2,900	16	.20	.22	41	3,840	240	3,000
	12-18-92	6.3	2,900	25	.30	.13	44	4,320	3,800	2,900
GS-6	4-15-92	19	4,000	4,100	2.8	8.3	34	15,000	52,000	680
	4-15-92	20	2,900	5,000	3.2	6.5	35	14,500	51,000	690
GS-7	4-14-92	3.1	1,700	20	.80	.39	38	2,610	3,600	630
GS-8A	4-14-92	2.6	5,900	60	9.8	.32	110	9,020	220,000	1,400
	12-14-92	2.3	5,700	51	4.8	.48	120	8,670	250,000	1,500
GS-8B	4-17-92	9.1	4,400	290	6.4	3.9	48	7,530	89,000	970
GS-11	12-13-92	2.3	2,900	25	2.9	.42	56	4,570	49,000	500
GS-14	12-14-92	2.8	6,400	36	6.4	.51	140	10,000	370,000	1,500
GS-15	12-19-92	5.1	6,300	67	4.5	.34	140	9,660	380,000	1,500
GS-16	12-16-92	2.5	8,300	40	7.0	1.3	140	12,800	560,000	1,900
GS-18	12-16-92	16	3,200	23	1.7	7.3	53	5,060	210,000	50
GS-19	12-16-92	13	810	24	.70	.47	77	1,230	38,000	80
GS-20	12-16-92	8.5	4,200	18	.80	.49	120	6,230	280,000	410
	1-28-93	13	2,900	22	1.3	--	60	1,280	6,000	20
GS-20-Seep	1-28-93	12	2,900	21	1.3	--	60	3,690	5,900	20
MRR-A ²	12-22-92	<.10	8,500	38	.40	1.9	190	13,200	720,000	1,700
MRR-A ³	12-22-92	1.4	4,800	22	.90	.94	130	3,820	280,000	940
MRR-B ²	12-22-92	--	--	--	--	--	--	--	--	--
MRD-Seep	7-07-93	2.3	2,900	22	2.3	.06	70	4,460	33,000	510
W-1D	12-19-92	1.6	6,000	29	6.8	.24	150	8,990	290,000	1,300
W-5D	12-22-92	2.0	8,100	38	.90	.080	150	12,200	500,000	1,800
Field blanks	4-21-92	<0.10	<0.10	0.30	<0.10	<0.01	<0.1	5	<10	<10
	12-22-92	<0.10	0.50	0.10	<0.10	<0.01	0.30	<1	30	<10

See footnotes at end of table.

Table 1. Chemical data for water samples from Mine Run Reservoir, wells, and two seeps at the Penn Mine, Calaveras County, California—*Continued*

Well or sample site	Date	Copper, dissolved (µg/L)	Iron, dissolved (µg/L)	Lead, dissolved (µg/L)	Manganese, dissolved (µg/L)	Silver, dissolved (µg/L)	Zinc, dissolved (µg/L)	δD (per mil, V-SMOW)	δ ¹⁸ O water (per mil, V-SMOW)	δ ¹⁸ O sulfate (per mil, V-SMOW)	δ ³⁴ S sulfate (per mil, CDT)
GS-1A	4-17-92	9,800	160	<1	27,000	<1.0	140,000	-36.5	-3.40	--	--
	12-15-92	13,000	1,900	<1	33,000	<1.0	190,000	-37.4	-3.31	-0.1	1.9
GS-1B	4-18-92	<10	<10	<1	20,000	<1.0	18,000	-40.0	-3.85	--	--
GS-2	4-14-92	<10	<10	<1	70	<1.0	20	-56.0	-7.65	--	--
GS-3	4-15-92	12,000	60	<1	25,000	<1.0	150,000	-35.0	-3.45	--	--
	12-19-92	11,000	80	<1	38,000	<1.0	250,000	-32.1	-2.32	-0.8	1.5
GS-4A	4-16-92	1,100	<10	<1	980	<1.0	39,000	-51.5	-6.60	--	--
	4-16-92	1,100	<10	<1	850	<1.0	34,000	-50.0	-6.65	--	--
GS-4B	4-16-92	130	20	<1	260	<1.0	12,000	-48.5	-6.30	--	--
	12-15-92	400	10	<1	120	<1.0	26,000	-46.5	-6.01	-0.8	2.0
GS-4C	4-18-92	30	<10	<1	790	<1.0	5,900	-48.5	-6.25	--	--
GS-5	4-13-92	2,600	130	<1	1,900	<1.0	78,000	-46.5	-5.40	--	--
	12-18-92	6,100	3,200	<1	4,600	<1.0	94,000	-42.9	-5.04	0.5	1.7
GS-6	4-15-92	12,000	930	4	24,000	<1.0	120,000	-35.0	-2.90	--	--
	4-15-92	13,000	950	4	25,000	<1.0	170,000	-33.0	-2.90	--	--
GS-7	4-14-92	14,000	100	<1	23,000	<1.0	83,000	-58.0	-8.20	--	--
GS-8A	4-14-92	86,000	110,000	<1	58,000	<1.0	--	-32.5	-2.65	--	--
	12-14-92	88,000	150,000	<1	52,000	<1.0	470,000	-33.9	-2.61	1.0	1.6
GS-8B	4-17-92	5,400	94,000	7	44,000	<1.0	300,000	-38.0	-3.85	--	--
GS-11	12-13-92	35,000	83,000	<1	37,000	<1.0	210,000	-48.8	-5.84	-0.2	2.0
GS-14	12-14-92	84,000	92,000	<1	55,000	<1.0	460,000	-27.7	-1.38	-1.0	1.5
GS-15	12-19-92	80,000	63,000	3	51,000	<1.0	450,000	-28.4	-1.47	--	1.0
GS-16	12-16-92	120,000	66,000	3	170,000	<1.0	630,000	-15.2	1.40	-0.7	1.4
GS-18	12-16-92	130	82,000	170	2,600	<1.0	400,000	-49.8	-7.39	2.4/1.8	4.1
GS-19	12-16-92	1,600	22,000	25	1,300	<1.0	1,800	-56.9	-7.99	1.8	2.3
GS-20	12-16-92	36,000	540,000	14	15,000	<1.0	62,000	-47.2	-6.81	1.6	2.6
GS-20 ¹	1-28-93	60	660,000	13	9,100	<1.0	41,000	-48.8	-7.31	2.5	4.8
GS-20-Seep	1-28-93	60	620,000	13	9,100	<1.0	48,000	-48.8	-7.32	2.3/2.2	4.6
MRR-A ²	12-22-92	110,000	160,000	<1	51,000	<1.0	570,000	-8.4	2.55	1.1	1.9
MRR-A ³	12-22-92	62,000	110,000	7	28,000	<1.0	200,000	-25.4	-2.12	-0.7	1.5
MRR-B ²	12-22-92	--	--	--	--	--	--	-3.6	3.78	--	--
MRD-Seep	7-07-93	25,000	90	5	14,000	<1.0	96,000	-27.4	-1.54	--	--
W-1D	12-19-92	30,000	54,000	190	62,000	<1.0	390,000	-21.7	-0.41	--	--
W-5D	12-22-92	130,000	62,000	<1	150,000	<1.0	620,000	-15.9	1.31	--	--
Field blanks	4-21-92	<10	4	<1	<1	<1.0	<3	--	--	--	--
	12-22-92	<10	<3	<1	<1	<1.0	5	--	--	--	--

¹Artesian flow.

²6 feet below water surface.

³1 foot below water surface.

Table 2. Chemical data, expressed as percentages by volume, for gas exsolved from water pumped from well GS-18 (shaft 3 area) at Penn Mine, Calaveras County, California, January 1993

	Sample 1	Sample 2
Helium (He)	0.0033	0.0036
Hydrogen (H ₂)	.0006	.0005
Argon (Ar)	.759	.750
Oxygen (O ₂)	.147	.314
Nitrogen (N ₂)	54.98	54.39
Methane (CH ₄)	.739	.745
Carbon dioxide (CO ₂)	45.54	45.99
Ethane (C ₂ H ₆)	.0020	.0017
Hydrogen sulfide (H ₂ S)	<.0005	<.0005
Totals	102.17	102.19

The slag materials exposed near Camanche Reservoir contain greater than 6 percent zinc by weight (Wiebelt and Ricker, 1948). No published data are available for the cadmium content of the slag; however, seven grab samples of massive slag analyzed by inductively coupled plasma after HF/HNO₃/HClO₄ digestion were found to have cadmium concentrations ranging from 14 to 1,700 ppm (parts per million) (mean = 280 ppm); the same seven samples showed a range in zinc concentration from 3.2 to 25 weight percent (mean = 7.8 weight percent) and a range in copper of 0.2 to 2.2 weight percent (mean = 0.8 weight percent) (M. Parsons, Stanford Univ., written commun., 1996). Thus, the slag could be a source of zinc, copper, and cadmium to ground water, especially if leached under acidic conditions.

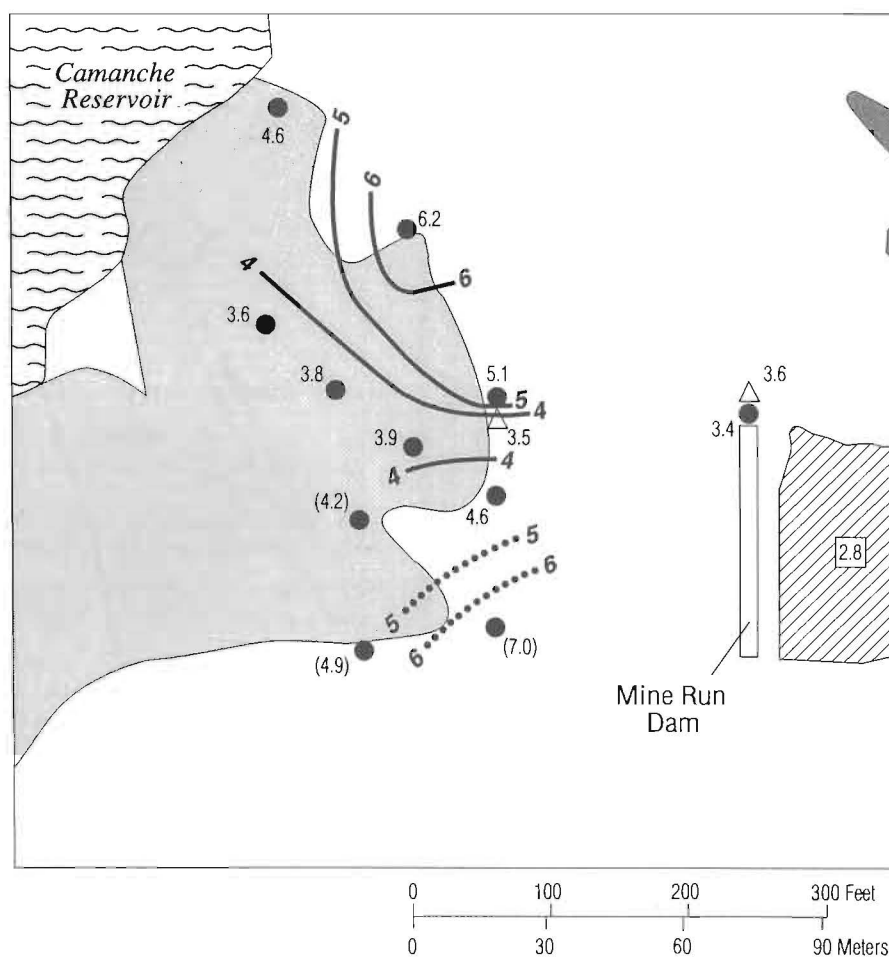
Dissolved metals found at elevated concentrations in acidic water at the Penn Mine include aluminum, cadmium, copper, iron, and zinc. Water with pH values less than 4.5 can contain several hundred to several thousand milligrams of dissolved aluminum per liter (Hem, 1985; Nordstrom and Ball, 1986; Alpers and Nordstrom, 1991). Dissolved aluminum in ground water at the Penn Mine ranged from less than 10 to 720,000 µg/L (micrograms per liter) (table 1). Copper may be present in concentrations as high as a few hundred milligrams per liter in acid mine drainage (Hem, 1985). Values for dissolved copper in ground water from the Penn Mine ranged from less than 10 to 130,000 µg/L (table 1). Concentrations of dissolved iron in ground water at the Penn Mine ranged from less than 10 to 660,000 µg/L (table 1). Dissolved zinc in ground water from the Penn Mine

ranged from 20 to 630,000 µg/L (table 1). Cadmium is found with zinc, including the sulfide mineral sphalerite and the sulfosalt mineral series tetrahedrite-tennantite, in most crustal environments; these minerals are present at Penn Mine. Dissolved concentrations of cadmium in ground-water samples from Penn Mine ranged from less than 10 to 3,700 µg/L (table 1).

The areal distribution of selected water-quality properties and constituents was plotted. The distribution map for pH in December 1992 is shown in figure 9. The other major constituents of acid mine drainage (iron, aluminum, and sulfate) and associated trace elements (copper, zinc, cadmium) show distributions similar to that of pH. Acid mine drainage is characterized in ground water by values of pH less than 5. Low values of pH are associated with high concentrations of sulfate at Penn Mine (fig. 10).

Concentrations of sodium and chloride at Penn Mine tend to increase with depth and were highest in the slate unit (Hamlin and Alpers, 1995). In the 200-foot boreholes, where the rock units were separated by inflatable packers in the vicinity of the metavolcanic-slate contact (GS-1, -4, and -8), chloride concentration ranged from 290 to 570 mg/L in the slate intervals and from 8.1 to 97 mg/L in the metavolcanic rock intervals; sodium concentration ranged from 360 to 810 mg/L in the slate intervals and from 29 to 280 mg/L in the metavolcanic rock intervals (table 1). The highest concentrations of chloride (5,000 mg/L) and sodium (3,200 mg/L) were found in the 400-foot borehole (GS-6), which penetrated more than 350 feet of the slate unit. These data strongly suggest that the source of sodium and chloride is associated with the slate unit.

Another way to delineate the plume of acid mine drainage in ground water downgradient from Mine Run Dam is by plotting the distribution of the stable isotopes deuterium [D or hydrogen-2 (²H)] and ¹⁸O. During the evaporation process, water molecules containing heavy isotopes tend to become concentrated in the residual water, and molecules containing lighter isotopes become enriched in the water vapor. Hence, isotopic values for bodies of surface water exposed to evaporation tend to be enriched in heavy isotopes relative to most ground water. The process of isotopic evaporative enrichment produces δD and δ¹⁸O values that lie on a line with a slope between 3 and 6 to the right of



EXPLANATION

- | | |
|--|-----------------------------|
| — Lines of equal pH based on December 1992 data | ● USGS well |
| Lines of equal pH based on April 1992 data | △ EBMUD well |
| | 3.5 pH value, December 1992 |
| | (4.9) pH value, April 1992 |

Figure 9. Areal distribution of pH in ground water in metavolcanic rocks at Penn Mine, Calaveras County, California, December 1992.

the meteoric line (Craig and others, 1963). This phenomenon is observed in a plot of isotope data from ground water and Mine Run Reservoir at the Penn Mine (fig. 11). The data can be fit by least-squares linear regression ($r^2=0.985$), which gives a line described by the equation

$$\delta D = 4.4 \delta^{18}O - 21. \quad (3)$$

The slope of this line suggests that the ground water downgradient from Mine Run Dam represents the mixing of evaporated water from Mine Run Reservoir with nonevaporated ground water. This interpretation would suggest that the chief source of dissolved metals and sulfate in the ground water is leakage from the unlined Mine Run Reservoir. Wells GS-2, -7, and -19 show the least enrichment in heavy isotopes and exhibit among the lowest

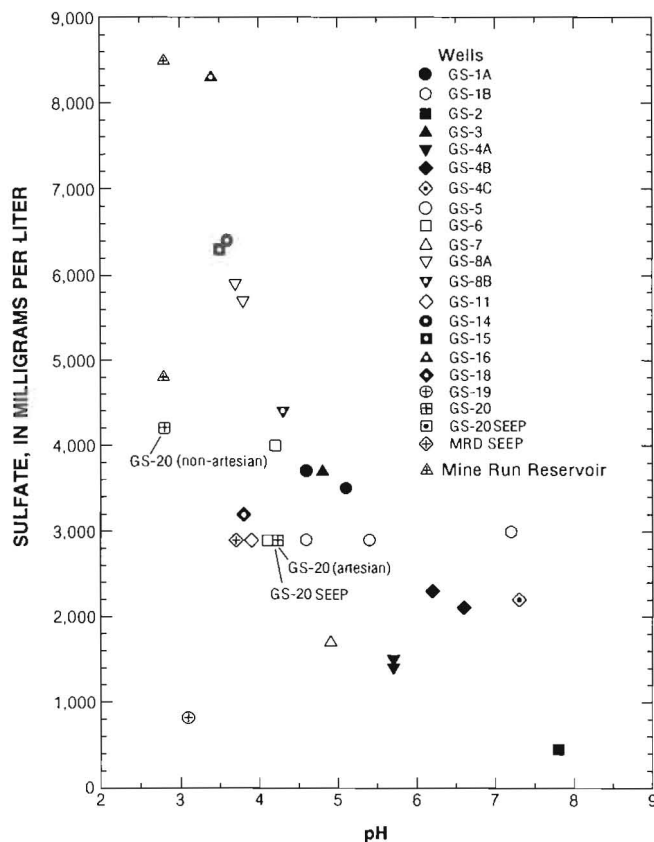


Figure 10. Relation between sulfate concentration and pH in ground water and in Mine Run Reservoir at Penn Mine, Calaveras County, California, April and December 1992, and January and July 1993.

levels of contamination by acid mine drainage. Samples from Mine Run Reservoir and wells GS-14 and -16 show the highest enrichment in heavy isotopes and highest levels of acid-mine-drainage contamination. The areal distribution of $\delta^{18}\text{O}$ in ground water is similar to the distributions of sulfate (table 1) and pH (fig. 9). This observation is consistent with Mine Run Reservoir providing the source of acidic, evaporated water found in the acid plume.

Geochemical Correlations

Correlations among dissolved constituents indicate the effects of acid mine drainage on ground-water quality at the Penn Mine. Dissolved iron correlates positively with sulfate in ground water, consistent with oxidation of pyrite as the probable source of these constituents (Hamlin and Alpers, 1995). Other constituents, such as aluminum and other dissolved metals, show a similar correlation with pH.

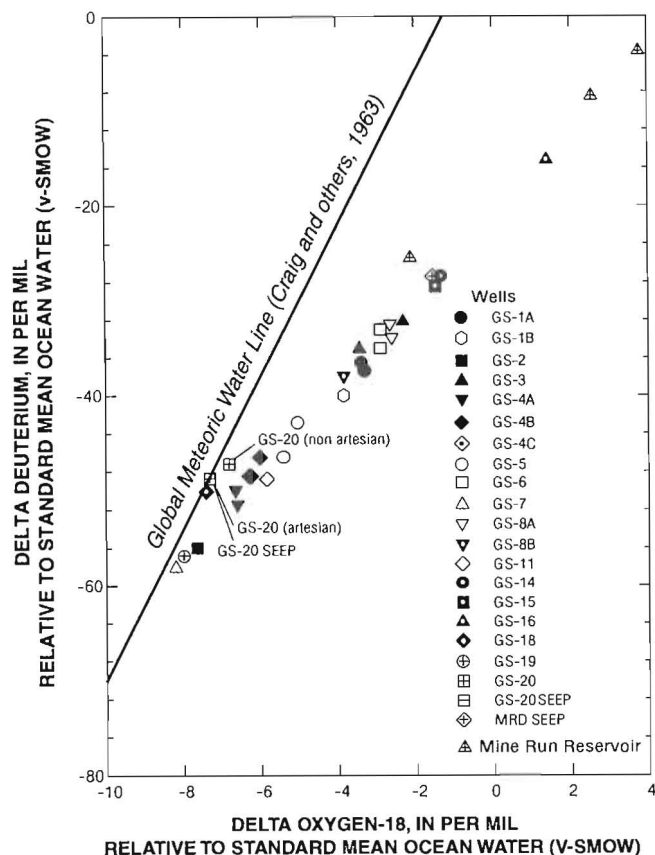


Figure 11. Stable-isotopic composition of water samples from wells, seeps, and Mine Run Reservoir at Penn Mine, Calaveras County, California, April and December 1992, and January and July 1993.

Concentrations of dissolved metals in natural waters can be limited by solubility equilibrium with solid phases. The concentrations of ferric iron and aluminum in ground water at the Penn Mine also are strongly dependent on pH (Hamlin and Alpers, 1995). Geochemical modeling with the WATEQ4F code (Ball and Nordstrom, 1991) suggests that dissolved ferric iron is probably in equilibrium with a form of hydrous ferric oxide or ferrihydrite [nominally $\text{Fe}(\text{OH})_3$] (Hamlin and Alpers, 1995). Sulfate concentrations are highest in low-pH waters, whereas iron concentrations can be limited by solubility of a sulfate mineral such as hydronium-bearing jarosite $[(\text{K}, \text{Na}, \text{H}_3\text{O}) \text{Fe}_3(\text{SO}_4)_2(\text{OH})_6]$ (Alpers and others, 1989) or schwertmannite $[\text{Fe}_8\text{O}_8(\text{OH})_6\text{SO}_4]$ (Bigham, 1994). Similarly, aluminum concentrations appear to be in equilibrium with gibbsite $[\text{Al}(\text{OH})_3]$, except in ground water with pH values less than 5 (Hamlin and Alpers, 1995). Again, sulfate becomes dominant at low pH and aluminum can be in equilibrium with an aluminum-sulfate mineral such as jurbanite $[\text{AlSO}_4(\text{OH}) \cdot 5\text{H}_2\text{O}]$.

Metal ratios can be useful indicators of anomalous chemical analyses resulting from either analytical error or geochemical processes. The ratio of zinc to cadmium (Zn/Cd) is commonly consistent within a single mineral deposit. The Zn/Cd ratio for all but three of the water samples (table 3) falls within the range of 11 to 420, which is consistent with Zn/Cd ratios in ores and mine waters from other massive sulfide deposits (Nordstrom and Ball, 1985). Zn/Cd ratios are considerably higher for samples taken from wells GS-18 (8,000), GS-20 (2,100 during artesian flow on January 28, 1993), and the GS-20 seep (2,400). Values of the ratio of zinc to copper (Zn/Cu) fall between 1 and 200 for all water samples (table 3), except again for GS-18 (3,100), GS-20 (680 during artesian flow), and the GS-20 seep (800). Water samples collected from well GS-20 in December 1992 did not have similar characteristics because artesian flow at well GS-20 had not yet begun. Subsequent artesian flow from well GS-20 and related seeps reflected discharge from the underground mine workings (characterized by water samples from GS-18) in response to rising hydraulic head.

The most likely explanation for the anomalously high values of the Zn/Cd and Zn/Cu ratios is that cadmium and copper have been preferentially scavenged by aqueous hydrogen sulfide (H₂S) in the underground mine workings. DiToro and others (1990) indicated the following sequence for metal sulfide solubility from most soluble to least soluble:

MnS > FeS > NiS~ZnS > CdS~PbS > CuS > HgS.

Therefore, cadmium and copper sulfides are less soluble than zinc sulfide and would be preferentially scavenged by any H₂S produced by sulfate reduction.

Heavy stable isotopes (δD and $\delta^{18}O$) were enriched in partially evaporated water from Mine Run Reservoir and in ground water affected by acid drainage from the reservoir (fig. 11). In contrast, ground water from the mine workings (GS-18 and GS-20 seep) falls on or near the global meteoric water line (fig. 11), showing no enrichment of these heavy isotopes.

Another distinctive characteristic of the water from wells GS-18, GS-20, and the GS-20 seep is the presence of exsolving gas. Chemical analysis of the exsolved gas from well GS-18 (table 2) indicates somewhat reducing conditions; the gas

Table 3. Weight ratios of metals in ground-water and surface-water samples from Penn Mine, Calaveras County, California

[All ratios reported with two significant figures. MRR, Mine Run Reservoir; MRD, Mine Run Dam; Zn, zinc; Cd, cadmium; Cu, copper. --, not determined because one or both of the concentrations was below the detection level]

Well name or sample site	Date	Zn/Cd	Zn/Cu
GS-1A	4-17-92	67	14
	12-15-92	83	15
GS-1B	4-18-92	41	--
GS-3	4-15-92	58	13
	12-19-92	68	23
GS-4A	4-16-92	35	35
	4-16-92	34	31
GS-4B	4-16-92	23	92
	12-15-92	29	65
GS-4C	4-18-92	11	200
GS-5	4-13-92	26	30
	12-18-92	32	15
GS-6	4-15-92	180	10
	4-15-92	250	13
GS-7	4-14-92	130	5.9
GS-8A	12-04-92	310	5.3
GS-8B	4-17-92	310	56
GS-11	12-13-92	420	6.0
GS-14	12-14-92	310	5.5
GS-15	12-19-92	300	5.6
GS-16	12-16-92	330	5.3
GS-18	12-16-92	8,000	3,100
GS-19	12-16-92	23	1.1
GS-20	12-16-92	150	1.7
GS-20 ¹	1-28-93	2,100	680
GS-20-Seep	1-28-93	2,400	800
MRR-A ²	12-22-92	340	5.2
MRR-A ³	12-22-92	210	3.2
MRD-Seep	7-07-93	190	3.8
W-1D	12-19-92	300	13
W-5D	12-22-92	340	4.8

¹Artesian flow.

²6 feet below water surface.

³1 foot below water surface.

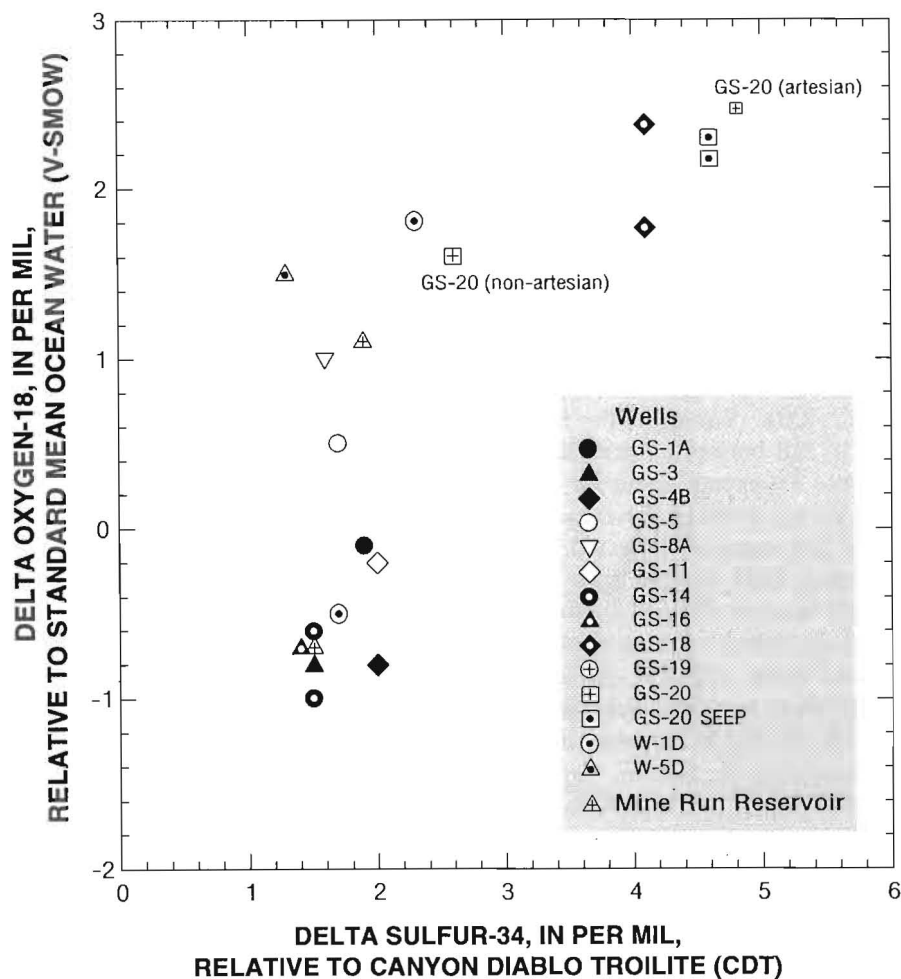


Figure 12. Relation between delta oxygen-18 and delta sulfur-34 in dissolved sulfate at Penn Mine, Calaveras County, California.

is dominated by carbon dioxide and nitrogen, with very little oxygen, and considerable methane and traces of hydrogen. Exsolution of dissolved gas is probably caused by the reduction in ambient pressure as water is brought to the surface from the mine workings. This occurred during pumping at well GS-18 (160 ft below the ground-water table) and at well GS-20 during periods of artesian flow from shaft 4 of the mine workings.

The relatively reducing environment required for reduction of sulfate to H_2S is consistent with the exsolved-gas chemistry for well GS-18 (table 2), which includes considerable methane (CH_4) and traces of hydrogen (H_2). The presence of detectable oxygen (O_2) in the exsolved gas, at concentrations of 0.15 to 0.31 volume percent (table 2), and the relatively oxidizing value of Eh in water

from well GS-18 (table 1) indicate redox disequilibrium among dissolved gases and between the dissolved gases and the aqueous phase. The redox disequilibrium could be caused by mixing of two or more waters with different dissolved gasses and dissolved metals in the underground mine workings. Stable-isotope data for sulfur and oxygen in dissolved sulfate are also consistent with the hypothesis of sulfate reduction and possible fluid mixing in the mine workings.

The stable isotopic composition of dissolved sulfate (table 1) also can be used to distinguish water samples from wells GS-18 and -20 and associated seeps from water samples taken elsewhere at the Penn Mine. The contrast in isotopic composition for the dissolved sulfate from the underground mine workings is shown in figure 12;

values of $\delta^{34}\text{S}$ in sulfate in three samples derived from the underground mine workings (GS-18, GS-20, while artesian, and GS-20-Seep) range from +4.1 to +4.8 per mil, about 3 per mil heavier than samples from Mine Run Reservoir and the wells down-gradient from Mine Run Dam, which have $\delta^{34}\text{S}$ values ranging from +1.0 to +2.0 per mil. Water samples from wells GS-19 and GS-20 (non-artesian) have $\delta^{34}\text{S}$ values intermediate between the samples from the underground mine workings and those from the Mine Run Dam area, indicating probable mixing. Values of $\delta^{18}\text{O}$ in sulfate range from -1.0 to +2.5 per mil, with the heaviest values in the sulfate from the mine workings.

With the exception of stable isotopes (δD and $\delta^{18}\text{O}$ in water, and $\delta^{34}\text{S}$ and $\delta^{18}\text{O}$ in dissolved sulfate) and dissolved copper and cadmium concentrations, the chemistry of acidic water in the underground mine workings (wells GS-18 and GS-20, while artesian) is similar to water in Mine Run Reservoir and to the associated acidic ground-water plume. Alpers and others (1994) described these data and presented several possible explanations. The most likely explanation is that reducing conditions have led to bacterially mediated sulfate reduction in the mine workings, which has depleted the dissolved sulfate in the lighter isotope ^{32}S , causing an increase in the $\delta^{34}\text{S}$ value of the residual sulfate. A similar effect would account for the higher values of $\delta^{18}\text{O}$ in dissolved sulfate. Alternative explanations involve lateral zoning of the relative abundance of sulfide minerals and the dissolution of primary sulfate minerals such as anhydrite, which occurs in some similar massive sulfide deposits. Neither of these alternative explanations is likely, however, given the lack of anhydrite and gypsum in the mine waste piles and no mention of these minerals in previous reports (for example, Heyl and others, 1948). Therefore, partial sulfate reduction is the favored hypothesis to explain the isotopic data and the relatively low aqueous copper and cadmium concentrations relative to zinc; copper and cadmium would be preferentially scavenged by hydrogen sulfide produced by sulfate reduction.

FLOW RATE AND METAL LOADING OF CONTAMINATED GROUND WATER

The flow rate of ground water in the fractured metamorphic-rock aquifer between Mine Run Dam and Camanche Reservoir was estimated by

¹Available from East Bay Municipal Utility District

Hamlin and Alpers (1995) using mathematical relations developed for porous media. According to Darcy's law, the flow rate, q , through a given cross-sectional area of aquifer is

$$q = KIA, \quad (4)$$

where K is the hydraulic conductivity averaged over the thickness of the aquifer, A is the cross-sectional area, and I is the hydraulic gradient (Driscoll, 1986).

A rough estimate of the width of the plume, based on lines of pH equal to 5 (fig. 9) in a section of the plume defined by wells GS-1A, W-1D, and GS-3 (fig. 3), is about 100 ft. Water-level and pumping-rate data for these wells collected during water-quality sampling in April and December 1992 were evaluated using the method described by Huntley and others (1992) to estimate values of hydraulic conductivity, K , for the metavolcanic rocks. Hamlin and Alpers (1995) described this method and used it to estimate values of K for the metavolcanic and slate units. The analysis utilizes a relationship derived for transmissivity (T) and specific capacity (Q/s) in fractured-rock systems:

$$T = 0.29(Q/s)^{1.18} \quad (5)$$

where Q is the pumping rate and s is the drawdown (Huntley and others, 1992). The values of T determined in this manner may be converted to hydraulic conductivity, K , by dividing by the saturated thickness of metavolcanic rocks. Estimated values of K are as follows: 0.2 ft/d for GS-1A (December 1992), 0.3 ft/d for W-1D (December 1992), 0.8 ft/d for W-1D (Brown and Caldwell Consultants, written commun., 1991)¹, 0.01 ft/d for GS-3 (April 1992; Hamlin and Alpers, 1995), and 0.07 ft/d for GS-3 (December 1992). The median value of K from these data is 0.2 ft/d for the metavolcanic rocks, which is similar to the value of 0.1 ft/d previously determined by Hamlin and Alpers (1995) using data from all wells completed in the metavolcanic unit. The geometric mean of the five K values for wells GS-1A, GS-3, and W-1D also is 0.1 ft/d.

Saturated thicknesses for wells GS-1A and -3 and a width of 100 ft were used to estimate the cross-sectional area of the plume in the metavolcanic rocks. The area of the polygon defined by

the saturated parts of these wells is approximately 5,750 ft². The hydraulic gradient (a unitless quantity) in this part of the contaminant plume can be estimated by using water-level data from wells GS-1A and GS-8A (appendix 4), which lie approximately along the axis of the contaminant plume as shown by lines of equal pH (fig. 9). The hydraulic gradient between these two wells ranged from about 0.14 (such as during August through December 1992) to zero (flat) or possibly a negative value (that is, west to east) during periods of submergence by Camanche Reservoir (such as during May through October 1993). Therefore, a value of 0.07 is used to represent the average gradient. Using the geometric mean value of 0.1 ft/d for the hydraulic conductivity of the metavolcanic rocks near wells GS-1A and -3,

$$q = (0.1 \text{ ft/d}) (5,750 \text{ ft}^2) (0.07) = 40 \text{ ft}^3/\text{d}.$$

This is equivalent to a discharge of about 300 gal/d through this 100-foot-wide section when the hydraulic gradient is 0.07. The actual value for q for the overall contaminant plume is dependent on the hydraulic gradient, which varies seasonally (see fig. 7A) and on the width of the contaminant plume which may vary over time and space. The hydraulic gradient for ground water was probably substantially flatter owing to increased pressure head when the wells in the slag area were inundated by Camanche Reservoir during May through October 1993. Depending on the degree of hydraulic connection, flow during such periods of submergence may have been from Camanche Reservoir to the ground-water system.

Ranges for metal-transport rates can be estimated using the estimates of ground-water flow along a path leading toward Camanche Reservoir, and values for metal concentration determined for the contaminant plume (table 1). Wells GS-1A, W-1D, and GS-3 are along a line that is roughly perpendicular to the axis of the plume and that approximates the width of the plume. Average metal concentrations determined in ground-water samples collected in April and December 1992 from these wells were: copper, 15 mg/L; zinc, 220 mg/L; and cadmium, 2.4 mg/L.

Daily metal loadings within the part of the contaminant plume at the base of Mine Run Dam were calculated using the median value of hydraulic conductivity (0.1 ft/d) applied to the portion of the plume that maintains a measurable hydraulic gradient. Using average metal concentrations and an estimated discharge rate of 40 ft³/d (300 gal/d)

for this part of the contaminant plume, the calculated metal loads within the plume were: copper, 17 g/d; zinc, 250 g/d; and cadmium, 2.7 g/d. Previous metal loading estimates by Hamlin and Alpers (1995) using a higher value of K (50 ft/d) are considered not realistic because this higher value of hydraulic conductivity applies to a part of the flow system [for example, wells GS-4A, -5, -8A, and -14 (figs. 3 and 7)] that has a much shallower hydraulic gradient, the direction of which appears to be highly variable depending on fluctuations in Camanche Reservoir levels.

Treatment of Mine Run Reservoir with lime during winter 1993 caused precipitation of dissolved solids and significantly reduced the concentration of dissolved metals. The effects of lime treatment and a shallower hydraulic gradient may have limited metal loadings to the plume during that period.

SUMMARY

The Penn Mine site encompasses an area of about 140 acres in the Foothill copper-zinc belt in northwestern Calaveras County, California. About 10.5 mi of underground workings were excavated to yield several acres of mill tailings and waste rock now exposed on the surface. Slag from smelters was disposed of in a 1,500-foot-long area adjacent to the former Mokelumne River channel in an area now frequently inundated by Camanche Reservoir. Historically, contaminated surface runoff from the mine flowed directly to the Mokelumne River; after the construction of Camanche Dam in 1963, the surface runoff flowed into the Camanche Reservoir. In an attempt to control discharge of contaminated surface water from the mine, diversions and impoundments were constructed in 1978. Use of sulfidic waste rock and mine tailings to construct dams and dikes, coupled with recirculation of contaminated water between impoundments, could have unintentionally enhanced the formation of acidic, metal-rich water. Although the impoundment system has greatly reduced surface discharges from the mine, the results of this study indicate that contamination of underlying ground water occurs through fractures in bedrock under the unlined impoundments. This contaminated water continues to flow through a fractured-rock aquifer toward Camanche Reservoir. To neutralize acidic drainage, lime treatment of water in the lowermost impoundment was initiated in 1993; pH was adjusted to a value greater than 7 for a short period of time, but the impoundment has since been allowed to resume its untreated condition.

Geologic controls over the movement and distribution of ground water at the Penn Mine include fractures in bedrock, faults, and the contact between the principal rock types in the area. Fractures that transmit ground water are present chiefly near the base of the metavolcanic unit, which overlies a metasedimentary unit that is significantly less permeable. This contact zone acts as a conduit that transmits water along its strike, which is generally N. 20° W. In a similar manner, ground-water flow along a fault surface generally is enhanced; whereas flow perpendicular to a fault surface generally is impeded.

The estimates of hydraulic conductivity were highest for fractured intervals of the metavolcanic unit. The lowest values of hydraulic conductivity were associated with the metasedimentary (slate) unit. The mean hydraulic conductivity for the metavolcanic unit was about 10 to 50 times higher than the hydraulic conductivity for the slate unit. These results support the concept that the contact zone between the metavolcanic and slate units is as a conduit for ground-water flow.

The hydraulic gradient for ground water in the slag area is generally from Mine Run Reservoir toward Camanche Reservoir. The slope of this gradient is affected by seasonal changes in recharge and in the water level of Camanche Reservoir. The average hydraulic gradient in the vicinity of shafts 3 and 4 generally follows the topography toward and along the Hinckley Run drainage. During January to May 1993, water levels rose in these shafts and numerous seeps developed near shaft 4 and well GS-20. Chemical data indicate that the source of the seepage from shaft 4 was water from the underground mine workings.

Acid-drainage constituents form a plume in ground water in the metavolcanic unit between Mine Run Dam and Camanche Reservoir. The plume is characterized by low pH values, by enriched heavy stable isotopes of hydrogen and oxygen in water (indicating evaporation), and by high concentrations of sulfate and dissolved metals. The highest concentrations of dissolved sodium and chloride were associated with the slate unit, indicating a source in this unit. The enrichment of heavy stable isotopes of hydrogen and oxygen in the water making up the contaminant plume indicates that Mine Run Reservoir is the likely source of contaminated water.

The composition of water from wells GS-18 and -20, which penetrate the underground mine workings, indicates a geochemical environment different from that of ground water downgradient from Mine Run Dam. Copper concentrations in water from the mine workings (GS-18 and -20) were 60 to 130 µg/L; whereas in ground water downgradient from Mine Run Dam, copper concentrations were as high as 130,000 µg/L. Zinc concentrations were similarly elevated in water from the mine workings (41,000 to 400,000 µg/L) and in ground water downgradient from Mine Run Dam (as high as 630,000 µg/L). The relatively lower copper concentrations in water from the underground mine workings may be the result of preferential scavenging (relative to zinc) by hydrogen sulfide, which is produced by sulfate reduction. Another distinctive characteristic of the water from the underground mine workings is the presence of exsolving gas containing hydrogen and methane, probably produced under somewhat reducing conditions. Isotopes of sulfur and oxygen in dissolved sulfate support the hypothesis that sulfate reduction is occurring in the underground mine workings. In contrast, water samples from wells downgradient from Mine Run Dam yielded dissolved sulfate that was similar isotopically to sulfate from the wastewater impoundments, showing no evidence of sulfate reduction.

The plume of acidic ground water downgradient from Mine Run Reservoir is roughly 100 ft wide at the base of Mine Run Dam. Discharge from the plume was estimated to be about 40 ft³/d (300 gal/d). Actual values for discharge vary with plume width, hydraulic gradient, and the level of Camanche Reservoir. Corresponding daily mass flows of dissolved metals in the contaminant plume toward Camanche Reservoir were estimated to be 17 g for copper, 250 g for zinc, and 2.7 g for cadmium. These estimates could be refined by additional ground-water monitoring and by numerical modeling of ground-water flow.

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Appendix 1. Lithologic logs and well-construction data from USGS monitoring wells GS-1 through GS-20 at Penn Mine site, Calaveras County, California

[ft, foot; in. inch; dia., diameter; frags., fragments; --, no data]

Well No.	Depth (ft)	Lithologic description	Depth of 10-in-dia. steel casing (ft)	Depth of blank PVC casing ¹ (ft)	Depth of slotted PVC casing ¹ (ft)	Depth of inflatable packer(s) (ft)
GS-1	0-15	Soil with pebbles	0-6	0-40	--	80
	15-28	Sandy, quartz, meta-volcanic rock frags.				
	28-70	Metavolcanic rock				
	70-200	Slate				
GS-2	0-30	Unconsolidated material, slag	0-6	0-40	--	--
	30-76	Metavolcanic rock				
	76-202	Slate				
GS-3	0-10	Unconsolidated material	0-6	0-30	--	--
	10-15	Slag				
	15-26	Unconsolidated material				
	26-105	Metavolcanic rock				
GS-4	105-202	Slate	0-6	0-20	--	55, 80
	0-1.5	Unconsolidated material				
	1.5-100	Metavolcanic rock				
GS-5	100-202	Slate	0-6	0-30	--	--
	0-16	Unconsolidated material				
	16-76	Metavolcanic rock				
GS-6	76-201	Slate	0-6	0-30	--	--
	0-24	Slag				
	24-46	Metavolcanic rock				
GS-7	46-401	Slate	0-6	0-40	0-58 (3-in. dia.)	--
	0-18	Slag				
	18-38	Unconsolidated material				
	38-58	Metavolcanic rock				
	58-202	Mixed metavolcanic rock and slate				

See footnote at end of table.

Appendix 1. Lithologic logs and well-construction data from USGS monitoring wells GS-1 through GS-20 at Penn Mine site, Calaveras County, California—*Continued*

Well No.	Depth (ft)	Lithologic description	Depth of 10-in-dia. steel casing (ft)	Depth of blank PVC casing ¹ (ft)	Depth of slotted PVC casing ¹ (ft)	Depth of inflatable packer(s) (ft)
GS-8	0-15	Unconsolidated material, slag	0-6	0-30	--	76
	15-63 63-202	Metavolcanic rock Slate				
GS-9	0-11	Unconsolidated material	0-3	0-10	10-20	--
	11-20	Metavolcanic rock				
GS-10	0-3.5	Unconsolidated material, slag	0-3	0-5	5-25	--
	3.5-25	Metavolcanic rock				
GS-11	0-10	Unconsolidated material, slag	0-3	0-24	--	--
	10-61 61	Metavolcanic rock Slate				
GS-12	0-15	Unconsolidated material	0-7	0-71	--	--
	15-63 63-115	Metavolcanic rock Slate				
GS-13	0-10	Unconsolidated material, slag	0-3.5	0-20 0-28 (4-in. dia.)	-- 28-63 (4-in. dia.)	--
	10-63	Metavolcanic rock				
GS-14	0-10	Unconsolidated material, slag	0-8	0-55	55-65	--
	10-63 63	Metavolcanic rock Slate				
GS-15	0-1	Unconsolidated material	0-7	0-74	--	--
	1-59 59-120	Metavolcanic rock Slate				
GS-16	0-181	Metavolcanic rock Slate	0-3.5	0-8	--	--
	181-183					

See footnote at end of table.

Appendix 1. Lithologic logs and well-construction data from USGS monitoring wells GS-1 through GS-20 at Penn Mine site, Calaveras County, California—*Continued*

Well No.	Depth (ft)	Lithologic description	Depth of 10-in-dia. steel casing (ft)	Depth of blank PVC casing ¹ (ft)	Depth of slotted PVC casing ¹ (ft)	Depth of inflatable packer(s) (ft)
GS-17	0-80	Metavolcanic rock, altered	0-4.5	--	--	--
GS-18	0-251	Metavolcanic rock, altered	0-3.5	0-4	--	--
	251	Top of mine workings, "300 level" near shaft 3				
	260	Bottom of mine workings				
GS-19	0-140	Metavolcanic rock, altered	0-2.5	0-3.5	--	--
	140-150	Shaft 3		0-100 (2-in. dia.)	100-140 (2-in. dia.)	
GS-20	0-11	Metavolcanic rock, altered	0-3.5	0-6	--	--
	11-23	Shaft 4		0-3 (2-in. dia.)	3-23 (2-in. dia.)	

¹Diameter of blank and slotted casing is 6 inches, unless otherwise indicated.

Appendix 2. Geophysical and selected acoustic-televiwer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California

EXPLANATION OF TELEVIEWER LOGS



Isolated planes intersecting borehole;
probably open fractures.



Fracture zone composed of several parallel
and intersecting fractures.



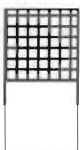
Faint discontinuous planes intersecting
borehole; probably foliation in greenschist.



Large opening intersecting borehole; shape
of top of opening may indicate orientation.



Intensely fractured and altered rock;
orientation of individual fractures difficult
to determine.



Bottom of casing above open borehole.

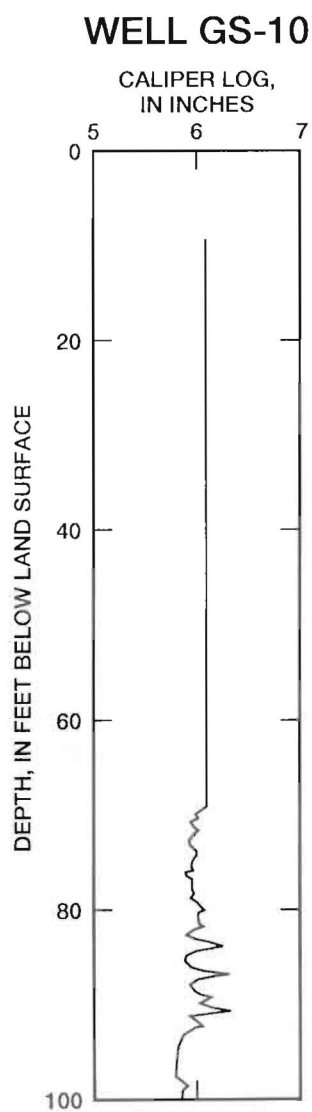


Top of fluid column in open borehole.



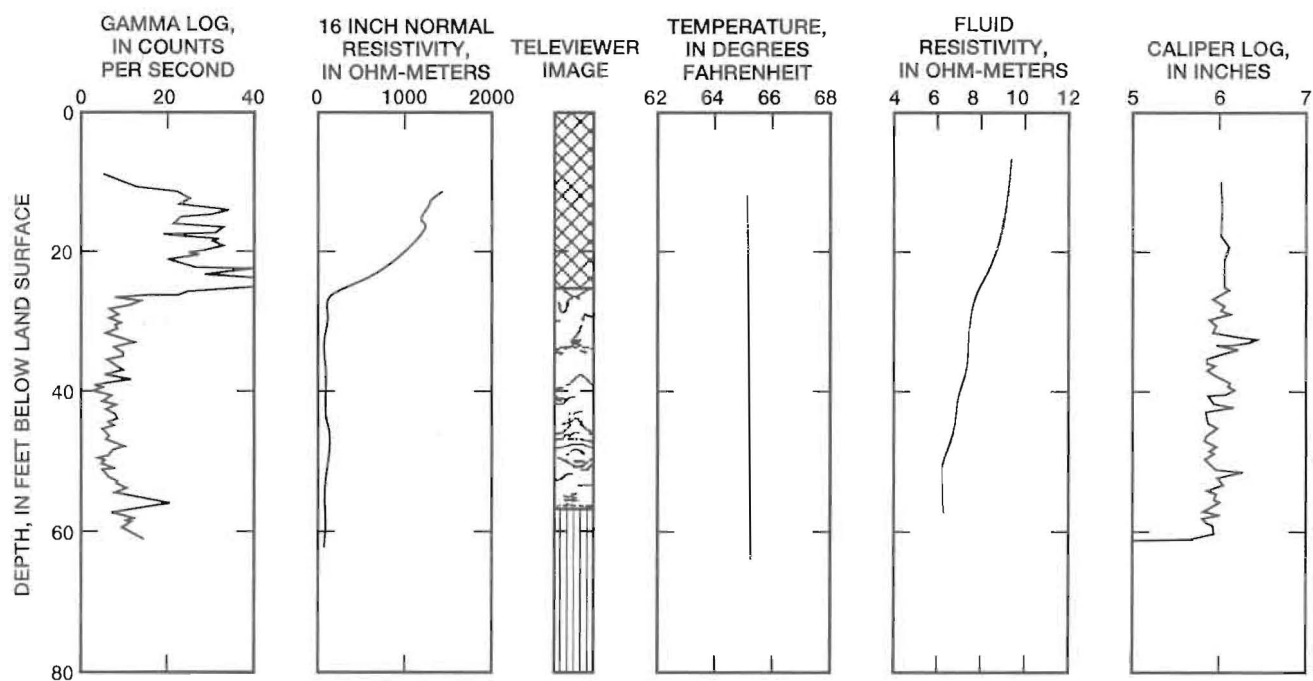
Lowermost interval of borehole inaccessible
to televiwer.

Appendix 2. Geophysical and selected acoustic-televviewer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California—*Continued*

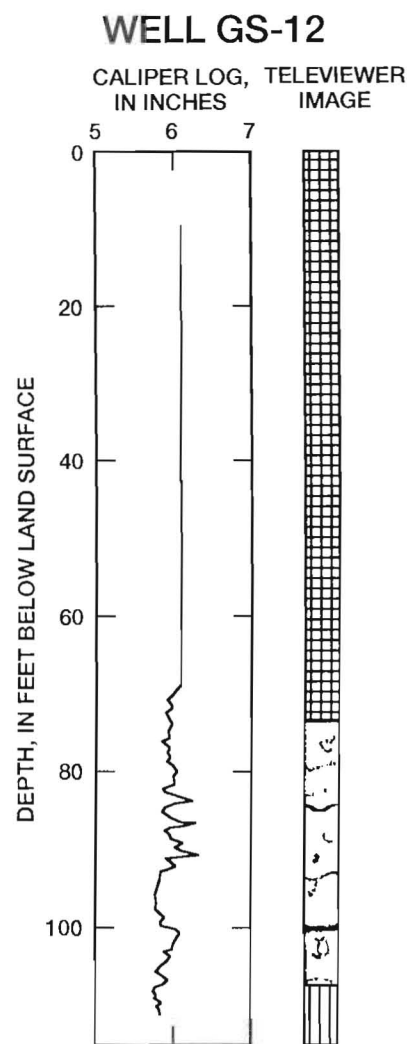


Appendix 2. Geophysical and selected acoustic-televviewer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California—*Continued*

WELL GS-11

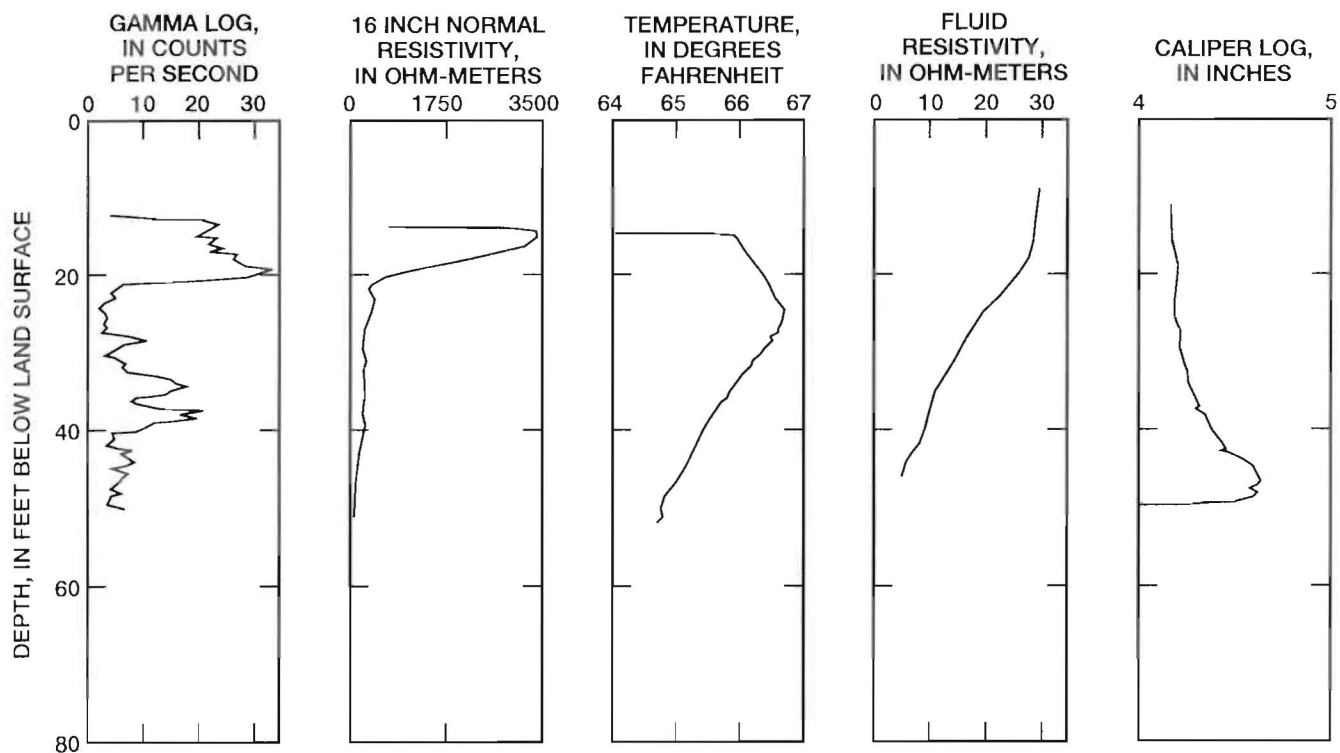


Appendix 2. Geophysical and selected acoustic-televiwer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California—*Continued*



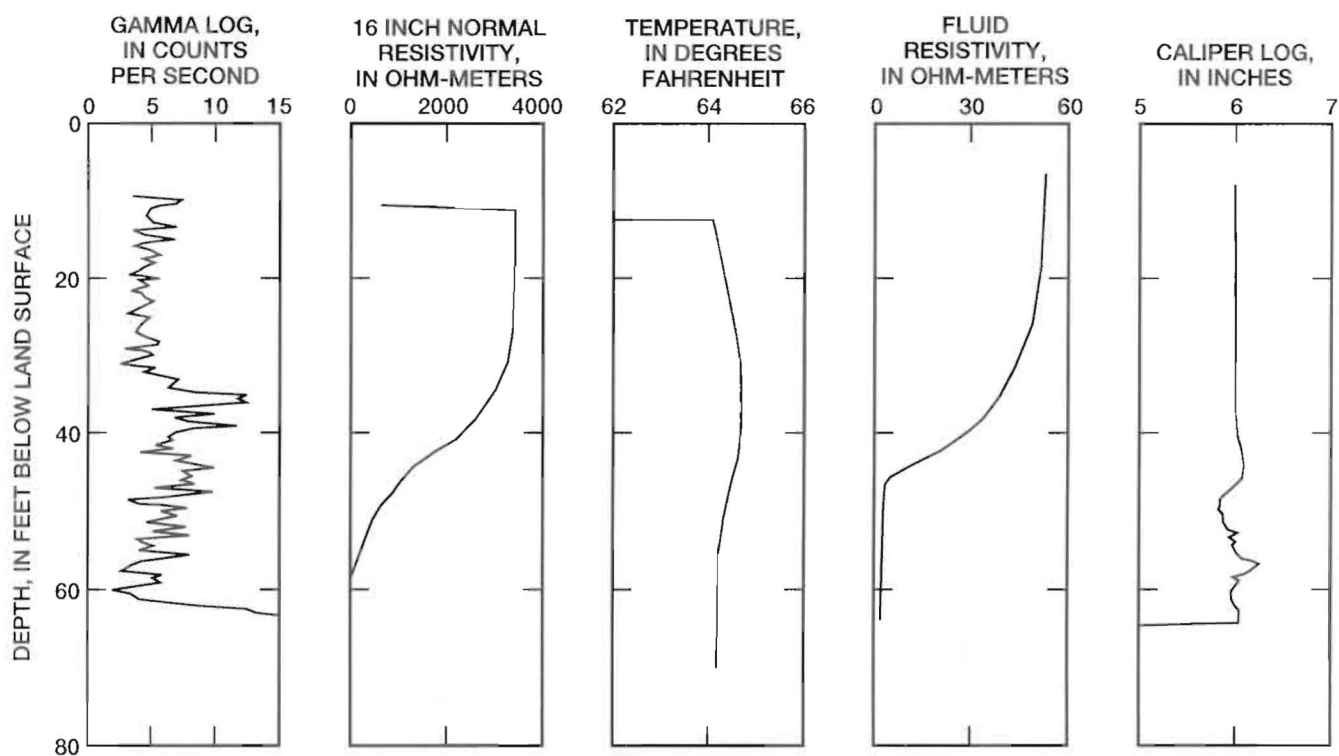
Appendix 2. Geophysical and selected acoustic-televviewer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California—*Continued*

WELL GS-13

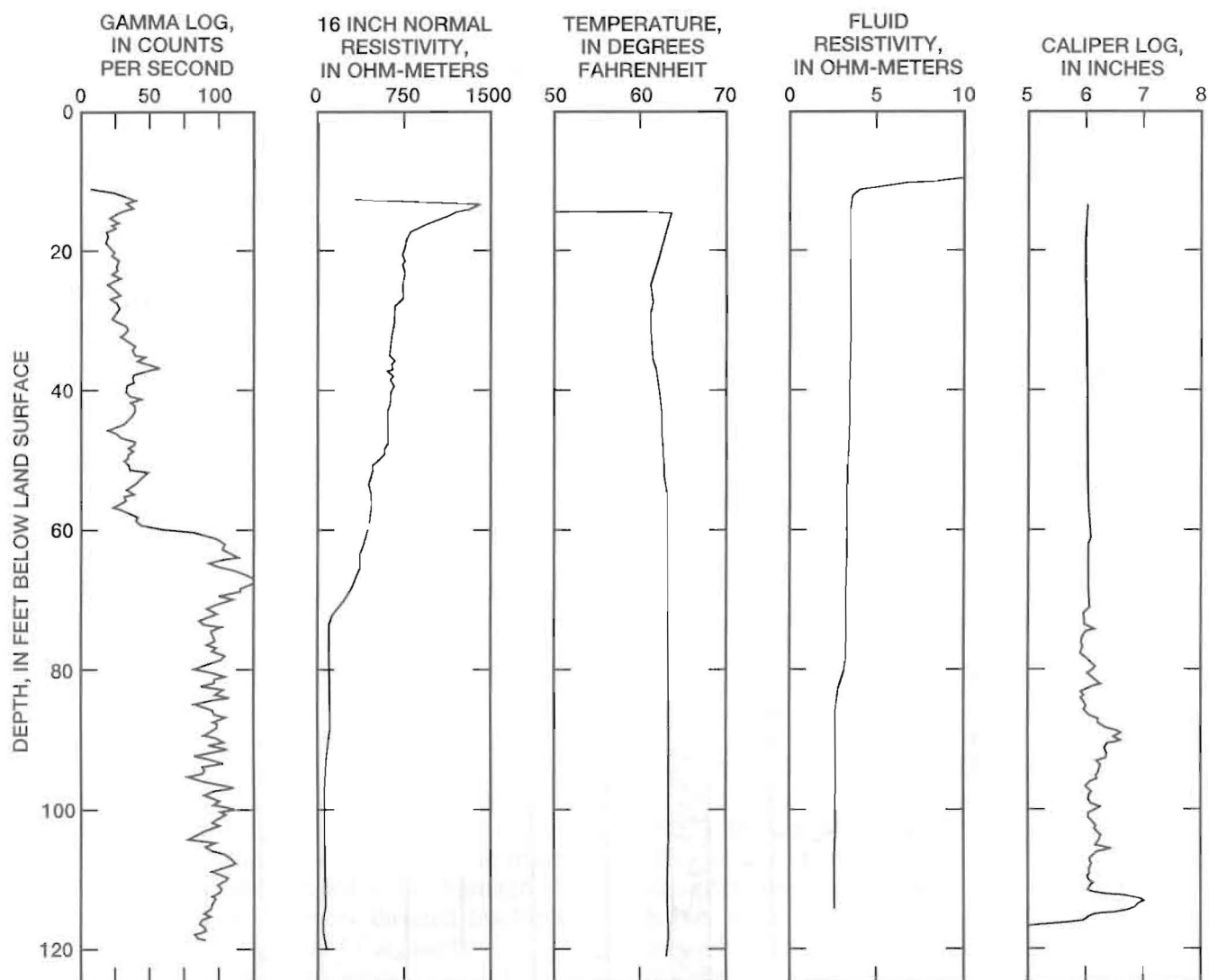


Appendix 2. Geophysical and selected acoustic-televviewer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California—*Continued*

WELL GS-14

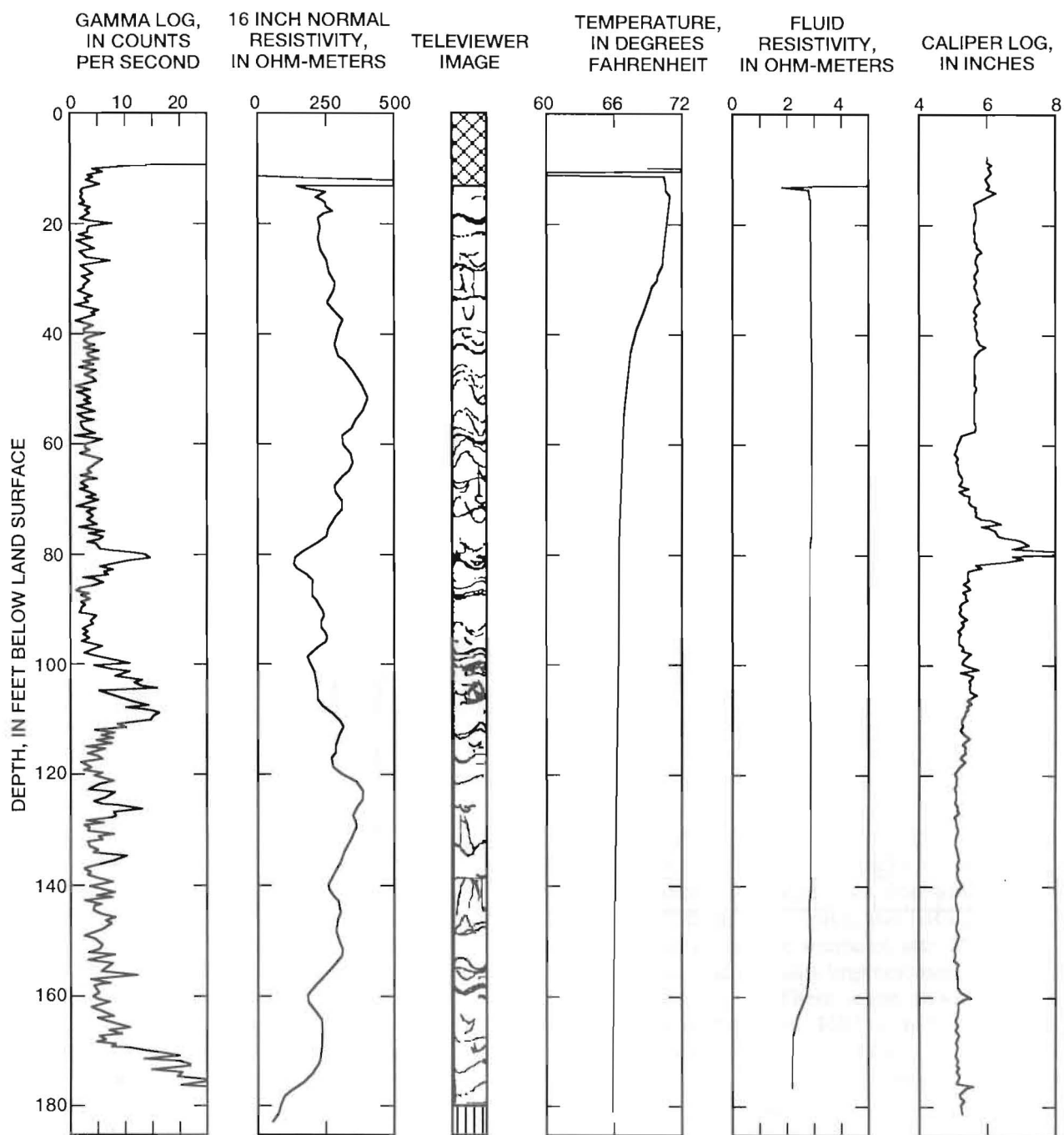


WELL GS-15

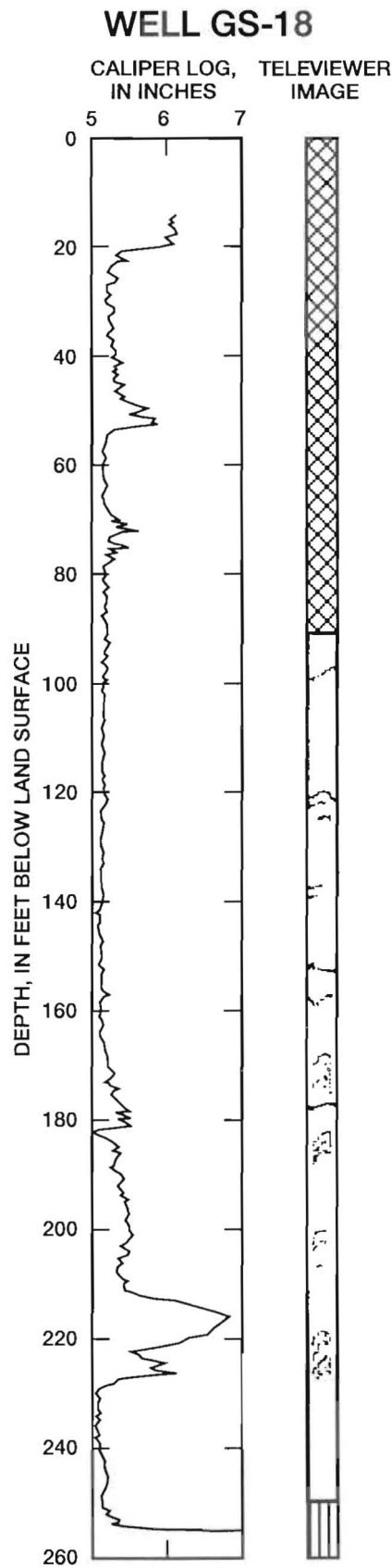


Appendix 2. Geophysical and selected acoustic-televviewer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California—*Continued*

WELL GS-16



Appendix 2. Geophysical and selected acoustic-televiwer logs from USGS monitoring wells GS-10, -11, -12, -13, -14, -15, -16, and -18 at Penn Mine site, Calaveras County, California—*Continued*



Appendix 3. Flowmeter data from USGS monitoring wells GS-10, -11, and -16 at Penn Mine site, Calaveras County, California, December 1993

[Bladder: +, bladder in place and inflated; 0, bladder on tool but deflated. Δt , average of three or more repeated measurements of time elapsed between heat pulse and detection made over a span of two minutes or less. ft, foot; s, second; gal/min, gallons per minute; NF, no flow detected; --, no data]

Well No.	Depth (ft)	Bladder ¹ (+/0)	Flow direction	Δt (s)	1/ Δt (1/s)	Flow (gal/min)	Injection rate (gal/min)	Normalized flow ² (gal/min)
Static tests								
GS-10								
	45	+	--	NF ³	NF	<0.01	--	<0.01
GS-11								
	85	+	--	NF	NF	<.01	--	<.01
GS-16								
	122	+	--	NF	<0.02	<.02	--	<.02
	55	+	Up	12.5	.08	+.07	--	+.07
	30	+	Up	19.0	.05	+.04	--	+.04
	20	+	Up	22.0	.05	+.04	--	+.04
	40	+	Up	16.0	.06	+.05	--	+.05
	60	+	Up	17.0	.06	+.05	--	+.05
	85	+	Down	14.5	.07	-.06	--	-.06
	110	+	Down	14.5	.07	-.06	--	-.06
	115	+	--	NF	<.02	<.02	--	<.02
	70	+	Up	13.5	.07	+.06	--	+.06
Injection tests								
GS-16								
	85	+	Down	5.0	.20	-.20	3.1	-.20
	110	+	Down	5.7	.18	-.17	3.1	-.17
	122	+	Down	28.0	.04	-.03	3.1	-.03
	145	+	Down	22.0	.05	-.04	3.1	-.04
	173	+	--	NF	<.02	<.02	3.1	<.02
	163	+	--	NF	<.02	<.02	3.1	<.02
	154	+	Down	18.0	.06	-.05	3.1	-.05
	122	+	Down	18.5	.05	-.04	3.1	-.04
	115	+	Down	7.9	.12	-.11	3.1	-.11
	110	+	Down	4.5	.22	-.22	3.1	-.22
	85	+	Down	4.6	.22	-.22	3.1	-.22
	75	0	Down	2.0	.50	-3.0	3.1	-3.0
	60	0	Down	1.9	.53	-3.2	3.1	-3.2
	50	0	Down	3.0	.33	-2.0	2.0	-3.2
	40	0	Down	3.1	.32	-1.9	2.0	-3.1
	30	0	Down	3.0	.33	-2.0	2.0	-3.2
	20	0	Down	2.8	.36	-2.2	2.0	-3.5
	15	0	Down	3.5	.29	-1.7	2.0	-2.7

¹An inflatable bladder, when inflated, focuses the entire flow in the borehole through the flowmeter. Measurements with the bladder inflated (+) are accurate to within ± 0.05 gal/min, and can resolve flow as small as 0.02 gal/min; measurements become very difficult to calibrate when flow exceeds 1.0 gal/min. Measurements made with packer deflated (0) are accurate to within ± 0.5 gal/min; these measurements are more nearly linear in the range of 1.0 to 5.0 gal/min.

²Rate of injection during test of GS-16 was reduced when measured downflow began to exceed 3.0 gal/min to keep flow within effective calibration range of the flowmeter; subsequent measurements are normalized to original injection rate using the method described by Paillet and others (1996) to account for the difference in magnitude of the flow regime.

³NF denotes no flow response detected, at a level less than 0.02 gal/min.

Appendix 4. Water level altitudes from USGS monitoring wells at Penn Mine site, Calaveras County, California, September 1992 to November 1993

[Location of wells shown in figure 3. --, no data; ii, well inundated by Camanche Reservoir; aa, artesian flow]

USGS well	GS-1A	GS-1B	GS-2	GS-3	GS-4A	GS-4B	GS-4C	GS-5	GS-6	GS-7	GS-8A	GS-8B	GS-9
Date	Altitude, in feet above sea level												
9-18-92	192.57	210.31	190.37	214.18	179.35	178.84	197.50	178.77	182.76	185.96	178.82	194.99	--
10-28-92	192.37	210.57	190.13	213.21	180.48	179.98	197.48	179.89	183.05	185.73	179.95	194.65	--
11-12-92	192.22	210.48	190.04	213.24	178.23	177.65	197.47	177.52	182.54	185.63	177.60	194.18	--
12-10-92	192.64	210.67	--	--	177.36	175.00	197.50	--	182.25	--	174.43	194.13	--
12-13-92	--	--	--	--	--	--	--	--	--	--	--	--	--
12-14-92	--	--	--	--	--	--	197.47	--	--	--	--	194.05	--
12-15-92	194.31	210.64	--	--	176.73	174.77	--	--	--	--	174.06	--	--
12-16-92	--	--	--	--	--	--	--	--	--	--	--	--	--
12-19-92	193.52	209.96	--	216.20	176.14	174.22	--	--	182.76	--	173.55	177.23	--
12-31-92	--	--	--	--	--	--	--	--	183.19	--	--	--	--
1-11-93	--	--	--	--	--	--	--	--	--	--	--	--	--
1-12-93	197.16	210.18	197.79	--	--	176.39	192.37	174.55	184.87	190.03	174.64	193.31	--
1-15-93	--	--	--	--	--	--	--	--	--	--	--	--	--
1-23-93	--	--	--	--	--	--	--	--	--	--	--	--	--
1-28-93	--	--	--	--	--	--	--	--	--	--	--	--	--
2-10-93	--	--	--	--	--	--	--	--	--	--	--	--	--
2-24-93	201.09	211.04	202.58	219.59	196.60	196.16	197.50	196.14	193.24	196.44	196.19	194.36	--
3-04-93	--	--	--	--	--	--	--	--	--	--	--	--	--
3-10-93	--	--	--	--	--	--	--	--	--	--	--	--	--
3-19-93	--	--	--	--	--	--	--	--	--	--	--	--	--
3-29-93	--	--	--	--	--	--	--	--	--	--	--	--	--
3-30-93	208.61	210.90	208.18	218.84	207.66	207.82	207.46	207.88	206.72	207.89	207.81	195.06	207.92
4-15-93	--	--	--	--	--	--	--	--	--	--	--	--	--
5-05-93	--	--	--	--	--	--	--	--	--	--	--	--	--
5-28-93	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii
7-07-93	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii
10-22-93	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii	ii
11-23-93	--	--	--	--	--	--	--	--	--	--	--	--	--
11-25-93	--	--	--	--	--	--	--	--	--	--	--	--	--

Appendix 4. Water level altitudes from USGS monitoring wells at Penn Mine site, Calaveras County, California, September 1992 to November 1993—Continued

USGS well	GS-10	GS-11	GS-12	GS-13	GS-14	GS-15	GS-16	GS-17	GS-18	GS-19	GS-20	Camanche Reservoir ¹
Date	Altitude, in feet above sea level											
9-18-92	--	--	--	--	--	--	--	--	--	--	--	179.13
10-28-92	--	--	--	--	--	--	--	--	--	--	--	180.34
11-12-92	--	177.84	--	177.31	177.81	--	242.48	--	--	265.82	267.63	178.00
12-10-92	--	174.85	--	--	--	--	--	--	267.37	268.67	267.44	174.82
12-13-92	196.02	174.79	--	174.34	174.33	173.48	--	--	268.52	270.09	268.64	174.47
12-14-92	--	--	--	--	174.14	--	--	--	268.65	270.16	268.74	174.32
12-15-92	196.05	174.48	--	172.52	174.05	--	--	--	268.80	270.33	268.89	174.17
12-16-92	--	--	--	--	--	--	--	--	268.87	270.30	268.98	174.00
12-19-92	--	--	--	--	--	--	--	--	--	--	--	173.65
12-31-92	--	--	--	--	--	--	--	--	271.61	272.20	271.65	172.60
1-11-93	198.49	--	198.30	174.59	174.60	173.71	244.32	--	--	--	--	173.16
1-12-93	--	--	--	--	--	--	--	--	--	--	--	173.48
1-15-93	--	175.25	--	--	--	--	--	--	--	--	280.81	175.04
1-23-93	--	--	210.52	--	--	--	--	--	--	283.29	aa	179.52
1-28-93	--	--	191.68	--	--	--	--	--	283.66	288.90	aa	182.48
2-10-93	--	--	--	--	--	--	--	--	282.70	293.28	aa	188.92
2-24-93	214.75	196.46	213.21	196.13	195.98	194.99	253.62	--	283.30	294.94	aa	196.04
3-04-93	--	--	--	--	--	--	--	--	282.18	291.10	aa	198.82
3-10-93	--	--	--	--	--	--	--	--	281.94	291.31	aa	200.08
3-19-93	--	--	--	--	--	--	--	--	281.64	291.88	aa	202.22
3-29-93	--	--	--	--	--	--	--	--	282.41	--	aa	207.48
3-30-93	207.08	207.91	212.97	207.88	207.66	206.71	--	--	--	--	aa	207.88
4-15-93	--	--	--	--	--	--	--	314.57	281.45	297.38	aa	213.52
5-05-93	--	--	--	--	--	--	252.19	314.03	280.27	296.45	280.73	213.39
5-28-93	ii	ii	ii	ii	ii	ii	251.35	313.04	278.74	290.43	278.11	221.40
7-07-93	ii	ii	ii	ii	ii	ii	252.76	312.97	276.77	287.30	276.59	231.12
10-22-93	ii	ii	ii	ii	ii	ii	250.32	--	271.50	278.68	271.01	219.99
11-23-93	--	--	--	--	--	--	--	313.02	270.65	--	--	218.73
11-25-93	--	--	--	--	--	--	--	--	--	--	276.00	218.67

¹Data for altitude of Camanche Reservoir surface provided by the East Bay Municipal Utility District (written commun., 1996).

