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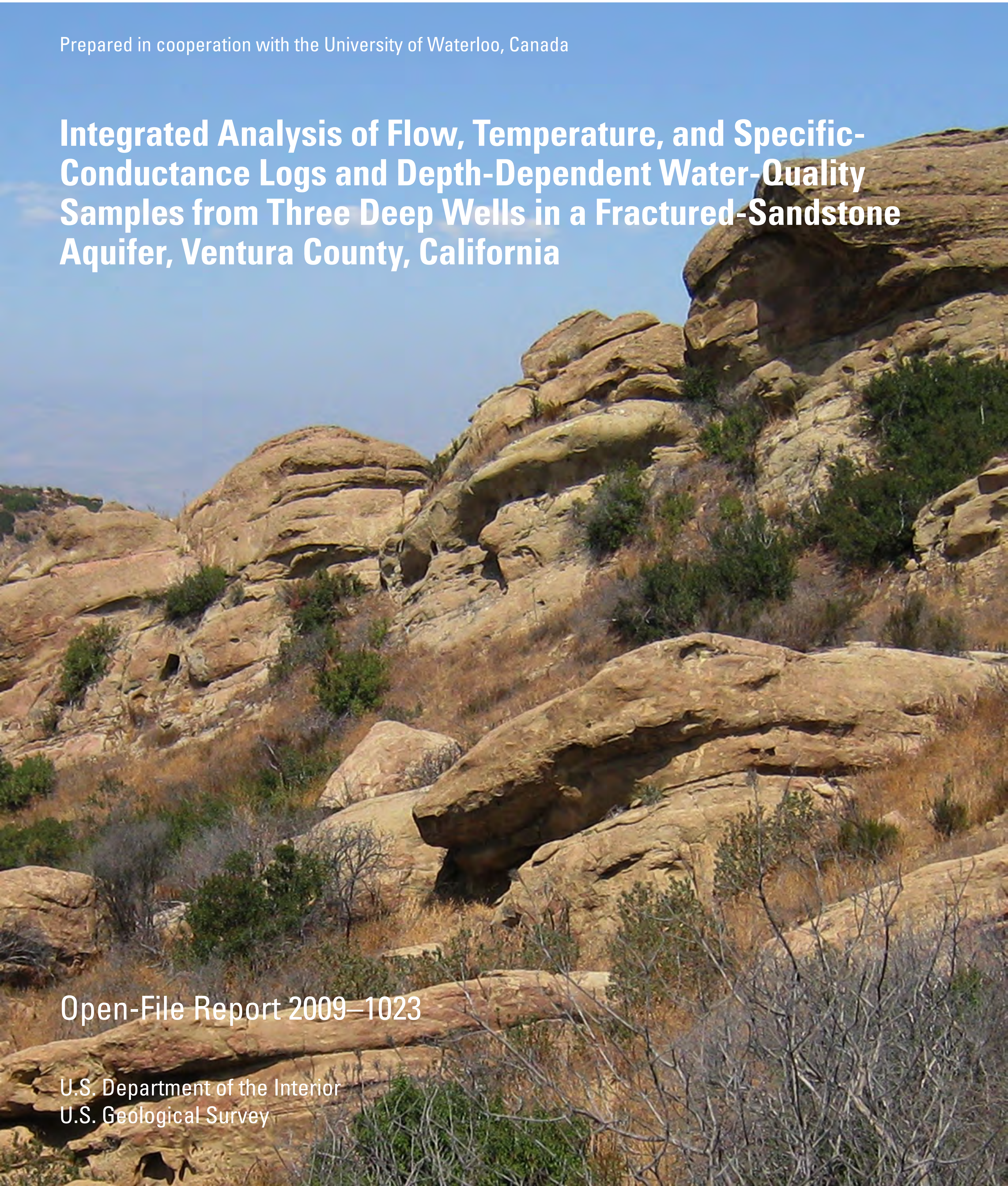

Open-File Report 2009–1023

U.S. Department of the Interior
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Cover. Outcrop of fractured sandstone at the Santa Susana Field Laboratory, Ventura County, California. Photograph courtesy of MWH Americas, Inc.

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

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

Integrated Analysis of Flow, Temperature, and Specific-Conductance Logs and Depth-Dependent Water-Quality Samples from Three Deep Wells in a Fractured-Sandstone Aquifer, Ventura County, California

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Abstract

Analysis of flow, temperature, and specific-conductance logs and depth-dependent water-quality samples collected under ambient and pumped conditions provided a preliminary delineation of flow zones and water quality in three deep abandoned water-supply wells. The integrated analysis was completed as part of the characterization of a fractured-sandstone aquifer in the mountainous setting of the Santa Susana Field Laboratory in southern Ventura County, California.

In the deepest well, which was 1,768 feet deep and had the highest specific capacity (120 gallons per minute per foot), flow zones were detected at 380 feet (base of casing) and at 440, 595, and 770 feet in the open hole. Under ambient conditions, measured flow was downward from the 380- and 440-foot zones to the 595- and 770-foot zones. Under pumped conditions, most of flow was contributed by the 595-foot zone. Flow from the 380- and 440-foot zones appeared to have lower specific conductance and higher trichloroethylene concentrations than that from the 595-foot zone.

In the shallowest well, which was reportedly 940 feet deep but only logged to 915 feet due to blockage, flow zones were detected behind the perforated casing and at 867 feet in the open hole. Under ambient conditions, downward and upward flows appeared to exit at a zone behind the perforated casing at 708 feet. Most of the pumped flow was contributed from zones behind the perforated casing between 565 and 708 feet. Pumped flow also was contributed by zones at 867 feet and below the logged depth. Volatile organic compounds were not detected in the ambient and pumped flows.

In the third well, which was 1,272 feet deep and had the lowest specific capacity (3.6 gallons per minute per foot), flow zones were detected in the open hole above and just below the water level near 337 feet and at 615, 785, 995, and 1,070 feet. Under ambient conditions, measured flow in well was downward from the shallowmost zones to the 995-foot zone. Fracture zones at 615, 785, and 995 feet each contributed about one-third of the pumped flow measured below the pump. Volatile organic compounds were not detected in the ambient and pumped flows.

Introduction

Analysis of flow, temperature, specific-conductance logs, and depth-dependent water-quality samples provides an efficient means for the preliminary delineation of flow zones and water quality in multiple-zone wells. The purpose of this study was to demonstrate the application of this integrated analysis as part of the geohydrologic characterization of deep wells completed in a fractured-sandstone aquifer.

This study was done in cooperation with the University of Waterloo, who is providing technical assistance to the Boeing Company in their ongoing investigation of volatile organic compound (VOC) contamination in the fractured sandstone underlying the mountainous setting of the Santa Susana Field Laboratory, southern Ventura County, California (fig. 1). The geophysical logging and water-quality sampling were completed in three deep abandoned water-supply wells during November 2005. This report describes the methods used in the study and presents the geophysical log and water-quality data and their preliminary analysis.

Methods

Geophysical logs and depth-dependent water-quality samples were collected from wells WS–12, WS–13, and WS–14. The geophysical logs included temperature, specific conductance, flow, caliper, and gamma. The caliper logs of wells WS–12 and WS–14 were previously collected by Schlumberger Water Services. Flow, temperature, specific-conductance logging, and depth-dependent water-quality sampling were completed under ambient and pumped

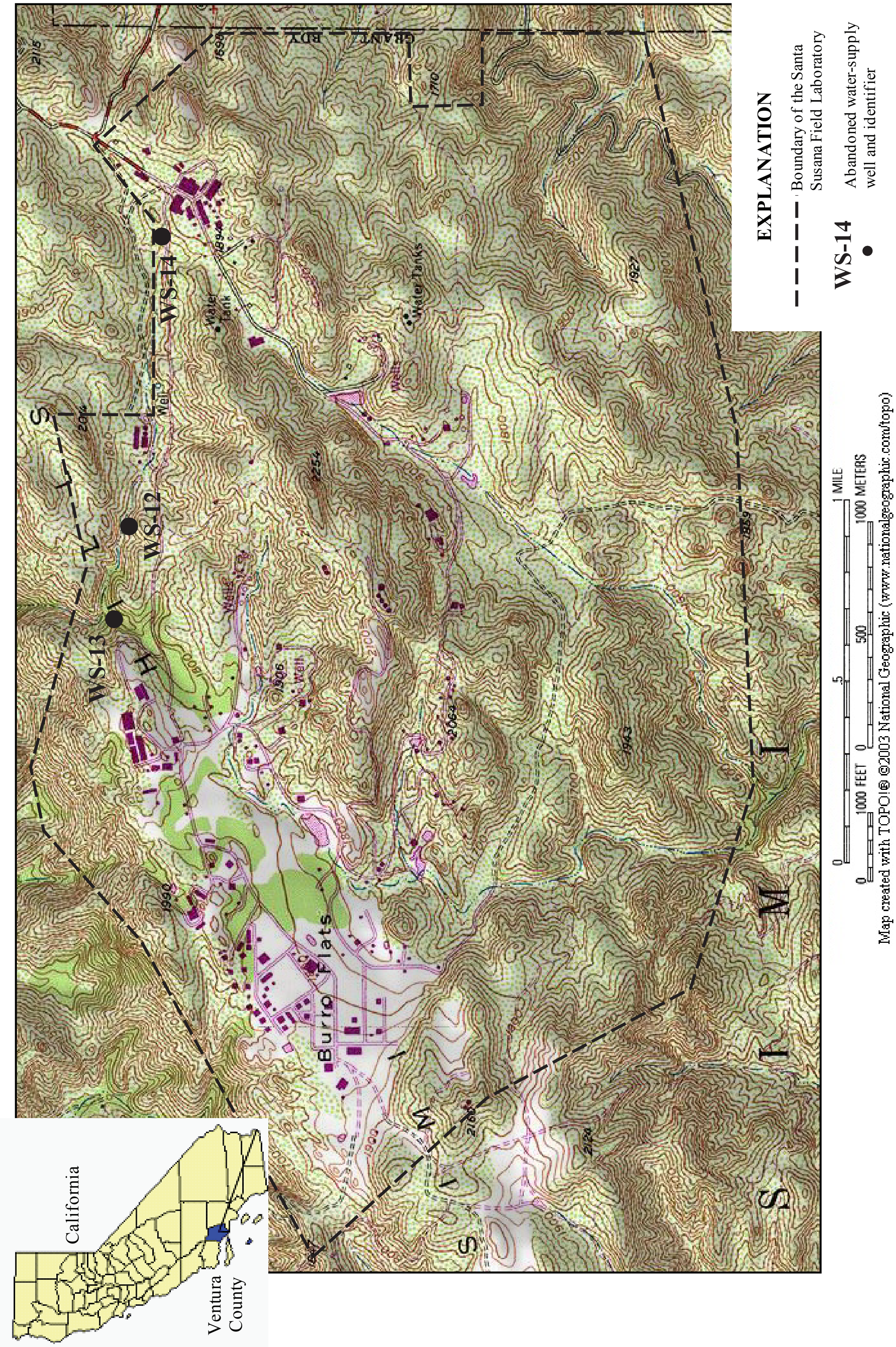

Figure 1. Location of Santa Susana Field Laboratory and abandoned water-supply wells, southern Ventura County, California.

conditions in each well. Pump setup and containment of the pumped discharge, monitoring of discharge rates and water levels, and water-quality sampling and analyses were coordinated by MWH Americas, Inc., site consultant to the Boeing Company. The logs and all other data are referenced to depth below top of well casing.

The geophysical logs and depth-dependent water-quality samples are briefly described below. Additional information on geophysical logs is presented in Keys (1990).

Temperature logs recorded the temperature of the water in the wellbores. Temperature logs were collected under ambient and pumped conditions. Temperature gradients less than the geothermal gradient in the surrounding rocks indicate intervals with vertical wellbore flow. As wellbore flow decreases, the temperature gradient of the wellbore water approaches the geothermal gradient. Downflow is characterized by wellbore water cooler than that in equilibrium with the geothermal gradient. Conversely, upflow is characterized by wellbore water warmer than that in equilibrium with the geothermal gradient. The geothermal gradient in the study area is not known. The generally accepted range for the geothermal gradient in southern California is 0.6 to 1.2°C per 100 ft. However, the geothermal gradient in this mountainous setting would be expected to be less than typical because of the dissipation of heat on the flanks of the topographic high (Peeter Pehme, University of Waterloo, written commun., 2008). Temperature logs were used with the specific-conductance and flow logs to identify flow zones and intervals of flow under ambient and pumped conditions.

Specific-conductance logs recorded the electrical conductivity of the water in the wellbores. The specific conductance of the water is related to the dissolved-solids concentration. Ambient and pumped logs of fluid resistivity, which is inversely related to specific conductance, were collected and converted to specific conductance at 25°C using the temperature logs. Specific-conductance logs were used with the temperature and flow logs to identify flow zones under ambient and pumped conditions and approximate the dissolved-solids concentration.

Flow logs recorded the direction and rate of vertical flow in the wellbores. An electromagnetic (EM) flowmeter (Young and Pearson, 1995) was used to measure vertical flow in this study. The flow of water (an electrical conductor) through an induced magnetic field generates a voltage gradient that, according to Faraday's Law, is proportional to its velocity. Stationary flow measurements were made under ambient conditions, and both trolling and stationary measurements were made under pumped conditions. The flow logs were used with the temperature and specific-conductance logs to identify major flow zones and the direction and rate of flow between flow zones under ambient and pumped conditions.

The measurement drift of the EM-flowmeter results in an approximate tool resolution of plus or minus 0.02 gal/min when it is configured with a fully fitted flow restrictor. The large diameters of the wells in this study necessitated the use of an underfit diverter. The flowmeter was configured with a 6.5-in.-diameter diverter. A bypass factor, or multiplication factor used to convert the flow rates measured using an underfit diverter to estimated flow rates (Paillet, 2004), were determined for each well. A bypass factor of 150 was estimated for well WS–12 on the basis of a set of flow measurements with the flowmeter in a stationary position just below the pump and within the 14-in.-diameter casing while pumping at 35, 55, and 75 gal/min. The tool response was linear over the range of flows tested. A bypass factor of 95 was estimated for well WS–13 on the basis of the flow measurement with the flowmeter in a stationary position just below the pump and within the 12-in.-diameter perforated casing while pumping at 99.5 gal/min. this estimated bypass factor was based on the assumption that none of the pumped discharge was contributed from the perforated interval above the pump. A bypass factor of 115 was estimated for WS–14 on the basis of its open-hole diameter of 12.75 in., the estimated bypass factors for WS–12 and WS–13, and the ratios of the cross-sectional areas of the three wellbores. The estimated bypass factors would suggest that the lower measurement limit was on the order of several gallons per minute. However, the response of the tool with the underfit diverter in these large-diameter wells to low-rate flows was not quantitatively evaluated. The appropriate bypass factors were applied to each set of ambient and pumped flowmeter measurements. The trolling flowmeter logs were calibrated to the stationary flowmeter measurements to provide a continuous estimate of flow under pumped conditions.

Through a comparison with hydraulic testing by use of inflatable straddle packers in open wells in fractured bedrock, Paillet (1998) showed that the flow-log method consistently detected flow zones with transmissivity values having the same order of magnitude as the most permeable zone in the well. In addition, about half of the flow zones with transmissivity values an order of magnitude less than the most permeable zone were detected, and fewer than 20 percent of the zones with transmissivity values two orders of magnitude lower were detected. In the present study, given the rugosity of the wellbores and use of the underfit diverters, flow zones with transmissivity values less than the same order of magnitude as the most permeable zone in the well were not likely to be detected by the flow-log method.

Caliper logs recorded the diameter of the wells. Changes in diameter are related to drilling and well construction, caving of non-competent rocks, and fracture zones. Because flow velocity varies with well diameter for a given wellbore flow, caliper logs are critical for the collection and analysis of flow logs. Stationary flowmeter measurements were collected in competent intervals above and below potential fracture zones as identified on the caliper logs.

Gamma logs record the amount of gamma radiation emitted by the rocks surrounding the wells. Clay-bearing rocks commonly emit relatively high gamma radiation because they include weathering products of potassium feldspar and mica and tend to concentrate uranium and thorium by ion absorption and exchange. Naturally occurring sources of gamma radiation include potassium-40 and daughter products of the uranium- and thorium-decay series. The vertical resolution of the gamma probe is 1 to 2 ft.

Depth-dependent water-quality samples provided for measurements of the quality of water in the wellbores at specific depths. Water samples were collected under ambient conditions and under pumped conditions at the same rates as collection of the flow logs. The sampler used in this study is a piston-driven device that is remotely controlled by a wireline to collect a small volume of water from the wellbore at a selected depth. The selection of the depths to sample was determined by analysis of the caliper, flowmeter, temperature, and specific-conductance logs. Depths were selected so that the water sampled was representative of the ambient or pumped flow from one or more identified flow zones (Williams and Conger, 1990). Additional samples were collected in the deeper intervals of wells WS–12 and WS–14, although the source(s) of this wellbore water was not determined from the geophysical logs. The water samples were analyzed for total dissolved solids, major anions and cations, and VOCs. The VOC analysis included trichloroethylene (TCE), *cis*-1,2-dichlorethene (*cis*-1,2-DCE), and *trans*-1,2-dichlorethene (*trans*-1,2-DCE).

Integrated Analysis of Logs and Water-Quality Samples

The geophysical logs and results of the depth-dependent water-quality sampling were analyzed along with the well-construction and specific-capacity test information for each of the three deep abandoned water-supply wells.

Well WS–12 was cased with 14-in.-diameter steel casing to a depth of 380 ft and was completed as a 14-in.-diameter open hole to a depth of 1,768 ft (table 1). Altitude of the well was 1,705.98 ft above NGVD 29. The well had an ambient water-level depth of 130.36 ft. The well was pumped at a rate of 75 gal/min, which resulted in 0.64 ft of drawdown after 150 minutes of pumping (fig. 2A). The specific capacity of the well was 120 (gal/min)/ft, which was the highest specific capacity of the three wells.

Under ambient conditions, measurable flow in well WS–12 was downward at a rate of several gallons per minute from near the base of casing at 380 ft and from a fracture zone at 440 ft (fig. 3A). This inflow had a specific conductance of less than 1,000 µS/cm at 25°C and total dissolved-solids concentration of 560 mg/L. Concentrations of TCE and *cis*-1,2-DCE were 26 and 20 µg/L, respectively, and *trans*-1,2-DCE was not detected. The flow log indicated that additional downward flow was contributed by the fracture zone at 595 ft, which is at a lithologic change indicated by the gamma log. However, the increase in the gradient of the temperature log from below the 595-ft zone compared to that above is not consistent with this zone contributing additional

Table 1. Well-construction, water-level, and specific-capacity information for abandoned water-supply wells WS–12, 13, and 14, Santa Susana Field Laboratory, Ventura County, California.

[Well-identification number assigned by site owner; altitude of top of casing in feet above National Geodetic Vertical Datum of 1929; latitude and longitude in decimal degrees in reference to the North American Datum of 1983; depth in feet below top of casing; diameter in inches; pumped rate in gallons per minute; drawdown at 150 minutes in feet; specific capacity in gallons per minute per foot of drawdown]

Well number	Latitude	Longitude	Altitude	Casing depth	Casing diameter	Open hole depth	Open hole diameter	Water level date	Depth	Pump rate	Drawdown	Specific capacity
WS–12	34.2383	118.6925	1,705.98	380	14	1,768	14	11/18/2005	130.36	75	0.64	120
WS–13	34.2383	118.6942	1,658.62	752[a]	12	940[b]	12.5	11/18/2005	82.70	99.5	2.96	34
WS–14	34.2372	118.6753	1,878.23	40	16	1,272	12.75	11/21/2005	336.82	59	16.28	3.6

[a] Casing perforated from 22 to 752 feet.

[b] Well blocked at 915 feet.

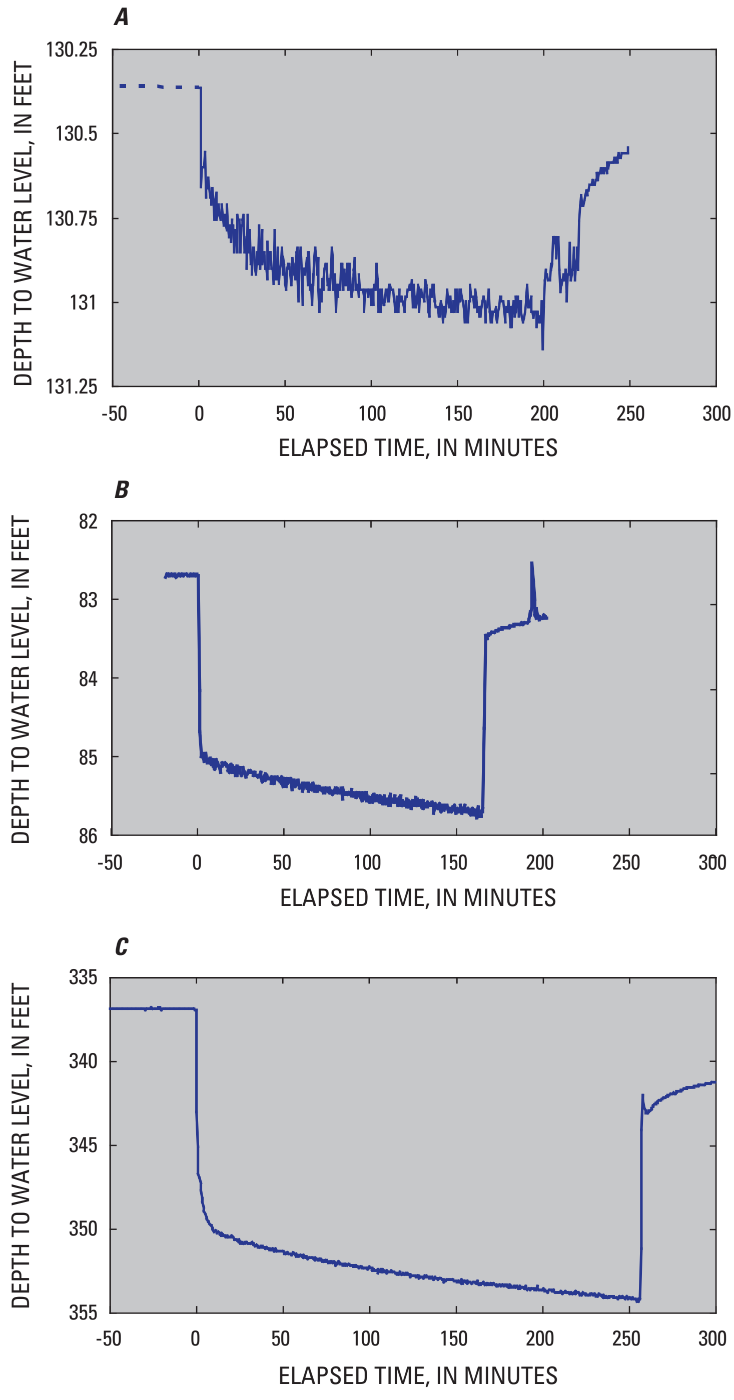

Figure 2. Depth to water level during ambient, pumping, and recovery conditions for abandoned water-supply well *(A)* WS–12, *(B)* WS–13, and *(C)* WS–14, Santa Susana Field Laboratory, Ventura County, California.

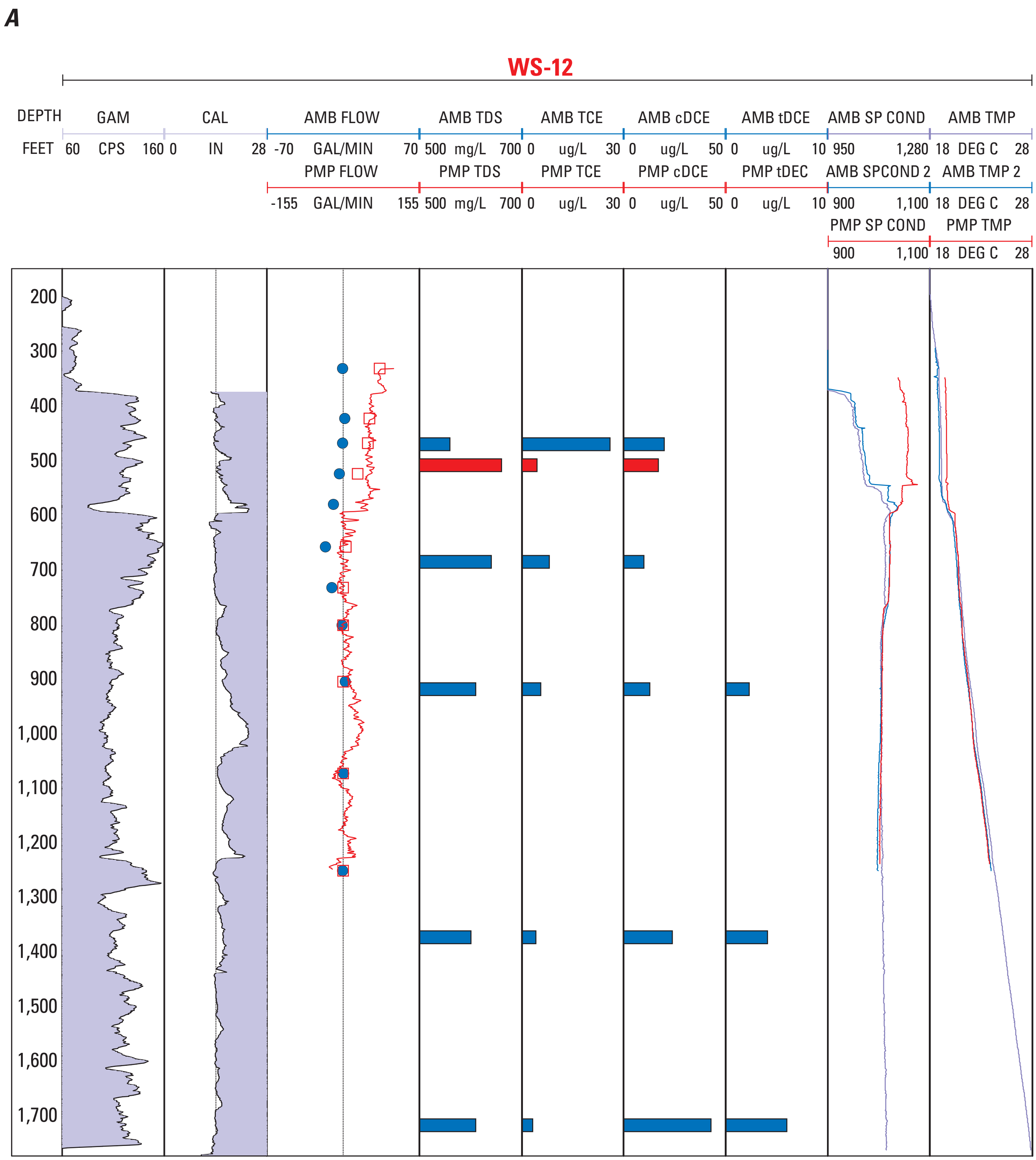

Figure 3. Geophysical logs and water-quality-sampling results for abandoned water-supply well *(A)* WS-12, *(B)* WS-13, and *(C)* WS-14, Santa Susana Field Laboratory, Ventura County, California. [DEPTH FEET (depth below top of casing, in feet); GAM CPS (gamma, in counts per second); CAL IN (caliper, in inches); AMB (ambient conditions); PMP (pumped conditions); FLOW GAL/MIN (ambient flow, in gallons per minute); TDS (total dissolved solids); SULF (dissolved sulfate), mg/L (milligrams per liter); cDCE (*cis*-1,2-DCE), tDCE (*trans*-1,2-DCE), µg/L (micrograms per liter); SP COND µS/cm 25°C (specific conductance, in microsiemens per centimeter at 25 degrees Celsius); and TMP DEG C (temperature, in degrees Celsius).]

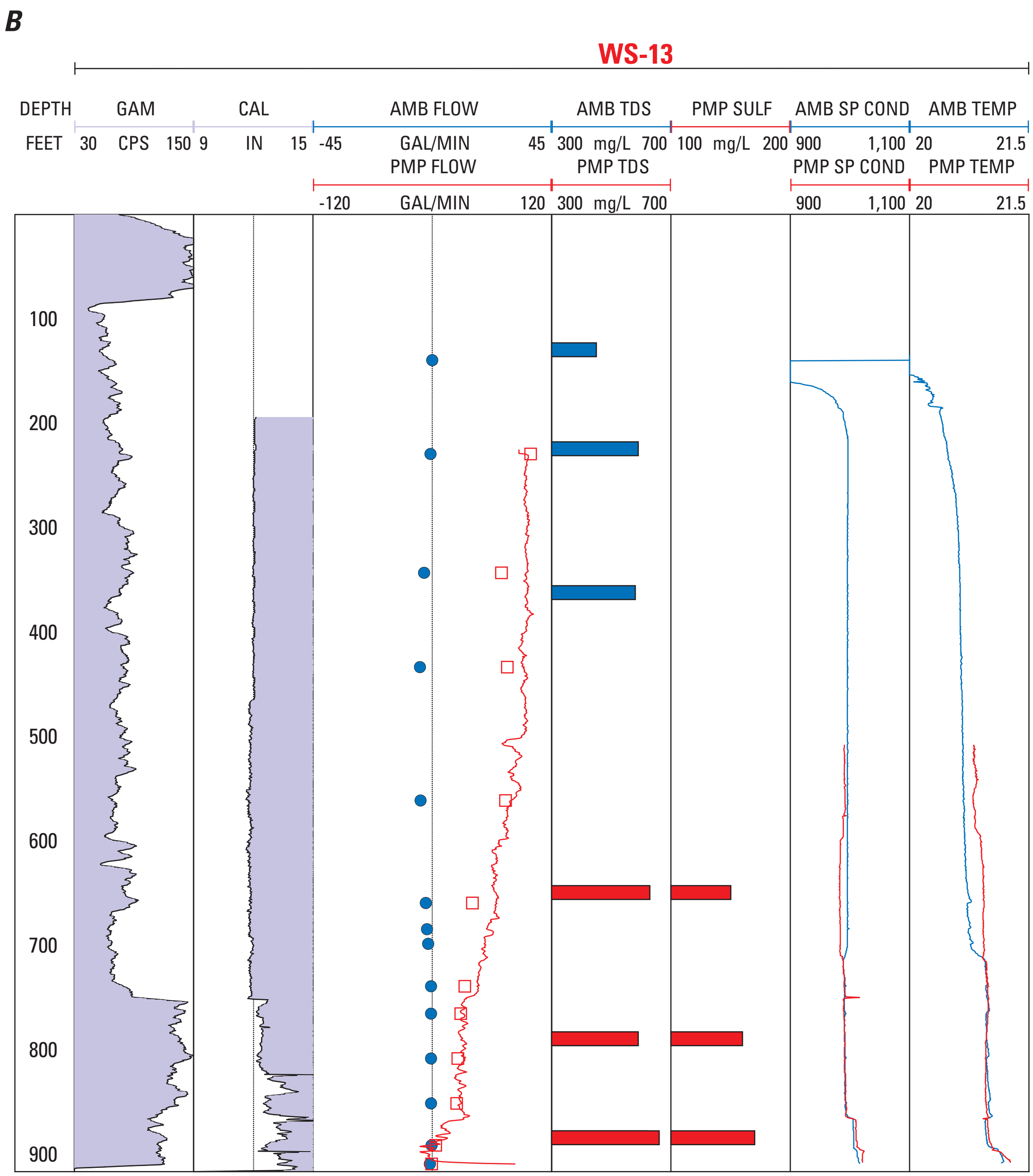

Figure 3. Geophysical logs and water-quality-sampling results for abandoned water-supply well *(A)* WS-12, *(B)* WS-13, and *(C)* WS-14, Santa Susana Field Laboratory, Ventura County, California. [DEPTH FEET (depth below top of casing, in feet); GAM CPS (gamma, in counts per second); CAL IN (caliper, in inches); AMB (ambient conditions); PMP (pumped conditions); FLOW GAL/MIN (ambient flow, in gallons per minute); TDS (total dissolved solids); SULF (dissolved sulfate), mg/L (milligrams per liter); cDCE (*cis*-1,2-DCE), tDCE (*trans*-1,2-DCE), µg/L (micrograms per liter); SP COND µS/cm 25°C (specific conductance, in microsiemens per centimeter at 25 degrees Celsius); and TMP DEG C (temperature, in degrees Celsius).]—Continued

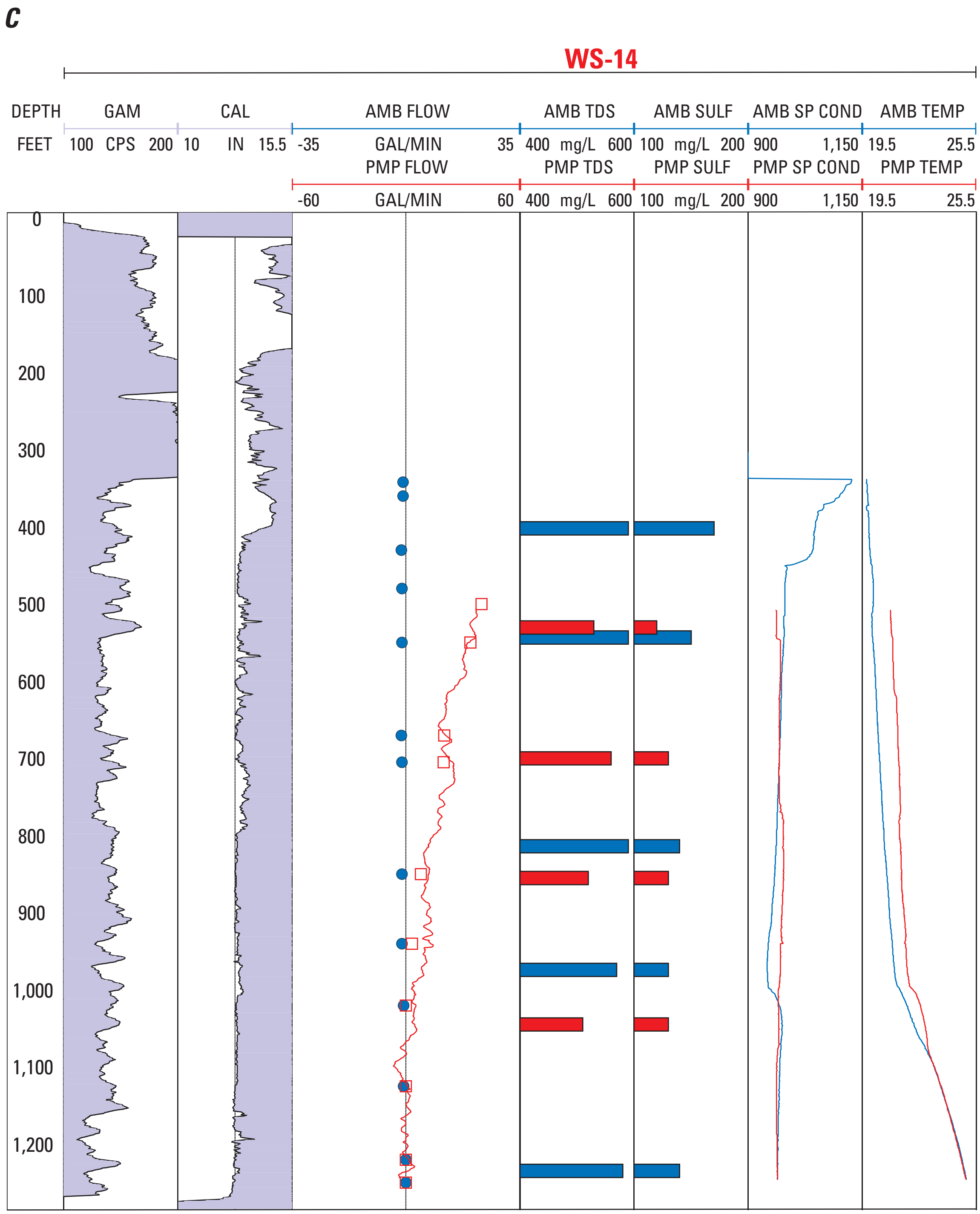

Figure 3. Geophysical logs and water-quality-sampling results for abandoned water-supply well *(A)* WS-12, *(B)* WS-13, and *(C)* WS-14, Santa Susana Field Laboratory, Ventura County, California. [DEPTH FEET (depth below top of casing, in feet); GAM CPS (gamma, in counts per second); CAL IN (caliper, in inches); AMB (ambient conditions); PMP (pumped conditions); FLOW GAL/MIN (ambient flow, in gallons per minute); TDS (total dissolved solids); SULF (dissolved sulfate), mg/L (milligrams per liter); cDCE (*cis*-1,2-DCE), tDCE (*trans*-1,2-DCE), µg/L (micrograms per liter); SP COND µS/cm 25°C (specific conductance, in microsiemens per centimeter at 25 degrees Celsius); and TMP DEG C (temperature, in degrees Celsius).]—Continued

downflow. The apparent increase in downflow may be related to the larger and more irregular borehole diameter in the interval above the 595-ft zone than that below, or possibly the presence of crossflow in this interval. Another explanation is that the thermal conductivity of the rocks below the 595-ft zone may be greater than those above, allowing for greater heat transfer and thereby increasing the temperature-log gradient (Peeter Pehme, University of Waterloo, written commun., 2008). Under the assumption that the 595-ft zone is contributing additional downflow, this inflow had a higher specific conductance and total dissolved-solids concentration but lower concentrations of TCE and *cis*-1,2-DCE than the inflow above.

Outflow of the measurable downward flow was to a fracture zone at 770 ft. The temperature-log gradient indicates little vertical flow in the well below this depth. The water in the wellbore below 770 ft had a relatively consistent specific conductance and total dissolved-solids concentration. TCE concentrations decreased with depth, and concentrations of *cis*-1,2-DCE and *trans*-1,2-DCE increased with depth. The water near the bottom of the well had concentrations of TCE, *cis*-1,2-DCE, and *trans*-1,2-DCE of 3, 43, and 6 µg/L, respectively. The source and residence time of the water in the well below 770 ft are unclear.

Under the pumped conditions, comparison of the ambient and pumped specific-conductance and temperature logs indicate little flow from below 770 ft. Under the pumped conditions, the 770-ft zone contributes about 5 gal/min. Most of the pumped flow, 50 gal/min, was from the 595-ft zone. The inflow from this zone had a specific conductance of more than 1,000 µS/cm at 25°C and a total dissolved-solids concentration of more than 650 mg/L. Concentrations of TCE and *cis*-1,2-DCE were less than 5 and 20 µg/L, respectively, and *trans*-1,2-DCE was not detected.

Well WS-13 is cased with 12-in.-diameter steel casing to a depth of 752 ft (table 1). The casing is perforated below 22 ft, and the well is completed as a 12.5-in.-diameter open hole to a depth of 940 ft. The geophysical logs end at 915 ft because of a blockage in the well. Altitude of the well is 1,658.62 ft above NGVD 29. The well had an ambient water-level depth of 82.70 ft. The well was pumped at a rate of 99.5 gal/min, which resulted in 2.96 ft of drawdown after 150 minutes of pumping (fig. 2B). The specific capacity of the well was 34 (gal/min)/ft.

Under the ambient conditions, downward flow due to inflow from fracture zones behind the perforated casing in well WS–13 progressively increased to a maximum of several gallons per minute at a depth of 560 ft (fig. 3B). Below this depth, the downward flow decreased because there was outflow to fracture zones behind the perforated casing. The last of this downward flow may exit at a fracture zone behind the perforated casing at 708 ft. The downward flow had a relatively consistent specific conductance (1,000 µS/cm at 25°C) and total dissolved solids (580 to 590 mg/L) and sulfate (150 mg/L). VOCs were not detected in this flow.

Ambient flow may be upwards from fracture zones below the logged depth of 915 ft and from the fracture zone at 867 ft. This upward flow has a slightly higher specific conductance and total dissolved-solids concentration than the water from fracture zones behind the perforated casing. VOCs were not detected in this water. The upward flow appeared to exit at the fracture zone behind the perforated casing at 708 ft.

Under the pumped conditions, comparison of the ambient and pumped specific-conductance and temperature logs indicates upward flow from fractures zones below the logged depth of 915 ft and from the fracture zone at 867 ft. Under the pumped conditions, the zones below 915 ft contributed about 5 gal/min and the 867-ft zone contributed about 20 gal/min. The rest of the pumped flow, 75 gal/min, was contributed by fracture zones behind the perforated casing, most of which were between 565 and 708 ft. The specific conductance of the pumped water from the 708-ft zone appeared to be lower than the specific conductance of the water from the 867-ft zone and zones below the logged depth. VOCs were not detected in the pumped flow.

Well WS–14 is cased with 16-in.-diameter steel casing to a depth of 40 ft and is completed as a 12.75-in.-diameter open hole to a depth of 1,272 ft (table 1). Altitude of the well is 1,878.23 ft above NGVD 29. The well had an ambient water-level depth of 336.82 ft. The well was pumped at a rate of 59 gal/min, which resulted in 16.28 ft of drawdown after 150 minutes (fig. 2C). The specific capacity of the well was 3.6 (gal/min)/ft, which was the lowest specific capacity of the three wells.

Under ambient conditions, flow in well WS–14 was downward from fracture zones above and just below the water level to a fracture zone at 995 ft at a rate near the lower measurement limit (fig. 3C). Inflow from fracture zones above the water level had a specific conductance of greater than 1,000 µS/cm at 25°C, while inflow from fracture zones just below the water level had a specific conductance of less than 1,000 µS/cm at 25°C. This apparent decrease in dissolved solids was reflected in the concentrations of dissolved sulfate and other ions but not in the total dissolved-solids concentrations. VOCs were not detected in the ambient flow

Under ambient conditions, the temperature gradient suggests little vertical flow in the well below the 995-ft fracture zone. However, the temperature log under pumped conditions indicates some inflow from 1,070 ft. Fracture zones at 615, 785, and 995 ft each contribute about one-third of the flow measured below the pump. The pumped -conditions specific-conductance log and total dissolved-solids concentrations indicate that the water from the 995-ft fracture has more dissolved solids than water from zones just below the water level, but less than water from zones above the water level. VOCs were not detected in the pumped flow.

Summary

Integrated analysis of flow, temperature, specific-conductance logs, and depth-dependent water-quality samples were used for the preliminary delineation of flow zones and contaminants in three deep abandoned water-supply wells completed in a fractured-sandstone aquifer. In the well WS–12, which was 1,768 ft deep and had the highest specific capacity of the three wells, flow zones were detected at 380, 440, 595, and 770 ft. Under ambient conditions, measured flow was downward from the 380- and 440-ft zones to the 595- and 770-ft zones. Under pumped conditions, most of the flow was contributed by the 595-ft zone. Flow from the 380- and 440-ft zones appeared to have lower specific conductance and higher TCE concentrations than flow from the 595-ft zone.

In well WS–13, which was reportedly 940 ft deep but only logged to 915 ft because of blockage, a flow zone was detected behind the perforated casing at 708 ft. Under ambient conditions, downward flow from zones behind the perforated casing and upward flow from zones at 867 ft and below the logged depth appeared to exit at the 708-ft zone. Most of the pumped flow was contributed from fracture zones behind the perforated casing between 565 and 708 ft. Zones at 867 ft and below the logged depth also contributed pumped flow. The specific conductance of the pumped water from the 708-ft zone appeared to be lower than the specific conductance of the water from zones at 867 ft and below the logged depth. VOCs were not detected in the ambient and pumped flows.

In well WS–14, which was 1,272 ft deep and had the lowest specific capacity of the three wells, measured ambient flow was downward from zones above and just below the water level to a zone at 995 ft. Additional flow zones were detected under pumped conditions at 615, 785, and 1,070 ft. The specific conductance of flow from the zones near the water level was higher than that from deeper zones. VOCs were not detected in the ambient and pumped flows.

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