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Hydrogeology and Geochemistry of the Fallon Basalt and Adjacent Aquifers, and Potential Sources of Basalt Recharge, in Churchill County, Nevada

Water-Resources Investigations Report 01-4130

Prepared in cooperation with the
BUREAU OF RECLAMATION and the
NEVADA DIVISION OF WATER RESOURCES
(in partnership with NAVAL AIR STATION FALLON)

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By Douglas K. Maurer *and* Alan H. Welch

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Carson City, Nevada
2001

U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS, VERTICAL DATUM, AND WATER-QUALITY UNITS

Multiply	By	To obtain
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	4,047	square meter
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
foot per second (ft/s)	0.3048	meter per second
square foot per day (ft^2/d)	0.09290	square meter per day
gallon (gal)	3.7854	liter
gallons per minute (gal/min)	3.7854	liters per minute
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile ($ft^3/s/mi$)	0.02832	cubic meter per second per mile
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Altitude, as used in this report, refers to distance above or below sea level.

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, square foot per day (ft^2/d), is used for convenience.

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

Water-quality units used in this report:

µg/L	microgram per liter	mL	millileter
µS/cm	microsiemen per centimeter	mmol/L	millimole per liter
mg/L	milligram per liter	pCi/L	picocurie per liter
mg/L/yr	milligram per liter per year		

Hydrogeology and Geochemistry of the Fallon Basalt and Adjacent Aquifers, and Potential Sources of Basalt Recharge, in Churchill County, Nevada

By Douglas K. Maurer *and* Alan H. Welch

ABSTRACT

The Fallon basalt aquifer serves as the sole source of municipal water supply for the Lahontan Valley in west-central Nevada. Principal users include the City of Fallon, Naval Air Station Fallon, and the Fallon Paiute–Shoshone Tribe. Pumpage from the aquifer increased from about 1,700 acre-feet per year in the early 1970's to more than 3,000 acre-feet per year in the late 1990's, and has been accompanied by declines in water levels and changes in water quality. In April 1997, the U.S. Geological Survey began a study in cooperation with the Nevada Division of Water Resources and the Bureau of Reclamation, U.S. Department of the Interior, to describe the hydrogeologic and geochemical framework of the Fallon basalt aquifer and to evaluate potential sources of recharge.

Volcanic activity from about 1 to 2.5 million years ago produced the basalt formation, which is exposed at Rattlesnake Hill, an eroded cone near Fallon that is about 1 mile in diameter. Most of the Fallon basalt is buried beneath as much as 600 feet of sediments deposited by ancient Lake Lahontan and by the Carson River. These deposits form the three sedimentary aquifers—shallow, intermediate, and deep—that surround the basalt.

Water-level, water-quality, lithologic, and borehole geophysical data from 19 wells installed for the study were combined for analysis with data from 97 existing wells. The lateral and vertical extent of the basalt was delimited by using electrical resistivity data from the 1970's, seismic-reflection data collected in 2000, and information from drillers' logs. These data show the basalt to be an asymmetrical, mushroom-shaped body that is about 4 miles wide and about 10 miles long from southwest to northeast. They provide reasonable confirmation of its lateral extent except near its northeastern boundary, where individual basalt flows may interfinger with sedimentary deposits. Drillers' logs show the basalt to be 400 to 600 feet below land surface near its southwestern extent, and about 200 to 300 feet below land surface near its northeastern extent.

The lithology of the basalt was found to be highly variable, ranging from highly porous to dense and massive. The lithology of the shallow and intermediate sedimentary aquifers surrounding the basalt also was found to be highly variable, changing abruptly from sand to clay in layers ranging in thickness from less than a foot to tens of feet. The thickest and most numerous sand layers are to the west, northwest, and southwest of Rattlesnake Hill. On the eastern and southeastern sides of the basalt, clay predominates in the overlying sediments and probably restricts recharge to the basalt from those directions. Deeper than about 600 feet below land surface, the lower boundary and lithology of the basalt could not be fully described because few wells completely penetrate the basalt. Below this depth, the quality of water and the volume of potable water within the basalt aquifer are not known.

In the basalt aquifer, water-level altitudes measured in 1998 were as much as 8 to 12 feet lower than those measured in 1978–80. Near the southwestern part of the basalt, water levels in the shallow sedimentary aquifer were as much as

40 feet higher than those in the basalt and as much as 30 feet higher in the upper part of the intermediate sedimentary aquifer. These findings suggest that the greatest potential for recharge to the basalt is near Rattlesnake Hill in the shallow sedimentary aquifer, and to the southwest, west, and northwest of Rattlesnake Hill where permeable sand layers in the upper parts of the intermediate sedimentary aquifer may contact the basalt. These sand layers, along with wells that penetrate both the sedimentary and basalt aquifers, also represent potential avenues of contamination to the basalt aquifer.

The stable-isotope composition and tritium concentration of ground water in the study area show: (1) the source of recharge to the shallow sedimentary aquifer is surface water released from Lahonton Reservoir, (2) the source of recharge to the intermediate sedimentary aquifer near the center of Lahontan Valley is not the shallow sedimentary aquifer but probably originates from the flow of the Carson River before construction of Lahonton Reservoir or from local precipitation, and (3) the source of a portion of recharge to the basalt aquifer is the shallow sedimentary aquifer near Rattlesnake Hill.

The stable-isotope compositions of the intermediate sedimentary aquifer and the basalt aquifer are similar. However, if the intermediate aquifer supplies recharge to the basalt, one must account for a source of additional chloride. Chloride concentrations in the southwestern part of the basalt are lower than are found elsewhere in the aquifer, suggesting inflow of more dilute water from the intermediate aquifer.

The stable-isotope composition and water chemistry of the basalt aquifer are unlike those of any other single source of water sampled in the study area, showing that recharge to the basalt must represent a mixture of water from different sources, or that dissolution of aquifer materials is taking place along ground-water flow paths. Recharge to the basalt may consist of water from the shallow sedimentary aquifer near Rattlesnake Hill and a combination of water from: (1) the intermediate sedimentary aquifer on the southwest, west, and northwestern sides of the basalt, with the addition of chloride from other ground-water sources or from dissolution of aquifer materials; (2) the intermediate sedimentary aquifer along the eastern side of the basalt or at depths greater than 300 to 500 feet along the southern side of the basalt; or (3) the upward flow of deeper ground water with high concentrations of chloride from the intermediate sedimentary, deep sedimentary, or basalt aquifers. Within the well bores of municipal supply wells, water from sources both near and thousands of feet from pumping wells may become mixed.

Declining water levels in the basalt aquifer in recent decades have been accompanied by increases in chloride concentrations in the southwest part of the aquifer. The source of chloride could be water originating in the intermediate or deep sedimentary aquifers adjacent to or underlying the southern edge of the basalt at depths greater than 300 to 500 feet, or it could be water from deeper than 600 feet in the basalt aquifer. Decreasing chloride concentrations seen in a well north of Fallon suggest inflow from less-saline sources in the intermediate aquifer overlying the northwest part of the basalt.

INTRODUCTION

The Carson Desert, at the terminus of the Carson River (fig. 1), was developed as an agricultural area after the Bureau of Reclamation's completion in 1915 of Lahontan Dam, which impounds the river in Lahontan Reservoir. The population of Fallon (fig. 2) has grown in the last 30 years from 3,000 in the early 1970's (Glancy, 1986, p. 27) to 8,200 in 1997 (Nevada State Demographer, written commun., 1998).

The sole source of water for municipal supply to the city of Fallon, Naval Air Station Fallon, and the Fallon Paiute–Shoshone Tribe is a basalt aquifer. Since the early 1970's, increased pumpage from the basalt aquifer has caused declines in water levels and is thought to have induced changes in water quality. Pumpage increased from about 1,700 acre-ft/yr in the early 1970's to about 3,000 acre-ft/yr in the early 1990's, resulting in a decline in water levels from less than 40 ft below land surface to as much as 50 ft below (fig. 3). Maurer and others (1996, p. 61) report that the dissolved chloride concentration in water pumped from the basalt by U.S. Navy wells increased from about 90 mg/L in the early 1960's to about 110 mg/L in 1992. These changes have led to concern about the continued viability of the basalt aquifer as a source of water in light of the increasing population of the area.

The basalt aquifer was first described by Glancy (1986). In April 1997, the U.S. Geological Survey (USGS) began a more detailed study of the Fallon basalt aquifer in cooperation with the Nevada Division of Water Resources (partners with Naval Air Station Fallon) and the Bureau of Reclamation. The objectives of the study were to compile and analyze existing data, obtain additional data from sedimentary aquifers surrounding the basalt, describe the hydrogeologic and geochemical framework of the basalt aquifer, evaluate potential pathways of recharge to the basalt aquifer, and provide a basis for future studies of the basalt aquifer.

Purpose and Scope

The purpose of this report is to summarize data on lithology, water levels, and water quality from the basalt aquifer and sedimentary aquifers adjacent to the basalt, and to describe the hydrogeologic and geochemical framework of the basalt aquifer. Data were compiled and collected from April 1997 through June 1999 from a total of 116 wells. Seismic-reflection data were collected in April 2000 to aid in delineating the lateral extent of the basalt aquifer. The seismic-reflection data and lithologic data from 48 existing wells and 9 test holes drilled for this study are presented, along with historical water-level and water-quality data, water levels measured at 36 wells, and water-quality analyses of samples collected from 31 wells. Data are analyzed to evaluate changes in dissolved chloride and arsenic concentrations over time in water from selected wells pumping from the basalt aquifer, and to evaluate and describe potential sources of recharge to the basalt.

Acknowledgments

The authors thank Francis Monastero of the China Lake Naval Air Weapons Station for providing age dates of basalt samples and for contributing to collection of seismic-reflection data; Mark Jones, Ed Muench, and Bob Seaver of Naval Air Station Fallon for providing data and access to Navy wells; B.J. Selinder, the Churchill County Road Department, and the Churchill County Board of Supervisors for permission to install wells on county property; Larry White and the City of Fallon for providing data and access to City wells; Alvin Moyle and George Martinez of the Fallon Paiute–Shoshone Tribe for permission to install wells on Tribal property and for providing data; Joanne Corkhill, Willis Hyde, and Lyman McConnell of the Truckee–Carson Irrigation District for permission to install wells on District property; Jerry Buck of the Agricultural Experiment Station, University of Nevada, Reno, for permission to install wells on University property; Robert Allan, John Serpa, Peggy Witte (Kent), and Marie York for permission to install wells on their private property; and Norm Parsons of Parsons Drilling and Jim Biffle of Welsco Drilling for aid in obtaining information on the basalt aquifer and existing wells.

PHYSICAL SETTING

The Fallon basalt aquifer is located in the Carson Desert Hydrographic Area[1], the terminus of the Carson River (fig. 1). Flow of the Carson River and diversions from the Truckee River are stored in Lahontan Reservoir; the water is used for irrigation of about 56,000 acres in Lahontan Valley (fig. 2), the name generally applied to the irrigated part of the Carson Desert (Maurer and others, 1996, p. 4). The study area is in the center of Lahontan Valley, extending about 5 to 8 mi from Rattlesnake Hill (fig. 2).

The irrigated lands form the Carson Division of the Newlands Project, which was constructed from 1902 to 1915. The outflow from Lahontan Reservoir averaged about 377,000 acre-ft/yr from 1967 to 1998 (Preissler and others, 1999, p. 177). About 170,000 acre-ft/yr is delivered to 1,500 farm headgates through about 340 mi of canals and laterals. About 350 mi of drains route return flow and ground-water seepage to wetland areas (Maurer and others, 1996, p. 16 and 24). Streamflow not used for irrigation and streamflow in

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[1]For scientific and administrative purposes, formal hydrographic areas in Nevada were delineated systematically in the late 1960's by the U.S. Geological Survey and the Nevada Division of Water Resources (Cardinalli and others, 1968; Rush, 1968). The official hydrographic-area names, numbers, and geographic boundaries continue to be used in U.S. Geological Survey scientific reports and Nevada Division of Water Resources administrative activities.

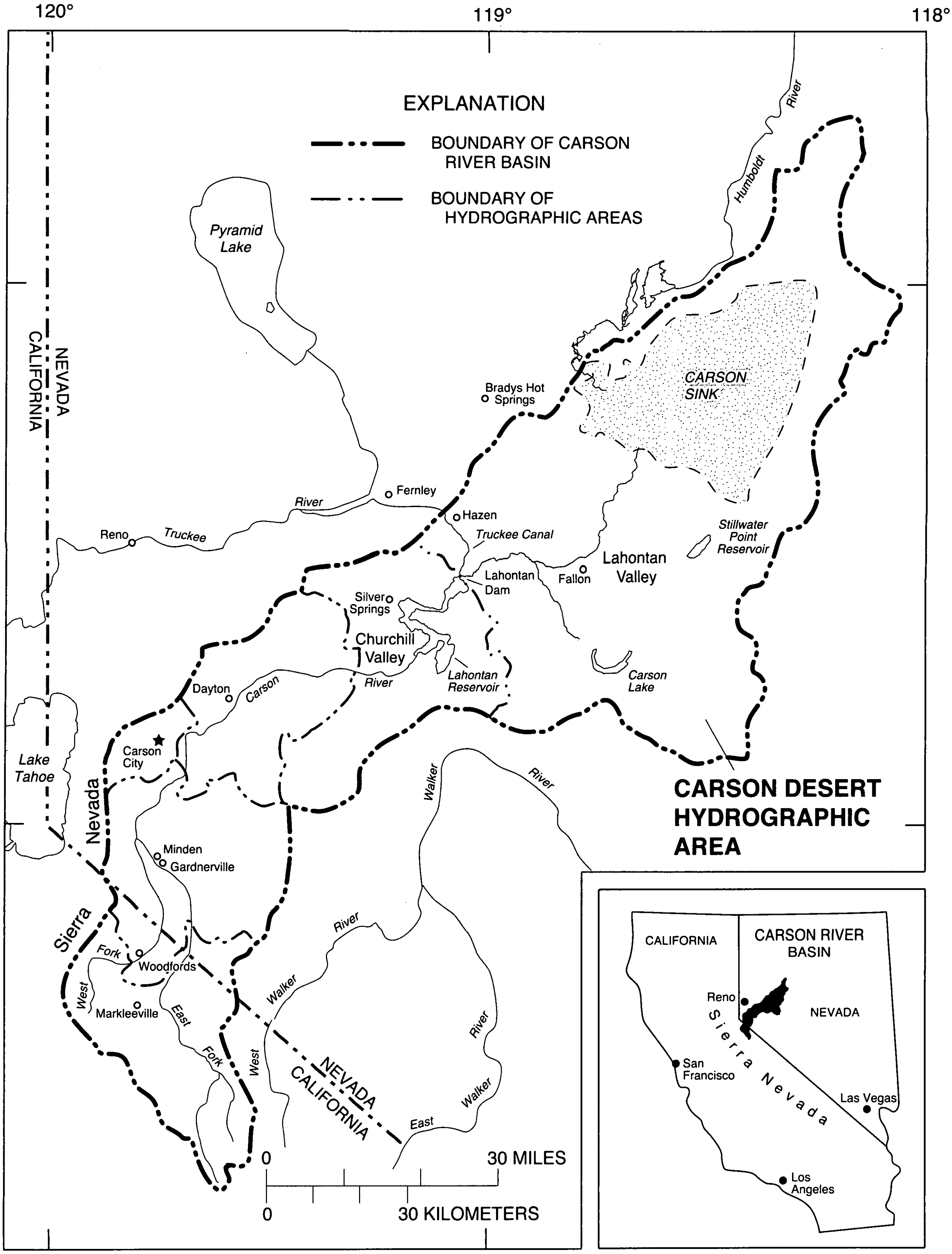
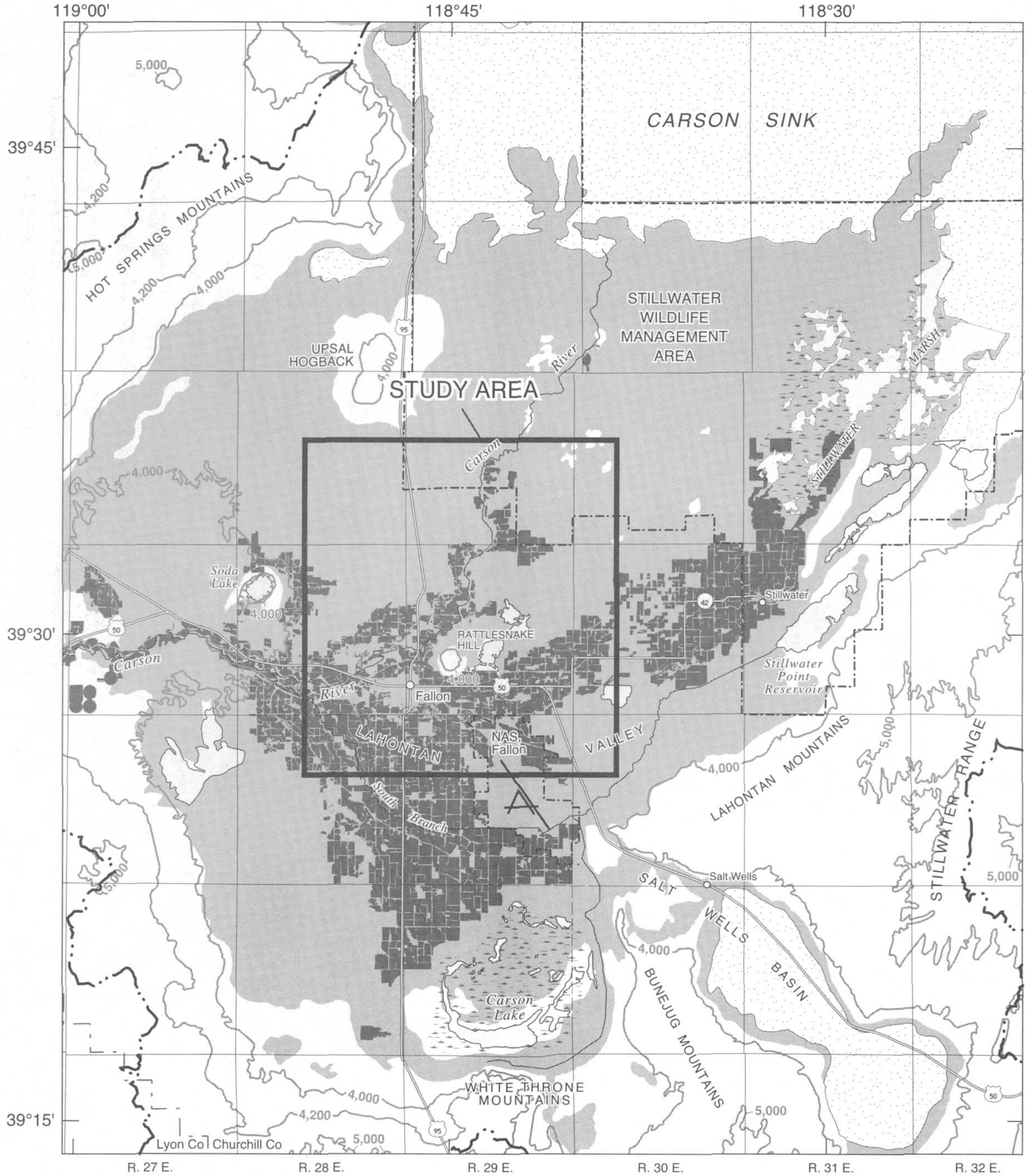


Figure 1. Geographic features of Carson Desert Hydrographic Area and Carson River Basin.



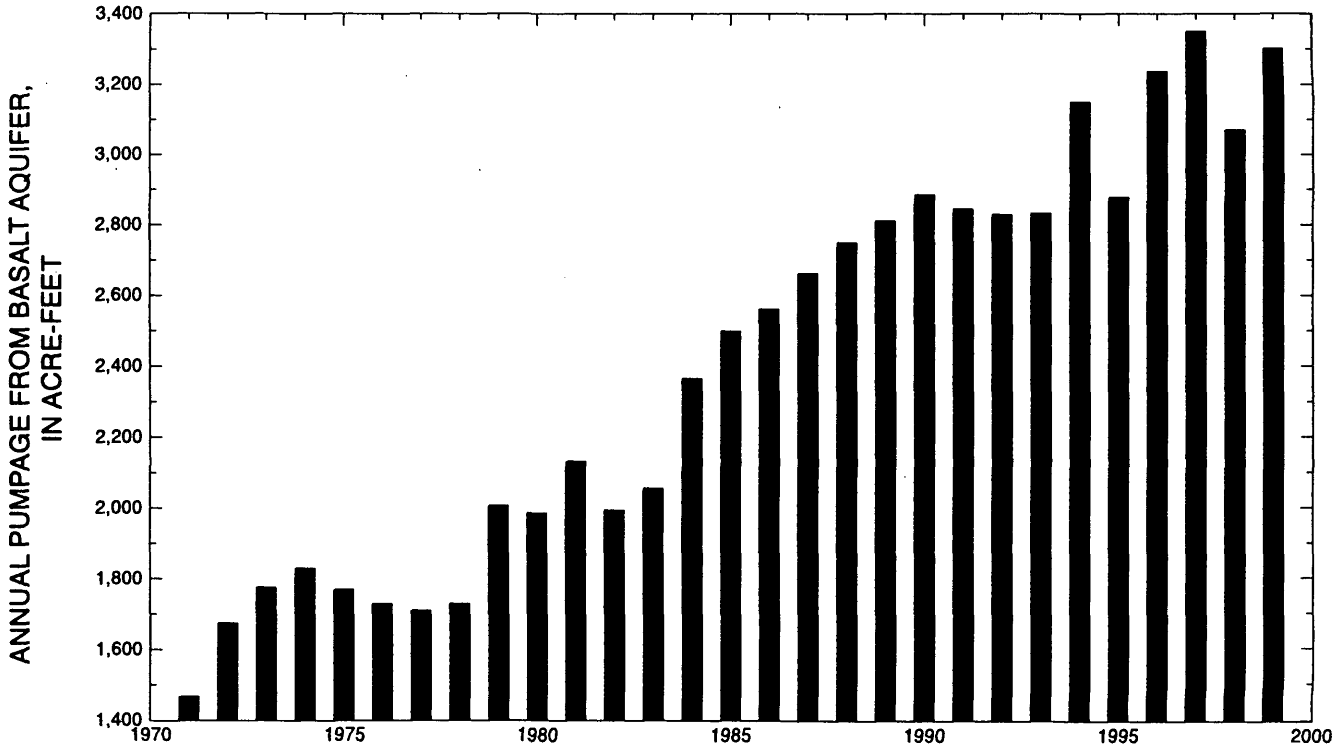
Roads and hydrology from U.S. Geological Survey digital data, 1:100,000, 1979-80. Hypsography and water bodies from U.S. Geological Survey digital data, 1:250,000, 1971
Universal Transverse Mercator Projection, Zone 11

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

- **Discharging playa** — From Glancy and Katzer (1975, pl. 1)
- **Phreatophytes** — From Glancy and Katzer (1975, pl. 1)
- **Irrigated land, 1984-90** — From Bureau of Reclamation digital data (Charles Johnson, Bureau of Reclamation, written commun., 1993)
- **Wetlands**
- **Hydrographic area boundary** — From Rush (1968)
- —4,200— **Topographic contour** — Shows altitude of land surface. Contour interval, 1,000 feet, with supplemental contour at 4,200 feet. Datum is sea level

Figure 2. Location of study area, irrigated land, phreatophytes, and discharging playas in the Carson Desert Hydrographic Area.



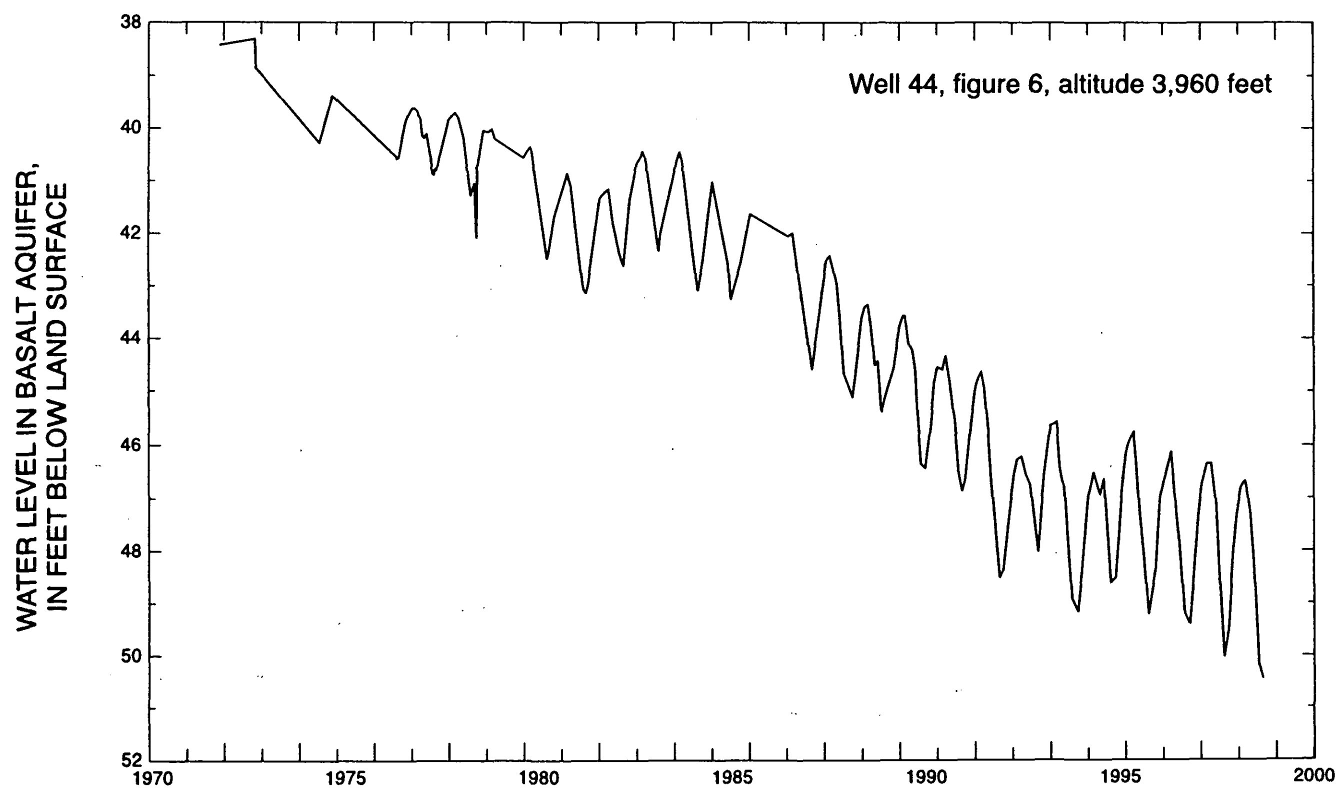


Figure 3. Annual pumpage from basalt aquifer and water-level changes in the basalt aquifer, 1970–99.

drains flows north to the Carson Sink, northeast to wetlands of the Stillwater Marsh, or south to the Carson Lake wetlands.

Alfalfa is the main irrigated crop in the valley along with pasture, other forage crops, and some cereal and vegetable crops. Cottonwood trees are abundant near homes and ranches in the irrigated part of the valley, willows line many of the canals, and cattails fill most drains. Non-irrigated areas are sparsely vegetated with greasewood, rabbitbrush, saltgrass, and marsh grasses, and the Carson Sink is largely barren.

The city of Fallon is the major population center in the area; in addition, about 15,000 people live in the surrounding unincorporated parts of Churchill County (Nevada State Demographer, written commun., 1998). Agriculture is a major economic base in the area, along with employment at Naval Air Station Fallon.

The floor of Lahontan Valley is a relatively flat plain that slopes from about 3,960 ft above sea level near Fallon to about 3,870 ft near the Carson Sink (fig. 1). Several low-lying mountain ranges surround the valley on the north, south, and west, rising to about 5,500 ft in altitude. To the east is the Stillwater Range, which reaches 8,800 ft in altitude.

The area is in the rain shadow of the Sierra Nevada; from 1960 to 1991 it received an average annual precipitation of 5.3 in. (Owenby and Ezell, 1992, p. 15). Summer temperatures reach an average maximum of about 90°F in July and August, and average minimum temperatures are about 18°F in December and January (Owenby and Ezell, 1992, p. 11). Open-water evaporation is about 5 ft/yr (Bureau of Reclamation, 1987, p. 1–7).

HYDROGEOLOGIC SETTING

Geologic History

Rocks and sediments in the Carson Desert record geologic history over two eras: the Mesozoic, from 240 to 66 Ma (million years ago), and the Cenozoic, from 66 Ma to the present. Consolidated sedimentary and igneous rocks of Mesozoic age, which form a basement beneath the entire area, are exposed mainly in the Stillwater Range and north of the Carson Sink. Elsewhere, Mesozoic rocks that underlie Cenozoic deposits are exposed only in small windows where Cenozoic deposits have been removed by erosion (Willden and Speed, 1974, p. 5).

The Cenozoic era is divided into two periods: the Tertiary, 66 Ma to about 2 Ma, and the Quaternary, about 2 Ma to the present. Thick sequences of volcanic rocks of Tertiary age are complexly interbedded with tuffaceous and variably consolidated sedimentary rocks and form the low-lying mountain ranges surrounding the Carson Desert on the west and south. At about 17 Ma, a period of extensional faulting began that has continued to the present (Stewart, 1980, p. 110). Movement along faults has uplifted the Stillwater Range and other surrounding mountains, creating a basin that has filled with sediments of Quaternary age.

The Quaternary period is divided into two epochs: the Pleistocene, 2 Ma to 10 ka (thousand years ago), and the Holocene, 10 ka to the present. During Pleistocene time in the Carson Desert, lakes formed, expanded, and dried up several times under the influence of changing glacial climates (Axelrod, 1956; Morrison, 1964). During high stands, the lakes coalesced to form ancient Lake Lahontan, which had a maximum depth of more than 500 ft in the Carson Desert (Davis, 1978, p. 2; Morrison, 1991, p. 288). High stands of Lake Lahontan were from 1.2 Ma to 850 ka, 650 to 600 ka, 400 to 130 ka, and 25 to 10 ka (Benson, 1991, p. 115; Benson and others, 1990, p. 241).

During high stands of Lake Lahontan, thick clay beds were deposited in the deeper parts of Lake Lahontan, deltas were formed on the western side of the valley where the Carson River entered the lake, and sand and gravel beaches and bars were formed by wave action along the shorelines (Morrison, 1964, p. 28–71). During interglacial periods when Lake Lahontan was dry, the Carson River meandered across the valley floor forming relict river channels, and large sand-dune and sand-sheet complexes covered much of the valley floor. As lake levels rose and fell, these depositional environments moved back and forth across the valley floor, creating a complex mixture of Quaternary sediments more than 2,500 ft thick (Maurer and others, 1996, pl. 1).

During Pleistocene time isolated volcanic activity produced Rattlesnake Hill, Upsal Hogback, and Soda Lake (fig. 2). Rattlesnake Hill, the exposed portion of an eroded volcanic cone, is about 1 mi in diameter and about 200 ft high with a shallow crater at its center (Morrison, 1964, p. 23). The remainder of the cone is buried under as much as 600 ft of Quaternary sediments. The cone was formed by repeated basalt flows issuing radially from Rattlesnake Hill for 2 to 7 mi (fig. 2) to produce the mushroom-shaped body of rock described by Glancy (1986, p. 14) that constitutes the basalt aquifer. A sample of the basalt from the highest point of Rattlesnake Hill, dated by whole-rock potassium-argon analysis, was found to be 1.03 ±0.05 Ma (Evans, 1980, p. 20). Morrison (1964, p. 23) cites stratigraphic evidence that the basalt is older than the early high stands of Lake Lahontan and was present during the entire history of the lake.

Upsal Hogback consists of seven overlapping, well-indurated basaltic cinder-tuff cones, dated at 35 to 11 ka (Morrison, 1964, p. 38; Davis, 1978, p. 24). The Soda Lake deposit consists of unconsolidated volcanic (basaltic) sand ejected from craters, probably between 11 and 6 ka (Morrison, 1964, p. 72, 112).

Holocene deposits in the Carson Desert are eolian, alluvial, fluvial, deltaic, and shallow-lake sediments deposited after the last high stand of Lake Lahontan. An extremely dry, windy period followed the last high lake stand from 7 to 4 ka, and shallow lakes were formed in the Carson Desert during the last 5 to 4 ka (Morrison, 1964, p. 103; Davis, 1978, p. 8). The last of the shallow lakes dried up just before non-natives entered the area in the 1800's (Davis, 1978, p. 8).

Ground-Water Hydrology

Previous studies in the area provide a general understanding of the aquifer systems in the study area and the large-scale direction of ground-water flow. However, the complex lithology of Quaternary sediments and the complex surface-water distribution system of canals and drains make a detailed understanding difficult. Studies have shown that the direction of ground-water flow, at a small scale, can vary greatly and is controlled by the location of canals and drains and by local irrigation practices (Lico and others, 1986, p. 93; Lico, 1992, p. 8).

Description of Aquifers

Glancy (1986) delineated three sedimentary aquifers in the Carson Desert—shallow, intermediate, and deep—and provided the first description of the basalt aquifer (fig. 4). Glancy (1986, p. 41) defined the shallow sedimentary aquifer as extending from the water table to a depth of 50 ft below land surface. The shallow sedimentary aquifer generally is an unconfined aquifer with the water table forming the upper surface. The depth to water in the shallow sedimentary aquifer before construction of the Newlands Project was 5 to 10 ft below land surface within 1 to 2 mi of the main channels of the Carson River, increasing to more than 25 ft in areas between the river channels (Seiler and Allander, 1993, p. 13). Infiltration from the canal system and irrigation caused water levels to rise in the shallow sedimentary aquifer; currently, the depth to water beneath much of the valley floor is from 5 to 10 ft below land surface (Seiler and Allander, 1993, p. 13).

Ground water in the shallow sedimentary aquifer generally is classified (Hem, 1985, p. 159) as moderately hard, the hardness being more than 70 mg/L in most water. Water hardness was used by Glancy (1986, p. 41) to differentiate the shallow and intermediate sedimentary aquifers. The shallow sedimentary aquifer also is characterized by abrupt changes in lithology and ground-water quality over short distances (Glancy, 1986, p. 41). The dissolved-solids concentration of water in the shallow sedimentary aquifer generally is between 200 to 600 mg/L beneath the west-central part of the valley, increasing to more than 10,000 mg/L about 10 mi north, east, and south of Fallon (Lico and Seiler, 1994, p. 33). The stable-isotope composition of water in the shallow sedimentary aquifer is consistent with recharge by water applied for irrigation (Lico and Seiler, 1994, p. 15).

The intermediate sedimentary aquifer extends from a depth of 50 ft below land surface to between 500 and 1,000 ft (fig. 4), and is a confined aquifer with water levels in wells rising to within 10 to 40 ft below land surface. The lower limit of extent is the approximate depth of sediments bearing freshwater near the basalt aquifer (Glancy, 1986, p. 51). However, the vertical extent of freshwater in the intermediate sedimentary aquifer is poorly understood because wells in the 500- to 1,000-ft depth range are sparse. Lico and Seiler (1994, p. 36) reported that water from a well 1,700-ft deep near Naval Air Station Fallon was similar in chemistry to water in the intermediate sedimentary aquifer, and stated that the 500- to 1,000-ft depth limit for the aquifer may be arbitrary.

The intermediate sedimentary aquifer is characterized by soft (Hem, 1985, p. 159), relatively fresh, and potable water beneath the west-central part of the valley. The hardness generally is less than 25 mg/L (Glancy, 1986, p. 56). The dissolved-solids concentration of water in the intermediate sedimentary aquifer ranges from 200 to 600 mg/L beneath the west-central part of the valley, increasing to more than 1,000 mg/L about 8 mi north of Fallon, about 5 mi east of Fallon, and about 6 mi south of Fallon (fig. 4; Lico and Seiler,

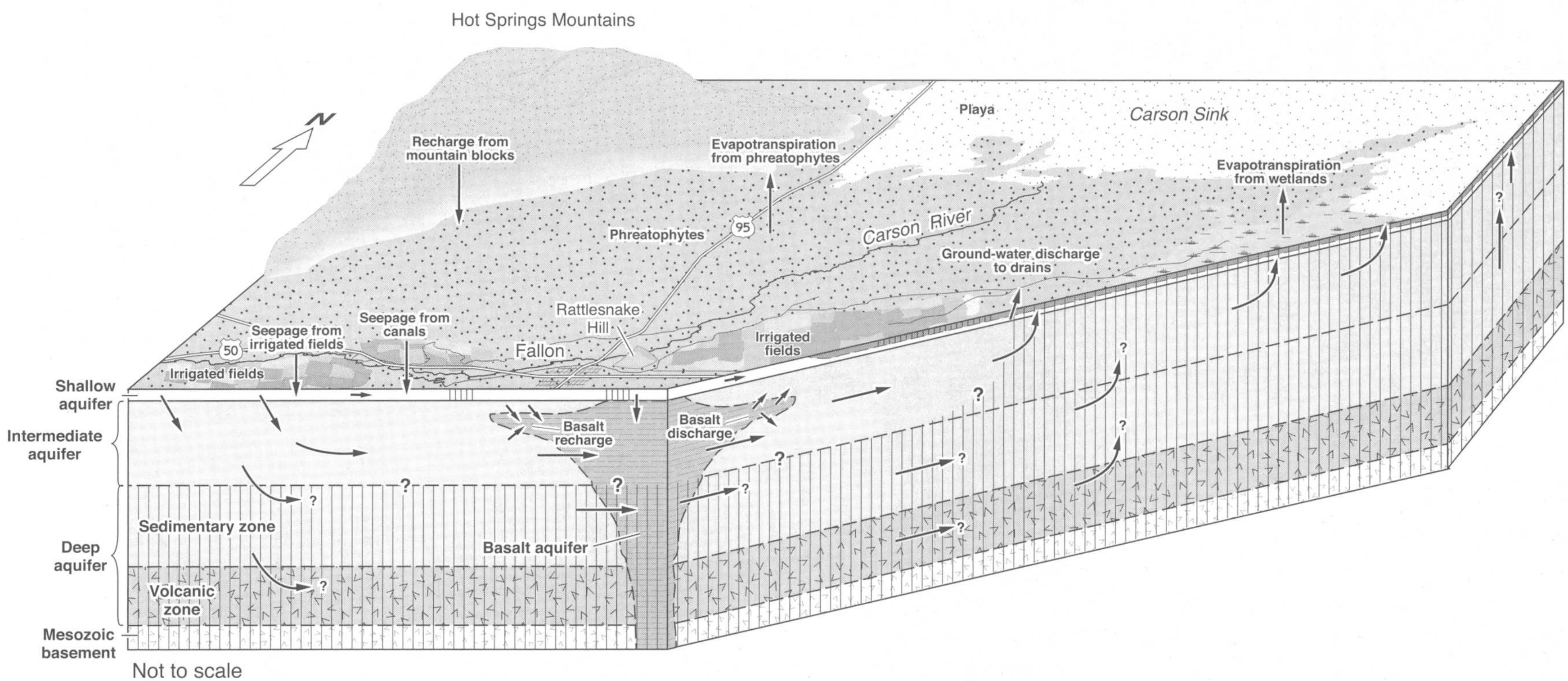


Figure 4. Conceptualization of ground-water flow in sedimentary and basalt aquifers in Lahontan Valley. Boundaries between aquifers are dashed where uncertain; arrows depicting ground-water flow paths are queried where uncertain. Vertical line indicates possible extent of nonpotable water.

1994, p. 33). The stable-isotope composition of water in the intermediate sedimentary aquifer suggests either that: (1) it is a mixture of water from the Carson River with an isotopically lighter water such as is found in Churchill Valley (fig. 1), or (2) it was recharged several hundred years ago (Welch and others, 1997, p. A31–32). Estimated ages of water from the intermediate sedimentary aquifer range from modern to 7,300 years (Lico and Seiler, 1994, p. 20).

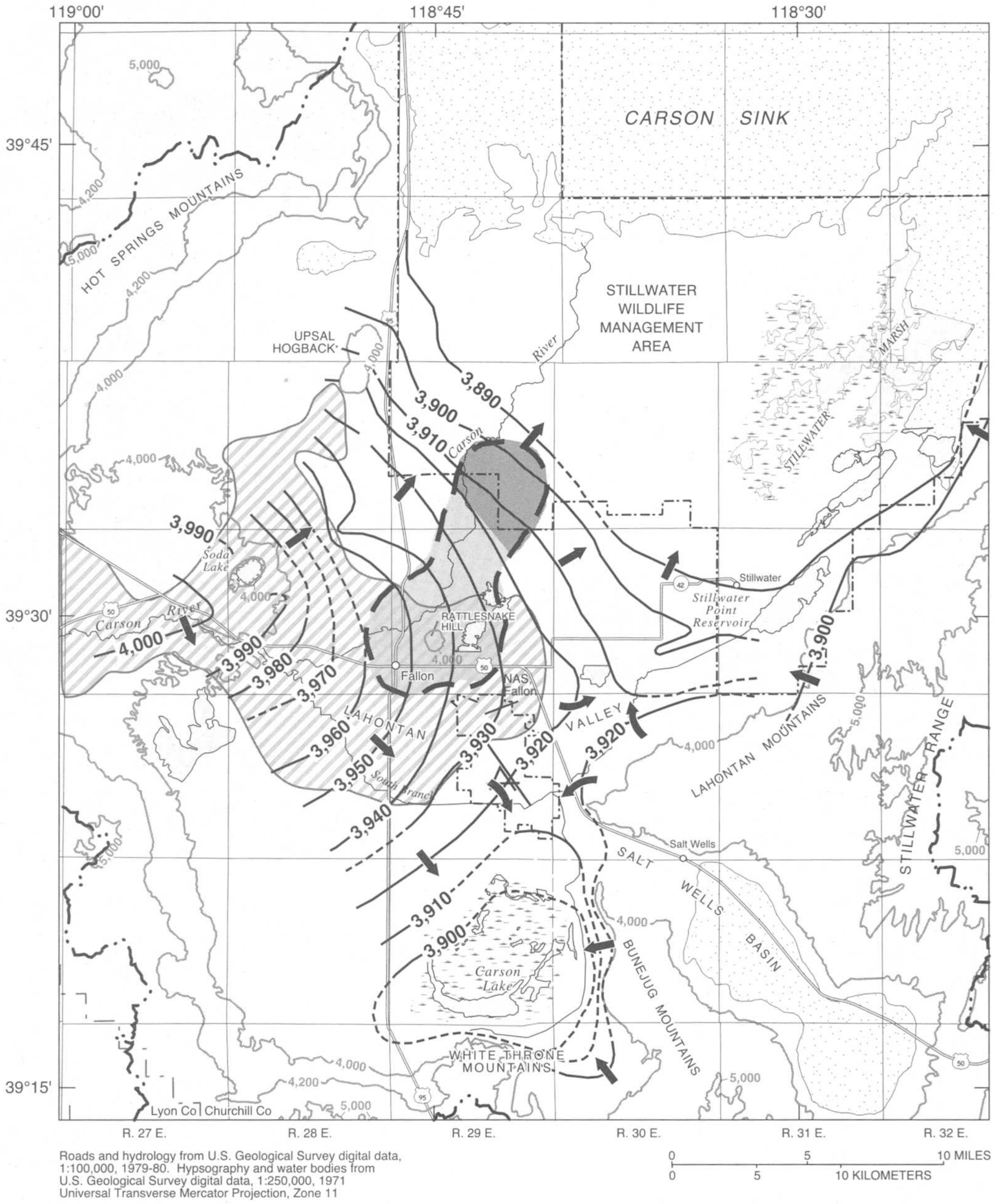
The deep sedimentary aquifer is defined to extend from 500 to 1,000 ft below land surface to depths of several thousand feet, and is thought to be mainly nonpotable (fig. 4; Glancy, 1986, p. 51 and 60). Little is known about the quality of water in the deep sedimentary aquifer because of the lack of samples obtained from wells greater than 1,000 ft deep in the Carson Desert. Maurer (1996, p. 38) suggests that the deep aquifer may include an upper sedimentary zone interbedded with a deeper volcanic zone.

Glancy (1986) delineates the extent of the basalt aquifer using lithologic descriptions from drillers' logs and surface electrical resistivity soundings. He describes it as an asymmetrical, mushroom-shaped body of basalt exposed at Rattlesnake Hill, with the bulk of the basalt surrounded by the sedimentary aquifers (fig. 4; Glancy, 1986, p. 13–14). In planimetric view the basalt is about 10 mi long in a southwest to northeast direction and about 4 mi wide (fig. 5). Drillers' logs show the basalt to be 400 to 600 ft below land surface near its southwestern extent about 2 mi southwest of Rattlesnake Hill, and about 200 to 300 ft below land surface near its northeastern extent 5–7 mi northeast of Rattlesnake Hill (fig. 5). Electrical resistivity data suggests that at depths greater than 1,000 ft below land surface, the basalt narrows to a thin neck that is approximately centered beneath Rattlesnake Hill. Thus the basalt is surrounded by, and in contact with, all three sedimentary aquifers.

Where it is exposed at Rattlesnake Hill, the basalt varies from dense lava flows to highly porous zones of loosely consolidated scoriaceous cinders (Glancy, 1986, p. 15). Glancy (1986, p. 15) suggests that the denser flows are fractured, resulting in a secondary permeability that connects the more porous, permeable zones, creating a highly transmissive body of basalt. Aquifer tests of the basalt show it to be very permeable, with transmissivities as great as 90,000 to 170,000 ft^2/d, and drawdowns of less than 3 ft for pumping rates of about 1,000 gal/min (Glancy, 1986, p. 15 and 18). The basalt aquifer also is a confined aquifer over much of its extent, with water levels in wells screened in the basalt rising to within 40 to 50 ft below land surface. However, near Rattlesnake Hill where the aquifer is found at shallow depths, it may be unconfined.

Ground water from the basalt is distinctly different from that in the sedimentary aquifers and its characteristics have a much narrower range (Glancy, 1986, p. 17; Maurer and others, 1996, p. 52). The concentration of dissolved solids in water from the basalt aquifer ranges from about 500 to 670 mg/L. It is alkaline with a median pH of 9.3 (Lico and Seiler, 1994, p. 36) and is uniformly soft with a hardness of 3 to 11 mg/L (Glancy, 1986, table 5). Dissolved arsenic concentrations exceed the maximum contaminant level of 0.01 mg/L promulgated by the USEPA on January 22, 2001 (U.S. Environmental Protection Agency, 2001), ranging from 0.07 to more than 0.14 mg/L (Maurer and others, 1996, p. 52). The combination of high pH and high arsenic concentrations is characteristic of ground water elsewhere in the western United States that also has high arsenic concentrations (Welch and others, 2000). Most of the arsenic in the basalt aquifer is present as arsenate (AsV). Although this form is less toxic than the more reduced arsenite (AsIII) when ingested in acute, short-term doses, evidence is lacking that demonstrates chronic, long-term ingestion of arsenate to be less toxic than arsenite (Allan Smith, University of California, Berkeley, School of Public Health, oral commun., 1998).

Glancy (1986, p. 21) suggests that a blend of water from the intermediate and deep sedimentary aquifers ranging from 73 to 96 percent and from 27 to 4 percent, respectively, could account for the dissolved-solids concentration in water in the basalt aquifer. Tritium concentrations in water from the basalt suggest that a modern, or shallow, source of recharge also exists (Glancy, 1986, p. 28; Lico and Seiler, 1994, p. 17). The measured tritium concentrations could be accounted for by as little as 20-percent modern water recharged from the shallow sedimentary aquifer or surface-water sources near Rattlesnake Hill (Lico and Seiler, 1994, p. 22). Evidence for sources of recharge to the basalt aquifer is discussed later in this report in the section titled "Sources of Recharge to the Basalt Aquifer—Inferences from Stable Isotopes and Water Chemistry."



EXPLANATION

Discharging playa — From Glancy and Katzer (1975, plate 1)

Downward vertical gradient from shallow aquifer to intermediate aquifers in late 1970's; beneath valley floor outside this area, vertical gradient was upward from intermediate aquifer to shallow aquifer in late 1970's and 1992 — Modified from Glancy (1986, fig. 26)

Downward vertical gradient from shallow and intermediate aquifers to basalt aquifer in late 1970's — Generalized from Glancy (1986, fig. 10)

Upward vertical gradient from basalt aquifer to shallow and intermediate aquifers in the late 1970's — Generalized from Glancy (1986, fig. 10)

—3,910 - - **Water-table contour** — Shows altitude of water table, 1992. From Seiler and Allander (1993, pl. 1). Dashed where uncertain. Contour interval, 10 feet. Datum is sea level

General direction of ground-water flow — From Seiler and Allander (1993, pl. 1)

Hydrographic area boundary — From Rush (1968)

—4,200— **Topographic contour** — Shows altitude of land surface. Contour interval 1,000 feet, with supplemental contour at 4,200 feet. Datum is sea level

Approximate extent of basalt at depth of 600 feet below land surface — From Glancy (1986)

Figure 5. Directions of vertical gradient among shallow and intermediate sedimentary and basalt aquifers and general direction of ground-water flow in shallow sedimentary aquifer, modified from Seiler and Allander (1993, pl. 1).

General Directions of Ground-Water Flow

Ground water in the shallow sedimentary aquifer flows from west to east beneath the valley (fig. 5) and generally northeastward north of Fallon toward the Carson Sink and southeastward south of Fallon toward Carson Lake (Seiler and Allander, 1993, pl. 1; Glancy, 1986, p. 42). Water-level fluctuations in the shallow sedimentary aquifer show that it is recharged by surface-water infiltration during the irrigation season (Glancy, 1986, p. 39). Water-level contours for wells screened in the intermediate sedimentary aquifer (Glancy, 1986, p. 53) show that ground-water in that aquifer flows in directions similar to those in the shallow sedimentary aquifer. In the west-central part of the valley, water levels are higher in the shallow sedimentary aquifer than in the intermediate sedimentary aquifer, allowing downward flow and recharge (fig. 5). Elsewhere in the valley, ground-water flow is upward from the intermediate to the shallow sedimentary aquifer where ground water is discharged to irrigation drains, by evapotranspiration from irrigated crops and natural vegetation, or by evaporation from bare soil (Glancy, 1986, p. 54). Maurer and others (1996, p. 80) suggest that relict stream channels of the Carson River and its distributaries, and laterally extensive sheets of eolian sand, could form preferential pathways for ground-water flow in the shallow and intermediate sedimentary aquifers.

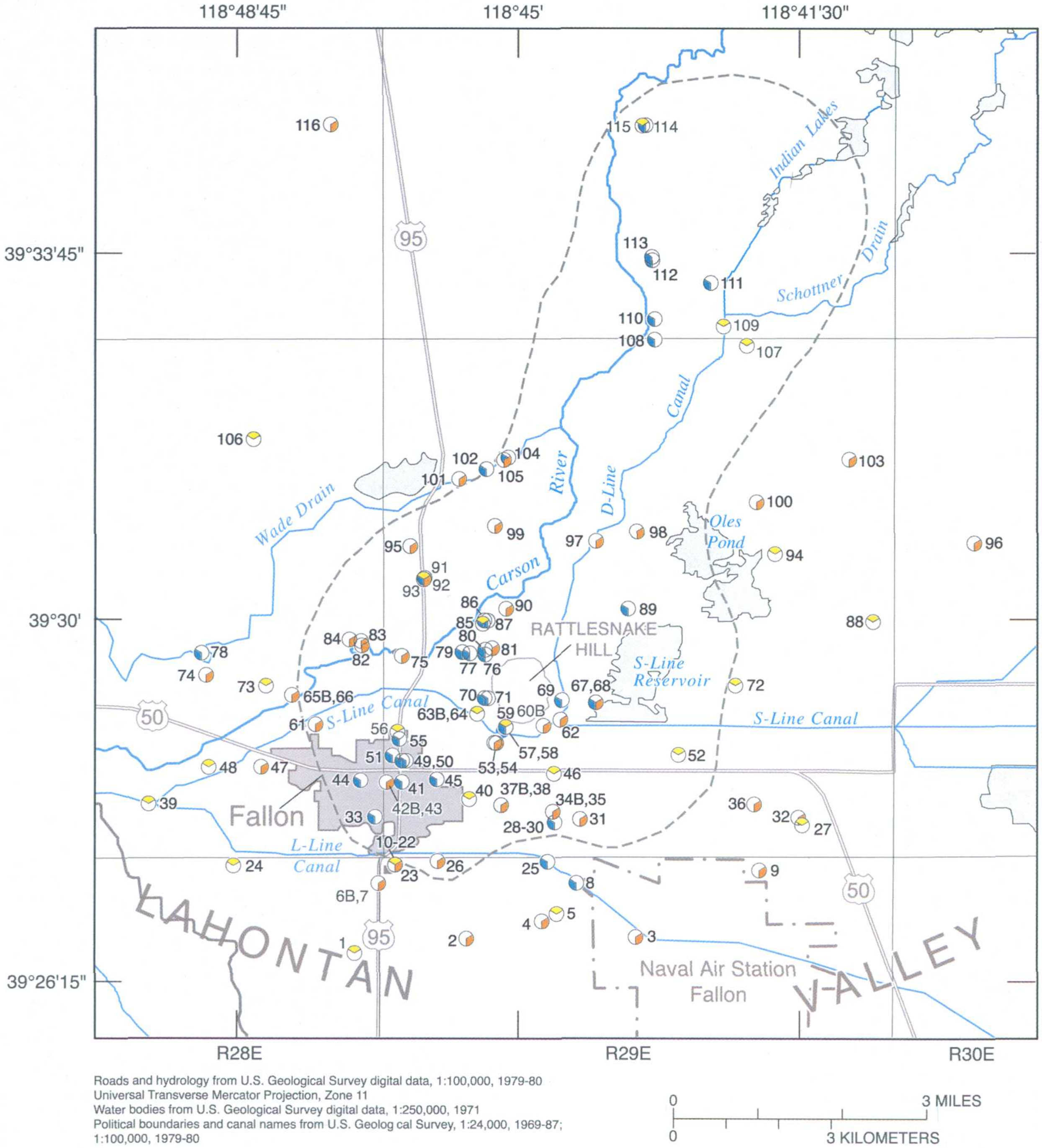
In the late 1970's, water-level altitudes in the basalt aquifer indicated a very flat potentiometric surface throughout the aquifer with a very slight hydraulic gradient toward the northeast (Glancy, 1986, p. 15 and 18). Variations in water quality and increasing ages of ground water in the basalt from southwest to northeast also suggest ground-water flow in that direction (Glancy, 1986, p. 17–18; Lico and Seiler, 1994, p. 22). Over the southwestern part of the basalt aquifer, water levels in the shallow and intermediate sedimentary aquifers are higher than those in the basalt aquifer, creating a downward vertical gradient and the potential for recharge (fig. 5). Over the northeastern part of the basalt aquifer, water levels in the shallow and intermediate sedimentary aquifers are lower than those in the basalt, creating an upward vertical gradient and the potential for discharge (Glancy, 1986, p. 27).

METHODS USED

To describe the hydrogeologic and geochemical framework of the basalt aquifer and to evaluate potential pathways of recharge to the basalt, existing data on lithology, water levels, and water quality were compiled from historical records and USGS databases and from drillers' logs submitted to the Nevada Division of Water Resources. These data were analyzed to determine where additional data were needed. Additional wells were needed near the exposed portion of the basalt at Rattlesnake Hill to evaluate the potential for recharge from the shallow sedimentary aquifer and nearby surface-water bodies. Wells also were needed from depths of 300 to 600 ft in the intermediate sedimentary aquifer to determine the distribution of lithology and water quality near the western and southern subsurface contact with the basalt where existing wells were lacking and where available water levels indicate the potential for recharge.

Nine wells were installed from depths of 20 to about 200 ft at five sites near Rattlesnake Hill, and ten wells were installed from depths of 300 to 650 ft in the intermediate sedimentary aquifer at five sites near the southwestern subsurface contact with the basalt (app. 1). At most sites, two wells were installed at different depths within the borehole. Water-level, water-quality, lithologic, and borehole geophysical data collected from these and 97 existing wells are presented in appendices 1–4; their locations are shown in figure 6. Wells screened in sedimentary formations in direct contact with the basalt provide the best information on the quality of water with the potential to recharge the basalt. These wells have been denoted as being in contact with the basalt in figure 6 and appendix 1. Well 58, which is located near the S-Line Canal and Rattlesnake Hill, probably yields water from both the shallow sedimentary aquifer in contact with the basalt and the uppermost part of the basalt aquifer.

Where possible, aquifer tests were made in wells installed for this study to provide preliminary estimates of hydraulic conductivity for the intermediate sedimentary and basalt aquifers. In four of the wells, static water level was too near the bottom of the well to allow pumping for aquifer testing. Water levels were periodically measured in wells installed for this study and in selected existing wells to determine the magnitude and timing of water-level fluctuations, and hydraulic head (app. 2). Stream stage also was measured relative to water levels measured in nearby wells to determine the



EXPLANATION

Well location and well number—The letter "B" indicates contact with basalt layer

- 63B Shallow aquifer
- 65B Intermediate aquifer
- 89 Basalt aquifer

----- **Approximate extent of basalt at depth of 600 feet below land surface**—From Glancy (1986)

Figure 6. Location of wells used for this study.

vertical hydraulic gradient (app. 3). Water samples were obtained from wells installed for this study and from selected existing wells to determine potential sources of recharge to the basalt aquifer (app. 4).

Seismic-reflection data were collected in April 2000 and provide additional data on the lateral extent of the basalt aquifer (Blackhawk Geometrics, 2000). About 13 mi of seismic-reflection data were collected along lines positioned near the edge of the basalt aquifer estimated from electrical resistivity and drillers' log data. Seismic data were recorded on a 120-channel seismograph, using a 10-second sweep, with geophone groups and shot points at 16.5-ft spacing. The seismic source was a buggy-mounted vibrator producing a 10-second sweep ranging from 25 to 240 hertz. Seismic-reflection data (pl. 1 and pl. 2) are shown with travel time in milliseconds for the vertical axis. Additional boreholes along the seismic lines, and borehole logs of sonic velocity, are required to correctly adjust the vertical scale to depth below land surface.

Well Installation and Aquifer Testing

Nineteen wells installed for this study were drilled between June 1997 and August 1998. Most wells are nested piezometers with 2-in.-diameter polyvinyl chloride casing and screens (0.02-in. slot) from 5 to 20 ft in length (app. 1) installed at different depths within an 8.5-in. borehole. Two wells were installed in most test holes; however, three were installed in test hole B-1 (wells 57–59, fig. 6, app. 1). At well 58, the lower part of the sand pack and bottom 2 ft of screen are adjacent to the basalt aquifer, while the upper 3 ft of screen and upper part of the sand pack are adjacent to the shallow sedimentary aquifer. Test holes B-1 and B-3 (well 69) were drilled using air rotary methods, while all others were drilled with mud rotary methods. Well 85 was installed using a hollow-stem auger. For wells drilled with mud, borehole geophysical logs of the holes were made. Target depths for installation of well screens were conductive, sandy zones below the depths of existing wells, about 300 ft, and near the contact with the basalt aquifer. Conductive, sandy zones were selected using the electrical resistivity logs and descriptions of cuttings returned to the surface during drilling. Drilling mud in the borehole then was thinned with water, the well screen and casing installed, and medium-grained aquarium sand emplaced by tremie pipe around the well screens. Bentonite grout was pumped by tremie pipe to seal intervals between screens set at different depths, and to land surface. Wells were developed by air lifting, surging, and pumping until clear.

Aquifer tests were made between August 1998 and April 1999 by setting a submersible pump from 15 to 20 ft below static water level and recording water levels with a pressure transducer at 1- to 2-second intervals. After being developed, wells were pumped at increasing rates ranging from 2.5 to 5 gal/min for a maximum of four steps and total pumping times of 10 to 25 min. Aquifer-test data were analyzed using three methods to estimate aquifer transmissivity. Transmissivity is numerically equal to the hydraulic conductivity of the aquifer, multiplied by its thickness (Lohman, 1972, p. 13). Hydraulic conductivity is defined as the volume of water that will move in time through an area of aquifer, under a hydraulic gradient, and has units of length per time (Lohman, 1972, p. 4). Because the thickness of the basalt aquifer and sedimentary aquifers vary, estimates of transmissivity were divided by the gravel-packed interval of the wells to obtain more widely applicable estimates of hydraulic conductivity.

The first method was applicable to all aquifer tests using the specific capacity of the wells and the equation from Prudic (1991, p. 11):

$$T = 15.32 \times SC \times (-5.77 - \log_e (r^2S/4Tt)), \qquad (1)$$

where T is the transmissivity, in feet squared per day,

SC is the specific capacity of the well, in gallons per minute per foot of drawdown,

r is the effective radius of the pumped well, in feet,

S is the storage coefficient in cubic feet of water per cubic feet of aquifer, and

t is the time in days that the well was pumped.

Equation 1 was solved using the measured drawdown during each step and an iterative computer program written by D.E. Prudic (U.S. Geological Survey, written commun., 1999). Prudic (1991, p. 13) found that estimates of transmissivity calculated with equation 1 were underestimated by factors of 1.3 to 2.4 compared to estimates obtained from other methods.

The second method used for analyzing aquifer test data was that of Harrill (1970) for recovery from a step-drawdown test using the equation:

$$T = 264 \times Q_n/ds', \qquad (2)$$

where T is transmissivity, in gallons per day per foot,
Q_n is the final discharge rate of the well, in gallons per minute, and
ds' is the change in residual drawdown, in feet per log cycle of time.

The value ds' is determined by plotting the log function:

$$(t_1^{(dQ1/dQn)})(t_2^{(dQ2/Qn)})\ldots(t_n^{(dQn/Qn)})/t', \qquad (3)$$

against s', the residual drawdown, on semilog paper,

where $t_1 \ldots t_n$ is the elapsed time, in minutes, since the pump was turned on or pumping rate changed,
$dQ1\ldots dQn$ is the incremental change in well discharge, in gallons per minute, and
t' is the elapsed time, in minutes, since the pump was turned off.

The residual drawdown is the difference between the drawdown caused by pumping and the drawdown remaining during recovery. Water-level data for the recovery period were plotted as described above and equation 2 was used to obtain transmissivity, which was transformed to units of square feet per day. Only well 38 had a smooth recovery curve; others showed oscillations during recovery which were not used in plotting the log function.

The Harrill method was not applicable for wells screened in the more transmissive zones because water levels recovered quickly after a short period of oscillations when the pump was turned off. For these wells, water-level oscillations were used to apply the third method developed by Kipp (1985) which accounts for inertial effects of well responses. This method calculates transmissivity using a series of type curves for the water-level oscillations recorded during recovery.

Water-Quality Sampling and Analysis

Ground-water samples were collected from 32 wells in the study area. Analyses of these samples are presented in appendix 4. A minimum of three well volumes of water was purged from each well before water samples were collected. During well purging and prior to sample collection, pumped water passed through a flow-through chamber instrumented to measure temperature, dissolved oxygen, pH, and specific conductance. Samples were collected when these parameters stabilized. Chemical stability is indicated when three successive measurements of temperature, pH, and specific conductance, taken at 5-min intervals, differ by less than 0.5°C, 0.1 pH unit, and 5 µS/cm at 25°C, respectively (Koterba and others, 1995). Field meters were calibrated at each site using appropriate pH buffers, conductivity standards, and—for the dissolved oxygen meter—an air-calibration chamber in water. Alkalinity was determined on-site by incremental titration of filtered sample water with sulfuric acid.

Water samples collected for determination of dissolved organic carbon and inorganic constituents other than for chemical speciation of arsenic and iron were processed in the field following standard USGS methods (Wood, 1976; Koterba and others, 1995) and shipped to the USGS National Water Quality Laboratory in Arvada, Colorado, for analysis (Wershaw and others, 1987; Fishman and Friedman, 1989; Brenton and Arnett, 1993). Water collected for speciation of arsenic and iron were filtered through a 0.1 µm filter, preserved with ultrapure HCl, and chilled between collection and analysis. The sample collection method for arsenic speciation is consistent with methods shown to preserve the oxidation state of inorganic arsenic (Wing, 1987; Aggett and Kriegman, 1987). Speciation of arsenic was performed using the methods of Crecelius and others (1986) at Battelle Northwest Laboratories. These procedures result in determinations of total inorganic arsenic and arsenite (AsIII). Arsenate (AsV) was calculated as the difference between these two values.

Samples collected for determination of the stable-isotopic composition of hydrogen and oxygen in water were collected in 60-mL glass bottles with polyseal caps. The hydrogen-isotope-ratio analyses were performed using a hydrogen equilibration technique (Coplen and others, 1991). Water samples are measured for delta O-18 using the CO_2 equilibration technique of Epstein and Mayeda (1953). The hydrogen and oxygen isotopic analyses were performed at the USGS Stable Isotope Laboratory in Reston, Virginia. Analytical uncertainties for deuterium and delta O-18 values are 2 and 0.2 permil, respectively.

HYDROGEOLOGIC FRAMEWORK OF BASALT AQUIFER

Age of Basalt Aquifer

The volcanic deposits of the basalt aquifer were formed more than 1 Ma. Samples obtained from the top of the basalt during drilling for this study were dated using the argon-argon method (Francis Monastero, Naval Air Weapons Station at China Lake, California, written commun., 1999). The age of the basalt 1.3 mi south and 2.5 mi west of Rattlesnake Hill at wells 37 and 65 was found to be 1.31 ±0.23 Ma and 1.5 ±0.23 Ma, respectively. These ages are slightly older than was determined for a sample from the highest point of Rattlesnake Hill, 1.03 ±0.05 Ma, using the potassium-argon method (Evans, 1980, p. 20). About 1.5 mi southeast of Rattlesnake Hill at well 34, an age of 2.5 ±0.3 Ma was determined. These dates show that the basalt was emplaced over a span of at least 1 million years, and was present during high and low stands of ancient Lake Lahontan in the Pleistocene epoch. Deposition of sediments since the basalt was emplaced has buried the main body of basalt to depths as great as 600 ft below land surface.

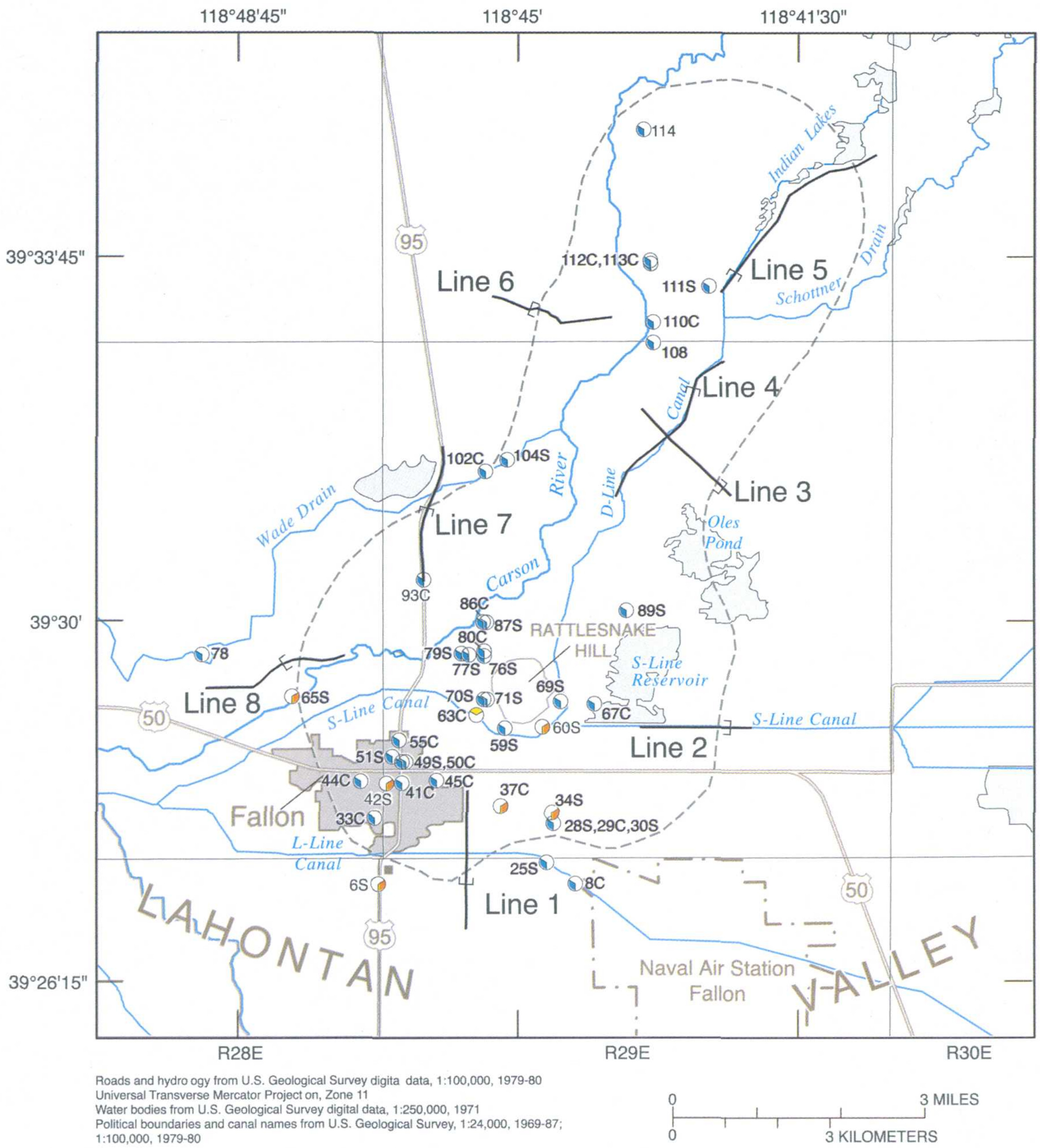
Lateral and Vertical Extent of Basalt Aquifer

Lithologic descriptions for wells extending to the basalt (fig. 7, app. 1), and surface electrical resistivity soundings using the Schlumberger array presented by Zohdy and others (1977) and Glancy (1986), were combined to produce three-dimensional models of the basalt aquifer (figs. 8*A* and *B*). These data suggest that the basalt is elongate in a southwest to northeast direction and is thickest near Rattlesnake Hill, thinning toward its edges, with a volcanic neck approximately centered beneath Rattlesnake Hill.

Representation of the lateral extent of the basalt aquifer shown in figures 8*A* and *B* was constrained by lithologic descriptions from drillers' logs (fig. 7, app. 1), and by the 25-ohm-meter contour of electrical resistivity at a depth of 600 ft below land surface (fig. 7), developed by Glancy (1986, p. 10), and the thickness of the basalt along profiles presented by Glancy (1986, p. 16 and 17). As described by Glancy (1986, p. 13), high-resistivity basalt containing high-resistivity freshwater may be distinguished from conductive clay and silt layers, particularly those containing saline water. The lateral boundary of the basalt determined from electrical resistivity data is uncertain, however, particularly where there is sand and gravel that contains freshwater and where electrical resistivity data are sparse near the northeastern part of the basalt. In addition, as the depth increases, electrical resistivity soundings integrate larger volumes of aquifer materials, increasing the uncertainty associated with interpretation of the data.

Seismic-reflection data collected in April 2000 were used as an additional means to detect the lateral extent of the basalt aquifer (Blackhawk Geometrics, 2000, p. 22–24). The seismic-reflection data were interpreted by Blackhawk Geometrics (2000, p. 21–24), by Francis C. Monastero of the Naval Air Weapons Station at China Lake, California (written commun., 2000), and by the senior author. These interpretations are considered preliminary until confirmed by additional geophysical data and boreholes along selected lines. The seismic-reflection data (fig. 7; pls. 1 and 2) show the top of the basalt as a high-amplitude reflector on most lines that can be distinguished by the onlap of overlying sedimentary reflectors (pl. 1; Blackhawk Geometrics, 2000, p. 21). The bottom of the basalt also may be shown on many of the lines as a strong reflector. The preliminary interpretations depicted on plates 1 and 2 represent the vertical and lateral extent of the basalt aquifer along each of the eight seismic lines. On most lines, the basalt is shown as a wedge-shape, thickening towards Rattlesnake Hill, the source of the flows.

To obtain approximate depths, in feet, for reflectors shown on plates 1 and 2, a datum correction of about 160 milliseconds may be subtracted from the time shown for the reflector, to obtain the total travel time for the seismic signal. This value represents the two-way travel time for the signal to move from land surface to the reflector and back to land surface. The resulting value may be divided by two to obtain the one-way travel time, in seconds, and that value divided by 1,000, then multiplied by 6,000 ft/s, an approximate seismic velocity for the saturated sediments, to obtain an approximate depth, in feet, to the reflector (David L. Berger, U.S. Geological Survey, oral commun.). The basalt thickness may be estimated by determining the travel time from top to bottom, in milliseconds, dividing by 2 and the result divided by 1,000, and then multiplying by 9,000 ft/s, an approximate seismic velocity for the basalt.



EXPLANATION

Well location and well number—The letter "**S**" indicates sand at contact with basalt; the letter "**C**" indicates clay at contact with basalt; no letter indicates driller's log not available

- 63S — Shallow aquifer
- 37S — Intermediate aquifer
- 8C — Basalt aquifer

Approximate extent of basalt at depth of 600 feet below land surface—From Glancy (1986)

Seismic reflection line—Bracket indicates approximate extent of basalt

Figure 7. Location of wells contacting basalt aquifer, location of seismic-reflection lines, and lithology of sedimentary aquifers at contact with basalt.

Along the western part of the basalt, freshwater in the overlying sedimentary aquifers decreases the electrical contrast between the sediments and the basalt, making detection of the basalt difficult. The western extent of the basalt at 600 ft in depth was approximated by Glancy (1986, p. 14). Near this boundary, well 65 (fig. 7) encountered basalt at a depth of 490 ft and penetrated 38 ft of basalt without encountering an underlying sedimentary aquifer (app. 1). Thus, near the western part of the basalt aquifer, basalt is present at somewhat shallower depths than estimated by Glancy (1986). Seismic-reflection data from line 8 (pl. 2), about 1/2 mi north of well 65, suggest that the western edge of the basalt may be near well 65 (Blackhawk Geometrics, 2000, p. 24). Farther west, at well 78, a basalt breccia was described at a depth of 1,076 ft. Glancy (1986, p. 7) concluded, however, that the basalt breccia probably was not part of the body of basalt tapped by municipal wells based on its great depth and different water quality. Reflectors are seen dipping toward the east at greater depths than the basalt aquifer on line 8 of the seismic-reflection data (pl. 2). These reflectors may be the basalt breccia encountered at well 78 and represent a deeper body of basalt underlying the western side of the Carson Desert.

On the southern boundary of the basalt, well 6 (fig. 7) penetrated about 10 ft of basalt detritus and perhaps a thin layer of basalt at a depth of 600 ft followed by 40 ft of underlying sand and clay. Basalt flows 19 and 3 ft thick were found at wells 25 and 8, at depths of 593 ft and 706 ft, respectively (app. 1). Midway between well 6 and wells 25 and 8, seismic-reflection data from line 1 (pl. 1) suggest that the lateral extent of the basalt is near the boundary estimated from the electrical resistivity data.

The basalt encountered at well 8 is at an altitude of 3,241 ft (app. 1), more than 100 ft deeper than at any other basalt well. Along with the greater depth of basalt at well 8, a large drawdown during pumping and a sampled dissolved-solids concentration of 950 mg/L, almost twice that found in other basalt wells, suggest that the well did not tap the main body of basalt (Glancy, 1986, p. 12). Kingman (1959, p. 20) thought that the offset in the basalt could be caused by a fault between wells 25 and 8. Alternatively, well 8 may have penetrated a deeper basalt flow extending further south than at well 25, with a lower transmissivity and higher dissolved-solids concentration.

Along the eastern edge of the basalt, wells in the intermediate sedimentary aquifer (wells 100 and 103, fig. 6) extend only to depths of about 550 ft without encountering basalt, thus do not confirm the boundary at a depth of 600 ft as estimated by the electrical resistivity data. Seismic-reflection data from lines 2 and 3 (pl. 1) suggest that the lateral extent of the basalt is near the boundary estimated from the electrical resistivity data.

Near the northeastern portion of the basalt, existing data do not allow exact determination of its extent. Electrical-resistivity data collected by Glancy (1986, p. 10) are sparse in that area. Wells 108 and 114 (fig. 7), drilled in the 1920's, reportedly penetrated basalt at about 300 ft (Glancy, 1986, p. 7); however, no drillers' logs are available for these wells. Basalt was confirmed by drillers' logs for wells 110–113 at depths of 175 to 262 ft (fig. 7; app. 1). As noted by Glancy (1986, p. 14) the top of the basalt appears to be considerably shallower in this area than near its southwestern extent. The altitude of basalt at wells 108 and 110–114 (fig. 7) is about 3,680 to 3,760 ft; 200–300 ft higher than at wells southwest of Rattlesnake Hill (app. 1). Glancy (1986, p. 14) suggests this could be caused by uplift along faults or by a buried basalt ridge extending northeast from Rattlesnake Hill. Inspection of drillers' logs for wells 2–3 mi northeast of Rattlesnake Hill shows that basalt has not been encountered to depths of about 140 ft below land surface or an altitude of about 3,800 ft. Alternatively, the shallow depth of the basalt at wells 108 and 110–114 could indicate a secondary vent beneath the northeastern portion of the basalt, with well 110 being closest to the vent where basalt was encountered at the shallowest depth of 175 ft. Seismic data along line 4 show a slight doming in the top of the basalt about 3,000 ft from the southern end of the line (pl. 1). This dome is coincident with the location of a northwest-trending fault zone mapped by Morrison (1964, p. 93), although offsets of reflectors are not apparent in the seismic data. The doming of the basalt also could be evidence of a secondary vent near the northeastern part of the basalt aquifer. Seismic-reflection data from line 4 also suggest that the edge of the basalt may be about 2,000 ft from the northern end of the seismic line.

Along seismic line 5, the basalt does not provide as clear a reflector as along other seismic lines, and along the northern end of the line, strong reflectors are discontinuous. The discontinuous reflectors could be evaporite deposits from shallow lakes, rather than the basalt aquifer (Blackhawk Geometrics, 2000, p. 23). Evaporite deposits greater than 2 ft thick have been encountered beneath the Indian Lakes area (Carl Thodal, U.S. Geological Survey, oral commun. 1999); however, basalt was encountered at well 111 near the southern end of line 5 (fig. 7). From the seismic data, a reflector may be seen to end about 1,300 ft from the southern end of the line (pl. 2). Near the northeastern-most extent of the basalt aquifer, basalt may be present as individual flows that interfinger with sedimentary deposits, rather than as a continuous sheet.

Along the northwestern part of the basalt, at well 104, basalt layers 3- and 5-ft thick were penetrated at depths of 480 and 552 ft, respectively, showing that the basalt is relatively thin in this area (fig. 7, app. 1). At well 102, about 0.3 mi west of well 104, drilling was stopped after the basalt was hit at 580 ft. Seismic-reflection data from lines 6 and 7 suggest that the extent of the basalt is near the boundary estimated from electrical resistivity data (pl. 2).

The altitude of the bottom of the basalt determined by seismic-reflection data is considered to be preliminary. The lower boundary of the basalt is poorly defined by lithologic descriptions from drillers' logs because few wells completely penetrate the basalt. However, basalt thickness estimated from the seismic-reflection interpretations shown on plates 1 and 2 (see description of calculation method in the beginning of this section) can be compared to the thickness estimated by Glancy (1986, p. 16 and 17) from electrical resistivity data. The two data sets are comparable near the ends of seismic lines 1–3 nearest to Rattlesnake Hill, and the point where seismic lines 3 and 4 cross (pl. 1). Near the end of seismic line 2, the thickness estimates are in good agreement. However, at the remaining points, the thickness estimated by electrical resistivity data are consistently about twice that estimated from the seismic-reflection data. The discrepancy cannot be resolved until additional test holes are installed to obtain data on the exact basalt thickness and seismic velocity near the two data sets.

The thick section of basalt near Rattlesnake Hill shown in figures 8*A* and *B* could be caused by intrusion into adjacent sediments as the basalt moved upward through the volcanic neck. Alternatively or in combination with intrusion, basalt flows may have been extruded onto the land surface near the volcanic neck, then buried by continued deposition of sediments, followed by additional basalt flows and sedimentation.

Some drillers' logs (wells 8, 25, 28, 30, 104, and 112; fig. 7) describe layers of cemented sand and gravel above, below, or interbedded with the basalt. At wells 77 and 87 about 0.5 mi northwest of Rattlesnake Hill, sand is penetrated below 12- and 14-ft-thick layers of basalt whose bases are at a higher altitude (3,770–3,780 ft, fig. 7, app. 1) than the main body of basalt. These observations, along with the age dates for the basalt, suggest that the basalt was not deposited as a contiguous mass. Deep wells through the thickest parts of the basalt would provide valuable information on how the basalt was emplaced and how contiguous the main body of basalt might be.

The three-dimensional model of the basalt presented in figure 8 is considered a reasonable approximation for the southern half of the basalt. However, the northeastern extent of the basalt may be more discontinuous than is suggested in figure 8. For this reason, the northeastern portion of the three-dimensional model best describes the lateral extent of where basalt flows are most likely to be present. Additional work is needed to refine our understanding of the northeastern extent of the basalt aquifer.

Lithology of Basalt and Sedimentary Aquifers

The movement of ground water in the sedimentary aquifers, between the surrounding sedimentary aquifers and the basalt aquifer, and within the basalt aquifer, is partly controlled by the lithology of the sediments and rocks that form the aquifers. Lithology is defined as the structure, mineralogic composition, and grain size of the sediments or rocks, and is indicative of how easily ground water may move through the aquifer materials. The hydraulic conductivity of aquifer materials is a more quantitative measure of the rates of ground water movement. The hydraulic conductivity of fine-grained, clayey sediments is low, and the hydraulic conductivity of sandy or gravely sediments is relatively high. Similarly, massive, unfractured basalt has a low conductivity and fractured, vesicular basalt can be highly conductive.

The lithology of the basalt aquifer and sedimentary aquifers adjacent to the basalt was determined using observations of drill cuttings and borehole geophysical logs from wells installed during this study. Also, lithologic descriptions were compiled from

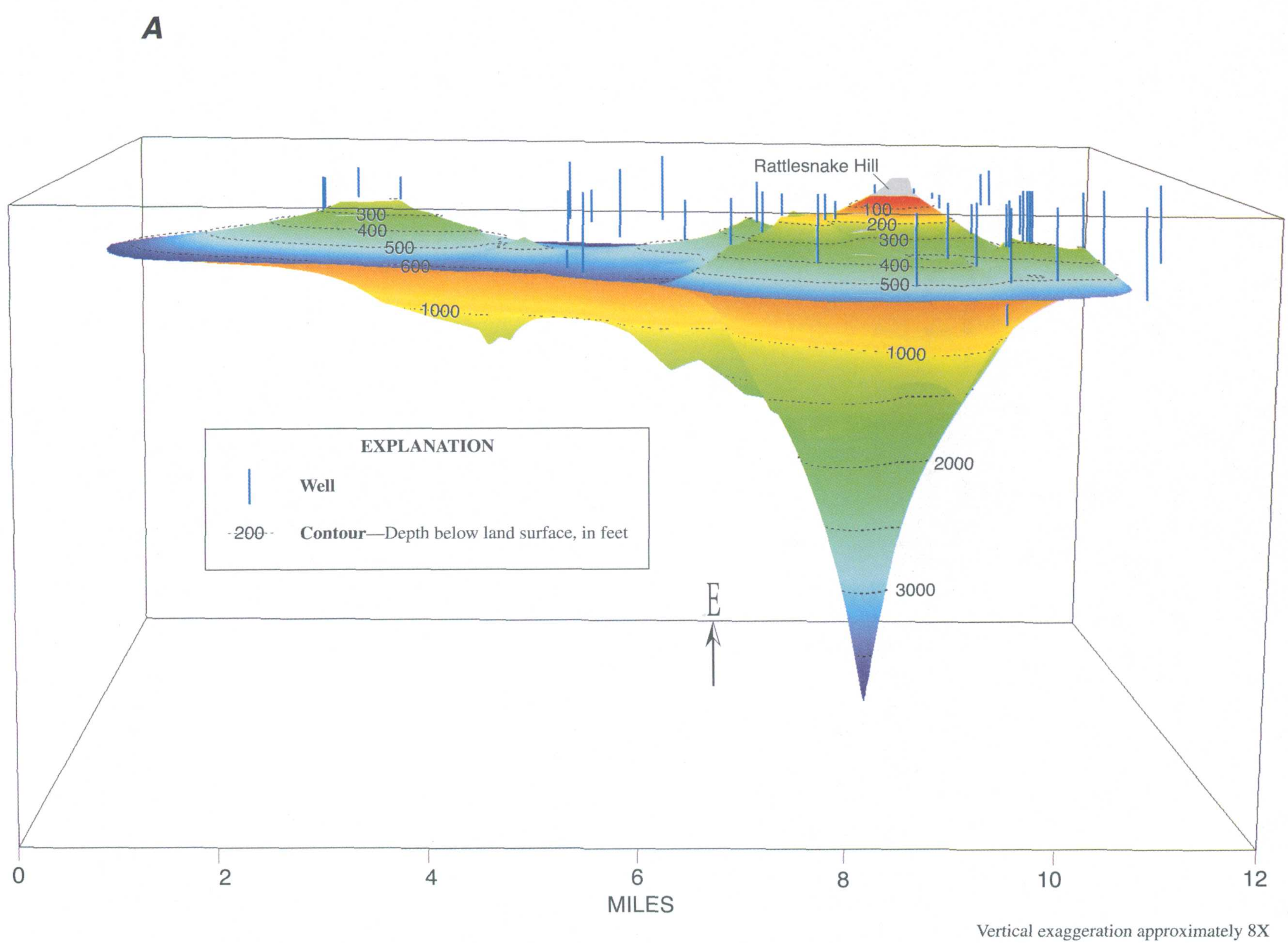


Figure 8. (*A*) Oblique view of basalt aquifer, looking toward east. Extent of basalt is based on drillers' logs for wells (for exact location of wells, see fig. 7) and on electrical resistivity soundings described by Glancy (1986, p. 10–17).

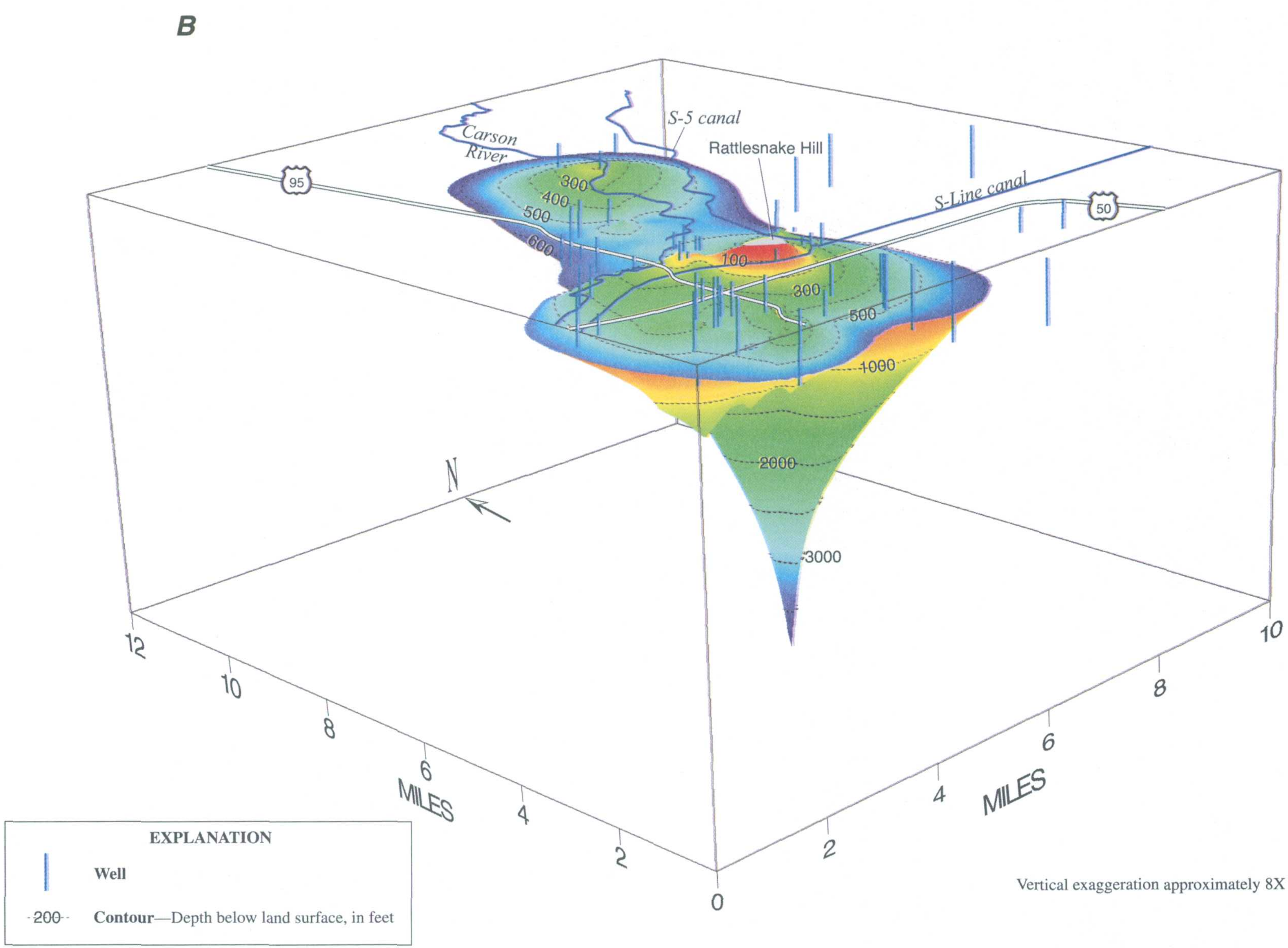


Figure 8. (*B*) Oblique view of basalt aquifer, looking toward northeast. Extent of basalt is based on drillers' logs for wells (for exact location of wells, see fig. 7) and on electrical resistivity soundings described by *Glancy* (1986, p. 10–17).

57 drillers' logs submitted to the Nevada Division of Water Resources from the deepest available wells in and near the Fallon basalt aquifer.

Descriptions of the basalt from drillers' logs suggest that it is highly variable in lithology; however, few wells penetrate the basalt for more than 70 ft (app. 1). Some logs describe the basalt simply as black rock, lava rock, or basalt. Most logs describe the basalt as black, but some describe the color varying to red or pink for 8- to 17-ft thicknesses (wells 28, 51, and 93, fig. 7). Many detailed logs describe from 3 to 45 ft of massive, hard basalt above more porous or fractured basalt (wells 29, 30, 49, 69, 70, 80, 93, 112, and 113) or above interbedded layers of sand, gravel, or cinders (wells 28, 51, and 87). Some logs describe the basalt simply as porous and fractured from the top to the total depth drilled for thicknesses of 4 to 48 ft (wells 33, 37, 57, 65, 67, and 79). At two wells, voids were noted as large as 5 ft which probably are open lava tubes (wells 50 and 51). As noted previously, in some logs, the basalt appears as relatively thin layers, suggesting that the basalt might not be a solid, contiguous mass over its entire extent. Because few wells penetrate the basalt more than about 70 ft, the lithology of the basalt is unknown at depths greater than about 600 ft below land surface (app. 1).

The mineralogic composition of the basalt has been described by Lico and Seiler (1994, p. 14) from X-ray diffraction analysis and thin-section petrography of samples from well 70 on the west side of Rattlesnake Hill. At that location, the basalt is composed largely of zoned plagioclase, sanidine, and augite. Alteration of the basalt consists of a slight chloritization of augite crystals, minor illitic or sericitic alteration along cleavage planes of the plagioclase crystals, and hematitic edges on iron-bearing minerals such as magnetite or ilmenite. Secondary minerals lining fractures and vesicles in the basalt are mainly calcite with about 2.5 mole percent magnesium, and minor quartz, phillipsite (a potassium calcium zeolite), and clay minerals.

Observations of cuttings from test holes drilled for this study show that the lithology of the shallow and intermediate sedimentary aquifers also is highly variable, changing abruptly and repeatedly from sand to clay over thicknesses of less than one foot to tens of feet. Sandy layers range from fine to very coarse sand, often containing large amounts of silt typical of deltaic deposition. Clayey layers range from soft to stiff and often are a mixture of clay with minor amounts of silt, sand, or fine gravel. They are variable in color, generally tan to brown above 100 ft in depth, but in all test holes a ubiquitous black, organic-rich clay and muck layer 10- to 50-ft thick was present at depths between 20 and 80 ft. Below about 100 ft in depth, clay is commonly gray to gray-green, green, or blue.

Electrical-resistivity borehole logs made in test holes drilled during this study confirm highly variable lithology throughout the depths of the test holes. The resistivity logs, arranged in a general west-to-east order in figure 9, show changes in lithology by inflections to the right near sand beds that have relatively high resistivity and inflections to the left near less-resistive clay beds. Basalt has very high resistivity and can be seen near the bottom of some logs when the basalt is penetrated sufficiently as at wells 65 and 67. The measured resistivity also may be affected by changes in water quality, with resistivity decreasing as water becomes more saline. The resistivity logs were corrected to true resistivity using an algorithm developed by Scott (1978) which applies Schlumberger departure curves to correct for the effects of borehole diameter and mud resistivity. Sheathing on the resistivity tool does not allow data to be recorded with reasonable accuracy for the upper 40 ft of each test hole. The frequent and abrupt changes in lithology record the frequently changing depositional environments in Lahontan Valley as the level of ancient Lake Lahontan varied over time.

The resistivity logs show sandy beds alternating with thin clay beds to depths of about 100 ft below land surface (altitude about 3,850 ft). A clayey unit from 50 to 70 ft thick is seen below depths of about 100 ft (altitude 3,840 ft) at well 42 near Fallon, increasing in depth to about 130 ft (altitude 3,870 ft) at well 34, 1 mi south of Rattlesnake Hill. At well 65 about 1.5 mi northwest of Fallon, the clayey unit is not as well defined, and at well 67 east of Rattlesnake Hill, the top of the unit is about 110 ft deep (altitude 3,850 ft). Beneath the clayey unit, sand beds from less than 10 to 20 ft in thickness alternate with clay beds from 10 to about 40 ft in thickness. On the western side of the study area at wells 65 and 42, sandy layers exceed a resistivity of 50 ohm-meters. Farther south and east of Rattlesnake Hill at wells 6 and 37, the resistivity of sandy layers is generally less than 50 ohm-meters, and at well 34, large portions of the log have resistivities less than 20 ohm-meters. East of Rattlesnake Hill, at well 67 below about 110 ft in depth (altitude 3,860 ft) sediments were mostly clay above the basalt with only minor layers of sand. Although some of the differences

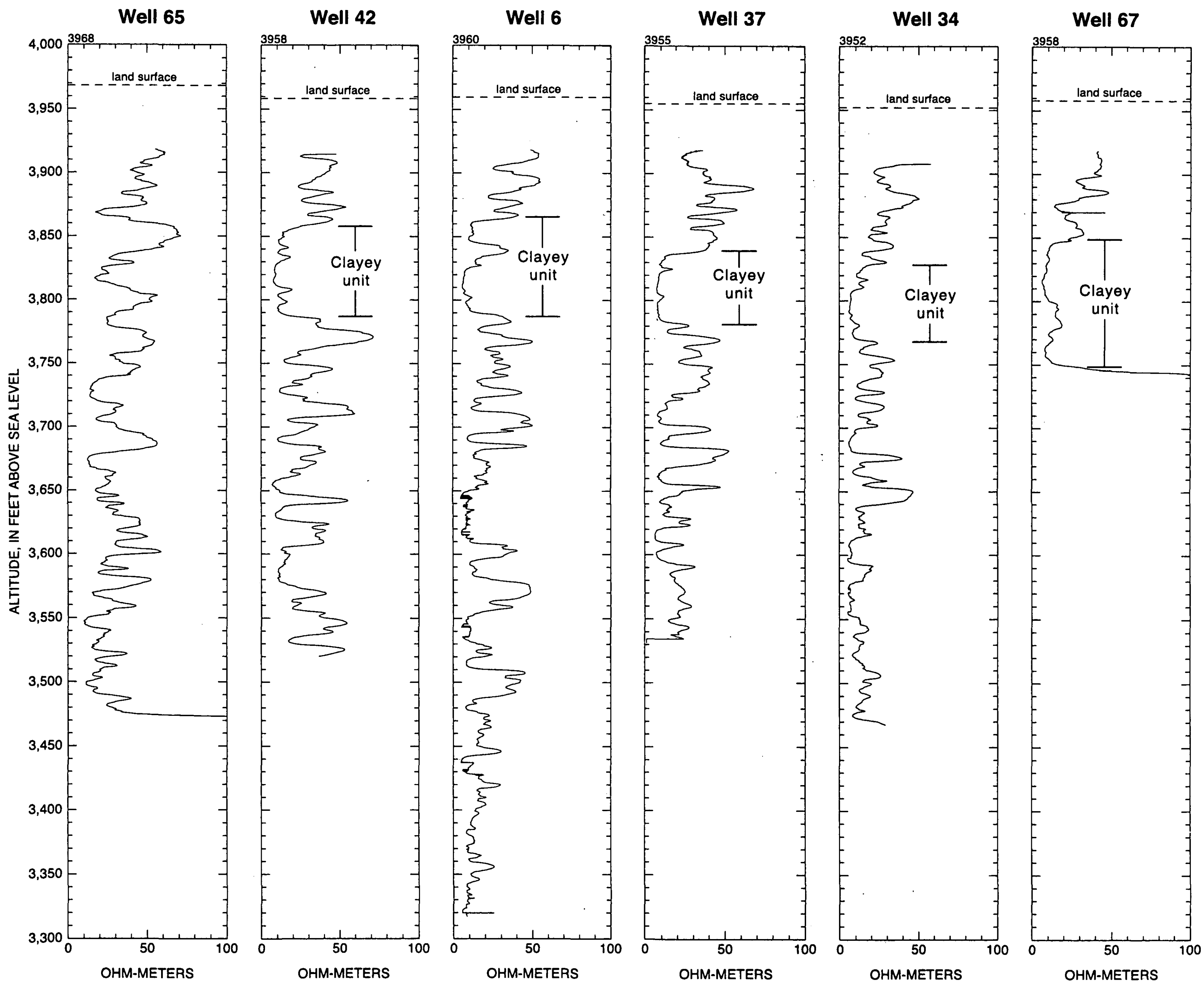


Figure 9. Electrical borehole resistivity of selected wells. Wells shown in general west to east order. Well locations shown in figure 6.

in resistivity may be caused by increasing salinity from west to east, the logs generally show a decrease in the sand content and an increase in the clay content of sediments in the intermediate aquifer from west to east.

As described in drillers' logs, the lithology of sediments in contact with the basalt is variable. In detailed logs, a layer of basaltic sand, gravel, and boulders from 3 to 23 ft thick sometimes is described overlying consolidated basalt (wells 25, 34, 42, 57, 69, 71, and 77; fig. 7, app. 1). In most wells adjacent to Rattlesnake Hill (fig. 7), sand and gravel is found overlying the basalt, and in some wells drilled for this study (wells 6, 34, 42, 57, and 65), gravels found above the basalt were extremely rounded and flattened, typical of gravels found on beaches. Because the basalt was present during high and low stands of Lake Lahontan, it seems likely that a mantle of beach deposits might cover the upper surface of the basalt. However, at some wells, a mantle of basalt fragments in a clay matrix 2- to 9-ft thick is found before penetrating consolidated basalt (wells 37, 41, 63, and 93). In wells further from Rattlesnake Hill and at greater depths, the distribution of either sand or clay in contact with the basalt is variable, even in wells separated by less than 100 ft (wells 28–30, 49 and 50, fig. 7). When the basalt was completely submerged, deep lake clays may have been deposited at the basalt contact, followed by partial erosion of the clay and deposition of beach deposits as lake levels fell. This resulted in a variable lithology of sediments in contact with the basalt.

Although descriptions from drillers' logs may be sometimes inaccurate and generalized, they provide a qualitative description of variations in subsurface lithology. To take advantage of the information supplied by drillers' logs, descriptions from logs were compiled to assess the lithology of sedimentary aquifers near the basalt. For compilation, sediments described as clay, silt, or sandy or gravely clay were grouped together representing layers potentially having hydraulic conductivities of less than 1–2 ft/d. Likewise, sediments described as sand, gravel, or sand or gravel with minor clay, were grouped together to represent layers potentially having hydraulic conductivities of greater than 5–10 ft/d.

In general, the thickest and most numerous sand layers are seen in wells southwest, west, and northwest of Rattlesnake Hill. In figures 10*A* and 10*B*, clay layers are shown in red and sand layers are shown in blue. On the southern edge of the basalt, sand layers are relatively few and thin (fig. 10*A*). On the southeast and eastern side of the basalt, the few available drillers' logs show that clay constitutes almost the entire thickness penetrated by wells (fig. 10*A*). Southwest and west of Rattlesnake Hill (fig. 10*B*), logs of wells near Fallon show relatively thick sand layers to depths of 100 to 200 ft. These layers may extend laterally toward Rattlesnake Hill, providing pathways of recharge to the basalt. However, this cannot be confirmed because of the lack of wells between Fallon and Rattlesnake Hill. Northwest of Rattlesnake Hill, sand layers are quite thick and numerous throughout the intermediate sedimentary aquifer overlying the basalt.

The distribution of relative hydraulic conductivity suggests that most recharge could occur along the southwestern, western, and northwestern sides of the basalt. Clay on the southeastern and eastern side of the basalt probably restricts recharge to the basalt from those directions.

Hydraulic Conductivity of Basalt and Sedimentary Aquifers

The hydraulic conductivity of aquifer materials may vary over several orders of magnitude. Hydraulic conductivities of aquifer materials were estimated using the three different methods described in the section titled "Methods Used" (table 1). The values are considered to be in reasonable agreement and provide a range of possible values for the intermediate sedimentary and basalt aquifers. As noted previously, estimates made using specific capacity may be underestimated by factors of 1.3 to 2.4. Estimates of hydraulic conductivity made using the Harrill or Kipp method (table 1) generally are greater than the estimate from specific capacity. Because wells were screened in the more sandy zones of the intermediate sedimentary aquifer, values are representative of the more conductive zones of this aquifer. Hydraulic conductivity of clayey units in the intermediate sedimentary aquifer could be less than these values by three to four orders of magnitude or more. Because the basalt aquifer is so highly conductive, it is possible that the values obtained from aquifer tests of wells screened in the basalt are limited by the conductivity of the combined well screen and sand-pack. For this reason, values of hydraulic conductivity presented for the basalt aquifer are considered minimum values.

Table 1. Summary of hydraulic conductivity estimated for selected wells

[Abbreviations: ft, feet; ft/d, feet per day; gal/min, gallons per minute; min, minutes]

Well (fig. 6)	Aquifer [1]	Maximum pump rate (gal/min)	Total pumping duration (min)	Maximum drawdown (ft)	Hydraulic conductivity from specific capacity [2] (ft/d)	Hydraulic conductivity from Harrill method [3] (ft/d)	Hydraulic conductivity from Kipp method [4] (ft/d)
6	I-C	4.6	20	1.3	12–14	—	20–30
7	I	4.6	20	2.3	7–8	—	10
34	I-C	4.6	22	2.2	21–24	61	40–42
35	I	4.8	25	1.8	12–22	15	—
37	I-C	4.7	22	3.2	8–9	22	—
38	I	4.8	20	5.9	3	14	—
42	I-C	4.6	21	1.8	25–28	39	28–30
43	I	4.8	21	3.9	5–6	8	—
57	B	4.7	20	.15	290–560	—	350–360
58	S-C	1.9	10	1.1	22–23	50	—
65	I-C	4.8	21	2.1	8–9	—	10
66	I	4.9	20	2.6	9	14	—
67	B	4.8	23	.5	130–170	—	260–450
68	I	4.9	20	1.9	13–16	22	—
69	B	4.3	14	.07	540–1,200	—	810–850

[1] B, basalt aquifer; S-C, shallow sedimentary aquifer in contact with basalt; I, intermediate sedimentary aquifer; I-C, intermediate sedimentary aquifer in contact with basalt.

[2] Calculated from equation 1 in text and an iterative computer program written by D.E. Prudic (U.S. Geological Survey, written commun., 1999). Range of values from specific capacity calculated for different pumping rates.

[3] Method of Harrill (1970).

[4] Method of Kipp (1985). Range of values obtained by varying specific storage from $1–2 \times 10^{-6}$ for sedimentary aquifers and use of different match points for well 67 screened in basalt aquifer.

Estimates of hydraulic conductivity of the sedimentary aquifers ranged from 3 to about 60 ft/d (table 1). Conductivity was less than 15 ft/d at wells 66, 43, 38, and 7, and greater than 20 ft/d at sites 34, 42, and 58 (fig. 6). Estimates of hydraulic conductivity of the basalt aquifer were all greater than 100 ft/d and as high as 1,200 ft/d at site 69. These values are within the range of values reported for silty sand and permeable basalt (Freeze and Cherry, 1979, p. 29).

Water-Level Fluctuations and Altitudes, and Vertical Hydraulic Gradients

Variations in the timing and magnitude of water-level fluctuations, differences in water-level altitudes, and vertical hydraulic gradients between aquifers can provide evidence of the location and sources of ground-water recharge and discharge. Since measurements were made by Glancy (1986) in the late 1970's, water levels in the basalt aquifer have changed in altitude and in their response to seasonal pumping. Historic water levels in the basalt measured at the Fallon–Mori well (well 44, fig. 6), which is equipped with a continuous recorder, show seasonal fluctuations of 2–4 ft superimposed on an overall water-level decline (figs. 3 and 11*A*). Decline began at a more rapid rate starting in about 1984, coincident with an increase in annual pumping from the basalt aquifer.

Water-level fluctuations measured in other basalt wells during 1997–99 show seasonal fluctuations of about 4 ft, with high water levels from December through March lagging slightly behind the period when pumpage from the basalt is at a minimum. Low water levels occur from August through September, also lagging slightly behind the period when pumpage for landscape irrigation is at a maximum (figs. 11*A* and 11*B*). The hydrographs in figure 11*A* have remarkably similar fluctuations in timing and amplitude from the southwestern end (well 44) to the northeastern end (well 112)

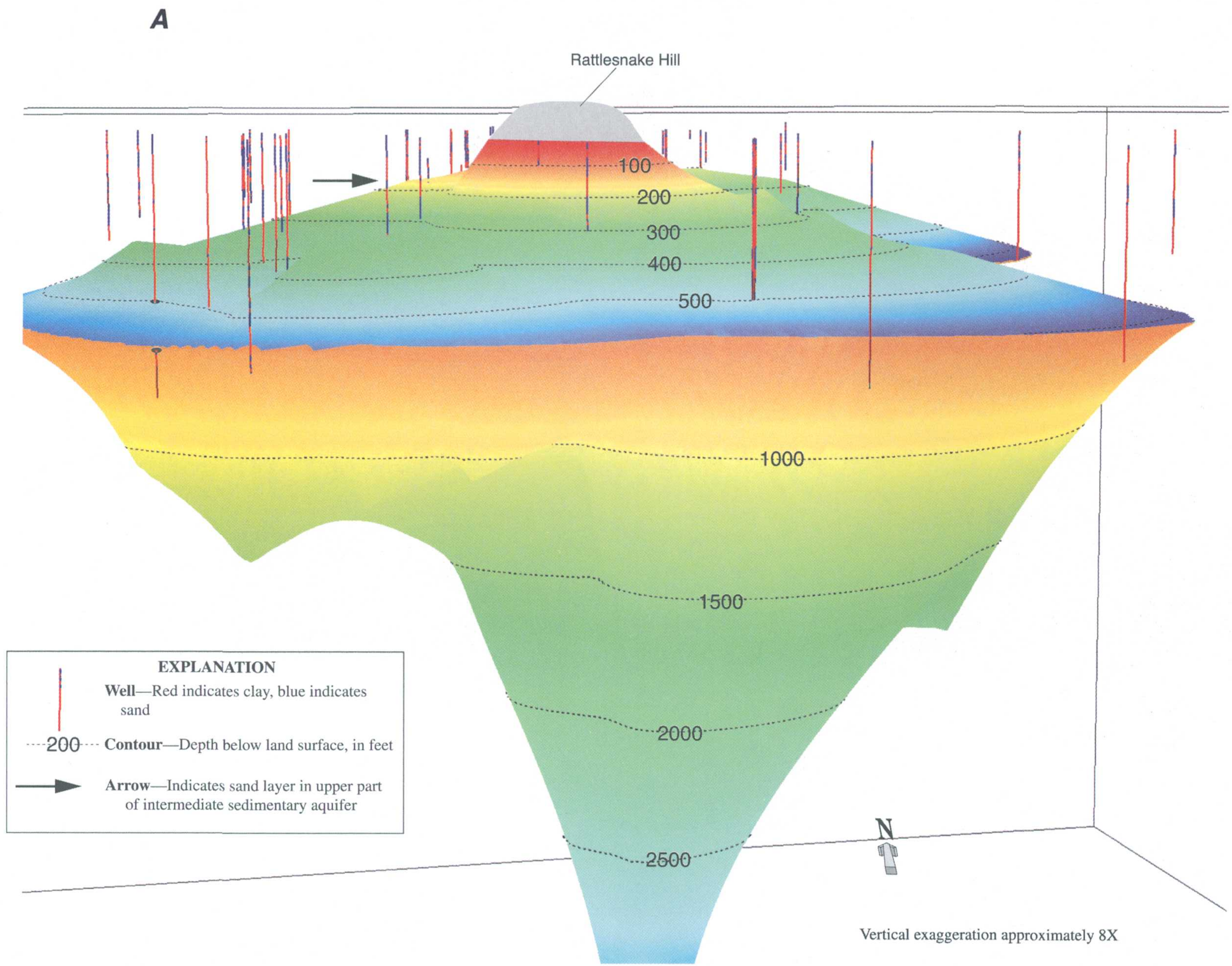


Figure 10. (*A*) Oblique view of basalt aquifer looking toward north. Extent of basalt is based on drillers' logs for wells (for exact location of wells, see fig. 7) and on electrical resistivity soundings described by Glancy (1986, p. 10–17). Vertical distribution of sand and clay is based on descriptions from drillers' logs. Clayey sediments shown in red; sandy sediments shown in blue. Scale is variable with perspective. Small arrows show location of sand layers and potential direction of recharge to basalt aquifer.

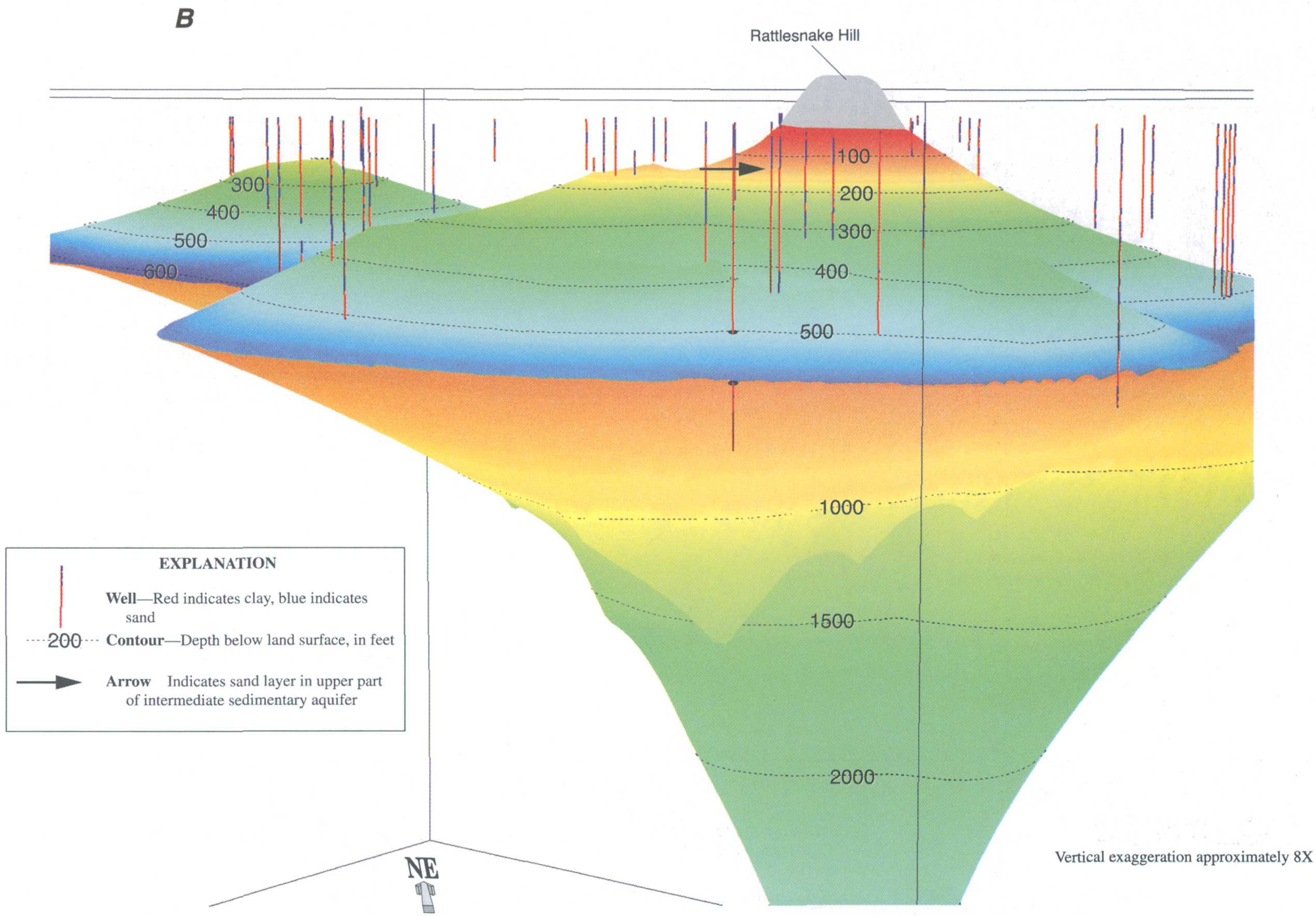


Figure 10. (*B*) Oblique view of basalt aquifer looking toward northeast. Extent of basalt is based on drillers' logs for wells (for exact location of wells, see fig. 7) and on electrical resistivity soundings described by Glancy (1986, p. 10–17). Vertical distribution of sand and clay is based on descriptions from drillers' logs. Clayey sediments shown in red; sandy sediments shown in blue. Scale is variable with perspective. Small arrows show location of sand layers and potential direction of recharge to basalt aquifer.

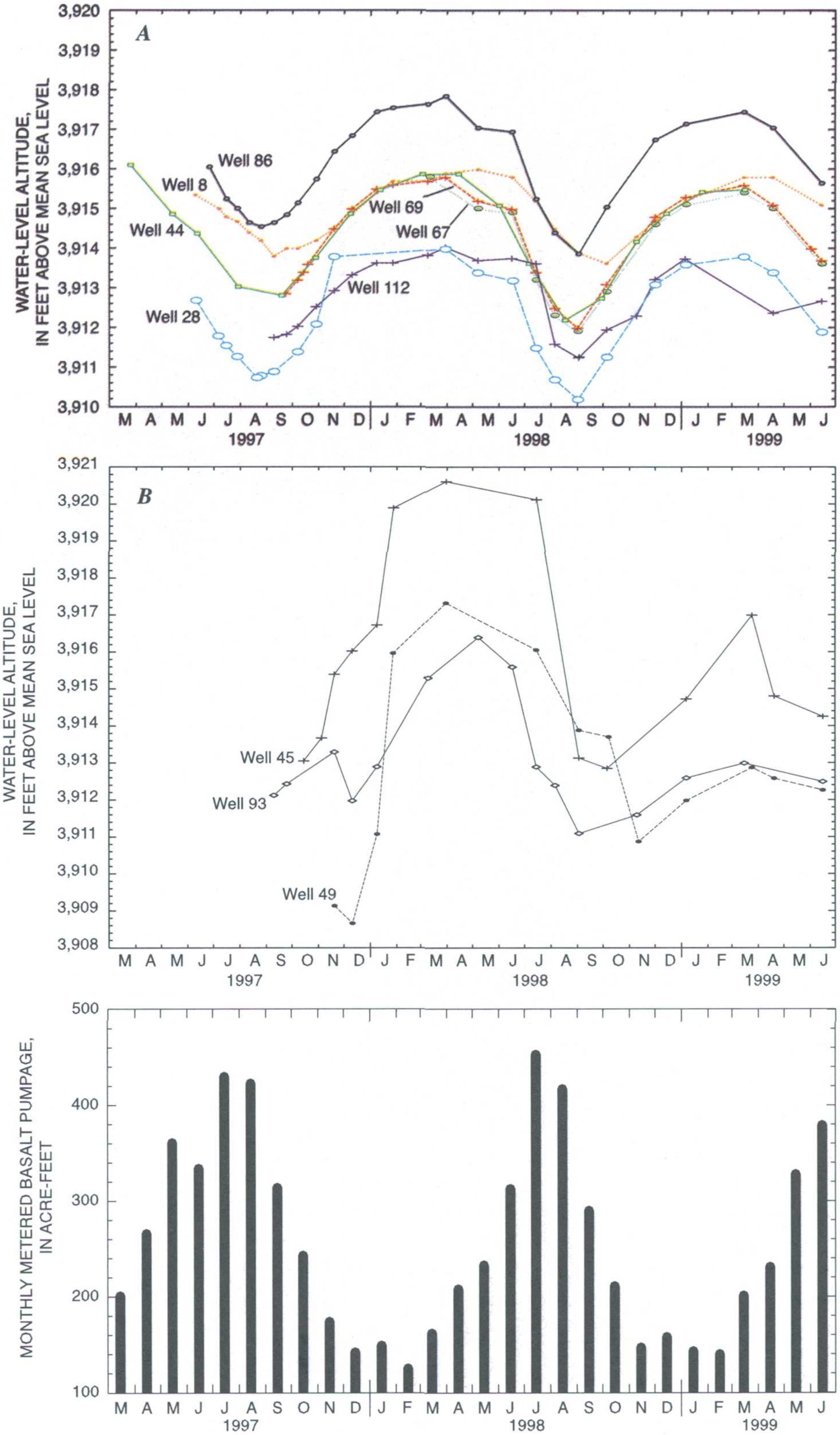


Figure 11. Ground-water pumpage and water-level fluctuations in (*A*) selected wells tapping basalt aquifer, March 1997 through June 1999; and (*B*) major pumping wells tapping basalt aquifer, March 1997 through June 1999. Well locations shown in figure 6.

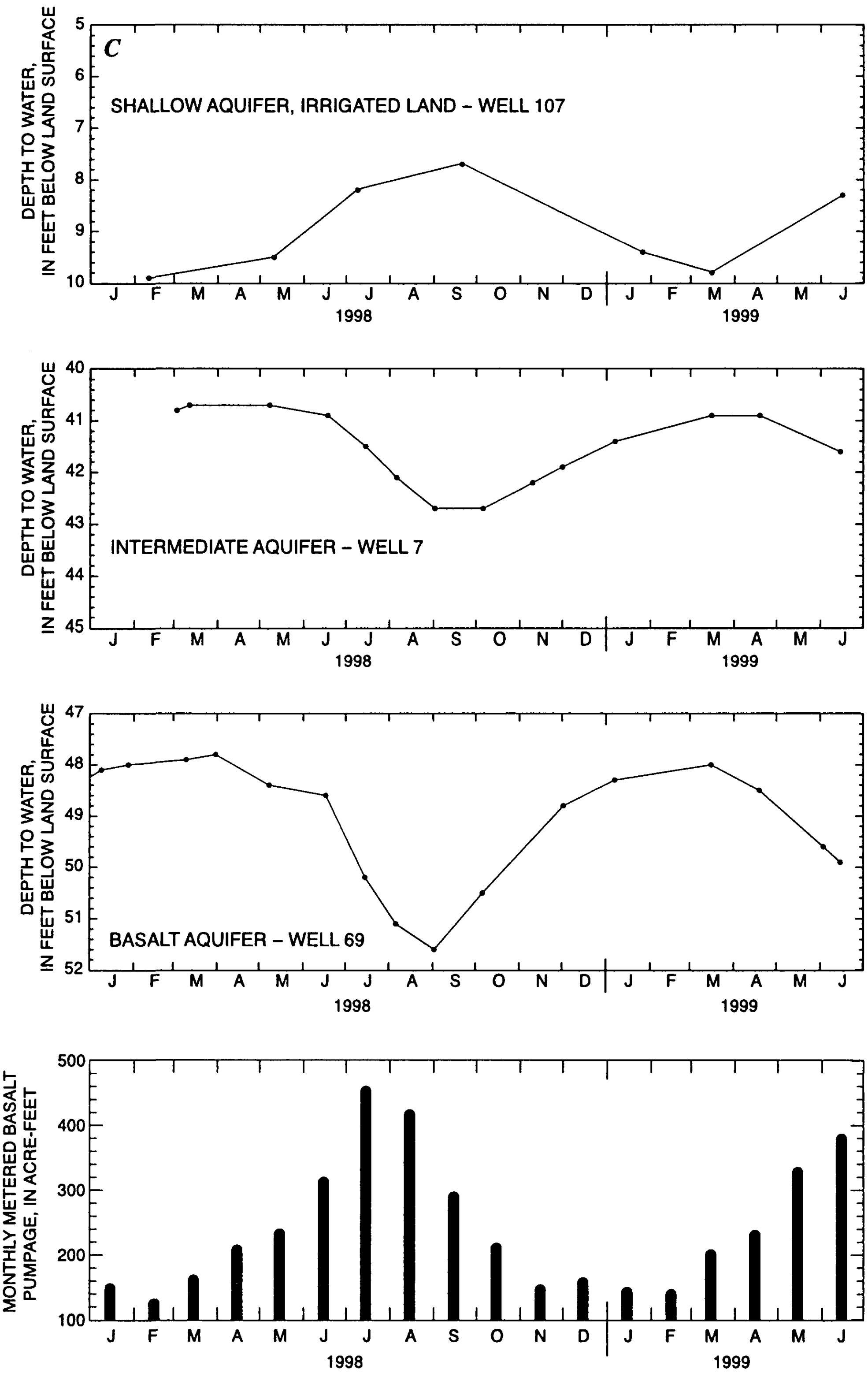


Figure 11. (*C*) Ground-water pumpage and water-level fluctuations in selected wells tapping shallow sedimentary, intermediate sedimentary, and basalt aquifers, January 1998 through June 1999. Well locations shown in figure 6.

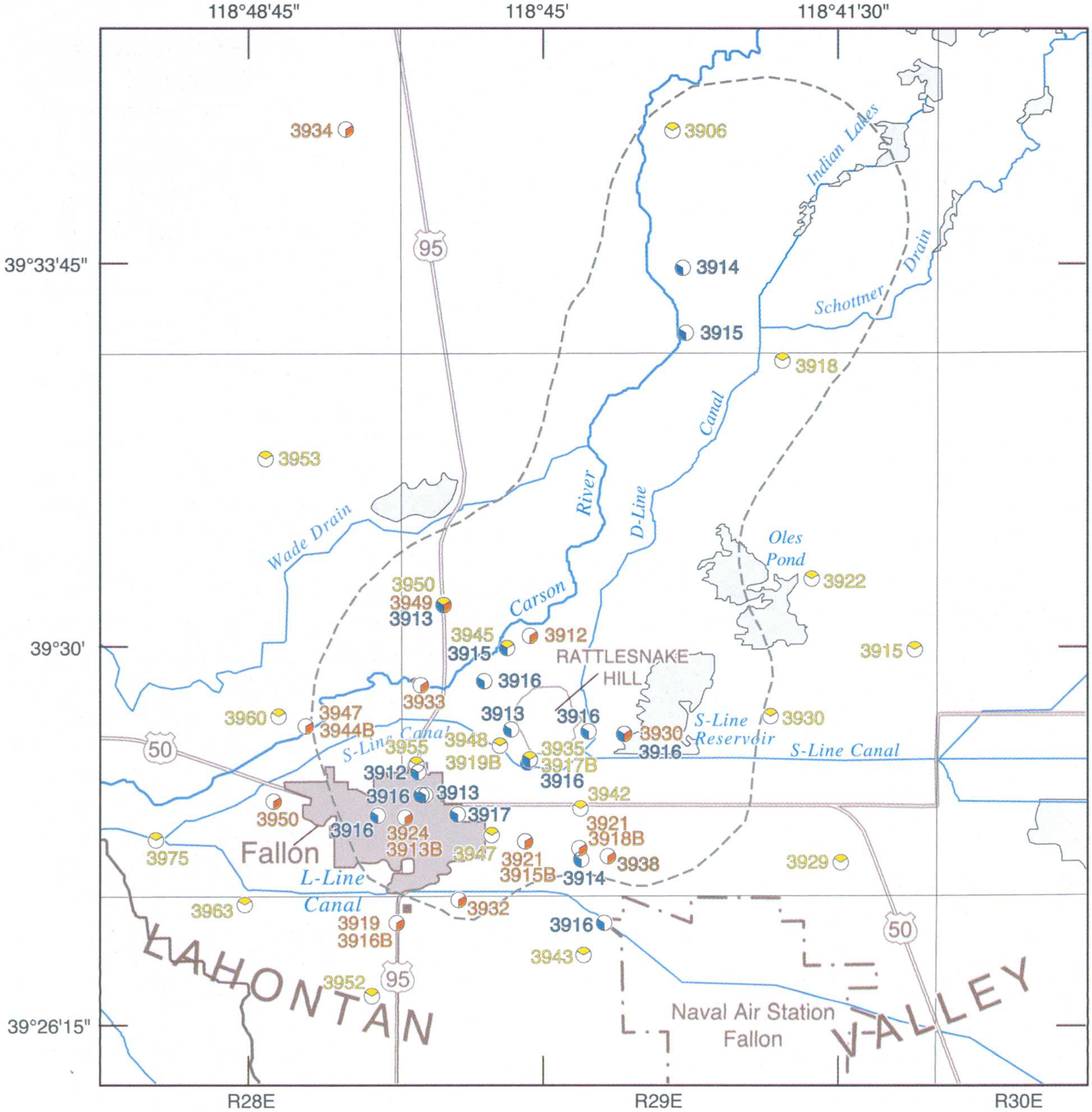
of the basalt. One exception is well 8 where minimum and maximum water levels occur 1 to 2 months later than at other basalt wells. This well penetrated basalt at greater depths than other basalt wells (see discussion in section titled "Lateral and Vertical Extent of Basalt") and could represent conditions in a body of basalt disconnected from, or poorly connected to, the main body of basalt. The more heavily pumped basalt wells west of Rattlesnake Hill showed greater seasonal fluctuations than other basalt wells in 1998, from 8–9 ft (fig. 11*B*).

As described by Glancy (1986, p. 39) and measured during this study, water levels in the shallow sedimentary aquifer fluctuate seasonally by 2 to 3 ft near irrigated areas in response to recharge from seepage beneath canals and irrigated fields (fig. 11C). High water levels occur near the end of the irrigation season from July through September, and low water levels occur from February through March, prior to the beginning of the irrigation season. Water levels measured in the intermediate sedimentary aquifer during this study also fluctuated 2 to 3 ft seasonally. However, unlike the shallow sedimentary aquifer and similar to the basalt aquifer, high water levels occur in winter months and low water levels occur in late summer (fig. 11C). Figure 11C shows a detailed comparison of the timing in typical fluctuations in the shallow sedimentary, intermediate sedimentary, and basalt aquifers. Glancy (1986, p. 39) reported that in the late 1970's water-level fluctuations in the intermediate sedimentary aquifer on the extreme western side of Lahontan Valley were similar to those in the shallow sedimentary aquifer, in phase with the irrigation season. However, water-level fluctuations of the intermediate sedimentary aquifer near the center of Lahontan Valley were not discussed by Glancy (1986). Thus, it is not clear if the difference in timing of water-level fluctuations is caused by the difference in location, or by changing conditions from 1970 to 1999.

An increase in pumpage from the intermediate sedimentary aquifer from the late 1970's to the late 1990's could partly explain the difference in timing of water-level fluctuations. In the early 1970's only about 100 wells were screened in the intermediate sedimentary aquifer (Glancy, 1986, p. 51). Maurer and others (1994, p. 39) reported that in 1993, as many as 1,000 wells might be withdrawing water from the intermediate sedimentary aquifer. From 1993 to 1999, about 900 additional wells have been installed (Kim Groenewold, Nevada Division of Water Resources, written commun., 1999) for a total of almost 2,000 wells currently pumping from the intermediate sedimentary aquifer. Most of these wells are used for domestic water supply with increased pumpage during summer months for lawn watering. Because the intermediate sedimentary aquifer is confined, increased pumping during summer months could cause widespread water-level declines in August and September. An alternative explanation could be that seasonal declines from pumping of the basalt aquifer propagate through the intermediate sedimentary aquifer and the basalt acts as a sink for groundwater flow.

Glancy (1986, p. 15) described a nearly flat potentiometric surface throughout the basalt aquifer based on water levels measured from 1978 to 1980. At that time, water-level altitudes across the aquifer varied less than 1.5 ft, from about 3,922 ft near Fallon to about 3,921 ft near the northeastern extent of the basalt (Glancy, 1986, p. 18). In August and September of 1998 when seasonal water levels were lowest, water levels in basalt wells ranged from about 3,914 to 3,910 ft (figs. 11*A* and *B*); about 8 to 12 ft lower than in winter months from 1978–80. In March 1999 when seasonal water levels were highest, water levels in basalt wells were 6 to 7 ft lower than in winter months from 1978–80. Water-level altitudes in the basalt were about 3,916 ft at non-pumping wells near Fallon and 3,914 to 3,915 ft near the northeastern extent of the basalt (wells 44, 110, and 112; figs. 6 and 12). Water-level altitudes at some major supply wells (wells 28, 49, 55, 70, and 92; figs. 6 and 12) were 2–4 ft lower than those not being heavily pumped, suggesting that cones of depression are forming around the wells.

Near the southwestern part of the basalt, water levels in the shallow sedimentary aquifer are 30–40 ft higher than those in the basalt (wells 55 and 56, wells 40 and 45, and wells 91 and 93; figs. 6 and 12), and water levels in the intermediate sedimentary aquifer are as much as 20–30 ft higher (wells 30 and 31, wells 51 and 66, and wells 92 and 93; figs. 6 and 12). Thus, the potential for recharge to the basalt aquifer exists over all of its southwestern extent. Higher water levels in the surrounding sedimentary aquifers than in the basalt were present before the declines in basalt water levels noted in recent years. Glancy (1986, p. 27) noted that water levels in the sedimentary aquifers were from 30 to 20 ft higher than in the basalt aquifer in the late 1970's. In 1958, during drilling of well 25, Kingman (1959, p. 16) reported that upon penetration of the basalt, the land surface began to subside, forming a



Roads and hydrology from U.S. Geologica Survey digital data, 1:100,000, 1979-80
Universal Transverse Mercator Projection, Zone 11
Water bodies from U.S. Geological Survey digital data, 1:250,000, 1971
Political boundaries and canal names from U.S. Geological Survey, 1:24,000, 1969-87; 1:100,000, 1979-80

0 — 3 MILES
0 — 3 KILOMETERS

EXPLANATION

Well location and water-level altitude in feet, March 1999—The letter "B" indicates contact with basalt layer

- 3950 Shallow aquifer
- 3944B Intermediate aquifer
- 3916 Basalt aquifer

– – – – – **Approximate extent of basalt at depth of 600 feet below land surface**—From Glancy (1986)

Figure 12. Water-level altitude at selected wells in March 1999. Well locations shown in figure 6.

depression 18 ft in diameter and 10 ft deep around the test hole. He noted similar occurrences in the drilling of basalt wells for the City of Fallon and stated that the problem probably was caused by a substantial difference in water levels between the sediments and the basalt. The depression probably was formed as water and sand in layers above the basalt flowed down the test hole into voids within the basalt.

Near the southwestern part of the basalt aquifer, as depth increases in the intermediate sedimentary aquifer, water levels become more similar to those in the basalt aquifer (for example, compare water levels at wells 6 and 7, 34 and 35, 37 and 38, and 43 and 42; figs. 6 and 12). Water levels in the intermediate aquifer in contact with the basalt are from about 4 ft higher to approximately equal to the lowest basalt water levels.

Differences in water-level altitude between surface-water bodies and underlying aquifers, between different aquifers, and at different depths within the same aquifer create a vertical hydraulic gradient. Where ground water is recharged from surface-water bodies and where ground-water flows from shallower aquifers to deeper aquifers, water-level altitude decreases with depth and the vertical hydraulic gradient is downward. In accordance with Darcy's Law (Freeze and Cherry, 1979, p. 28), the volume of ground water flowing in a given direction is directly proportional to the hydraulic gradient in that direction, the hydraulic conductivity of aquifer materials, and the area through which the water flows. Thus, given equal hydraulic conductivity and flow area, ground-water flow will be greater under a larger hydraulic gradient.

In appendix 3, water levels of surface-water bodies and water levels measured at nearby or nested wells of different depths were used to calculate vertical hydraulic gradients near the southwestern part of the basalt where potential for recharge is greatest. The gradients were calculated by dividing the difference in water-level altitude, in feet, by the vertical distance, in feet, over which the water levels were measured. The vertical distance was determined from the mid-point of the gravel-packed or open interval of wells, or of the streambed of surface-water bodies. The resulting value for the vertical hydraulic gradient is dimensionless. To show the seasonal range in vertical gradients, water levels measured in September 1998 and March 1999 were used for calculations. All calculated vertical gradients for the southwestern part of the basalt aquifer were downward, indicating a potential for recharge to the basalt.

The largest vertical gradients were measured in wells near Rattlesnake Hill, where gradients from the S-Line Canal to underlying aquifers and within the shallow sedimentary aquifer in contact with the basalt ranged from 1.48 to 0.496 (wells 57–59, 63, and 64; fig. 6, app. 3). When the vertical hydraulic gradient is greater than 1.00, the upper body of water is separated from the lower body by an unsaturated zone (D.E. Prudic, U.S. Geological Survey, oral commun., 1999) and a layer of low permeability that restricts downward flow. At sites with gradients greater than 1.0, water is flowing downward at a rate restricted by the hydraulic conductivity of the streambed or of the shallow sedimentary aquifer above the basalt. Gradients measured from the shallow sedimentary aquifer in contact with the basalt to the basalt aquifer are less, from about 0.053 to 0.033 (wells 57 and 58, fig. 6, app. 3).

Away from Rattlesnake Hill, vertical gradients measured from surface-water bodies to the shallow and intermediate sedimentary aquifers also are less, ranging from 0.061 to 0.043 at wells 85 and 66 (fig. 6) near the Carson River, respectively. East of Rattlesnake Hill near S-Line Reservoir, the vertical gradient from the reservoir water surface to the intermediate sedimentary aquifer at well 68 was 0.151 during winter months, decreasing to 0.125 in summer months.

At other wells in the study area, vertical gradients between well pairs in the intermediate sedimentary aquifer and between wells in the shallow sedimentary aquifer and the basalt aquifer range from 0.222 to 0.013 (app. 3). At most well pairs, the vertical gradient is greater in late summer than in early spring. In summer, shallow water levels rise in response to recharge from irrigation, and deeper water levels decline in response to summer pumping, which increases the gradient. Because downward gradients generally are greater during summer months, downward ground-water flow and recharge also are greater during the summer.

The vertical hydraulic gradient decreases with depth below land surface (fig. 13). Depths representative of the calculated vertical gradients were determined as the average of the mid-point depths of the gravel-packed intervals of the well pairs. The vertical hydraulic gradient is greatest between the basalt aquifer and the shallow and upper part of the intermediate sedimentary aquifers. The decrease in gradient with depth suggests that the rate of ground-water flow through the intermediate sedimentary aquifer also decreases with depth, and that the potential for recharge to the basalt aquifer is greatest where the basalt and the shallow and

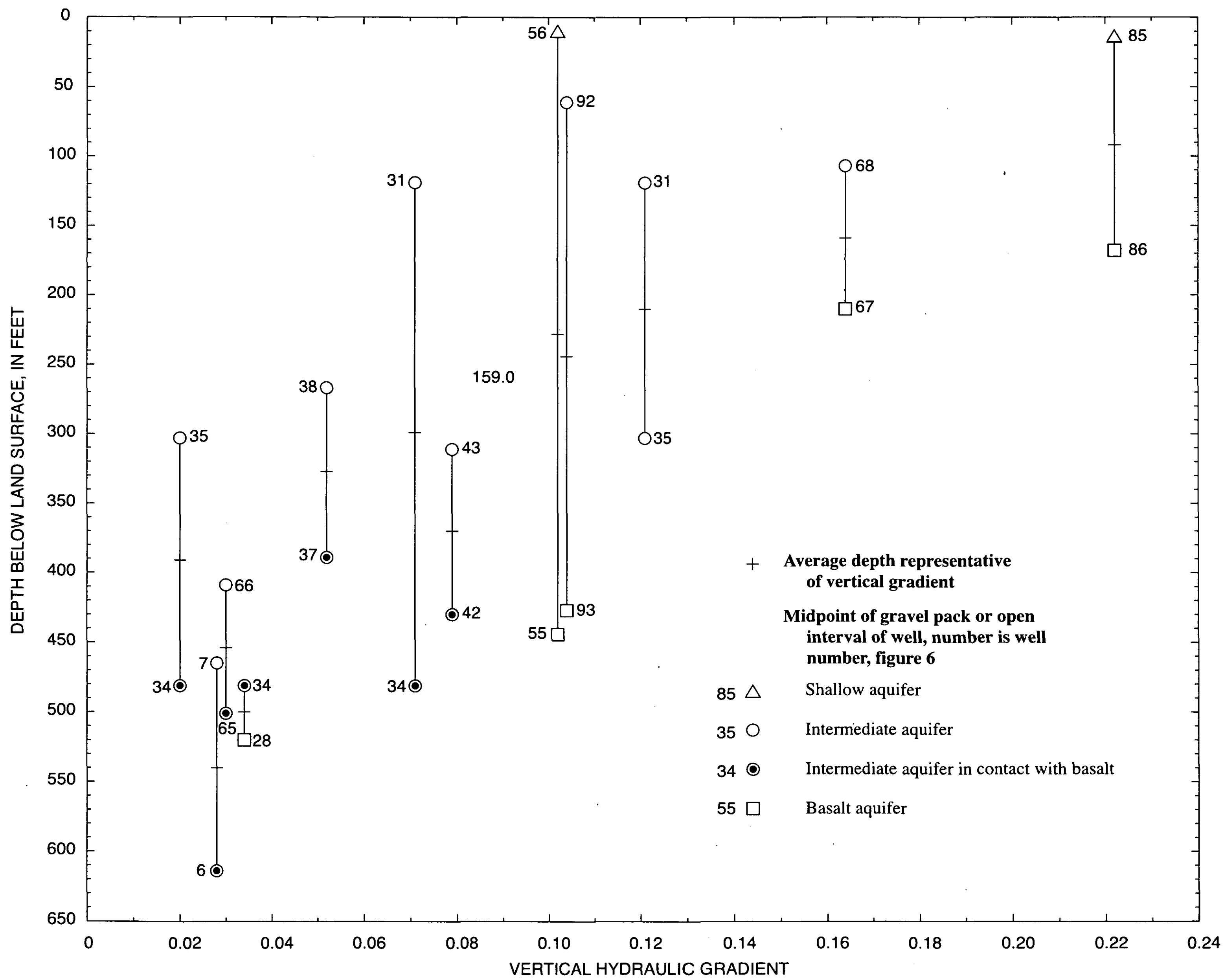


Figure 13. Variation of vertical hydraulic gradient with depth between well pairs in the shallow and intermediate sedimentary aquifers, and the basalt aquifer, September 1998.

upper part of the intermediate sedimentary aquifers are in contact. Transmissive sand layers in the shallow and the upper part of the intermediate sedimentary aquifers provide a pathway for recharge to the basalt aquifer.

The exact location and distribution of such sand beds is not known; however, in the shallow aquifer, recharge is possible over a relatively small area surrounding Rattlesnake Hill. In the intermediate aquifer, recharge is possible over a much larger area. The complex layering of sand and clay in the intermediate aquifer and the lack of wells between Fallon and Rattlesnake Hill makes delineation of laterally extensive sand layers difficult. Lithologic data presented in the previous section suggest that the most likely areas of the upper part of the intermediate aquifer that contribute recharge to the basalt are southwest, west, and northwest of Rattlesnake Hill (fig. 10).

GEOCHEMICAL FRAMEWORK OF BASALT AQUIFER

A general description of the geochemical characteristics of the basalt and sedimentary aquifers has been presented in the section titled "Description of Aquifers." Existing geochemical data for water in the basalt aquifer are limited to wells that tap only the uppermost part of the basalt. Because few wells penetrate the basalt more than about 70 ft (app. 1), the quality of water in the basalt aquifer is unknown at depths greater than about 600 ft below land surface. Thus, the volume of potable ground water stored in the basalt aquifer also is unknown.

The following sections present historic water-quality data and water-quality data collected during this study to provide a more complete description of the geochemical framework of the basalt aquifer. Previous discussions of the chemistry and hydrology of Lahontan Valley (Glancy, 1986; Lico and Seiler, 1994; Welch and others, 1997; Welch and Lico, 1998) provide the basis for evaluation of data collected for this study. Welch and others (1997) discuss the general principles of isotope hydrology in relation to the Carson River Basin. In addition to samples taken from 32 wells for this study, extensive water-quality sampling in Lahontan Valley was done from 1987–90 as part of a National Water-Quality Assessment Program of the USGS, and summarized by Whitney (1994). These data and historic water-quality data collected by the USGS in Lahontan Valley and stored in electronic databases also were used for evaluation. Water-quality data for sites sampled during this study are tabulated in appendix 4.

Sources of Recharge to the Basalt Aquifer—Inferences from Stable-Isotope and Water Chemistry

The major-ion and stable-isotope composition of ground water in the basalt aquifer and sedimentary aquifers provide insight into possible sources of recharge to the basalt aquifer. In terms of major-ion composition, water in the basalt aquifer is dominated by sodium and bicarbonate. Magnesium and calcium concentrations are distinctly lower in the basalt aquifer compared to ground water in the shallow sedimentary aquifer and somewhat lower than water in the intermediate sedimentary aquifer (Lico and Seiler, 1994, p. 32).

Since the basalt was emplaced more than 1 Ma, changing conditions may have significantly affected the water chemistry of recharge to the basalt aquifer and surrounding sedimentary aquifers. During the Pleistocene epoch, recharge processes were dominated by varying levels of ancient Lake Lahontan. After the last high stand of Lake Lahontan, recharge was dominated by the natural inflow of the Carson River and water chemistry was affected by evapotranspiration from native phreatophytes and evaporation from shallow lakes. After the Newlands Project was completed in 1915, recharge was dominated by surface water applied for irrigation and water chemistry was affected by evaporation from Lahontan Reservoir, water imported from the Truckee River, and evapotranspiration from irrigated crops. Since about 1965, increased pumping from the basalt has induced additional recharge from the surrounding sedimentary aquifers, causing small but measurable changes in water chemistry, as discussed in the following section, "Water-Quality Trends Over Time." The effect of these changing conditions over time on the water chemistry of recharge to the basalt aquifer must be considered when evaluating sources of recharge.

Changes in the source of surface water entering Lahontan Valley and changes in the amount of evapotranspiration could most greatly affect the composition of stable isotopes and chloride concentration of recharge to aquifers in Lahontan Valley. From samples taken since 1985 and values stored in USGS databases, the present-day Carson River has delta deuterium values ranging from about -98 to -110 permil upstream from Lahontan Reservoir at Fort Churchill (fig. 14). The stable-isotope composition of the Carson River below Lahontan Reservoir has not been extensively sampled but probably is heavier (having permil values that are less negative) because of the effect of evaporation from the reservoir and because isotopically much heavier water from the Truckee River (fig. 14) is diverted into the reservoir (Lico and Seiler, 1994, p. 15).

Ground water in the study area has three distinct stable-isotope compositions (fig. 14). Water from the shallow sedimentary aquifer has delta deuterium values less negative than about -100 permil; water from the intermediate sedimentary and basalt aquifers ranges from -105 to -117 permil; and water from the intermediate sedimentary aquifer at depths greater than about 300 ft along the southern edge of the basalt aquifer is more negative than -124 permil.

The stable-isotope composition of ground water in the shallow sedimentary aquifer may be derived from the mixing of water from the Carson and Truckee Rivers and by its subsequent evaporation from Lahontan Reservoir or during irrigation. This composition is consistent with recharge by water from the reservoir (Lico and Seiler, 1994; Welch and others, 1997). From the water table to a depth of 50 ft, ground water becomes isotopically lighter at greater depths (fig. 15), suggesting that ground water in the shallow sedimentary aquifer is a mixture of recent recharge of water from the reservoir with older, isotopically lighter ground water. Near the center of Lahontan Valley, water from depths greater than about 50 ft, the upper boundary of the intermediate sedimentary aquifer, is distinctly lighter (more negative) than is water from the shallow sedimentary aquifer (fig. 15). This depth corresponds to the change in cation composition noted by Glancy (1986).

The change in stable-isotope composition at a depth of 50 ft suggests that, near the center of Lahontan Valley, recharge of water under the current hydrologic regime is restricted to the upper 50 ft of the aquifer system. This is not the case west of Soda Lake (fig. 2), where Lico and Seiler (1994, p. 16), using data on stable isotopes and tritium concentrations, showed that water from depths of 99 and 179 ft in the intermediate sedimentary aquifer was recharged from the shallow sedimentary aquifer or from surface-water sources.

Tritium concentrations greater than 1 pCi/L indicate recharge of water after major releases of tritium to the atmosphere during nuclear testing that began in the 1950's. Near the center of the valley, tritium concentrations of water from the intermediate sedimentary aquifer also suggest a lack of recharge since the 1950's (Lico and Seiler, 1994, p. 18). Carbon-14 ages estimated for ground water sampled from wells in the intermediate aquifer near the center of the valley range from 1,100 to 7,700 years (Lico and Seiler, 1994, p. 20). Water in the basalt aquifer has been estimated to range in age from about 1,000 to 8,000 years using carbon-14 (Lico and Seiler, 1994, p. 20). However, the method for estimating ages from carbon-14 data, although widely used, does not account for potential exchange of carbon-14 in the ground water with carbonate minerals in the aquifer. Thus, the ages estimated using carbon-14 are most useful as maximum limits and the water could actually be of younger age.

The stable-isotope compositions of water from the basalt aquifer and the intermediate sedimentary aquifer near the center of the valley also are similar, suggesting a similar source of recharge to both aquifers. However, because evaporation makes water isotopically heavier (less negative), evaporation of the present-day mixture of Carson and Truckee River water from Lahontan Reservoir or during irrigation cannot produce water with an isotope composition like that found in the intermediate sedimentary and basalt aquifers (fig. 14; Lico and Seiler, 1994, p. 15).

Before construction of Lahontan Reservoir, the isotopic composition of Carson River streamflow flow entering Lahontan Valley probably was lighter than at present because evaporation from the reservoir and inflow from the Truckee River were not taking place. In addition, former levels of Pyramid Lake and the reforming of cirque glaciers in the Sierra Nevada indicate that the climate was wetter in the Lahontan area from about 600 to 50 years ago and had been dominated by winter precipitation (Lico and Seiler, 1994, p. 18; Davis, 1982, p. 69). These conditions likely would cause precipitation and Carson River streamflow to be isotopically lighter, although there are no direct data to support this hypothesis. Ground water found in deep aquifers in Carson Valley likely was recharged by the Carson River (fig. 14; Welch and others, 1997, p. A19). Assuming that ground water in the deep aquifers of Carson Valley is largely unaffected by human activities, its stable-isotope composition may be similar to Carson River streamflow that entered Lahontan Valley before

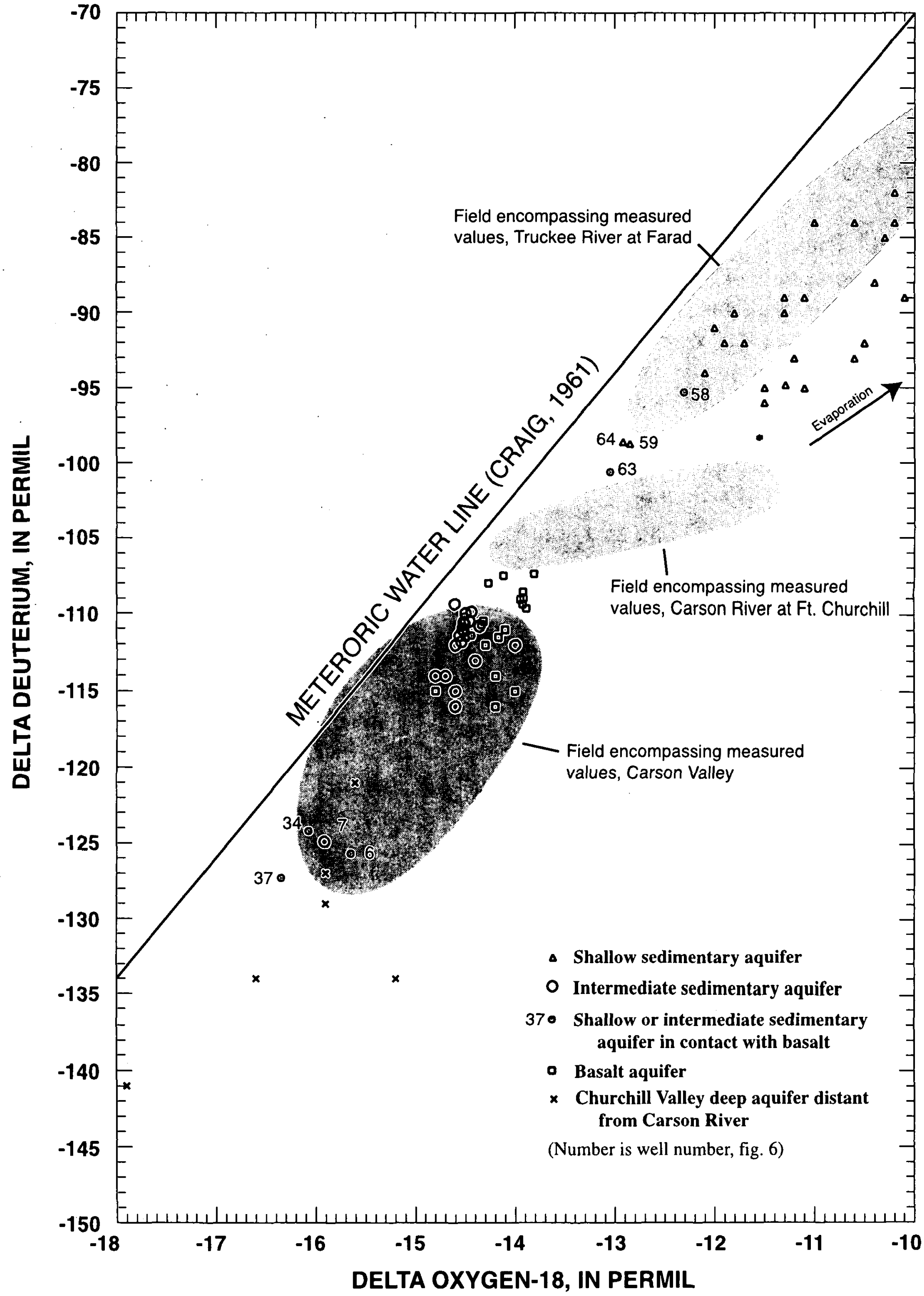


Figure 14. Relation between delta deuterium and delta oxygen-18.

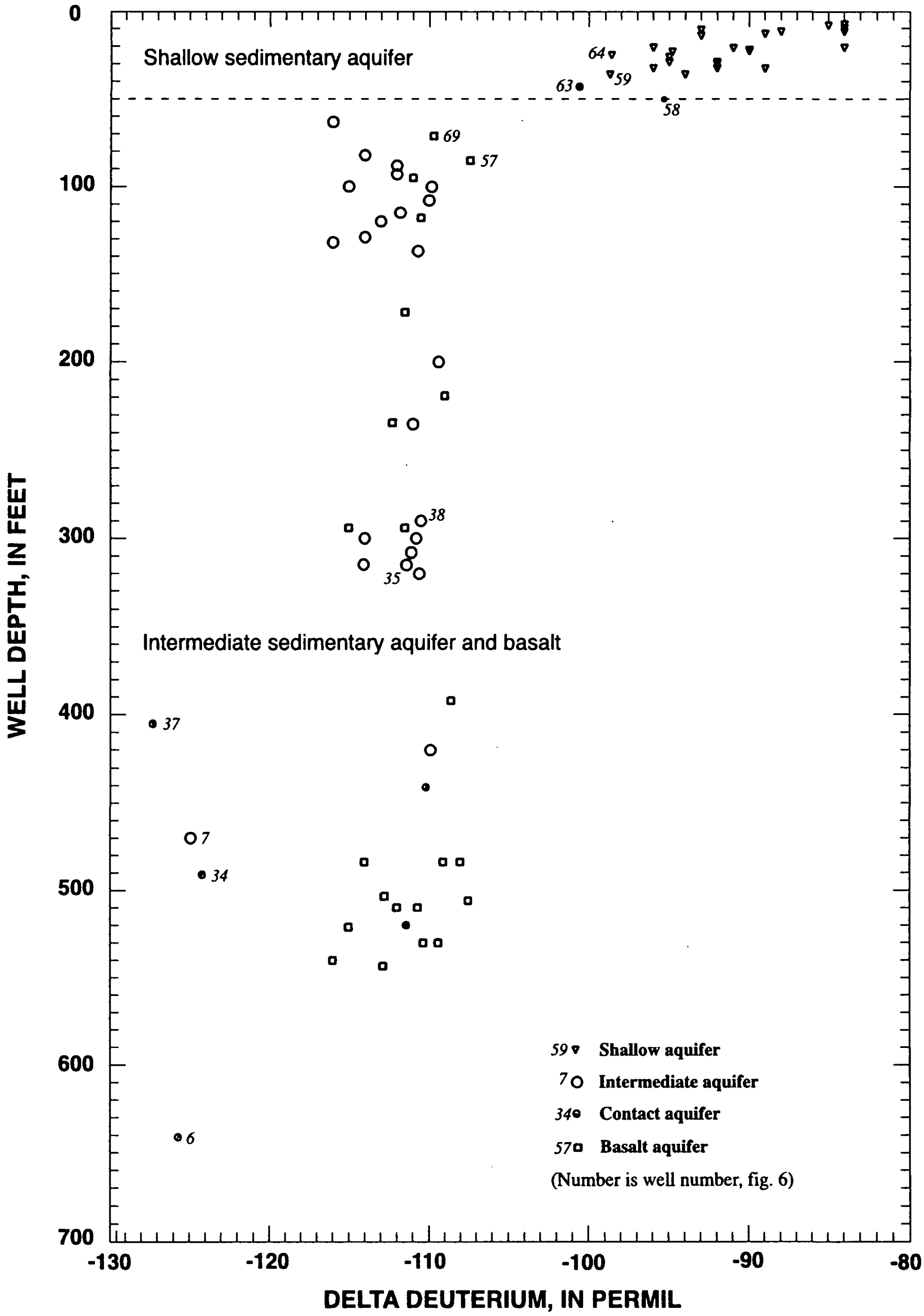


Figure 15. Relation between delta deuterium and well depth.

construction of Lahontan Reservoir. Agricultural irrigation can increase evaporation, which affects the isotope composition and chloride concentration of water. The generally low chloride content of ground water in Carson Valley suggests that evaporation has not greatly affected the ground water prior to recharge (fig. 16).

Most water currently in the intermediate sedimentary and basalt aquifers has a stable-isotope composition similar to the range found in deep aquifers in Carson Valley, a finding that is consistent with recharge from streamflow of the Carson River before construction of Lahontan Reservoir (figs. 14 and 16). Alternatively, mixing of present-day Carson River water with water having a lighter stable-isotope composition could produce a composition similar to that in the intermediate sedimentary and basalt aquifers (Welch and others, 1997, p. A31). However, the generally low tritium concentrations of water in the intermediate sedimentary aquifer near the center of the valley suggest that such mixing probably is not occurring.

The isotopically lightest water in the intermediate sedimentary aquifer is from four wells installed for this study near the southern edge of the basalt (wells 6, 7, 34, and 37; fig. 14). This water is distinctly lighter than that found at any other wells previously sampled in the intermediate sedimentary and basalt aquifers (figs. 14 and 16). Wells 6, 34, and 37 tap the intermediate sedimentary aquifer in contact with the basalt at depths of 600, 481, and 380 ft, respectively (app. 1). Well 7 taps the intermediate sedimentary aquifer at a depth of 460 ft. At the same sites but at shallower depths, wells 35 and 38 tap the intermediate sedimentary aquifer at maximum depths of 315 and 290 ft, respectively, and have a stable-isotope composition similar to that measured in other wells in the intermediate sedimentary aquifer (figs. 14 and 15; app. 4). Thus, the stable-isotope composition of water in the intermediate sedimentary aquifer changes at some depth greater than 300 ft along the southern edge of the basalt. Because water with this stable-isotope composition has been sampled at only four wells, the distribution of water of this composition in Lahontan Valley is unknown. The composition of this deep, isotopically lighter water is within the range of that found in Carson and Churchill Valleys (figs. 14 and 16).

Ground water in the adjacent Churchill Valley, sampled in locations distant from the Carson River that are unlikely to be affected by recharge from the river, is isotopically similar to that found below 300 ft near the southern edge of the basalt (fig. 14). Estimated carbon-14 ages for water from the same wells in Churchill Valley at which isotope samples were obtained are only slightly older than those reported for the shallower part of the intermediate aquifer in Lahontan Valley, ranging from maximum values of 2,900 to 11,000 years (Thomas and Lawrence, 1994, p. 45). Thomas and Lawrence (1994, p. 18 and 47) conclude that this ground water was recharged during a past cooler climate. Alternatively, the lighter composition could be a result of the rain shadow effect of the Sierra Nevada causing isotopically lighter local recharge from mountain ranges surrounding Churchill Valley (Ingraham and Taylor, 1991, p. 87). Local recharge from mountains surrounding Lahontan Valley also may be isotopically lighter. Thus, the two distinct stable-isotope compositions of water in the intermediate sedimentary aquifer may be the result of recharge of Carson River streamflow during two separate periods before construction of Lahontan Reservoir, or by recharge from the Carson River before construction of the reservoir and recharge from local precipitation in the surrounding mountains.

The areal distribution of dissolved chloride in the basalt and sedimentary aquifers provides evidence of recharge to the basalt aquifer from the intermediate sedimentary aquifer (fig. 17). Chloride concentrations in the basalt aquifer generally are lowest (less than 90 mg/L) in the southwestern part of the aquifer, increasing to more than 100 mg/L to the east and north. This suggests inflow of more dilute water from the intermediate sedimentary aquifer into the southwestern part of the basalt aquifer.

Figures 16 and 17 show that chloride concentrations in the basalt aquifer are higher than in water from most wells tapping the intermediate sedimentary aquifer. Water from well 9 on the southeastern side of the study area, and well 90, which probably is near the top of the basalt, is similar in chloride concentration to water from the basalt aquifer. Water from three wells (wells 7, 34, and 37; well locations, fig. 6; chloride concentrations, fig. 17) deeper than 300 ft along the southern edge of the basalt also has chloride concentrations similar to that of the basalt aquifer. Water from only one well (well 6) at a depth of 600 ft has chloride concentrations greater than that of the basalt aquifer. At the same site, well 7 at a depth of 470 ft has ground water with chloride concentrations of 79 mg/L (fig. 15, app. 4). This suggests that chloride concentrations in the intermediate sedimentary aquifer may increase to more than 110 mg/L at some depth greater than about 500 ft

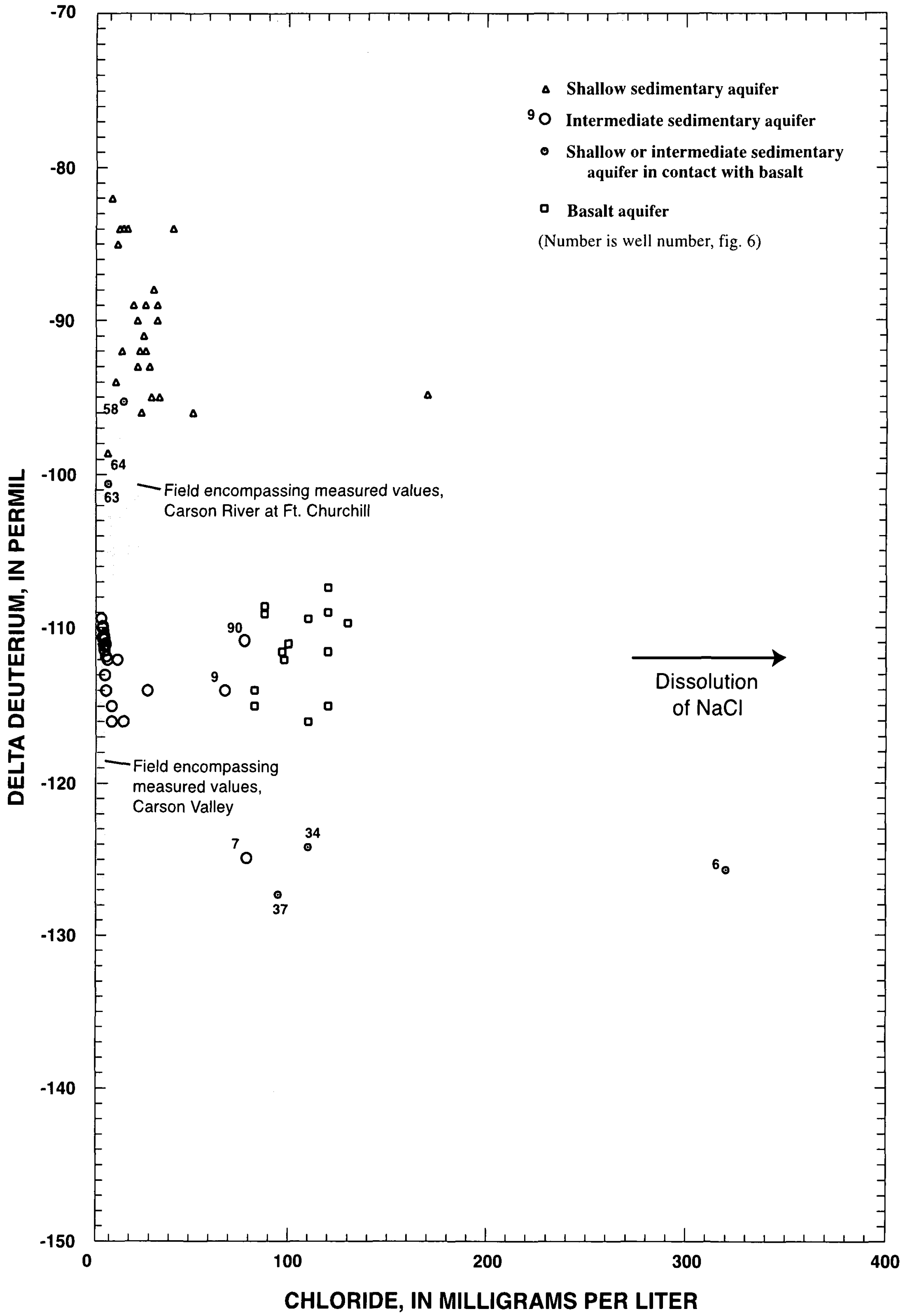


Figure 16. Relation between delta deuterium and chloride.

along the southern edge of the basalt. Data on chloride concentrations in water from wells tapping the intermediate sedimentary aquifer along the eastern edge of the basalt are lacking and the concentration of chloride in that part of the intermediate aquifer is unknown, but probably increases toward the northeast.

Therefore, if the upper part of the intermediate sedimentary aquifer near the southwestern part of the basalt supplies recharge to the basalt aquifer, one must account for a source of additional chloride. Potential sources of chloride include ground water with chloride concentrations greater than about 100 mg/L, or dissolution of aquifer materials.

Present-day concentrations of chloride in the shallow sedimentary aquifer generally are well below 100 mg/L (figs. 16 and 17) except in areas downgradient from the basalt aquifer where recharge to the basalt aquifer cannot take place. However, chloride concentrations in ground water of the shallow sedimentary aquifer before construction of Lahontan Reservoir appear to have been higher than those currently found as suggested by data collected in 1904 (Stabler, 1904, map 6024). The chloride may have entered the basalt aquifer from the shallow sedimentary aquifer near Rattlesnake Hill; Stabler's map shows chloride concentrations in that area ranging from 100 to 200 mg/L.

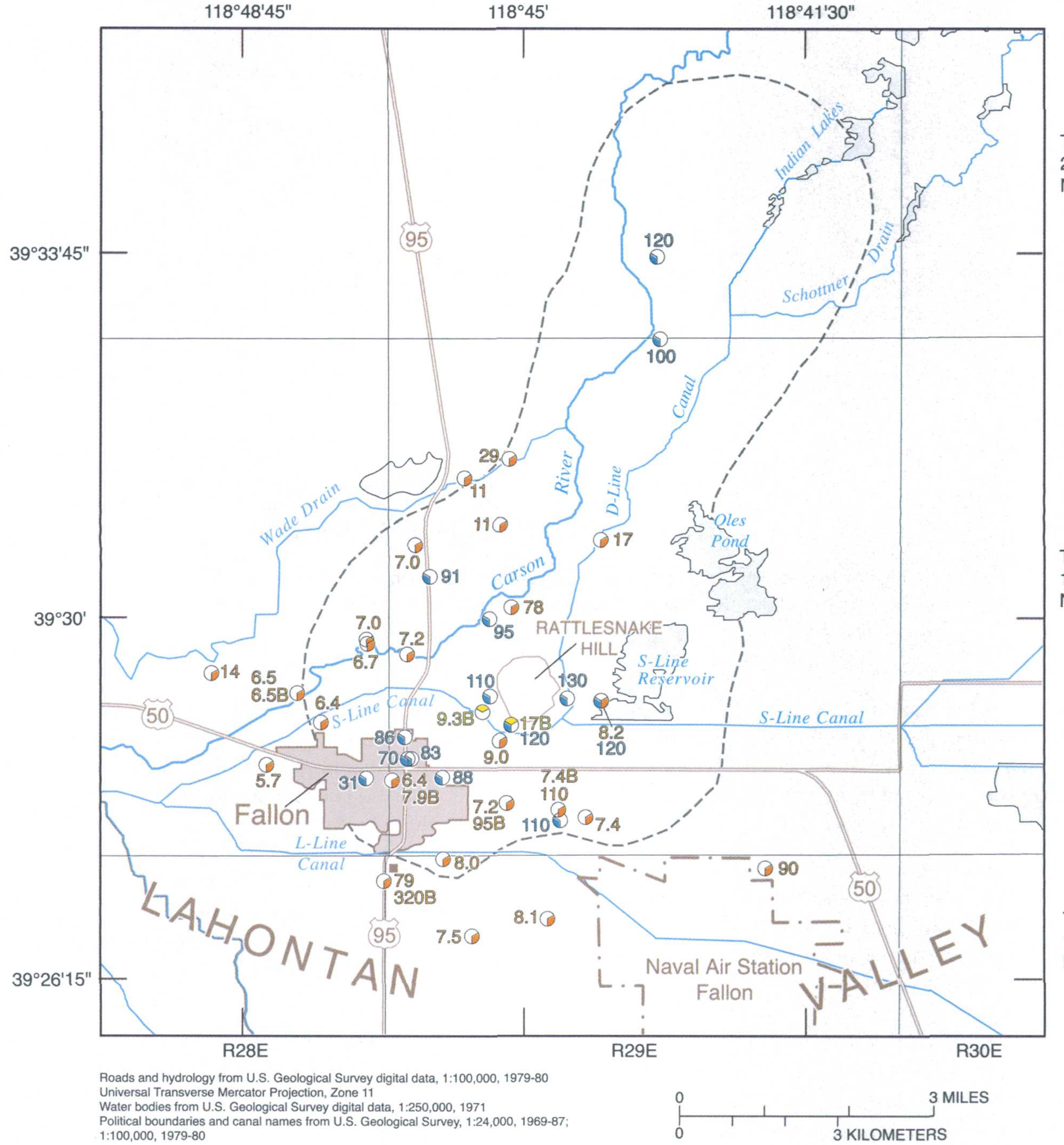
Other potential ground-water sources of chloride include: (1) the intermediate sedimentary aquifer along the southern edge of the basalt at depths greater than 300 to 500 ft, as described above, (2) the intermediate sedimentary aquifer along the eastern edge of the basalt where data from the intermediate sedimentary aquifer are lacking, (3) the intermediate or deep sedimentary aquifers adjacent to or underlying the basalt aquifer at depths greater than that sampled from existing wells, and (4) the basalt aquifer itself from depths greater than that sampled from existing wells. Recharge from these sources may be a slow, diffuse process where sediments adjacent to the basalt have a low hydraulic conductivity.

Potential sources of chloride from dissolution of aquifer materials include the basalt aquifer and the surrounding sedimentary aquifers. In the basalt aquifer, chloride could be released from fluid inclusions in plagioclase feldspar that makes up the basalt (Lico and Seiler, 1994, p. 48). Geochemical modeling by Lico and Seiler (1994, p. 48) indicates that reactions between water from the sedimentary aquifers and the basalt may dissolve plagioclase feldspar at a rate of 3–4 mmol/L. Roedder (1984, p. 473) reports that extrusive volcanic rocks such as the basalt have numerous fluid inclusions that may be high in salinity. In the sedimentary aquifers or in sediments interbedded within the basalt aquifer, dissolution of halite (NaCl) formed during low stands of Lake Lahontan may contribute to the chloride content of water in the basalt. However, halite deposits have not been reported in drillers' logs of existing wells.

The chemistry of water from wells near Rattlesnake Hill indicates recharge to the basalt aquifer from the shallow sedimentary aquifer. Near Rattlesnake Hill, the stable-isotope composition of water from four wells in the shallow sedimentary aquifer (wells 58, 59, 63, 64; fig. 6) ranges from the lightest shallow ground water sampled in the study area (well 58) to a composition similar to that found in the present-day Carson River above Lahontan Reservoir at Fort Churchill (well 63; figs. 14 and 15). These wells are near or in contact with the basalt aquifer and are located adjacent to the S-Line canal, the most likely source of recharge for these sites. The similarity in delta deuterium and chloride concentrations at two of these wells with that of the Carson River (figs. 14 and 16) is consistent with recent recharge from the S-Line canal.

Tritium concentrations in water from wells near Rattlesnake Hill confirm recharge to the basalt after above-ground nuclear testing in the 1950's. Tritium concentrations in water from wells 57, 58, 67, and 69 are 6.6, 16.2, 5.5, and 6.5 pCi/L, respectively (app. 4). Wells 57 and 69 tap the shallowest part of the basalt aquifer near Rattlesnake Hill and well 67 taps the basalt aquifer near S-Line Reservoir (fig. 6). Well 58, with the highest tritium concentrations, taps the shallow sedimentary aquifer in contact with the basalt near Rattlesnake Hill, and probably also yields water from the uppermost part of the basalt aquifer.

As shown by water chemistry and suggested by water level and lithologic data, the source of recent recharge to the basalt near Rattlesnake Hill is the shallow sedimentary aquifer, which, in turn, is recharged by seepage from surface-water bodies such as the S-Line Canal and Reservoir, and the Carson River. Seepage tests made by the Bureau of Reclamation (Darren Knuteson, written commun., 1990) indicate that the seepage rate for the 1.9-mi segment of the S-Line Canal adjacent to Rattlesnake Hill was 0.45 ft^3/s/mi at the end of a 5-day test. Assuming that the rate is applicable to the entire irrigation season and the canal is full from March through November, the annual volume of seepage may be about 500 acre-ft. Seepage tests on the S-Line Reservoir (Darren Knuteson, Bureau of Recla-



EXPLANATION

Well location and chloride concentration in milligrams per liter, 1998–99—The letter "B" indicates contact with basalt layer

- 9.3B Shallow aquifer
- 14 Intermediate aquifer
- 88 Basalt aquifer

– – – – – **Approximate extent of basalt at depth of 600 feet below land surface**—From Glancy (1986)

Figure 17. Concentration of dissolved chloride at selected wells. Well locations shown in figure 6.

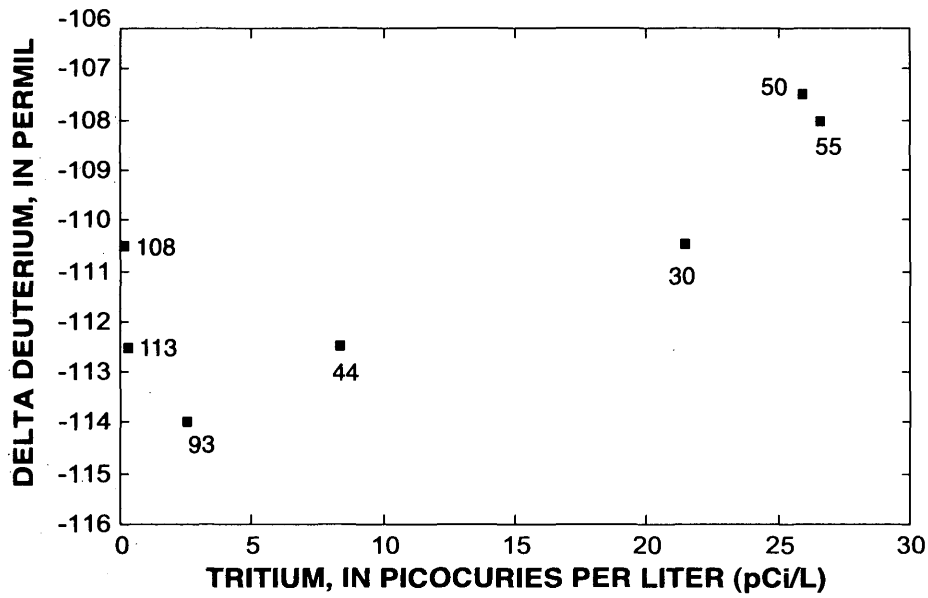


Figure 18. Relation between delta deuterium and tritium in water from wells 30, 44, 50, 55, and 93 (fig. 6) tapping the basalt aquifer sampled in 1977 and 1978 (Glancy, 1986, p. 34).

mation, written commun., 1990) indicate an annual seepage loss of 1,460 acre-ft. The portion of seepage from these sources that recharges the basalt aquifer is not known, but could be best estimated using a numerical ground-water flow model.

Tritium concentrations reported for water from the basalt aquifer in areas distant from Rattlesnake Hill range from 0.6 to 26 pCi/L (Lico and Seiler, 1994, p. 20). The lowest concentrations were obtained from wells 108 and 113 near the northeast end of the basalt, while wells 28–30, 49, 50, 55, and 70 had the highest concentrations—all greater than 14 pCi/L. The higher concentrations suggest a recent source of recharge. Well 70, drilled in 1980, encountered basalt at a depth of 39 ft near Rattlesnake Hill. Thus, the high concentrations of tritium probably are truly representative of recent recharge. However, wells on the northwest end of the basalt where the vertical gradient is downward produce water that is the heaviest, in terms of deuterium composition, found in the basalt aquifer. Figure 18 shows that water from wells with the greatest concentration of tritium also have a correspondingly heavier deuterium composition, more similar to that of the shallow sedimentary aquifer. The data shown in figure 18 represent analyses of water from the basalt reported by Glancy (1986, p. 34) and sampled in 1977 and 1978. In the late 1970's, tritium concentrations were greater than during sampling for this study, providing more contrast between recently recharged water and older water. The data suggest that in wells on the northwest side of the basalt water may be moving downward from shallower depths along or through the casing. These wells were drilled in the 1940's and 1960's and their well casings could be deteriorating, allowing water to enter the casing from shallow depths. Thus, the presence or lack of tritium in water from the basalt aquifer in areas distant from Rattlesnake Hill cannot be confirmed from available data.

The major-ion and stable-isotope composition of ground water in the basalt aquifer is unlike any single source of water sampled in the study area (Glancy, 1986, p. 17; Lico and Seiler, 1994, p. 25, 26, 32 and 45). Table 2 compares the water chemistry of the sedimentary aquifers to water from the basalt aquifer. The comparison shows that ground water in the basalt aquifer is not a result of recharge from any single source without mixing with other sources or dissolution of aquifer materials along ground-water flow paths.

Possible scenarios for recharge to the basalt aquifer, consistent with observed changes in chloride concentration over time as discussed in the previous section and the geochemical data presented in this section, include a component of recharge from the shallow sedimentary aquifer near Rattlesnake Hill mixed with:

Table 2. Water chemistry of sedimentary aquifers compared to water from the basalt aquifer

Aquifer	Geographic area	Wells (fig. 6)	Comparison with basalt aquifer
Shallow	Throughout study area	10–22, 24, 29, 48, 52, 64, 73, 85	Cation composition is different [1] and stable isotopes are heavier [2]
Shallow in contact with basalt	Near Rattlesnake Hill	58, 63	
Intermediate	Throughout study area	All intermediate aquifer wells [3] except wells 6, 7, 34, and 37	Stable isotopes are similar [4]; chloride concentrations are lower
Intermediate	Near southwest edge of basalt	7	Stable isotopes are lighter [5]; chloride concentration is lower
Intermediate in contact with basalt	Area overlying southwest part of basalt	6, 34, and 37	Stable isotopes are lighter; chloride concentrations are similar or greater

[1] Calcium and magnesium concentrations range from 18 to 190 mg/L and from 4.4 to 22 mg/L, respectively, in the shallow aquifer. Concentrations of both cations at wells 58 and 63 are greater than 4 mg/L. In comparison, the calcium and magnesium concentrations in the basalt aquifer are less than or equal to 4 mg/L, except at wells 44 and 57. Glancy (1986) suggests that water pumped at well 44 is affected by leakage along the casing annulus; well 57 is affected by recharge from the shallow aquifer near Rattlesnake Hill.

[2] Deuterium content is less negative than -100 permil.

[3] Wells 2, 4, 9, 26, 31, 35, 38, 43, 47, 53, 61, 66, 68, 74, 75, 90, 97, 99, 101, and 105.

[4] Deuterium content is between -105 and -117 permil.

[5] Deuterium content is more negative than -124 permil.

(1) water from the intermediate sedimentary aquifer on the southwest, west, and northwestern sides of the basalt along with addition of chloride; (2) water from the intermediate sedimentary aquifer along the eastern side of the basalt or at depths greater than 300 to 500 ft along the southern side of the basalt; or (3) water from the upward flow of deeper, unsampled ground water with high chloride concentrations from either the intermediate or deep sedimentary aquifers or the basalt aquifer. Rather than any one of the scenarios being the sole recharge process, recharge to the basalt aquifer could occur as some combination of the three scenarios.

All three recharge scenarios require mixing of water, in some cases from sources relatively distant from each other. Water from different sources could be mixed when ground-water flow is induced toward pumping municipal wells. During pumping, flow induced toward the well and mixed within the well bore may be derived from points both near and far from the pumping well. Flow entering the upper part of the well bore may be derived from points close to the well, while flow entering the lower part of the well bore may be derived from points thousands of feet from the well (Halford, 1998, p. 63). The relative amounts of flow to the well bore depend on the lateral ground-water velocity near the well and the recharge rate in the area contributing flow to the well.

Water-Quality Trends Over Time

The concentrations of dissolved chloride and arsenic in samples taken from selected wells during the past two decades were evaluated to determine if statistically significant changes over time may be detected. Consistent changes in water quality over time may be caused by increased pumping from the basalt aquifer. These changes and differences in the geochemical composition of ground water in the basalt and sedimentary aquifers have been evaluated to determine potential sources of recharge to the basalt.

Local, long-term trends in chloride concentrations have been reported for the basalt aquifer from about 1962 to 1992 (Maurer and others, 1996). Although arsenic concentrations may have changed during this same period, the lack of consistent sample processing and analytical methods could mask small changes. Selected wells tapping the basalt aquifer were sampled between 1997 and 1999 using consistent field and laboratory methods. The purpose of the sampling

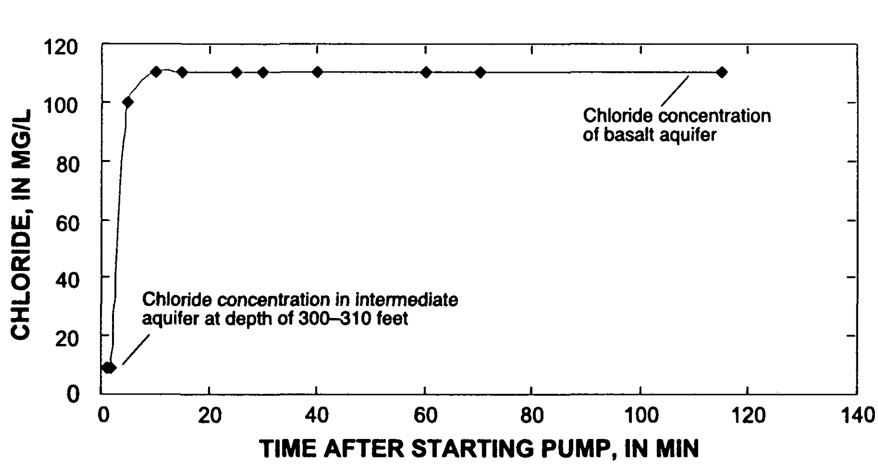


Figure 19. Variation in dissolved chloride concentration shortly after beginning of pumping at well 30 (fig. 6).

was to detect changes in water quality in the basalt aquifer, with an emphasis on arsenic and chloride, at a quarterly time scale. Annual data collection for a few wells included analysis of major and trace inorganic constituents.

Given the relatively large differences in water levels between aquifers, a concern during sampling for this study was the potential for vertical leakage along domestic and municipal well casings that could influence interpretation of water-quality data. To test for leakage, well 30 (fig. 6), which had been idle for about one day, was sampled initially at start-up and at close time intervals after start-up. Well 30 was installed in 1962, with steel casing extending about 8 ft into the basalt aquifer and an open hole extending an additional 23 ft into the basalt. A 10-ft grout seal was placed around the casing near the top of the basalt. Upon sampling in 1998, chloride concentrations were quite low initially, but within 10 min reached a constant value similar to that previously sampled from the well (fig. 19). The volume of water in the well casing is about 5,050 gal, which could be removed in less than 5 min with the pumping rate of 1,160 gal/min. Accordingly, the low chloride water probably was present in the casing before the pump was turned on and was removed within 10 min of start-up. A likely source of the water is the overlying intermediate sedimentary aquifer, which has a chloride concentration of about 7 mg/L in the vicinity of well 30 (wells 31, 35, and 38; well locations, fig. 6; chloride concentrations, fig. 17; app. 4). At a depth of about 200 ft above the top of the basalt, the intermediate aquifer at well 35 has a hydraulic head about 4 ft higher than the basalt aquifer at well 30. Low chloride concentrations and the higher hydraulic head in the intermediate sedimentary aquifer both are consistent with flow from the intermediate aquifer into well 30, possibly through a leaking grout seal or openings in the well casing caused by corrosion.

Despite the potential for inflow of water with a low chloride concentration, the chloride concentrations in water from Navy wells 1–3 (wells 28–30), along with Fallon wells 1–4 (wells 45, 49, 50, and 55), have increased over time (figs. 20*A* and 20*B*). In contrast, chloride concentrations in water from an industrial supply well north of Fallon (well 93) appear to have decreased over time (fig. 20*C*). Analyses of samples collected prior to 1978 from non-USGS sources show a large range, possibly caused by sample collection prior to proper purging of the well bore. Based on analyses both from USGS and other sources, chloride concentrations in the three closely spaced Navy wells near the southern edge of the basalt aquifer appear to have increased from 1962 to 1999. Based solely on USGS data, the chloride concentrations appear to have increased from less than 100 mg/L in 1978 to about 110 mg/L in 1999 (fig. 20). Although it is not known how long the wells may have been pumping prior to sample collection for non-USGS data, and different sampling and laboratory methods may introduce a bias, a linear correlation was calculated for a combined dataset of USGS and non-USGS chloride analyses in order to evaluate a possible long-term trend. The coefficient of determination and slope (table 2) are similar to the results using USGS data alone. Although the coefficients of determination are

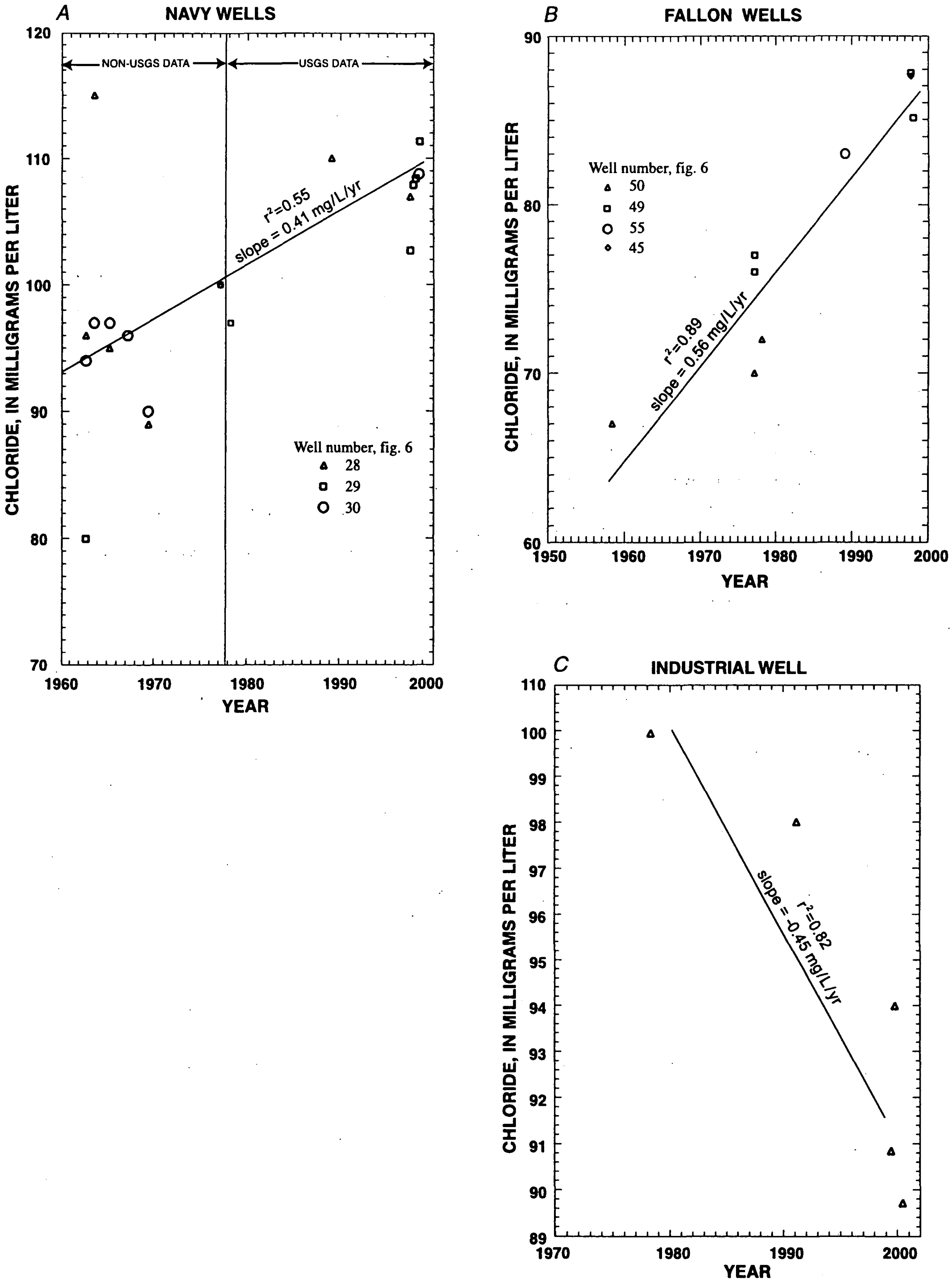


Figure 20. Relation between chloride concentrations and time at (*A*) Navy wells (wells 28–30, fig. 6); (*B*) Fallon wells (wells 45, 49, 50, and 55); and (*C*) an industrial well (well 93).

Table 3. Summary statistics for linear correlations between chloride and arsenic with time. Only data collected by the USGS were included in the correlations except as noted. The units for the slope are milligrams per year for chloride and micrograms per year for arsenic.

Constituent	Well or group of wells	Well numbers (fig. 6)	Number of analyses	Coefficient of determination (r^2)	Slope	[1]Pr>ITI
Chloride	Navy wells	28–30	9	0.51	0.46	0.0001
			[2]40	.55	.43	.0001
	Fallon wells	45, 49, 50, 55	14	.89	.56	.0001
	Industrial well	93	5	[3].82	-.45	.034
Arsenic	Navy wells	28–30	9	.60	1.30	.014
	Fallon wells	45, 49, 50, 55	13	.05	(4)	.45
	Industrial well	93	5	[3].07	(4)	.68

[1] Pr>ITI is the t-test for the slope, with the probability of a higher absolute t. Values less than 0.05 and 0.01 are considered significant and highly significant, respectively.

[2] USGS and non-USGS data included in correlation.

[3] Correlation excluded one sample with atypically low chloride and arsenic concentrations of 39 mg/L and 53 mg/L, respectively. These low concentrations may be due to sampling soon after the pump was turned on, although this cannot be determined from field notes taken at the time of sampling. For the arsenic correlation, the sample collected in 1978 also was excluded because of an unacceptably high leverage value of 0.84.

[4] The slope is not listed when it is not significant (the Pr>ITI is greater than 0.05).

fairly low, 0.51 and 0.55, these data suggest that the chloride concentrations at the Navy wells have increased at a rate of about 0.4 mg/L/yr for nearly the past four decades, a total increase of about 16 mg/L. These slopes are highly significant for both regressions, as indicated by results of a t-test (table 3), showing that chloride concentrations have increased over time.

As shown in figure 17 and discussed previously, the intermediate sedimentary aquifer overlying the basalt near the Navy wells is not a likely source of higher chloride concentrations. The intermediate sedimentary aquifer adjacent to or underlying the basalt at depths greater than 500 ft along the southern edge of the basalt may be the source of higher chloride.

Chloride concentrations at Fallon municipal wells (wells 45, 49, 50, and 55) have increased from about 67 mg/L in 1958 (Glancy, 1986) to about 86 mg/L in the late 1990s (fig. 20*B*). The coefficient of determination of 0.89 suggests that the trend is meaningful and the t-test suggests that the slope is highly significant (table 3) and that chloride concentrations have increased over time. As is the case for the Navy wells, water in the overlying intermediate sedimentary aquifer near the Fallon wells has lower chloride concentrations than water in the basalt aquifer. For example, wells 43, 53, and 61 (fig. 17) have chloride concentrations of less than 10 mg/L (app. 4; Whitney, 1994). Accordingly, the overlying intermediate sedimentary aquifer near Fallon is not a likely source of the higher-chloride water. Ground water in the intermediate sedimentary aquifer, in contact with the basalt at depths greater than 300 ft about 1 mi south and southeast of the Fallon wells, has chloride concentrations greater than 90 mg/L (wells 6, 34, and 37; fig. 15). Ground water from this area could be the source of the higher chloride sampled in the Fallon wells.

In contrast to the Navy and Fallon wells, chloride concentrations in water from an industrial well tapping the basalt aquifer (well 93) have decreased from 100 mg/L in 1978 to about 90 mg/L in 1998 (fig. 20*C*). The high coefficient of determination, 0.82, suggests that the slope of -0.45 mg/L/yr trend is meaningful and the t-test suggests that the slope is significant, showing that chloride concentrations have decreased over time. Potential sources of lower-chloride ground water include the shallow and intermediate sedimentary aquifers in contact with the basalt to the south (wells 42, 63, and 65; fig. 15) and the intermediate sedimentary aquifer (wells 75, 82, 83, 95, 97, 99, and 101) in the vicinity of well 93, which all have

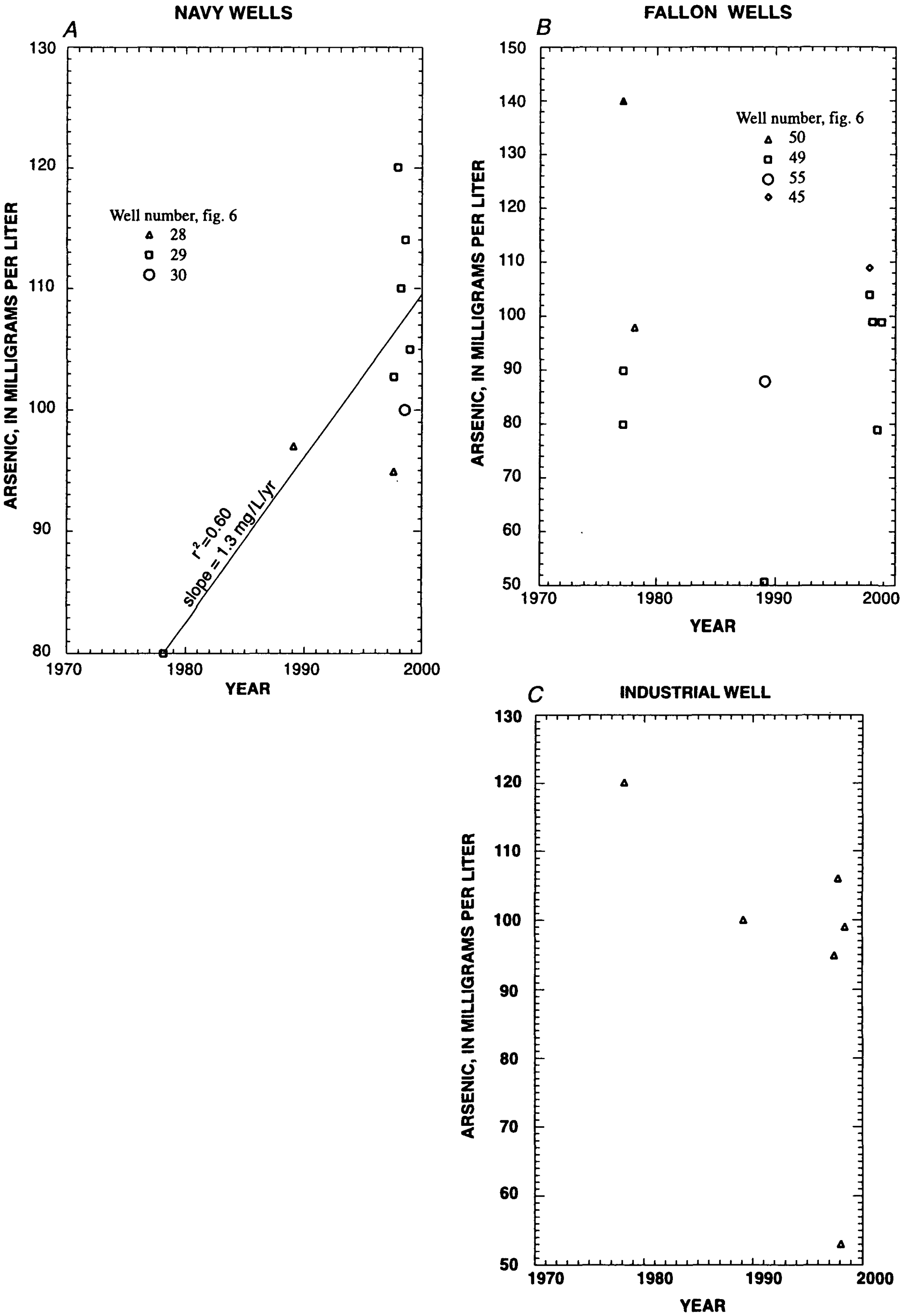


Figure 21. Relation between arsenic concentrations and time at (*A*) Navy wells (wells 28–30, fig. 6); (*B*) Fallon wells (wells 45, 49, 50, and 55); and (*C*) an industrial well (well 93).

chloride concentrations of less than 20 mg/L. In this case, a leaking well casing may contribute to decreasing chloride concentrations over time.

Changes in arsenic concentration over time do not show consistent trends (figs. 21*A*–*C*). A significant slope, based on results of a t-test, suggests that arsenic concentrations in water from the Navy wells may have increased from 1978 to 1999; however, the single analysis for 1978 has a high influence on the correlation as shown by a Cook's D value of 0.83 (fig. 21*A*; table 3). (See Helsel and Hirsch, 1992, p. 247–249 for a discussion of Cook's D.) Although arsenic concentrations may have increased from 1978 to 1999, the available data are insufficient to clearly support this conclusion. The arsenic data for the Fallon wells have a low coefficient of determination of 0.05 (fig. 21*B*; table 3). Arsenic data for well 93 also have a low coefficient of determination of 0.07 when the single value for 1978 is excluded (fig. 21*C*; table 3). This value is excluded because of high influence on the regression as suggested by a Cook's D value of 0.84 and low values for both arsenic and chloride. The low values may be due to sampling prior to proper purging of the well. Thus, available data do not clearly support trends in arsenic concentration for water from the basalt aquifer over a period of about two decades.

Changes in chloride concentrations for nearly the past four decades coincide with declining water levels in the basalt aquifer. As water levels in the basalt decline, additional ground-water flow is induced from the surrounding sedimentary aquifers into the basalt. Near Fallon and along the southern edge of the basalt, chloride concentrations are increasing, showing inflow from more saline sources. The source could be the intermediate sedimentary aquifer adjacent to or underlying the southern edge of the basalt at depths greater than 300 to 500 ft below land surface. Alternatively, the source of higher chloride could be from the basalt itself from depths greater than those penetrated by existing wells. North of Fallon, chloride concentrations are decreasing, showing inflow from less-saline sources. The source probably is water from the intermediate sedimentary aquifer overlying the northwestern part of the basalt. These sources of induced recharge are consistent with those determined from the analysis of stable-isotope and water chemistry discussed in the previous section.

AQUIFER VULNERABILITY

The large difference in water levels between the basalt aquifer and the overlying shallow and intermediate sedimentary aquifers creates a potential for contamination of the basalt aquifer. As shown by analysis of data on chloride and tritium, it is possible that wells drilled more than 30 years ago into the basalt have corroding well casings or leaking well seals. Such wells potentially could transmit contamination from the overlying sedimentary aquifers into the basalt. More recently drilled wells that are not sealed above the basalt, or that are screened or gravel-packed across contact of the basalt, provide avenues for contamination of the basalt aquifer from shallower depths.

In addition, if the sedimentary aquifers become contaminated by faulty septic systems or by leaking underground storage tanks, the basalt aquifer is vulnerable to contamination through sand layers in the shallow sedimentary aquifer and upper parts of the intermediate sedimentary aquifer that intersect the basalt. Areas in which this is likely are near and to the southwest, west, and northwest of Rattlesnake Hill.

SUGGESTIONS FOR FUTURE STUDY

One of the objectives of this study was to determine information needed from future studies of the basalt aquifer. The distribution of water quality within the basalt itself currently is not known. Data from wells with depths of greater than 1,000 ft extending through the basalt to underlying sedimentary aquifers would greatly increase our understanding of the hydrogeochemical setting of the basalt aquifer. Such wells would allow us to determine the amount of potable water in the aquifer and the extent of recent recharge to the basalt as well as the variability of lithology within the basalt and potential sources of chloride to the basalt. Continued monitoring of such wells also would increase our understanding of mixing processes within the basalt.

The present rate of pumping from the basalt aquifer (about 3,000 acre-ft/yr in the late 1990's) is causing continued water-level declines in the basalt and appears to be causing changes in the quality of water pumped from the basalt. One possible way to reduce these effects would be to limit or reduce the rate of pumping from the basalt aquifer. This option would require development of an additional source of municipal supply. Alternatively, during wet years when surface water released from Lahontan Reservoir is plentiful, properly treated surface water could be injected into the basalt aquifer. Prior to such injection, a study of potential geochemical reactions between the injected water, ground water in the basalt, and the basalt itself would show the potential for undesirable changes in water quality.

Additional drilling of test holes near the northeastern extent of the basalt would help refine our understanding of its lateral and vertical extent, and additional test holes between Fallon and Rattlesnake Hill would provide data on the lateral extent and location of sand layers that may transmit recharge to the basalt.

SUMMARY AND CONCLUSIONS

The sole source of water for municipal supply to the city of Fallon, Naval Air Station Fallon, and the Fallon Paiute–Shoshone Tribe is a basalt aquifer, informally called the Fallon basalt aquifer for purposes of this report. Since the early 1970's, increased pumpage from the Fallon basalt aquifer has caused water-level declines and water-quality changes, prompting concern about the continued viability of the aquifer as a source of municipal supply. In April, 1997 the U.S. Geological Survey began a study of the Fallon basalt aquifer in cooperation with the Nevada Division of Water Resources (partners with Naval Air Station Fallon), and the Bureau of Reclamation to compile and analyze existing data, obtain additional data, describe the hydrogeologic and geochemical framework of the basalt aquifer, evaluate potential sources of recharge to the aquifer, and provide a basis for directing future studies.

The Fallon basalt aquifer is exposed at Rattlesnake Hill, an eroded volcanic cone about 1 mi in diameter and 200 ft high near the center of Lahontan Valley. The basalt was formed by repeated volcanic flows 1 to 2.5 Ma ago, issuing radially to form an asymmetrical mushroom shape and formation about 10 mi long and 4 mi wide. During the Pleistocene epoch in Lahontan Valley, lakes as deep as 500 ft formed, expanded, and dried up several times under the influence of changing glacial and interglacial climates. Sediment deposition during this time buried most of the basalt under a complex mixture of deep-lake clay, deltaic sand and silt, sand and gravel beach deposits, relict river channel deposits, and sand-dune complexes.

The lateral and vertical extent of the basalt has been delimited by combining descriptions from available drillers' logs, electrical-resistivity data collected in the 1970's, and seismic-reflection data collected in April 2000. These data provide reasonable confirmation of the lateral extent of the basalt except near its northeastern boundary where the basalt may be present as individual flows interfingered with sedimentary deposits. The lower boundary of the basalt is poorly known over much of its extent because few wells completely penetrate the basalt.

Where it is exposed at Rattlesnake Hill, the basalt varies from dense lava flows to highly porous zones of loosely consolidated scoriaceous cinders. Descriptions from drillers' logs also suggest highly variable lithology away from Rattlesnake Hill, although few wells penetrate the basalt for more than 70 ft. Based on descriptions from drillers' logs, the basalt varies from black to red or pink in color, and from massive and hard to porous and fractured, with interbedded layers of sand, gravel, or cinders. In some logs, near its periphery the basalt appears as relatively thin layers suggesting that it might not be a solid, contiguous mass over its entire extent. Some wells have encountered voids as large as 5 ft that probably are lava tubes. The lithology of the basalt is unknown beneath about 600 ft below land surface. Minimum estimates of hydraulic conductivity of the basalt in wells drilled for this study range from 100 to 1,200 ft/d.

The sedimentary aquifers surrounding the basalt have been divided into a shallow water table aquifer extending from 5 to 10 ft below land surface to a depth of 50 ft; an intermediate aquifer extending from 50 ft to 500–1,000 ft; and a deep aquifer extending to several thousand feet in depth. Lithology of the sedimentary aquifers also is highly variable, changing abruptly from sand to clay over thicknesses of less than one foot to tens of feet. As described in drillers' logs, the thickest and most numerous sand layers in the intermediate aquifer are found in wells southwest, west, and northwest of Rattlesnake Hill. On the southern edge of the basalt, sand layers are relatively thin and interbedded with thick layers of clay. On the southeast and eastern side of the basalt, clay layers comprise almost the entire thickness penetrated by wells, probably restricting recharge to the basalt from those directions. Borehole resistivity logs suggest a decrease in sand content and an increase in clay content in sediments of the intermediate aquifer south and east of Rattlesnake Hill. In most wells adjacent to Rattlesnake Hill, sand and gravel is found overlying the basalt. Sand layers in the intermediate aquifer have hydraulic conductivities ranging from 3 to 60 ft/d. The hydraulic conductivity of clay layers in the intermediate aquifer could be less than these values by three to four orders of magnitude or more.

In August and September 1998 when seasonal water levels are lowest, water-level altitudes in the basalt aquifer were 8 to 12 ft lower than in summer months from 1978 to 1980. In March 1999 when seasonal water levels were highest, water-level altitudes in the aquifer were 6 to 7 ft lower than in winter months from 1978 to 1980. Water-level altitudes in some supply wells were 2–4 ft lower than in those not being heavily pumped, suggesting that cones of depression are forming around the wells.

Near the southwestern part of the basalt, water levels in the shallow sedimentary aquifer are as much as 40 ft higher than those in the basalt aquifer, and, in the upper part of the intermediate sedimentary aquifer, as much as 20–30 ft higher. Water levels in the intermediate sedimentary aquifer become similar with increasing depth to those in the basalt aquifer, suggesting that the potential for recharge to the basalt aquifer is greatest in the upper part of the intermediate sedimentary aquifer.

The greatest potential for recharge to the basalt aquifer exists where laterally extensive layers of permeable sand in the shallow sedimentary aquifer and upper parts of the intermediate sedimentary aquifer may intersect the basalt. Although the exact location and distribution of such sand beds are unknown, in the shallow sedimentary aquifer, recharge is possible over a relatively small area surrounding Rattlesnake Hill. In the intermediate sedimentary aquifer, recharge is possible over a much larger area southwest, west, and northwest of Rattlesnake Hill where sand layers are thickest and most numerous.

Water in the basalt aquifer is dominated by sodium and bicarbonate. Sodium and chloride concentrations generally are higher in the basalt aquifer compared to water in the intermediate sedimentary aquifer and the shallow and intermediate sedimentary aquifers in contact with the basalt. In contrast, magnesium and calcium concentrations are distinctly lower in the basalt aquifer compared to water in the shallow sedimentary aquifer and somewhat lower than water in the intermediate sedimentary aquifer and the shallow and intermediate aquifers in contact with the basalt. Because few wells penetrate the basalt more than about 70 ft, the quality of water and the volume of potable water in the basalt aquifer are unknown at depths beneath about 600 ft below land surface.

Changing conditions over time could affect the stable-isotope composition and chloride concentration of recharge to the basalt aquifer. Ground water in the study area has three distinct stable-isotope compositions. Water from the shallow sedimentary aquifer has delta deuterium values less negative than about -100 permil; water from the intermediate sedimentary and basalt aquifers ranges from -105 to -117 permil; and water from depths greater than 300 ft in the intermediate sedimentary aquifer along the southern edge of the basalt is more negative than -124 permil.

The stable-isotope composition of ground water in the shallow sedimentary aquifer may be derived by mixing water from the Carson and Truckee Rivers and subsequent evaporation from Lahontan Reservoir or during irrigation, and is consistent with recharge by water from the reservoir. From the water table to a depth of 50 ft, ground water becomes isotopically lighter at greater depths, suggesting that ground water in the shallow sedimentary aquifer is a mixture of recent recharge of water from the reservoir with older, isotopically lighter ground water. Near the center of Lahontan Valley, water from depths greater than about 50 ft, the upper boundary of the intermediate aquifer, is distinctly lighter (more negative) than water from wells in the shallow sedimentary aquifer. This suggests that near the center of Lahontan Valley, recharge of water under the current hydrologic regime is restricted to the upper 50 ft of the aquifer system. Water from the intermediate sedimentary aquifer at depths greater than 300 ft along the southern edge of the basalt is distinctly lighter than that above 300 ft. The two distinct stable-isotope compositions for water in the intermediate sedimentary aquifer suggest that the aquifer was recharged from streamflow of the Carson River before construction of Lahontan Reservoir, and/or from local recharge from surrounding mountains.

The major-ion composition, stable-isotope composition, and chloride concentrations of ground water in the basalt aquifer are unlike those in any single source of water sampled in the study area. This shows that ground water in the basalt aquifer is not a result of recharge from any single source without mixing with other sources or dissolution of salts or aquifer materials along ground-water flow paths.

The stable-isotope compositions of water from the intermediate sedimentary and basalt aquifers are similar, suggesting that the aquifers have a similar source of recharge. However, if the intermediate sedimentary aquifer supplies recharge to the basalt, a source of additional chloride is required. Chloride concentrations in the southwest part of the basalt aquifer are lower than elsewhere in the aquifer, suggesting inflow of more dilute water from the intermediate aquifer. The stable-isotope and tritium concentrations in water from shallow wells near Rattlesnake Hill show recent recharge from nearby surface-water bodies to the shallow sedimentary aquifer and recharge from the shallow sedimentary aquifer to the basalt aquifer.

Possible scenarios for recharge to the basalt consistent with the variations in water chemistry include a component of recharge from the shallow sedimentary aquifer near Rattlesnake Hill mixed with: (1) water from the intermediate sedimentary aquifer on the southwest, west, and northwestern sides of the basalt along with addition of chloride either from other groundwater sources with high concentrations of chloride, or dissolution of feldspar within the basalt aquifer or halite within sedimentary aquifers; (2) water from the intermediate sedimentary aquifer along the eastern side of the basalt or at depths greater than 300 to 500 ft along the southern side of the basalt; or (3) water from the upward flow of deeper, unsampled ground water with a higher chloride concentration from either the intermediate, deep, or basalt aquifers. Rather than any one of the scenarios being the sole recharge process, recharge to the basalt aquifer could occur as some combination of the three scenarios. Water from sources both near and thousands of feet from pumping wells may become mixed within the well bores of municipal supply wells as flow is induced toward the pumping wells.

Changes in chloride concentrations immediately after pumping at one well suggests that wells 30–40 years old may have leaking well casings or annular flow from shallow depths to the basalt aquifer. Increases in chloride over the past two decades were detected at the Navy and Fallon municipal wells. The source of increasing chloride could be the intermediate or deep sedimentary aquifers adjacent to or underlying the southern edge of the basalt at depths greater than 300 to 500 ft below land surface. Alternatively, the source of higher chloride could be from the basalt aquifer itself from depths greater than those penetrated by existing wells. Decreasing chloride concentrations at an industrial well north of Fallon suggest inflow from less saline sources, probably from the intermediate sedimentary aquifer overlying the northwestern part of the basalt.

Wells that are open to both the sedimentary and basalt aquifers, and sand layers in the shallow sedimentary and upper parts of the intermediate sedimentary aquifer that intersect the basalt also are potential avenues of contamination to the basalt aquifer.

Wells completed at depths up to 1,000 ft extending through the basalt to underlying sedimentary aquifers would provide much needed information. Such wells would allow determination of the amount of potable water in the basalt aquifer, the variability of lithology within the basalt, and potential sources of chloride to the basalt. Continued monitoring of such wells also would increase our understanding of mixing processes within the basalt aquifer.

Water-level declines and changes in water quality in the basalt aquifer may be reduced by limiting the rate of pumping, or by injecting treated surface water into the basalt. Assuming the continued growth of Fallon, limiting the rate of pumping would necessitate development of an additional source of municipal supply. For injection of surface water, a study would be needed of potential geochemical reactions between the injected water, ground water in the basalt, and the basalt itself.

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APPENDICES

Appendix 1. Location of wells, well construction data, and data on basalt aquifer

Standard Site Identification: The standard site identification is based on the grid system of latitude and longitude. The number consists of 15 digits. The first six denote the degrees, minutes, and seconds of latitude; the next seven denote the degrees, minutes, and seconds of longitude; and the last two digits (assigned sequentially) identify the sites within a 1-second grid. For example, site 392642118470901 is at 39°26′42″N latitude and 118°47′09″W longitude, and is the first site recorded in that 1-second grid. The assigned number is retained as a permanent identifier even if a more precise latitude and longitude are determined.

Local Site Identification: A local site identification is used in Nevada to identify a site by hydrographic area (Rush, 1968) and by the official rectangular subdivision of the public lands referenced to the Mount Diablo base line and meridian. Each site designation consists of four units: The first unit is the hydrographic area number. The second unit is the township, preceded by an N or S to indicate location north or south of the base line. The third unit is the range, preceded by an E to indicate location east of the meridian. The fourth unit consists of the section number and letters designating the quarter section, quarter-quarter section, and so on (A, B, C, and D indicate the northeast, northwest, southwest, and southeast quarters, respectively), followed by a number indicating the sequence in which the site was recorded. For example, site 101 N18 E28 12ABAC1 is in the Carson Desert (Hydrographic Area 101). It is the first site recorded in the northeast quarter of the northwest quarter of the northeast quarter of the southeast quarter of section 12, Township 18 north, Range 28 east, Mount Diablo base line and meridian.

Well[1]	USGS site designations		Site use[2]	Aquifer[3]	Latitude	Longitude	Altitude of land surface (feet)	Depth of hole (feet)	Depth of well (feet)	Depth to top of open interval (feet)	Depth to bottom of open interval (feet)	Top of basalt or basalt detritus		Extent of basalt penetration	
	Standard ID	Local ID										Depth (feet)[4]	Altitude (feet)[4]	Depth (feet)[4]	Altitude of basalt penetration (feet)[4]
1	392642118470901	101 N18 E28 12ABAC1	U	S	39°26′42″	118°47′09″	3,960	15	15	12	15				
2	392648118454001	101 N18 E29 05CCCB1	D	I	39°26′48″	118°45′40″	3,953	120	120	115	120				
3	392649118432601	101 N18 E29 03CCCB1	C	I	39°26′50″	118°43′25″	3,940	602	—	—	—				
4	392659118444001	101 N18 E29 05DDAB1	D	I	39°26′59″	118°44′40″	3,936	129	129	14	27				
										109	129				
5	392705118443001	101 N18 E29 04CBBD1	U	S	39°27′05″	118°44′30″	3,945	—	19	—	—				
*6	392722118464701	101 N18 E29 06BCBB1	U	I–C	39°27′22″	118°46′47″	3,959.5	650	641	600	620	*600	*3,359.5	*10	*3,349.5
*7	392722118464702	101 N18 E29 06BCBB2	U	I	39°27′22″	118°46′47″	3,959.5	650	470	460	470				
8	392723118441501	101 N18 E29 04BDBA1	U	B	39°27′25″	118°44′15″	3,946.7	779	—	706	776	**706	3,240.7	**3	3,237.7
9	392730118414801	10 1N18 E29 02BADA1	D	I	39°27′30″	118°41′48″	3,930	83	82	79	82				
10	392730118463801	101 N18 E29 06BBCA1	U	S	39°27′30″	118°46′38″	3,960	59	20.9	16	20.9				
11	392730118463802	101 N18 E29 06BBCA2	U	S	39°27′30″	118°46′38″	3,960	37	32.7	30	32.7				
12	392730118463803	101 N18 E29 06BBCA3	U	S	39°27′30″	118°46′38″	3,960	15	11.9	9	11.9				
13	392730118463804	101 N18 E29 06BBCA4	U	S	39°27′30″	118°46′38″	3,960	8	7.6	5	7.6				
14	392731118463801	101 N18 E29 06BBCA5	U	S	39°27′31″	118°46′38″	3,960	10	9.5	7	9.5				
15	392731118463802	101 N18 E29 06BBCA6	U	S	39°27′31″	118°46′38″	3,960	22	22	20	22				
16	392731118463803	101 N18 E29 06BBCA7	U	S	39°27′31″	118°46′38″	3,960	35	32.9	30	32.9				
17	392733118463801	101 N18 E29 06BBBD5	U	S	39°27′33″	118°46′38″	3,960	15	10.9	8	10.9				
18	392733118463802	101 N18 E29 06BBBD6	U	S	39°27′33″	118°46′38″	3,960	24	21	18	21				
19	392733118463803	101 N18 E29 06BBBD7	U	S	39°27′33″	118°46′38″	3,960	30	29	26	29				
20	392735118463802	101 N18 E29 06BBBD2	U	S	39°27′35″	118°46′38″	3,960	30	8.4	6	8.4				
21	392735118463803	101 N18 E29 06BBBD3	U	S	39°27′35″	118°46′38″	3,960	30	22.9	20	22.9				
22	392735118463804	101 N18 E29 06BBBD4	U	S	39°27′35″	118°46′38″	3,960	40	36	31	36				
23	392735118463801	101 N18 E29 06BBBD1	U	I	39°27′35″	118°46′38″	3,960	66	62	55	62				
24	392735118484501	101 N18 E28 02BABB1	U	S	39°27′35″	118°48′45″	3,970	27	12	22	27				
25	392736118443801	101 N19 E29 33CBBB1	C	B	39°27′35″	118°44′40″	3,950	626	—	—	—	*586	*3,364	*7	*3,357
												593	3,357	19	3,338
26	392736118460401	101 N18 E29 06ABAB1	D	I	39°27′35″	118°46′05″	3,959	235	235	228	235				

Appendix 1. Location of wells, well construction data, and data on basalt aquifer—Continued

Well[1]	USGS site designations: Standard ID	USGS site designations: Local ID	Site use[2]	Aquifer[3]	Latitude	Longitude	Altitude of land surface (feet)	Depth of hole (feet)	Depth of well (feet)	Depth to top of open interval (feet)	Depth to bottom of open interval (feet)	Top of basalt or basalt detritus: Depth (feet)[4]	Top of basalt or basalt detritus: Altitude (feet)[4]	Extent of basalt penetration: Depth (feet)[4]	Extent of basalt penetration: Altitude of basalt penetration (feet)[4]
27	392759118411601	101 N19 E29 35DAA 1	U	S	39°28′00″	118°41′15″	3,935.59	10	10	8	10				
28	392800118443201	101 N19 E29 33CBBC1	S	B	39°28′00″	118°44′30″	3,950.7	540	540	518	535	496	3,454.7	44	3,410.7
29	392801118443201	101 N19 E29 33CBBB1	S	B	39°28′00″	118°44′30″	3,950.7	530	530	500	530	500	3,450.7	30	3,420.7
30	392802118443201	101 N19 E29 33CBBB2	S	B	39°28′00″	118°44′30″	3,950.7	531	531	508	531	500	3,450.7	31	3,419.7
31	392803118442101	101 N19 E29 33CAAB1	D	I	39°28′01″	118°44′10″	3,950	137	137	122	137				
32	392802118411701	101 N19 E29 35DAAB1	D	I	39°28′02″	118°41′17″	3,934	280	280	268	278				
33	392803118465301	101 N19 E28 36DAAA1	D	B	39°28′05″	118°46′55″	3,960	558	558	—	—	510	3,450	48	3,402
*34	392804118443101	100 N19 E29 33CBBB1	U	I-C	39°28′04″	118°44′31″	3,952.3	491	491	481	491	*480	*3,472.3	*11	*3,461.3
												491	3,461.3		
*35	392804118443102	101 N19 E29 33CBBB2	U	I	39°28′04″	118°44′31″	3,952.3	491	315	300	310				
36	392810118415301	101 N19 E29 35BDAC1	D	I	39°28′10″	118°41′53″	3,937	250	250	232	235				
*37	392810118451401	101 N19 E29 32BDAC1	U	I-C	39°28′10″	118°45′14″	3,954.8	424	405	380	400	419	3,535.8	5	3,530.8
*38	392810118451402	101N19 E29 32BDAC2	U	I	39°28′10″	118°45′14″	3,954.8	424	290	270	285				
39	392817118495501	101 N19 E28 34BCAA1	U	S	39°28′15″	118°49′55″	3,980	29	13	8	13				
40	392816118453901	101 N19 E29 32BCBB1	U	S	39°28′15″	118°45′40″	3,955	—	21	—	—				
41	392824118463201	101 N19 E29 31BABC1	C	B	39°28′25″	118°46′30″	3,960	444	444	220	300	418	3,542	26	3516
										395	420				
*42	392824118464201	101 N19 E29 31BBBD1	U	I-C	39°28′24″	118°46′42″	3,958.4	441	441	430	440	*420	*3,538.4	*19	*3,519.4
												439	3,519.4	2	3,517.4
*43	392824118464202	101 N19 E29 31BBBD2	U	I	39°28′24″	118°46′42″	3,958.4	441	320	305	315				
44	392825118470501	101N19 E28 36AABC1	U	B	39°28′25″	118°47′05″	3,962.23	813	540	505	540	520	3,442.23	69	3,373.23
												*589	*3,373.23	*25	*3,348.23
45	392826118460501	101N19 E29 31ABAC1	S	B	39°28′26″	118°46′05″	3,960.4	392	392	350	390	335	3,625.4	57	3,568.4
46	392831118443201	101N19 E29 28CCCC1	U	S	39°28′30″	118°44′30″	3,950.25	26	26	19	26				
47	392838118482301	101N19 E28 26DCDB1	D	I	39°28′33″	118°48′23″	3,970	200	200	195	200				
48	392835118490501	101N19 E28 27DDDA1	D	S	39°28′35″	118°49′05″	3,976	26	26	—	—				
49	392837118462901	101N19 E29 30CDBC2	S	B	39°28′35″	118°46′30″	3,958.63	521	521	458	521	455	3,503.63	66	3,437.63
50	392837118463201	101N19 E29 30CDBC1	S	B	39°28′35″	118°46′30″	3,959.44	506	506	496	506	448	3,511.44	58	3,453.44
51	392840118464001	101N19 E29 30CCAB1	C	B	39°28′40″	118°46′40″	3,960	510	—	—	—	462	3,498	48	3,450
52	392842118425401	101N19 E29 27CDAA1	U	S	39°28′42″	11842′54″	3,936	15	12.3	10	12.3				
53	392847118451801	101N19 E29 29CACA1	D	I	39°28′45″	118°45′20″	3,960	93	93	83	93				
54	392848118451801	101N19 E29	D	I	39°28′48″	118°45′18″		100	100	80	100				
55	392850118463401	101N19 E29 30CBAD1	S	B	39°28′50″	118°46′35″	3,959.55	484	484	404	484	423	3,536.55	61	3,475.55
56	392850118463502	101N19 E29 30CBAD3	U	S	39°28′50″	118°46′35″	3,959.9	12	12	10	12				
*57	392851118451301	101N19 E29 29CAAC1	U	B	39°28′51″	118°45′13″	3,960.8	103	85	80	85	*41	*3,918.8	*7	*3,912.8
												48	3,912.8	55	3,857.8
*58	392851118451302	101N19 E29 29CAAC2	U	[5]S-C, B	39°28′51″	118°45′13″	3,960.8	103	50	45	50	48	3,912.8	2	3,910.8
*59	392851118451303	101N19 E29 29CAAC3	U	S	39°28′51″	118°45′13″	3,960.8	103	36	21	26				

Appendix 1. Location of wells, well construction data, and data on basalt aquifer—Continued

Well[1]	USGS site designations: Standard ID	USGS site designations: Local ID	Site use[2]	Aquifer[3]	Latitude	Longitude	Altitude of land surface (feet)	Depth of hole (feet)	Depth of well (feet)	Depth to top of open interval (feet)	Depth to bottom of open interval (feet)	Top of basalt or basalt detritus: Depth (feet)[4]	Top of basalt or basalt detritus: Altitude (feet)[4]	Extent of basalt penetration: Depth (feet)[4]	Extent of basalt penetration: Altitude of basalt penetration (feet)[4]
60	392857118444001	101N19 E29 29ADDC1	C	I-C	39°28′57″	118°44′40″	3,963	84	79	69	79	79	3,884	5	3,879
61	392859118474001	101N19 E28 25BCDD1	D	I	39°29′00″	118°47′40″	3,968	120	108	—	—				
62	392902118442601	101N19 E29 28BCCA1	C	I	39°29′00″	118°44′25″	3,960	102	100	90	98				
*63	392902118453401	101N19 E29 29BCDB1	U	S-C	39°29′02″	118°45′34″	3,965.1	49	43	39	44	35	3,930.1	14	3,916.1
*64	392902118453402	101N19 E29 29BCDB2	U	S	39°29′20″	118°45′34″	3,965.1	49	25	20	25				
*65	392911118475901	101N19 E28 26AADD1	U	I-C	39°29′11″	118°47′59″	3,968.2	528	520	500	515	490	3,478.2	38	3,440.2
*66	392911118475902	101N19 E28 26AADD2	U	I	39°29′11″	118°47′59″	3,968.2	528	420	400	415				
*67	392913118440001	101N19 E29 28ABCB1	U	B	39°29′13″	118°44′00″	3,958.4	219	219	214	219	210	3,748.4	9	3,739.4
*68	392913118440002	101N19 E29 28ABCB2	U	I	39°29′13″	118°44′00″	3,958.4	219	115	100	110				
*69	392914118442701	101N19 E29 28BBCA1	U	B	39°29′14″	118°44′27″	3,963.6	71	71	61	71	*29	*3,934.6	*3	*3,931.6
												32	3,931.6	39	3,892.6
70	392907118453701	101N19 E29 29BACB1	S	B	39°29′15″	118°45′27″	3,974.2	95	95	39	95	30	3,944.2	65	3,879.2
71	392915118452501	101N19 E29	S	B	39°29′15″	118°45′25″	3,974	130	130	60	130	*33	*3,941	*23	*3,918
												56	3,918	74	3,844
72	392924118420901	101N19 E29 23CCDC1	U	S	39°29′25″	118°42′10″	3,937	—	19	—	—				
73	392925118482001	101N19 E28 23DCDB1	U	S	39°29′25″	118°48′20″	3,975	—	30	—	—				
74	392929118490701	101N19 E28 22DDAD1	D	I	39°29′30″	118°49′05″	3,980	—	88	80	87				
75	392944118463202	101N19 E29 19CACB2	S	I	39°29′40″	118°46′30″	3,960	332	308	200	220	332	3,628		
76	392942118452701	101N19 E29 20CBAD1	D	B	39°29′42″	118°45′27″	3,960	155	155	147	155	133	3,827	22	3,805
77	392942118453901	101N19 E29 20CBCB1	D	B	39°29′42″	118°45′39″	3,962	186	186	184	186	*158	*3,804	*15	*3,789
												173	3,789	12	3,777
78	392942118491001	101N19 E28 22DAAC1	D	B	39°29′40″	118°49′10″	3,975	1,076	—	—	—	**1,050	**2,925	**26	**2,899
79	392943118454501	101N19 E29 19DAAD1	D	B	39°29′43″	118°45′45″	3962.65	185	185	178	183	176	3,786.65	9	3,777.65
80	392945118452701	101N19 E29 20CBAA1	D	B	39°29′45″	118°45′27″	3,957	150	150	145	150	135	3,822	15	3,807
81	392946118452101	101N19 E29 20CABB1	D	I	39°29′45″	118°45′20″	3,962	100	100	90	100				
82	392947118470301	101N19 E28 24DABB1	D	I	39°29′45″	118°47′05″	3,960.74	95	95	81	95				
83	392950118470401	101N19 E28 24ADCC1	S	I	39°29′50″	118°47′05″	3,962.33	312	312	284	312				
84	392951118471301	101N19 E28 24ACDC1	C	I	39°29′50″	118°47′15″	3,960	387	340	270	340				
*85	393021118452901	101N19 E29 20BBDD2	U	S	39°30′03″	118°45′29″	3,951.5	23	23	13	23				
86	392958118433501	101N19 E29 20BBDD1	D	B	39°30′02″	118°45′28″	3,962.04	172	172	165	171	159	3,803.04	13	3,790.04
87	393002118452501	101N19 E29 20BDBB1	D	B	39°30′02″	118°45′25″	3,960	187	187	185	187	167	3,793	14	3,779
												182	3,778	4	3,774
88	393003118402001	101N19 E29 24ABDD1	U	S	39°30′03″	118°40′20″	3,920	14	12	11	12				
89	393009118453501	101N19 E29 21AAAC1	D	B	39°30′09″	118°45′35″	3,940	450	450	277	307	403	3,537	7	3,530
										410	450	435	3,505	15	3,490
90	393008118452401	101N19 E29 20BAAD1	D	I	39°30′10″	118°45′09″	3,959	300	300	295	300				
91	393026118461401	101N19 E29 18DCBB1	U	S	39°30′26″	118°46′14″	3,957.69	10	10	7	10				

Appendix 1. Location of wells, well construction data, and data on basalt aquifer—Continued

Well[1]	USGS site designations		Site use[2]	Aquifer[3]	Latitude	Longitude	Altitude of land surface (feet)	Depth of hole (feet)	Depth of well (feet)	Depth to top of open interval (feet)	Depth to bottom of open interval (feet)	Top of basalt or basalt detritus		Extent of basalt penetration	
	Standard ID	Local ID										Depth (feet)[4]	Altitude (feet)[4]	Depth (feet)[4]	Altitude of basalt penetration (feet)[4]
92	393026118461403	101N19 E29 18DCBB3	U	I	39°30′26″	118°46′14″	3,957.59	62	62	60	62				
93	393027118461501	101N19 E29 18DCBB1	S	B	39°30′25″	118°46′15″	3,956.59	510	510	344	510	452	3,504.59	58	3,446.59
94	393049118413501	101N19 E29 14ACB 2	U	S	39°30′45″	118°41′35″	3,931.36	12	12	10	12				
95	393048118462501	101N19 E29 18CAC 1	D	I	39°30′32″	118°46′28″	3,954	281	281	274	279				
96	393050118385801	101N19 E30 17BCCC1	C	I	39°30′50″	118°39′00″	3,915	550	—	—	—				
97	393051118435801	101N19 E29 16ACBB1	D	I	39°30′51″	118°43′58″	3,953	132	132	117	127				
98	393057118432501	101N19 E29 16 2	?	I	39°31′	118°43′	3,955	—	132	—	—				
99	393101118451801	101N19 E29 17BABD1	D	I	39°31′00″	118°45′20″	3,950	100	100	86	96				
100	393115118415001	101N19 E29 11CDCC1	C	I	39°31′15″	118°41′50″	3,927	545	—	—	—				
101	393129118454601	101N19 E29 07DAAD1	D	I	39°31′30″	118°45′45″	3,960	63	63	50	60				
102	393134118452601	101N19 E29 08BCDD1	C	B	39°31′35″	118°45′25″	3,945	580	—	—	—	580	3,365		
103	393141118403701	101N19 E29 12 1	C	I	39°31′40″	118°40′35″	—	550	—	—	—				
104	393141118450901	101N19 E29 08BDAD1	D	B	39°31′41″	118°45′09″	3,944	568	568	548	568	480	3,464	3	3,467
												552	3,392	5	3,387
105	393930118445201	101N19 E29 08DABC1	D	I	39°31′40″	118°45′10″	3,938	300	300	85	135				
										230	240				
										290	300				
106	393155118483002	101N19 E28 11ABB 2	U	S	39°31′55″	118°48′30″	3,982.11	35	35	31	32				
107	393252118415901	101N19 E29 02BABB1	U	S	39°32′50″	118°42′00″	3,927.38	28	21	16	21				
108	393252118431401	101N20 E29 34CCDC1	I	B	39°32′50″	118°43′15″	3,629.72	300	118	—	—	300	3,629.72		
109	393304118421801	101N20 E29 34 1	?	S	39°33′	118°42′	3,925	33	33	—	—				
110	393305118431401	101N20 E29 34CBDC1	D	B	39°33′05″	118°43′15″	3,930	205	—	—	—	175	3,755	30	3,725
111	393327118423001	101N20 E29 34ADBD1	D	B	39°33′27″	118°42′30″	3,923	256	256	236	256	236	3,687	20	3,667
112	393341118431601	101N20 E29 34BBAC1	D	B	39°33′40″	118°43′15″	3,923.64	343	294	220	240	240	3,683.64	70	3,610.64
113	393342118431601	101N20 E29 34BBAC1	I	B	39°33′42″	118°43′16″	3,924	295	295	280	295	262	3,662	33	3,629
114	393502118432201	101N20 E29 22CBBA1	C	B	39°35′02″	118°43′22″	3,908	—	—	—	—	300	3,608		
115	393458118431101	101N20 E29 22CBAC1	U	S	39°35′06″	118°43′22″	3,914.02	14	12	9	12				
116	393506118473001	101N20 E28 24BDD 1	U	I	39°35′05″	118°47′30″	3,962.5	131	131	129	131				

[1] Asterisk (*) indicates that well was installed for this study.

[2] U, unused observation well; D, domestic well; S, public or industrial supply well; I, irrigation well; C, capped or destroyed well.

[3] S, shallow aquifer; S-C, shallow aquifer in contact with basalt; I, intermediate aquifer; I-C, intermediate aquifer in contact with basalt; B, basalt aquifer.

[4] * indicates basalt detritus; ** indicates that basalt probably is not part of Fallon basalt.

[5] Well is open to both the shallow sedimentary aquifer in contact with the basalt and to the basalt aquifer.

Appendix 2. Water-level measurements for selected wells

USGS site identification: The standard site identification is based on the grid system of latitude and longitude. The number consists of 15 digits. The first six denote the degrees, minutes, and seconds of latitude; the next seven denote the degrees, minutes, and seconds of longitude; and the last two digits (assigned sequentially) identify the sites within a 1-second grid. For example, site 392642118470901 is at 39°26′42″N latitude and 118°47′09″W longitude, and is the first site recorded in that 1-second grid. The assigned number is retained as a permanent identifier even if a more precise latitude and longitude are determined.

Well number (fig. 6)	USGS site identification		Water level									
	Standard ID	Local ID	Date	Feet	Date	Feet	Date	Feet	Date	Feet	Date	Feet
1	392642118470901	101 N18 E28 12ABAC1	01-14-1997	8.22	05-11-1997	7.63	09-16-1997	7.2	03-20-1998	8.8	12-01-1998	7.9
			01-27-1997	8.27	06-03-1997	7.08	10-01-1997	7.5	05-07-1998	7.5	01-06-1999	8.5
			02-24-1997	8.29	06-18-1997	.22	10-15-1997	7.8	06-18-1998	7.1	02-11-1999	8.7
			03-07-1997	8.32	07-11-1997	8.41	10-29-1997	7.4	07-13-1998	7.0	03-16-1999	8.5
			03-25-1997	8.35	07-24-1997	7.38	11-19-1997	7.8	09-02-1998	7.0	06-15-1999	7.1
			04-08-1997	7.93	08-14-1997	7.1	01-22-1998	8.3	10-08-1998	7.1		
			04-21-1997	8.02	08-29-1997	7.1	02-13-1998	8.4	11-09-1998	7.8		
5	392705118443001	101 N18 E29 04CBBD1	01-29-1997	5.52	07-29-1997	7.74	03-16-1999	2.4	06-17-1999	2.5		
			05-09-1997	4.36	11-06-1997	2.0	04-19-1999	2.7				
6	392722118464701	101 N18 E29 06BCBB1	03-03-1998	43.3	05-08-1998	40.7	11-10-1998	42.2	09-02-1998	46.8	04-19-1999	43.8
			03-12-1998	43.2	06-18-1998	40.9	12-01-1998	41.9	10-06-1998	45.9	06-15-1999	45.2
			05-08-1998	43.9	07-15-1998	41.5	01-07-1999	41.4	11-10-1998	44.9	03-03-1998	40.8
			06-18-1998	44.1	08-06-1998	42.1	03-16-1999	40.9	12-01-1998	44.4	03-12-1998	40.7
			07-15-1998	45.5	09-02-1998	42.7	04-19-1999	40.9	01-07-1999	43.9		
			08-06-1998	46.3	10-06-1998	42.7	06-15-1999	41.6	03-16-1999	43.5		
7	392722118464702	101 N18 E29 06BCBB2	03-03-1998	40.8	06-18-1998	40.9	09-02-1998	42.7	12-01-1998	41.9	04-19-1999	40.9
			03-12-1998	40.7	07-15-1998	41.5	10-06-1998	42.7	01-07-1999	41.4	06-15-1999	41.6
			05-08-1998	40.7	08-06-1998	42.1	11-10-1998	42.2	03-16-1999	40.9		
8	392723118441501	101 N18 E29 04BDBA1	06-10-1997	31.35	09-10-1997	32.9	01-09-1998	31.3	07-15-1998	31.5	01-07-1999	31.5
			07-08-1997	31.7	09-25-1997	32.7	01-28-1998	31.0	08-06-1998	32.2	03-16-1999	30.9
			07-16-1997	31.9	10-08-1997	32.7	03-10-1998	31.0	09-02-1998	32.8	04-19-1999	30.9
			07-29-1997	32.02	10-30-1997	32.5	03-31-1998	30.8	10-06-1998	33.07	06-15-1999	31.6
			08-12-1997	32.3	11-20-1997	32.2	05-08-1998	30.7	11-10-1998	32.4		
			08-26-1997	32.5	12-11-1997	31.84	06-18-1998	30.9	12-02-1998	32.0		
26	392736118460401	101N18 E29 06ABAB1	09-10-1997	27.2	12-11-1997	26.29	03-31-1998	27.1	08-06-1998	29.2	01-07-1999	27.0
			09-25-1997	27.7	01-09-1998	26.7	05-08-1998	—	09-02-1998	29.6	03-16-1999	26.8
			10-30-1997	—	01-28-1998	27.2	06-18-1998	26.7	11-10-1998	28.6	04-19-1999	27.6
			11-20-1997	26.5	03-10-1998	27.2	07-15-1998	27.5	12-02-1998	27.8	06-15-1999	29.9
27	392759118411601	101 N19 E29 35DAA1	01-28-1997	6.48	11-04-1997	6.8	07-09-1998	6.5	03-16-1999	7.0		
			04-22-1997	6.32	02-11-1998	6.7	09-21-1998	5.9	06-16-1999	5.6		
			07-28-1997	6.03	05-11-1998	6.4	01-26-1999	6.6				
28	392800118443201	101 N19 E29 33CBBC1	06-11-1997	38.0	08-26-1997	39.9	03-31-1998	36.7	09-02-1998	40.5	04-19-1999	37.3
			07-07-1997	38.9	09-10-1997	39.8	05-08-1998	37.3	10-06-1998	39.43	06-15-1999	38.8
			07-16-1997	39.14	10-08-1997	39.3	06-18-1998	37.5	12-02-1998	37.6		
			07-29-1997	39.42	10-30-1997	38.6	07-15-1998	39.2	01-07-1999	37.1		
			08-21-1997	39.95	11-20-1997	36.9	08-06-1998	40.0	03-16-1999	36.9		

Appendix 2. Water-level measurements for selected wells—Continued

Well number (fig. 6)	USGS site identification		Water level									
	Standard ID	Local ID	Date	Feet	Date	Feet	Date	Feet	Date	Feet	Date	Feet
31	392803118442101	101N19 E29 33CAAB1	07-02-1991	10	10-08-1997	11.7	01-28-1998	11.2	08-06-1998	12.8	01-07-1999	11.2
			08-12-1997	12.2	10-30-1997	11.6	03-10-1998	11.3	09-02-1998	12.9	03-16-1999	11.7
			08-26-1997	12.4	11-20-1997	11.5	03-31-1998	11.4	10-06-1998	11.70	06-15-1999	12.4
			09-10-1997	12.3	12-11-1997	11.0	05-08-1998	11.5	11-10-1998	11.2		
			09-25-1997	12.7	01-09-1998	11.3	06-18-1998	11.9	12-02-1998	11.2		
34	392804118443101	100 N19 E29 33CBBB1	08-11-1998	40	10-06-1998	39.71	12-02-1998	38.0	03-16-1999	37.2	06-15-1999	39.1
			08-19-1998	40.42	11-10-1998	38.6	01-07-1999	37.5	04-19-1999	37.6		
35	392804118443102	101 N19 E29 33CBBB2	08-11-1998	37	10-06-1998	36.52	12-02-1998	35.7	03-16-1999	34.8	06-15-1999	35.9
			08-19-1998	36.98	11-10-1998	36.1	01-07-1999	35.2	04-19-1999	35.0		
37	392810118451401	101 N19 E29 32BDAC1	03-12-1998	39.0	05-08-1998	39.9	08-06-1998	42.7	11-10-1998	41.0	03-16-1999	39.6
			03-31-1998	39.3	06-18-1998	40.3	09-02-1998	43.2	12-01-1998	40.4	04-19-1999	40.0
			04-08-1998	39.2	07-15-1998	41.9	10-06-1998	42.1	01-07-1999	40.0	06-15-1999	41.5
38	392810118451402	101N19 E29 32BDAC2	03-12-1998	33.0	05-08-1998	34.0	08-06-1998	36.3	11-10-1998	35.6	03-16-1999	34.3
			03-31-1998	33.8	06-18-1998	34.5	09-02-1998	36.8	12-01-1998	35.1	04-19-1999	34.5
			04-08-1998	33.7	07-15-1998	35.6	10-06-1998	36.5	01-07-1999	34.6	06-15-1999	35.6
42	392824118464201	101N19 E29 31BBBD1	08-13-1998	48	10-06-1998	47.4	01-07-1999	45.4	04-19-1999	45.3		
			08-19-1998	47.96	12-02-1998	45.9	03-16-1999	45.0	06-17-1999	45.6		
43	392824118464202	101N19 E29 31BBBD2	08-13-1998	38	10-06-1998	37.6	01-07-1999	34.8	04-19-1999	35.1		
			08-19-1998	38.48	12-02-1998	35.7	03-16-1999	34.5	06-17-1999	35.8		
44	392825118470501	101N19 E28 36AABC1	03-26-1997	46.12	09-19-1997	49.41	03-04-1998	46.35	08-18-1998	50.03	01-26-1999	46.80
			05-14-1997	47.36	10-29-1997	48.46	04-15-1998	46.34	09-30-1998	49.48		
			06-12-1997	47.85	12-09-1997	47.35	06-02-1998	47.14	11-10-1998	48.05		
			07-30-1997	49.19	01-13-1998	46.75	07-07-1998	48.60	12-15-1998	47.34		
45	392826118460501	101N19 E29 31ABAC1	10-15-1997	47.35	12-11-1997	44.38	03-31-1998	39.79	10-06-1998	47.55	04-20-1999	45.60
			11-05-1997	46.73	01-09-1998	43.68	07-15-1998	40.28	01-07-1999	45.68	06-16-1999	46.15
			11-20-1997	45.01	01-28-1998	40.51	09-03-1998	47.27	03-25-1999	43.41		
46	392831118443201	101 N19 E29 28CCCC1	01-28-1997	7.30	07-28-1997	7.87	03-16-1999	8.7	06-15-1999	9.6		
			04-22-1997	7.49	11-04-1997	6.6	04-19-1999	9.0				
47	392838118482301	101 N19 E28 26DCDB1	07-16-1997	24.10	08-26-1997	24.8	10-08-1997	23.8	12-11-1997	21.0	03-10-1998	21.1
			07-29-1997	24.98	09-10-1997	24.4	10-30-1997	24.0	01-09-1998	20.5	03-31-1998	20.9
			08-12-1997	24.1	09-25-1997	24.5	11-20-1997	21.6	01-28-1998	21.2	06-08-1998	21.9
49	392837118462901	101 N19 E29 30CDBC2	11-20-1997	49.50	01-28-1998	42.67	09-03-1998	44.75	01-07-1999	46.65	06-16-1999	46.37
			12-11-1997	49.97	03-31-1998	41.31	10-08-1998	44.93	03-25-1999	45.76		
			01-09-1998	47.56	07-15-1998	42.58	11-12-1998	47.76	04-20-1999	46.05		
50	392837118463201	101 N19 E29 30CDBC1	11-12-1998	44.99	01-07-1999	43.81	04-20-1999	46.05	06-16-1999	46.72		
55	392850118463401	101 N19 E29 30CBAD1	10-15-1997	46.62	11-20-1997	51.25	01-09-1998	48.48	07-15-1998	42.47	10-08-1998	48.21
			11-05-1997	46.06	12-11-1997	49.25	03-31-1998	47.35	09-03-1998	49.34	01-07-1999	47.11

Appendix 2. Water-level measurements for selected wells—Continued

Well number (fig. 6)	USGS site identification		Water level									
	Standard ID	Local ID	Date	Feet	Date	Feet	Date	Feet	Date	Feet	Date	Feet
56	392850118463502	101 N19 E29 30CBAD3	01-14-1997	5.19	04-21-1997	5.30	08-29-1997	5.4	03-10-1998	5.6	11-10-1998	5.2
			01-27-1997	5.13	05-11-1997	5.30	09-16-1997	5.40	03-31-1998	5.5	12-02-1998	5.3
			02-22-1997	5.17	06-03-1997	5.19	10-01-1997	5.4	05-08-1998	5.5	01-07-1999	5.4
			02-24-1997	5.24	06-20-1997	5.07	10-15-1997	5.4	06-18-1998	5.3	06-18-1998	5.3
			03-07-1997	5.26	07-11-1997	5.13	10-29-1997	5.4	07-15-1998	5.4		
			03-25-1997	5.26	07-24-1997	5.23	01-22-1998	5.6	08-06-1998	5.5		
			04-08-1997	5.30	08-14-1997	5.40	01-28-1998	5.6	09-02-1998	5.5		
57	392851118451301	101 N19 E29 29CAAC1	06-14-1997	46	07-29-1997	46.90	10-30-1997	46.2	05-08-1998	45.8	01-07-1999	45.7
			06-16-1997	46.4	08-12-1997	47.2	11-20-1997	46.5	06-18-1998	46.1	03-16-1999	45.4
			06-19-1997	46.6	08-21-1997	48.4	12-11-1997	46.0	07-15-1998	47.6	04-19-1999	45.8
			07-01-1997	47.0	08-26-1997	48.4	01-09-1998	45.6	08-06-1998	48.5	05-06-1999	46.2
			07-08-1997	47.3	09-10-1997	48.2	01-28-1998	45.4	09-03-1998	49.0	06-15-1999	47.3
			07-11-1997	47.09	09-25-1997	48.1	03-10-1998	45.4	10-06-1998	47.9	12-02-1998	44.0
			07-16-1997	47.6	10-08-1997	45.2	03-31-1998	45.2	12-02-1998	44.0		
58	392851118451302	101 N19 E29 29CAAC2	06-14-1997	45	08-12-1997	46.3	11-20-1997	44.2	06-18-1998	44.3	03-16-1999	43.9
			06-16-1997	45.1	08-21-1997	46.4	12-11-1997	43.8	07-15-1998	45.6	04-19-1999	44.4
			06-19-1997	45.2	08-26-1997	46.3	01-09-1998	43.6	08-06-1998	46.2	05-06-1999	44.6
			07-01-1997	45.6	09-10-1997	45.9	01-28-1998	43.6	09-03-1998	46.6	06-15-1999	45.5
			07-08-1997	45.8	09-25-1997	45.5	03-10-1998	46.5	10-06-1998	45.4		
			07-16-1997	46.1	10-08-1997	45.3	03-31-1998	43.3	12-02-1998	46.2		
			07-29-1997	46.14	10-30-1997	44.8	05-08-1998	44.2	01-07-1999	43.8		
59	392851118451303	101 N19 E29 29CAAC3	06-14-1997	24	08-12-1997	23.4	11-20-1997	24.8	06-18-1998	25.4	03-16-1999	26.0
			06-19-1997	24.5	08-21-1997	24.3	12-11-1997	25.8	07-15-1998	25.3	04-19-1999	26.0
			07-01-1997	24.6	08-26-1997	24.3	01-09-1998	26.0	08-06-1998	25.0	05-06-1999	25.1
			07-08-1997	24.5	09-10-1997	24.1	01-28-1998	26.0	09-03-1998	24.8	06-19-1999	25.1
			07-11-1997	24.44	09-25-1997	24.1	03-10-1998	25.9	10-06-1998	24.7		
			07-16-1997	24.5	10-08-1997	24.2	03-31-1998	25.8	12-02-1998	25.6		
			07-29-1997	24.22	10-30-1997	24.5	05-08-1998	26.0	01-07-1999	26.0		
63	392902118453401	101 N19 E29 29BCDB1	06-15-1997	25	07-16-1997	38.1	10-08-1997	38.7	03-31-1998	45.5	12-02-1998	45.8
			06-16-1997	29.2	07-29-1997	38.83	10-30-1997	39.0	06-18-1998	45.4	01-07-1999	45.8
			06-17-1997	30.5	08-12-1997	38.6	11-20-1997	39.3	07-15-1998	45.4	03-25-1999	45.9
			06-19-1997	25.7	08-21-1997	38.4	12-11-1997	42.1	08-06-1998	45.5	04-19-1999	45.7
			07-01-1997	30.5	08-26-1997	38.5	01-09-1998	45.1	09-03-1998	45.6	05-06-1999	45.7
			07-08-1997	36.8	09-10-1997	38.3	01-28-1998	45.6	10-06-1998	45.6	06-15-1999	45.7
			07-11-1997	37.86	09-25-1997	38.6	03-10-1998	45.6	11-12-1998	45.7		

Appendix 2. Water-level measurements for selected wells—Continued

Well number (fig. 6)	USGS site identification		Water level									
	Standard ID	Local ID	Date	Feet	Date	Feet	Date	Feet	Date	Feet	Date	Feet
64	392902118453402	101 N19 E29 29BCDB2	06-15-1997	14	08-12-1997	14.6	11-20-1997	15.5	06-18-1998	12.7	01-07-1999	24.5
			06-16-1997	10.1	08-21-1997	14.8	12-11-1997	24.5	07-15-1998	12.8	03-25-1999	17.5
			06-19-1997	14.1	08-26-1997	14.7	01-09-1998	24.7	08-06-1998	13.0	04-19-1999	16.7
			07-01-1997	14.6	09-10-1997	14.9	01-28-1998	24.7	09-03-1998	13.0	05-06-1999	16.9
			07-08-1997	15.4	09-25-1997	14.3	03-10-1998	24.7	10-06-1998	13.2	06-19-1999	15.7
			07-16-1997	15.4	10-08-1997	14.0	03-31-1998	24.5	11-12-1998	13.4		
			07-29-1997	15.29	10-30-1997	14.4	05-08-1998	13.6	12-02-1998	17.9		
65	392911118475901	101 N19 E28 26AADD1	03-12-1998	24.5	06-17-1998	24.7	09-03-1998	26.5	12-01-1998	25.6	04-19-1999	24.7
			03-31-1998	24.3	07-15-1998	25.40	10-06-1998	26.5	01-07-1999	25.0	06-15-1999	25.4
			05-08-1998	24.5	08-06-1998	26.0	11-10-1998	25.9	03-16-1999	25.6		
66	392911118475902	101 N19 E28 26AADD2	03-12-1998	21.4	06-17-1998	21.9	09-03-1998	23.7	11-10-1998	23.0	03-16-1999	21.7
			03-31-1998	21.5	07-15-1998	22.37	10-06-1998	23.7	12-01-1998	22.5	04-19-1999	21.9
			05-08-1998	21.7	08-06-1998	23.3	11-01-1998	22.6	01-07-1999	22.1	06-15-1999	22.7
67	392913118440001	101 N19 E29 28ABCB1	03-12-1998	42.6	07-15-1998	45.2	10-06-1998	45.5	03-16-1999	43.0		
			05-08-1998	43.4	08-06-1998	46.1	12-02-1998	43.8	04-19-1999	43.4		
			06-17-1998	43.5	09-02-1998	46.5	01-07-1999	43.3	06-15-1999	44.8		
68	392913118440002	101 N19 E29 28ABCB2	03-12-1998	28.6	07-15-1998	29.1	10-06-1998	29.3	03-16-1999	28.5		
			05-08-1998	28.4	08-06-1998	29.6	12-02-1998	28.6	04-19-1999	28.6		
			06-17-1998	28.4	09-02-1998	29.7	01-07-1999	28.6	06-15-1999	28.9		
69	392914118442701	101 N19 E29 28BBCA1	09-24-1997	51	11-20-1997	49.1	03-31-1998	47.8	09-02-1998	51.6	04-19-1999	48.5
			09-24-1997	50.74	12-11-1997	48.6	05-08-1998	48.4	10-06-1998	50.5	06-03-1999	49.6
			10-08-1997	50.4	01-09-1998	48.1	06-17-1998	48.6	12-02-1998	48.8	06-15-1999	49.9
			10-15-1997	50.2	01-28-1998	48.0	07-15-1998	50.2	01-07-1999	48.3		
			10-20-1997	50.0	03-10-1998	47.9	08-06-1998	51.1	03-16-1999	48.0		
70	392907118453701	101 N19 E29 29BACB1	07-01-1997	61.28	08-13-1997	62.5	12-11-1997	60.3	06-18-1998	58.5	10-08-1998	62.1
			07-18-1997	61.99	08-26-1997	62.6	03-31-1998	59.3	07-15-1998	60.1	01-07-1999	59.69
			07-29-1997	62.25	09-10-1997	62.5	05-08-1998	58.8	09-03-1998	61.4		
72	392924118420901	101 N19 E29 23CCDC1	01-28-1997	7.44	11-04-1997	6.4	07-09-1998	6.1	03-16-1999	7.5		
			04-22-1997	6.57	02-11-1998	6.9	09-21-1998	5.8	06-16-1999	6.5		
			07-28-1997	6.00	05-11-1998	6.2	01-26-1999	7.2				
73	392925118482001	101 N19 E28 23DCDB1	01-14-1997	14.61	04-08-1997	14.82	08-14-1997	13.4	02-13-1998	13.9	10-08-1998	13.2
			01-27-1997	14.65	04-21-1997	14.95	08-29-1997	12.4	03-20-1998	14.4	11-09-1998	13.4
			02-11-1997	14.66	05-11-1997	14.20	10-01-1997	13.7	05-07-1998	15.0	01-06-1999	13.8
			02-24-1997	14.69	06-03-1997	12.94	10-15-1997	13.9	06-18-1998	13.3	03-16-1999	15.0
			03-07-1997	14.73	06-20-1997	13.64	10-29-1997	13.2	07-13-1998	13.1	06-15-1999	13.6
			03-25-1997	14.84	07-11-1997	13.27	01-25-1998	13.9	09-02-1998	12.9		
75	392944118463202	101 N19 E29 19CACB2	03-31-1998	26.1								

Appendix 2. Water-level measurements for selected wells—Continued

Well number (fig. 6)	USGS site identification		Water level									
	Standard ID	Local ID	Date	Feet	Date	Feet	Date	Feet	Date	Feet	Date	Feet
79	392943118454501	101 N19 E29 19DAAD1	06-04-1997	47.79	09-25-1997	49.9	01-28-1998	47.2	08-06-1998	50.3	01-07-1999	47.6
			07-16-1997	49.4	10-08-1997	49.5	03-10-1998	47.1	09-03-1998	50.8	03-16-1999	46.7
			07-29-1997	49.71	10-30-1997	48.9	03-31-1998	46.9	10-06-1998	49.7	04-19-1999	47.1
			08-12-1997	50.0	11-20-1997	48.3	05-08-1998	47.6	11-10-1998	48.6	06-15-1999	48.6
			08-26-1997	50.2	12-11-1997	47.9	06-17-1998	47.7	11-12-1998	48.5		
			09-10-1997	50.0	01-09-1998	47.3	07-15-1998	48.6	12-02-1998	48.1		
85	393021118452901	101 N19 E29 20BBDD2	09-04-1997	6	10-30-1997	7.0	03-10-1998	7.1	08-06-1998	5.8	03-16-1999	6.1
			09-10-1997	6.5	11-20-1997	6.9	03-31-1998	7.3	09-03-1998	6.1	04-19-1999	7.0
			09-17-1997	6.5	12-11-1997	6.9	05-08-1998	6.2	10-06-1998	6.4	06-15-1999	5.5
			09-25-1997	6.9	01-09-1998	7.1	06-17-1998	4.3	12-02-1998	6.6		
			10-08-1997	7.0	01-18-1998	7.1	07-15-1998	5.2	01-07-1999	6.7		
86	392958118433501	101 N19 E29 20BBDD1	06-26-1997	45.99	09-25-1997	47.2	01-28-1998	44.5	08-06-1998	47.65	04-19-1999	45.0
			07-16-1997	46.8	10-08-1997	46.9	03-10-1998	44.4	09-03-1998	48.18	06-15-1999	46.4
			07-29-1997	47.04	10-30-1997	46.3	03-31-1998	44.2	10-06-1998	47.0		
			08-12-1997	47.4	11-20-1997	45.6	05-08-1998	45.0	12-02-1998	45.3		
			08-26-1997	47.5	12-11-1997	45.2	06-17-1998	45.1	01-07-1999	44.9		
			09-10-1997	47.4	01-09-1998	44.6	07-15-1998	46.8	03-16-1999	44.6		
88	393003118402001	101 N19 E29 24ABDD1	01-28-1997	4.27	06-03-1997	4.84	09-16-1997	5.59	02-13-1998	4.7	10-08-1998	4.4
			02-24-1997	4.15	06-20-1997	5.15	10-01-1997	5.77	03-20-1998	4.9	11-09-1998	4.8
			03-07-1997	4.12	07-11-1997	5.21	10-15-1997	5.6	05-07-1998	4.2	12-11-1998	4.7
			04-08-1997	3.85	07-24-1997	4.53	10-29-1997	5.4	06-18-1998	3.8	01-06-1999	4.8
			04-21-1997	4.01	08-14-1997	5.84	11-19-1997	5.6	07-13-1998	3.7	02-16-1999	4.8
			05-11-1997	4.28	08-29-1997	6.05	01-22-1998	4.8	09-02-1998	3.8	06-16-1999	4.8
89	393009118453501	101 N19 E29 21AAAC1	07-16-1997	18.4	10-08-1997	34.0	03-10-1998	16.6	03-10-1998	16.6	03-16-1999	16.4
			07-29-1997	18.57	10-30-1997	18.5	03-31-1998	16.5	09-02-1998	18.3	09-02-1998	18.3
			08-12-1997	18.7	11-20-1997	17.8	05-08-1998	17.3	10-06-1998	17.2	04-19-1999	16.3
			08-26-1997	18.8	12-11-1997	17.6	06-17-1998	17.0	11-10-1998	16.9	06-15-1999	17.0
			09-10-1997	18.8	01-09-1998	17.4	07-15-1998	18.0	12-02-1998	16.6		
			09-25-1997	18.7	01-28-1998	17.1	08-06-1998	18.4	01-07-1999	16.6		
90	393008118452401	101 N19 E29 20BAAD1	07-16-1997	49.3	09-25-1997	49.7	01-09-1998	47.1	06-18-1998	47.6	12-02-1998	48.0
			07-29-1997	49.58	10-08-1997	49.4	01-28-1998	47.0	07-15-1998	49.2	01-07-1999	47.4
			08-12-1997	49.9	10-30-1997	49.0	03-10-1998	47.0	08-06-1998	49.1	03-16-1999	47.1
			08-26-1997	49.5	11-20-1997	48.2	03-31-1998	46.8	09-03-1998	50.7	04-19-1999	47.5
			09-10-1997	49.94	12-11-1997	47.8	05-08-1998	47.6	10-06-1998	49.6	06-15-1999	48.8
91	393026118461401	101 N19 E29 18DCBB1	01-14-1997	7.42	04-21-1997	7.46	08-29-1997	7.2	03-10-1998	7.4	10-06-1998	6.9
			01-27-1997	7.36	05-11-1997	7.46	09-16-1997	7.09	03-31-1998	7.6	11-10-1998	6.7
			02-11-1997	7.44	06-03-1997	6.86	10-01-1997	7.2	05-08-1998	7.3	12-01-1998	6.9
			02-24-1997	7.49	06-20-1997	7.02	10-15-1997	7.0	06-18-1998	6.8	01-07-1999	7.2
			03-07-1997	7.53	07-11-1997	7.15	10-29-1997	7.1	07-15-1998	7.0	03-16-1999	7.7
			03-25-1997	7.59	07-24-1997	7.09	01-22-1998	7.3	08-06-1998	6.7	04-19-1999	7.6
			04-08-1997	7.64	08-14-1997	7.3	01-28-1998	7.3	09-03-1998	7.0	06-15-1999	6.7

Appendix 2. Water-level measurements for selected well—Continued

Well number (fig. 6)	USGS site identification		Water level									
	Standard ID	Local ID	Date	Feet	Date	Feet	Date	Feet	Date	Feet	Date	Feet
92	393026118461403	101N19 E29 18DCBB3	01-14-1997	8.80	04-21-1997	9.07	08-29-1997	9.4	03-10-1998	8.7	10-06-1998	8.0
			01-27-1997	8.75	05-11-1997	9.28	09-16-1997	9.19	03-31-1998	8.7	11-10-1998	7.6
			02-11-1997	8.68	06-03-1997	9.03	10-01-1997	9.1	05-08-1998	8.6	12-01-1998	7.7
			02-24-1997	8.73	06-20-1997	8.90	10-15-1997	9.0	06-18-1998	7.9	01-07-1999	8.1
			03-07-1997	8.72	07-11-1997	9.04	10-29-1997	8.9	07-15-1998	8.0	03-16-1999	8.6
			03-25-1997	8.90	07-24-1997	9.16	01-22-1998	8.7	08-06-1998	8.0	04-19-1999	8.7
			04-08-1997	9.08	08-14-1997	9.4	01-28-1998	8.7	09-03-1998	8.2	06-15-1999	8.7
93	393027118461501	101N19 E29 18DCBB1	09-10-1997	44.47	12-11-1997	44.62	05-08-1998	40.2	08-06-1998	44.2	01-07-1999	44.0
			09-25-1997	44.16	01-09-1998	43.7	06-17-1998	41.0	09-03-1998	45.5	03-16-1999	43.6
			11-20-1997	43.3	03-10-1998	41.3	07-15-1998	43.7	11-10-1998	45.0	06-16-1999	44.1
94	393049118413501	101 N19 E29 14ACB2	07-28-1997	8.67	02-11-1998	9.3	07-09-1998	8.7	01-26-1999	9.0	06-16-1999	8.6
			11-03-1997	9.2	05-11-1998	9.2	09-21-1998	9.3	03-16-1999	9.3		
106	393155118483002	101N19E2811ABB2	04-22-1997	28.77	05-05-1998	29.1	09-22-1998	30.0	03-16-1999	29.1	06-16-1999	29.5
			02-10-1998	29.3	07-08-1998	29.4	01-26-1999	29.2	05-04-1999	29.1		
107	393252118415901	101 N19 E29 02BABB1	01-28-1997	9.10	11-04-1997	7.2	07-09-1998	8.2	03-16-1999	9.8		
			04-22-1997	9.04	02-11-1998	9.9	09-21-1998	7.7	06-16-1999	8.3		
			07-28-1997	7.63	05-11-1998	9.5	01-26-1999	9.4				
110	393305118431401	101 N20 E29 34CBDC1	07-18-1997	11.09	09-25-1997	11.65	01-09-1998	9.98	06-17-1998	9.59	11-10-1998	10.27
			07-29-1997	11.82	10-08-1997	11.35	01-28-1998	9.83	07-15-1998	9.61	12-02-1998	9.44
			08-12-1997	11.52	10-30-1997	10.84	03-10-1998	9.77	08-06-1998	11.16	01-07-1999	9.09
			08-26-1997	11.43	11-20-1997	10.46	03-31-1998	9.71	09-02-1998	10.43	03-16-1999	8.84
			09-10-1997	11.58	12-11-1997	10.07	05-08-1998	9.66	10-06-1998	10.67	06-15-1999	8.43
112	393341118431601	101 N20 E29 34BBAC1	09-10-1997	11.88	12-11-1997	10.3	05-08-1998	9.93	10-06-1998	11.68	06-15-1999	10.96
			09-25-1997	11.8	01-09-1998	10.0	06-17-1998	9.88	11-10-1998	11.33		
			10-08-1997	11.6	01-28-1998	10.0	07-15-1998	10.01	12-02-1998	10.41		
			10-30-1997	11.1	03-10-1998	9.8	08-06-1998	12.04	01-06-1999	9.89		
			11-20-1997	10.7	03-31-1998	9.6	09-03-1998	12.39	04-19-1999	11.26		
115	393458118431101	101 N20 E29 22CBAC1	01-14-1997	8.74	03-25-1997	8.45	06-20-1997	7.26	09-16-1997	8.94	12-02-1998	8.2
			01-27-1997	8.69	04-08-1997	8.42	07-11-1997	7.87	10-01-1997	9.0	01-06-1999	8.0
			02-11-1997	8.62	04-21-1997	8.39	07-24-1997	8.16	10-15-1997	8.9	03-16-1999	7.7
			02-24-1997	8.58	05-11-1997	8.49	08-14-1997	8.52	11-19-1997	9.1	06-16-1999	6.4
			03-07-1997	8.53	06-03-1997	8.24	08-29-1997	8.76	11-09-1998	8.3		
116	393506118473002	101 N20E2824BDD2	01-28-1997	29.76	02-10-1998	—	07-08-1998	—	01-26-1999	—	06-16-1999	—
			04-22-1997	29.72	05-05-1998	—	09-22-1998	—	05-04-1999	—		

Appendix 3. Vertical hydraulic gradient calculated for selected wells and surface-water bodies

Well or surface-water body (fig. 6)	Aquifer [1]	Mid-point altitude (feet) [2]	Difference in mid-point altitude (feet)	Water level		Difference in water-level altitude (feet)	Vertical hydraulic gradient [3]
				Date	Altitude (feet)		
Stream stage, S-Line Canal 59	— S	3,956.0 3,936.8	19.2	09/03/98 09/03/98	3,959.5 3,936.0	23.5	1.22
Stream stage, S-Line Canal 59	— S	3,955.1 3,936.8	18.3	03/16/99 03/16/99	3,957.2 3,934.8	22.4	1.22
Stream stage, S-Line Canal 58	— S-C, B	3,956.0 3,915.8	40.2	09/03/98 09/03/98	3,959.5 3,914.2	45.3	1.13
Stream Stage, S-Line Canal 58	— S-C, B	3,955.1 3,915.8	39.3	03/16/99 03/16/99	3,957.2 3,916.9	40.3	1.03
Stream stage, S-Line Canal 57	— B	3,956.0 3,870.8	85.2	09/03/98 09/02/98	3,959.5 3,911.8	47.7	.560
Stream stage, S-Line Canal 57	— B	3,955.1 3,870.8	84.3	03/16/99 03/16/99	3,957.2 3,915.4	41.8	.496
59 58	S S-C, B	3,936.8 3,915.8	21.0	09/03/98 09/03/98	3,936.0 3,914.2	21.8	1.04
59 58	S S-C, B	3,936.8 3,915.8	21.0	03/16/99 03/16/99	3,934.8 3,916.9	17.9	.854
58 57	S-C B	3,915.8 3,870.8	45.0	09/03/98 09/03/98	3,914.2 3,911.8	2.4	.053
58 57	S-C, B B	3,915.8 3,870.8	45.0	03/16/99 03/16/99	3,916.9 3,915.4	1.5	.033
Stream stage, S-Line Canal 64	— S	3,957.5 3,945.6	11.9	09/03/98 09/03/98	3,960.2 3,952.1	8.1	.680
Stream stage, S-Line Canal 64	— S	3,954.7 3,945.6	9.1	03/25/99 03/25/99	3,959.5 3,947.6	11.9	1.31
Stream stage, S-Line Canal 63	— S-C	3,957.5 3,923.6	33.9	09/03/98 09/03/98	3,960.2 3,919.6	40.6	1.20
Stream stage, S-Line Canal 63	— S-C	3,954.7 3,923.6	31.1	03/25/99 03/25/99	3.959.5 3.919.2	40.3	1.30
64 63	S S-C	3,945.6 3,923.6	22.0	09/03/98 09/03/98	3,952.1 3,919.6	32.5	1.48
64 63	S S-C	3,945.6 3,923.6	22.0	03/25/99 03/25/99	3,947.6 3,919.2	28.4	1.29
Stream stage, Carson River 85	— S	3,944.7 3,936.5	8.2	03/31/98 03/31/98	3,944.7 3,944.2	0.5	.061
85 86	S B	3,936.5 3,794.0	142.5	03/31/98 03/31/98	3,944.2 3,917.8	26.4	.185
85 86	S B	3,936.5 3,794.0	142.5	09/03/98 09/03/98	3,945.5 3,913.9	31.6	.222

Appendix 3. Vertical hydraulic gradient calculated for selected wells and surface-water bodies—Continued

Well or surface-water body (fig. 6)	Aquifer[1]	Mid-point altitude (feet) [2]	Difference in mid-point altitude (feet)	Water level		Difference in water-level altitude (feet)	Vertical hydraulic gradient [3]
				Date	Altitude (feet)		
Stream stage, S-Line Reservoir	—	3,936.1	84.7	09/02/98	3,928.7	12.8	0.151
68	I	3,851.4		09/02/98	3,941.5		
Stream stage, S-Line Reservoir	—	3,936.1	84.7	03/16/99	3,930.3	10.6	.125
68	I	3,851.4		03/16/99	3,940.9		
68	I	3,851.4	102.5	09/02/98	3,928.7	16.8	.164
67	B	3,748.9		09/02/98	3,911.9		
68	I	3,851.4	102.5	03/16/99	3,929.9	14.4	.141
67	B	3,748.9		03/16/99	3,915.4		
7	I	3,494.5	149.0	09/02/98	3,916.8	4.1	.028
6	I-C	3,345.5		09/02/98	3,912.7		
7	I	3,494.5	149.0	03/16/99	3,918.6	2.6	.018
6	I-C	3,345.5		03/16/99	3,916.0		
31	I	3,831.5	181.7	09/01/98	3,937.1	22.0	.121
35	I	3,649.8		09/01/98	3,915.1		
31	I	3,831.5	181.7	03/16/99	3,938.3	20.8	.114
35	I	3,649.8		03/16/99	3,917.5		
31	I	3,831.5	359.7	09/01/98	3,937.1	25.5	.071
34	I-C	3,471.8		09/01/98	3,911.6		
31	I	3,831.5	359.7	03/16/99	3,938.3	23.2	.064
34	I-C	3,471.8		03/16/99	3,915.1		
35	I	3,649.8	178.0	09/01/98	3,915.1	3.5	.020
34	I-C	3,471.8		09/01/98	3,911.6		
35	I	3,649.8	178.0	03/16/99	3,917.5	2.4	.013
34	I-C	3,471.8		03/16/99	3,915.1		
34	I-C	3,471.8	40.6	09/01/98	3,911.6	1.4	.034
28	B	3,431.2		09/02/98	3,910.2		
34	I-C	3,471.8	40.6	03/16/99	3,915.1	1.3	.032
28	B	3,431.2		03/16/99	3,913.8		
38	I	3,688.3	122.0	09/02/98	3,918.0	6.4	.052
37	I-C	3,566.3		09/02/98	3,911.6		
38	I	3,688.3	122.0	03/16/99	3,920.5	5.3	.043
37	I-C	3,566.3		03/16/99	3,915.6		
43	I	3,647.4	118.5	09/01/98	3,919.8	9.4	.079
42	I-C	3,528.9		09/01/98	3,910.4		
43	I	3,647.4	118.5	03/16/99	3,923.9	10.5	.089
42	I-C	3,528.9		03/16/99	3,913.4		

Appendix 3. Vertical hydraulic gradient calculated for selected wells and surface-water bodies—Continued

Well or surface-water body (fig. 6)	Aquifer [1]	Mid-point altitude (feet) [2]	Difference in mid-point altitude (feet)	Water level: Date	Water level: Altitude (feet)	Difference in water-level altitude (feet)	Vertical hydraulic gradient [3]
Carson River at Coleman dam	—	3,960.9	401.2	01/07/99	3,963.4	17.3	0.043
66	I	3,559.7		01/07/99	3,946.1		
66	I	3,559.7	92.5	09/03/98	3,944.5	2.8	.030
65	I-C	3,467.2		09/03/98	3,941.7		
66	I	3,559.7	92.5	03/16.99	3,946.5	3.9	.042
65	I-C	3,467.2		03/16/99	3,942.6		
56	S	3,948.9	433.3	09/03/98	3,954.4	44.2	.102
55	B	3,515.6		09/03/98	3,910.2		
56	S	3,948.9	433.3	01/07/99	3,954.5	42.1	.097
55	B	3,515.6		01/07/99	3,912.4		
91	S	3,949.2	52.6	09/03/98	3,950.7	1.3	.025
92	I	3,896.6		09/03/98	3,949.4		
91	S	3,949.2	52.6	03/16/99	3,950.0	1.0	.019
92	I	3,896.6		03/16/99	3,949.0		
92	I	3,896.6	367.0	09/03/98	3,949.4	38.3	.104
93	B	3,529.6		09/03/98	3,911.1		
92	I	3,896.6	367.0	03/16/99	3,949.0	36.0	.098
93	B	3,529.6		03/16/99	3,913.0		
31	I	3,831.5	359.7	03/16/99	3,938.3	23.2	.064
34	I-C	3,471.8		03/16/99	3,915.1		

[1] Indicates aquifer in which well is screened: S, shallow aquifer; S-C, shallow aquifer in contact with basalt; I, intermediate aquifer; I-C, intermediate aquifer in contact with basalt; B, basalt aquifer; —, surface-water body.

[2] Altitude of middle of gravel-packed interval or open interval of well, or bottom of streambed.

[3] Equal to difference in water-level altitude divided by difference in mid-point altitude.

Appendix 4. Water-quality data for wells sampled during this study

[Abbreviations: µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picoCuries per liter; E, estimated value. Symbols: <, less than; ±, plus or minus; —, not determined. The uncertainty associated with the tritium analysis is the counting uncertainty expressed as two times the standard deviation, in pCi/L]

Aquifer	Site number	Date	Specific conductance (µS/cm)	pH (standard units)	Water temperature (°C)	Dissolved oxygen (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L as HCO_3)	Carbonate (mg/L)
Shallow aquifer	64	08/11/1997	329	7.4	20.5	3.0	20	4.6	39	3.1	130	<1
	85	10/27/1997	2,270	7.3	13.0	.6	190	41	283	11.0	654	<1
Shallow aquifer in contact with basalt aquifer	63	08/07/1997	337	7.8	18.5	.5	21	4.8	41	3.2	137	<1
	[1]58	08/05/1997	832	7.0	17.0	1.4	97	15	57	4.8	381	<1
Intermediate aquifer	7	05/21/1998	644	7.9	21.5	.2	7.3	1.4	129	8.9	163	<1
	26	08/18/1997	448	8.3	20.0	0	1.6	.13	94	5.2	209	<1
	31	08/14/1997	580	8.8	17.0	.1	.36	.11	120	2.5	237	19
	35	09/17/1998	505	9.3	18.5	.1	.9	.18	107	3.2	171	31
	38	05/19/1998	421	9.1	18.5	.2	.93	.096	100	3.0	159	22
	43	09/18/1998	290	8.5	19.0	.1	9.5	.85	43	11.0	103	3
	47	08/12/1997	320	8.3	16.5	.1	3.3	.43	60	8.0	132	<1
	66	05/28/1998	273	8.2	20.0	.2	7.1	1.4	49	4.9	106	<1
	68	05/20/1998	800	9.2	18.5	.3	.9	.42	195	3.1	342	41
	75	10/20/1997	306	8.3	18.0	.3	4.8	.4	60	8.0	128	<1
	90	08/13/1997	933	9.1	21.0	.1	.88	.31	197	6.4	224	43
Intermediate aquifer in contact with basalt aquifer	6	05/21/1998	1,340	8.2	21.0	.3	24	1.6	253	7.6	108	<1
	34	09/17/1998	1,040	8.7	21.0	.1	2.3	.7	244	8.7	407	13
	37	05/19/1998	800	8.0	20.0	.6	4.6	2.1	181	6.0	279	<1
	42	09/16/1998	307	8.2	20.0	.3	3.6	.72	59	6.6	111	1
	65	05/28/1998	272	8.3	21.0	.1	7.0	1.9	51	5.1	106	<1
Basalt aquifer	29	05/27/1998	1,000	9.3	20.5	.9	1.3	.52	219	7.8	224	31
	30	06/23/1997	1,040	9.1	20.5	1.0	1.7	.52	210	7.2	220	37
	30	11/04/1998	1,000	9.2	19.5	1.0	1.3	.52	222	8.4	230	34
	45	10/21/1997	914	9.1	20.0	.7	1.6	.53	196	7.3	266	24
	55	10/21/1997	906	9.0	19.5	.5	1.6	.54	194	7.4	212	26
	55	11/03/1998	873	9.2	18.5	.4	1.5	.5	196	7.2	196	25
	57	08/04/1997	1,160	9.0	22.5	2.0	7.0	1.9	223	8.2	249	30
	67	05/20/1998	1,080	9.2	21.0	.8	1.2	.53	240	7.9	216	34
	69	10/20/1997	1,110	9.1	22.5	.9	1.7	.9	236	7.8	245	30
	70	06/25/1997	1,010	9.2	20.5	1.0	1.5	.61	209	7.6	230	32
	70	01/20/1999	989	9.2	19.0	.7	—	—	—	—	—	<1
	86	06/26/1997	1,010	9.1	20.0	.3	1.1	.38	200	6.9	200	43
	93	06/27/1997	946	9.2	22.0	.4	1.6	.36	195	6.7	200	35
	112	11/02/1998	1,160	9.4	17.5	.8	.9	.22	257	7.3	268	53

Appendix 4. Water-quality data for wells sampled during this study—Continued

Aquifer	Site number	Date	Chloride (as Cl) (mg/L)	Sulfate (as SO_4) (mg/L)	Fluoride (as F) (mg/L)	Bromide (as Br) (mg/L)	Iodide (as I) (mg/L)	Silica (as SiO_2)	Solids, residue upon evaporation (mg/L)	Solids, dissolved, sum of constituents (mg/L)
Shallow aquifer	64	08/11/1997	9.0	35	0.68	<0.010	0.011	26	217	203
	85	10/27/1997	170.0	410	.34	.140	.047	31	1,510	1,460
Shallow aquifer in contact with basalt aquifer	63	08/07/1997	9.3	35	.68	<0.010	.011	27	226	210
	58	08/05/1997	17.0	78	.39	.027	.007	40	527	497
Intermediate aquifer	7	05/21/1998	79	51	.55	.170	.022	56	434	435
	26	08/18/1997	8.0	33	.76	.015	.011	51	316	296
	31	08/14/1997	7.4	43	1.40	.018	.015	29	375	345
	35	09/17/1998	7.4	32	1.30	.011	.008	40	329	309
	38	05/19/1998	7.2	34	1.20	.018	.015	40	295	287
	43	09/18/1998	6.4	34	.66	.019	.005	35	203	194
	47	08/12/1997	5.7	34	.48	<0.010	.007	44	238	221
	66	05/28/1998	6.5	35	.28	.021	.006	58	221	216
	68	05/20/1998	8.2	51	2.10	.030	.008	31	530	515
	75	10/20/1997	7.2	34	.54	.011	.007	48	233	226
	90	08/13/1997	78	70	1.00	.150	.018	25	564	533
	95	05/18/1999	7.0	—	—	—	—	—	—	—
Intermediate aquifer in contact with basalt aquifer	6	05/21/1998	32.0	94	.46	.660	.038	47	812	800
	34	09/17/1998	11.0	18	1.40	.210	.017	50	684	649
	37	05/19/1998	95	24	.95	.460	.016	57	653	530
	42	09/16/1998	7.9	36	.36	.015	.005	64	245	234
	42	09/16/1998	7.9	36	.34	.024	.006	64	243	—
	65	05/28/1998	6.5	36	.28	.021	.006	64	228	224
Basalt aquifer	29	05/27/1998	110	92	.77	.210	.002	26	608	598
	30	06/23/1997	100	91	.78	.200	.003	26	621	586
	30	11/04/1998	110	91	.82	.210	.003	26	617	607
	45	10/21/1997	88	85	.74	.160	.003	30	549	565
	55	10/21/1997	88	85	.70	.150	.002	30	548	539
	55	11/03/1998	86	83	.74	.170	.002	30	544	527
	57	08/04/1997	120	100	.85	.210	.004	25	682	648
	67	05/20/1998	120	100	.88	.220	.003	24	654	640
	69	10/20/1997	130	100	.85	.210	.004	25	672	656
	70	06/25/1997	100	94	.87	.160	.002	27	600	587
	70	11/05/1998	110	99	.90	.200	.002	26	652	641
	86	06/26/1997	95	88	.86	.170	.003	27	1,180	561
	93	06/27/1997	91	87	.87	.160	.011	28	579	544
	112	11/02/1998	120	59	1.40	.220	.017	26	684	661

Appendix 4. Water-quality data for wells sampled during this study—Continued

Aquifer	Site number	Date	Ortho-phosphorous (mg/L as P)	Organic carbon, dissolved (mg/L)	Arsenic (μg/L)	Inorganic arsenic (As^{3+} + As^{5+}) (μg/L)[2]	As^{3+} (μg/L)	As^{5+} (μg/L)[3]	Iron (μg/L)	Manganese (μg/L)	Tritium (pCi/L)	Delta deuterium (permil)	Delta oxygen-18 (permil)
Shallow aquifer	59	08/05/1997	—	—	—	—	—	—	—	—	—	-98.7	-12.8
	64	08/11/1997	0.280	2.1	46	42	<1	42	3.3	232	—	-98.6	-12.9
	85	10/27/1997	.090	7.1	—	10	<1	10	<0.9	497	—	-94.8	-11.3
Shallow aquifer in contact with basalt aquifer	63	08/07/1997	.280	2.0	44	38	<1	38	<3.0	204	—	-100.6	-13.0
	58	08/05/1997	—	—	12	10	<1	10	9.6	<1.0	—	-95.3	-12.3
Intermediate aquifer	7	05/21/1998	6.800	.8	31	20	18	2	22	140	—	-124.9	-15.9
	26	08/18/1997	.200	.5	29	42	34	8	42	15	—	-111.0	-14.5
	31	0814/1997	1.800	1.1	420	420	76	344	150	29	—	-110.7	-14.5
	35	09/17/1998	.470	1.0	—	23	23	<1	25	8.6	0.3 ± 0.6	-111.4	-14.6
	38	05/19/1998	.310	.7	24	19	11	8	41	4.4	—	-110.5	-14.5
	43	09/18/1998	.044	.4	—	21	5	16	<10	17	0.3 ± 0.6	-110.6	-14.5
	47	08/12/1997	.160	.5	19	15	14	1	34	24	—	-109.4	-14.6
	66	05/28/1999	.300	.2	14	12	2	10	<10	94	—	-109.9	-14.4
	68	05/20/1998	4.200	1.8	640	660	75	585	270	35	—	-111.8	-14.5
	75	10/20/1997	.084	.2	18	14	14	<1	5.5	25	—	-111.1	-14.5
	90	08/13/1997	.340	—	120	117	<1	117	9.7	2.3	—	-110.8	-14.4
Intermediate aquifer in contact with basalt aquifer	6	05/21/1998	.170	.2	46	24	20	4	<10	61.0	—	-125.7	-15.6
	34	09/17/1998	.280	—	—	12	11	1	15	6.6	—	-124.2	-16.1
	37	05/19/1998	6.800	1.5	46	33	2	31	1,200	162.0	—	-127.3	-16.4
	42	09/16/1998	.085	.2	—	36	34	2	<10	37.0	0.3 ± 0.6	-110.2	-14.5
	58	08/05/1997	—	—	12	10	<1	10	9.6	<1.0	—	-95.3	-12.3
	65	05/28/1998	.333	.2	43	36	34	2	11	20.0	—	-111.4	-14.4
Basalt aquifer	29	05/27/1998	.290	.4	100	89	<1	89	<10	<4.0	—	-109.4	-13.9
	30	06/23/1997	.200	.5	100	—	—	—	6.8	<1.0	—	—	—
	30	11/04/1998	.230	1.0	110	94	<1	94	<10	<3.0	—	—	—
	45	10/21/1997	.220	.5	110	93	<1	93	9.4	<1.0	—	-108.6	-13.9
	55	10/21/1997	.220	.5	100	107	<1	107	<3.0	<1.0	—	-109.1	-14.0
	55	11/03/1998	.220	.6	99	98	<1	98	<10	<3.0	—	—	—
	57	08/04/1997	.230	.5	120	—	—	—	9.3	<1.0	—	-107.4	-13.8
	57	05/06/1999	—	—	—	—	—	—	—	—	6.6 ± 0.6	—	—
	67	05/20/1998	.280	.6	110	79	<1	79	<10	<4.0	5.5 ± 0.6	-109.0	-13.9
	69	10/20/1997	.270	.7	140	122	<1	122	5.2	<1.0		-109.7	-13.9
	69	05/28/1999	—	—	—	—	—	—	—	—	6.5 ± 0.6	—	—

Appendix 4. Water-quality data for wells sampled during this study—Continued

Aquifer	Site number	Date	Ortho-phosphorous (mg/L as P)	Organic carbon, dissolved (mg/L)	Arsenic (μg/L)	Inorganic arsenic (As^{3+} + As^{5+}) (μg/L)[2]	As^{3+} (μg/L)	As^{5+} (μg/L)[3]	Iron (μg/L)	Manganese (μg/L)	Tritium (pCi/L)	Delta deuterium (permil)	Delta oxygen-18 (permil)
Basalt aquifer	70	06/25/1997	0.290	0.6	110	—	—	—	17	<1.0	—	—	—
	70	11/05/1998	.320	.7	130	120	<1	120	E9.6	<3.0	—	—	—
	86	06/26/1997	.260	.5	100	—	—	—	8	<1.0	—	—	—
	93	06/27/1997	.260	.5	95	—	—	—	13	1.8	—	—	—
	93	10/23/1998	—	—	—	—	—	—	—	—	—	-110.7	-14.3
	112	11/02/1998	.440	1.1	140	169	114	54	12	2.9	—	-111.5	-14.5

[1] Well probably also yields water from the uppermost part of the basalt aquifer.

[2] Inorganic arsenic and arsenite was analyzed at Battelle Northwest Laboratories, as discussed in the text.

[3] Arsenate is calculated as the difference between inorganic arsenic and arsenite.

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