

GEOHYDROLOGY OF A DEEP-AQUIFER MONITORING-WELL SITE AT MARINA, MONTEREY COUNTY, CALIFORNIA

Prepared in cooperation with
MONTEREY COUNTY WATER RESOURCES AGENCY

Water-Resources Investigations Report 02-4003

Base image for cover illustration provided

courtesy of the **Monterey Bay Aquarium Research Institute.**

Geohydrology of a Deep-Aquifer System Monitoring-Well Site at Marina, Monterey County, California

By R.T. Hanson, Rhett R. Everett, Mark W. Newhouse, Steven M. Crawford, M. Isabel Pimentel, *and* Gregory A. Smith

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02-4003

Prepared in cooperation with the
Monterey County Water Resources Agency

4024-13

Sacramento, California
2002

U.S. DEPARTMENT OF THE INTERIOR

GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

For additional information write to:

District Chief
U.S. Geological Survey
Placer Hall, Suite 2012
6000 J Street
Sacramento, CA 95819-6129

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Federal Center
Denver, CO 80225

CONTENTS

Abstract.....	1
Introduction	2
Description of Study Area	3
Land and Water Use.....	3
Geohydrology of The Salinas Valley	3
Approach to Investigation.....	6
Acknowledgments	6
Geohydrologic Description of DMW1	8
Geologic Data	8
Geophysical Data.....	12
Paleontologic Data.....	18
Hydrostratigraphy of DMW1 Site	18
Hydraulics.....	20
Water-Level Measurements	21
Hydraulic Properties	21
Water Chemistry	22
Chemical Characteristics of Water from Monitoring and Supply Wells	22
Source, Age, and Movement of Ground Water.....	23
Seawater Intrusion and Saline Ground Water	25
Summary and Conclusions	33
References Cited.....	34
Appendix 1: Cuttings and Core Descriptions for the DMW1 Monitoring Site.....	38
Appendix 2: Paleontologic Analyses for the DMW1 Monitoring Site.....	65
Appendix 3: Water-Chemistry Data for the DMW1 Monitoring Wells and Core Pore Waters	69

FIGURES

1. Map showing location of deep-aquifer system monitoring-well site in the Salinas Valley, at Marina, California	4
2. Map showing location of deep-aquifer system monitoring-well site and selected water-supply wells, Marina, California	5
3. Schematic diagram showing well construction and lithology for the deep-aquifer system, Marina, California ...	7
4. Photographs of cores 1 to 19 from the deep-aquifer system monitoring-well site, Marina, California	9
5–13. Graphs showing:	
5. Lithology and geophysical logs for the deep-aquifer system monitoring-well site, Marina, California.....	13
6. Acoustic and borehole inclinometer geophysical logs for the deep-aquifer system monitoring-well site, Marina, California	14
7. Multi-spectral natural gamma geophysical logs for the deep-aquifer system monitoring-well site, Marina, California	15
8. Geophysical logs for the deep-aquifer system monitoring-well site, Marina, California	17
9. Relation between chloride concentration and electromagnetic conductivity for core pore-water and well-water samples from the deep-aquifer system monitoring-well site, Marina, California	19
10. Trilinear diagram of major-ion chemistry for selected ground-water samples from the deep-aquifer system in the Salinas Valley, 1995, 1997, and 2000 with samples from DMW-1 wells, 2000.....	24
11. Ratios of chloride-to-boron, chloride-to-iodide, and chloride-to-bromide plotted against chloride for ground-water and surface-water samples in the Salinas Valley, California	26
12. Deuterium and oxygen isotope values for selected ground-water and surface-water samples from the Salinas Valley, California.....	29
13. Strontium-87/86 ratios plotted against strontium, and boron-11 plotted against chloride-to-boron ratios for selected wells in the Salinas Valley, California.....	30

TABLES

1. Summary of well completion for the deep-aquifer system monitoring-well site, Marina, California..... 8
 2. Summary of slug-test estimates of hydraulic properties for the deep-aquifer system site, monitoring-well, Marina, California..... 22

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

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi ²)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second
foot per day (ft/d)	370.37037	millidarcy
foot per day per foot (ft/d/ft)	1	meter per day per meter
foot squared per day (ft ² /d)	0.0929	meter squared per day
gallon per minute (gal/min)	0.06308	liter per second

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

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

Vertical Datum

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

Water-Quality Information

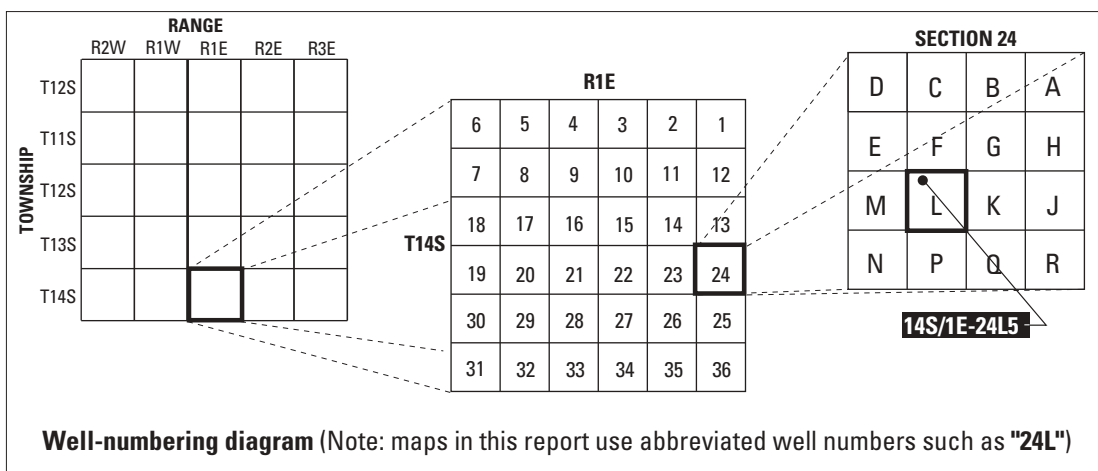
Concentrations of constituents in water samples are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is equivalent to “parts per million” and micrograms per liter is equivalent to “parts per billion.” Selected constituents also are expressed in terms of millimoles, which is the concentration in milligrams per liter divided by the atomic weight of the element. Specific conductance is given in microseimens per centimeter at 25°C (µS/cm at 25°C). Tritium activity is given in picocuries per liter (pC/L). Carbon-14 data are expressed as percent modern carbon (pmc), and carbon-13 data are expressed in delta notation as per mil differences relative to the ratio of carbon-13 to carbon-12.

Abbreviations

cm	centimeter
DMW1	deep-aquifer system multiple-well monitoring site number 1
EM	electromagnetic conductivity
EPA	U.S. Environmental Protection Agency
ft bls	feet below land surface
g/cm ³	gram per cubic centimeter
km/s	kilometer per second
km-g/s-cm ³	kilometer grams per second-centimeter cubed
MCL	Primary maximum contaminant level
MCWD	Marina Coast Water District
MCWRA	Monterey County Water Resources Agency
mmho/m	millimho per meter
per mil	part per thousand
PMC	percentage modern carbon
pvc	polyvinyl chloride
SMCL	Environmental Protection Agency secondary maximum contaminant level

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. The identification consists of the township number, north or south; the range number, east or west, and the section number. Each section is further divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with 'A' in the northeast corner of the section and progressing in a sunusoidal manner to 'R' in the southwest corner. Within the 40-acre tracts, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernadino (S). All wells in the study area are referenced to the Mount Diablo base line and meridian (M). Well numbers consist of 15 characters and follow the format 014S001E24L005M. In this report, well numbers (except in tables) are abbreviated and written 14S/1E-24L5. Wells in the same township and range are referred to by only their section designation, 24L5.



Geohydrology of a Deep-Aquifer System Monitoring-Well Site at Marina, Monterey County, California

By R.T. Hanson, Rhett R. Everett, Mark W. Newhouse, Steven M. Crawford, M. Isabel Pimentel, and Gregory A. Smith

ABSTRACT

In 2000, a deep-aquifer system monitoring-well site (DMW1) was completed at Marina, California to provide basic geologic and hydrologic information about the deep-aquifer system in the coastal region of the Salinas Valley. The monitoring-well site contains four wells in a single borehole; one completed from 930 to 950 feet below land surface (bls) in the Paso Robles Formation (DMW1-4); one 1,040 to 1,060 feet below land surface in the upper Purisima Formation (DMW1-3); one from 1,410 to 1,430 feet below land surface in the middle Purisima Formation (DMW1-2); and one from 1,820 to 1,860 feet below land surface in the lower Purisima Formation (DMW1-1). The monitoring site is installed between the coast and several deep-aquifer system supply wells in the Marina Coast Water District, and the completion depths are within the zones screened in those supply wells. Sediments below a depth of 955 feet at DMW1 are Pliocene age, whereas the sediments encountered at the water-supply wells are Pleistocene age at an equivalent depth.

Water levels are below sea level in DMW1 and the Marina Water District deep-aquifer system supply wells, which indicate that the potential for seawater intrusion exists in the deep-aquifer

system. If the aquifers at DMW1 are hydraulically connected with the submarine outcrops in Monterey Bay, then the water levels at the DMW1 site are 8 to 27 feet below the level necessary to prevent seawater intrusion. Numerous thick fine-grained interbeds and confining units in the aquifer systems retard the vertical movement of fresh and saline ground water between aquifers and restrict the movement of seawater to narrow water-bearing zones in the upper-aquifer system.

Hydraulic testing of the DMW1 and the Marina Water District supply wells indicates that the tested zones within the deep-aquifer system are transmissive water-bearing units with hydraulic conductivities ranging from 2 to 14.5 feet per day. The hydraulic properties of the supply wells and monitoring wells are similar, even though the wells are completed in different geologic formations.

Geophysical logs collected at the DMW1 site indicate saline water in most water-bearing zones shallower than 720 feet below land surface and from about 1,025 to 1,130 feet below land surface, and indicate fresher water from about 910 to 950 feet below land surface (DMW1-4), 1,130 to 1,550 feet below land surface, and below 1,650 feet below land surface. Temporal differences between electromagnetic induction logs indicate possible seasonal seawater intrusion

in five water-bearing zones from 350 to 675 feet below land surface in the upper-aquifer system.

The water-chemistry analyses from the deep-aquifer system monitoring and supply wells indicate that these deep aquifers in the Marina area contain potable water with the exception of the saline water in well DMW1-3. The saline water from well DMW1-3 has a chloride concentration of 10,800 milligrams per liter and dissolved solids concentration of 23,800 milligrams per liter. The source of this water was determined not to be recent seawater based on geochemical indicators and the age of the ground water. The high salinity of this ground water may be related to the dissolution of salts from the saline marine clays that surround the water-bearing zone screened by DMW1-3. The major ion water chemistry of the monitoring wells and the nearby MCWD water-supply wells are similar, which may indicate they are in hydraulic connection, even though the stratigraphic layers differ below 955 feet below land surface.

No tritium was detected in samples from the deep monitoring wells. The lack of tritium suggest that there is no recent recharge water (less than 50 years old) in the deep-aquifer system at the DMW1 site. The carbon-14 analyses of these samples indicate ground water from the monitoring site was recharged thousands of years ago.

INTRODUCTION

In the Salinas Valley, located in the central coastal area of California (fig. 1), extensive agriculture and subsequent urbanization has resulted in extensive ground-water development and seawater intrusion within the upper-aquifer system (California State Water Resources Board, 1953; California Department of Water Resources, 1973; Yates, 1988). As a result, local water purveyors in the Marina area have installed water-supply wells in the deep-aquifer system to help meet water-resource needs. Because the hydrogeology of the deep-aquifer system is not well understood, the U.S. Geological Survey, as part of a cooperative study with the Monterey County Water Resources Agency (MCWRA), drilled Deep Monitoring Well 1 (DMW1) at a site between the coast and several supply wells

that tap the deep aquifers within the Marina Coast Water District (fig. 1) (Hanson, 2001). This well, which includes four separate monitoring wells within the 2,000-foot-deep borehole, was installed during April and May 2000.

The purpose of this well and the related investigation was to help resolve several hydrogeologic issues regarding the deep-aquifer system that were identified by local agencies (M. B. Feeney, written commun., 1999). The hydrogeologic issues include

- (1) the continuity or connectivity of the aquifers that constitute the deep-aquifer system;
- (2) the age of the sediments that compose the deep-aquifer system;
- (3) the mechanism of recharge and age of ground water in the deep-aquifer system; and
- (4) the relation of water pressures in the deep-aquifer system to pressures in the submarine outcrops in Monterey Bay, the presumed source of seawater intrusion.

To address these issues, geologic, geophysical, hydraulic, and water-chemistry data were collected from the DMW1 borehole and monitoring wells to help answer the following specific questions about the deep aquifer systems in the Marina area:

- (1) What are the sources of recharge?
- (2) To what depth is ground water actively recharged?
- (3) At what rate does ground water move through the aquifers?
- (4) What is the nature of confining units between aquifers?
- (5) What is the source (or sources) of saline water?
- (6) How does the chemical composition of surface waters compare with the composition of ground waters?
- (7) What are the water-quality and chemical characteristics of the deep-aquifer system?
- (8) How do the aquifer systems penetrated by the monitoring wells correlate with those penetrated by the nearby deep-aquifer system supply wells?
- (9) Are the water-bearing units at site DMW1 hydraulically connected to the water-bearing units at the water-supply wells?

This report summarizes the geologic and hydrologic data collected at the DMW1 site, including possible relations with aquifers penetrated in nearby deep-aquifer system supply wells. A single monitoring-well site will not provide all the answers to

these questions, but will provide an initial basis for developing a geohydrologic framework of the deep-aquifer system and will guide further investigations of the deep-aquifer system in the Marina-former Fort Ord region of the Salinas Valley.

Description of Study Area

The Salinas Valley is a long, narrow trough extending about 70 mi northwest from the Monterey County line toward the southern part of Monterey Bay (fig. 1). The Salinas River drains an area of about 4,400 mi² in coastal central California.

The climate of the Monterey Bay region is characterized as mediterranean, with an average rainfall of about 22 in. in Watsonville and 14 in. in Salinas and adjacent coastal areas. The rainy season typically extends from November through April, and rainfall is greatest in the nearby mountains. The coastal climate is mild, and the average annual temperature is 14°C (58°F) in Salinas, California (National Oceanic and Atmospheric Administration, 2000).

The main population centers in the coastal region of the Salinas Valley include the city of Marina, the community of Castroville, Sand City, and the cities of Seaside and Monterey. The population of Marina has steadily declined during the last decade from 26,415 in 1990 to 17,471 in 1999 (U.S. Census Bureau, 2001). The former Fort Ord also was a major population center near Marina, and its closing may have contributed to this population decline. Inland, the city of Salinas represents the largest urban center in the largely agricultural-based Salinas Valley. In contrast to Marina, the population of Salinas has grown from 108,863 in 1990 to 123,607 in 1999 (U.S. Census Bureau, 2001).

Land and Water Use

The Marina and former Fort Ord region of the Salinas Valley is a mix of agriculture and urban land and water use (Templin and others, 1996). The main urban land-use area is the city of Marina, which, along with the surrounding urban areas, is served by ground water provided by the Marina Coast Water District (MCWD) (fig. 2). The surrounding agricultural areas are served by ground water pumped from individual wells owned by farmers. Most of the ground-water use in the vicinity of the DMW1 site is for urban water supply.

Until 1982, ground water was pumped from wells tapping the upper-aquifer system in the Marina area such as MCWD 9 that was completed to 588 ft below land surface (bls) in January 1979. By 1982, salinity and dissolved-solids concentrations were increasing in the “180-foot” and “400-foot” aquifers, and in 1983 MCWD completed its first deep-aquifer system water-supply well, well No. 10 (fig. 2) (Geoconsultants, Inc., 1983). The successful completion of this well was followed by the installation of two more deep-aquifer system water-supply wells, MCWD 11 and 12, in 1986 and 1989, respectively (Geoconsultants, Inc., 1986, 1989). Three other deep-aquifer system wells (Fontes No. 1, Mulligan Hill No. 1, and well No. 3, fig. 2) were previously completed just to the north of Salinas River between 1976 and 1983.

Geohydrology of the Salinas Valley

The Salinas Valley contains an extensive alluvial aquifer system bounded by bedrock mountains (fig. 1) and in part by the Zayante-Vergeles Fault zone on the northeast and by the fault zone that includes the Navy-Tularcitos, Chupines, Seaside, and Ord Terrace Faults (Wagner and others, 2000; Rosenberg, 2001) on the southwest (fig. 2). The alluvial deposits of the aquifer system are as great as 2,000 ft thick and are composed of river and sand dune deposits of Holocene and Pleistocene age that are underlain by the Aromas Sand and Paso Robles Formation of Pleistocene age. The Purisima Formation of Pliocene age underlies the Paso Robles Formation and the Aromas Sand. The Monterey Formation (shale) of Miocene age underlies the Purisima Formation and is, in turn, underlain by the granitic basement rocks (Green, 1970). The Monterey Formation and the granitic basement represent the relatively impermeable bedrock that underlies the regional alluvial aquifer systems.

In the Marina area, previous investigators (Geoconsultants, Inc., 1993) have grouped the water-bearing sediments into an upper- and a deep-aquifer system. The upper-aquifer system includes the shallow perched aquifer, the “180-foot” aquifer, the “400-foot” aquifer, and the “900-foot” aquifer. The Salinas Valley has undergone extensive ground-water development in the upper-aquifer system, which is locally composed of river channel and sand dune deposits of Holocene and Pleistocene age (Green, 1970). The term “400-foot” aquifer is extended in some parts of the Salinas Valley,

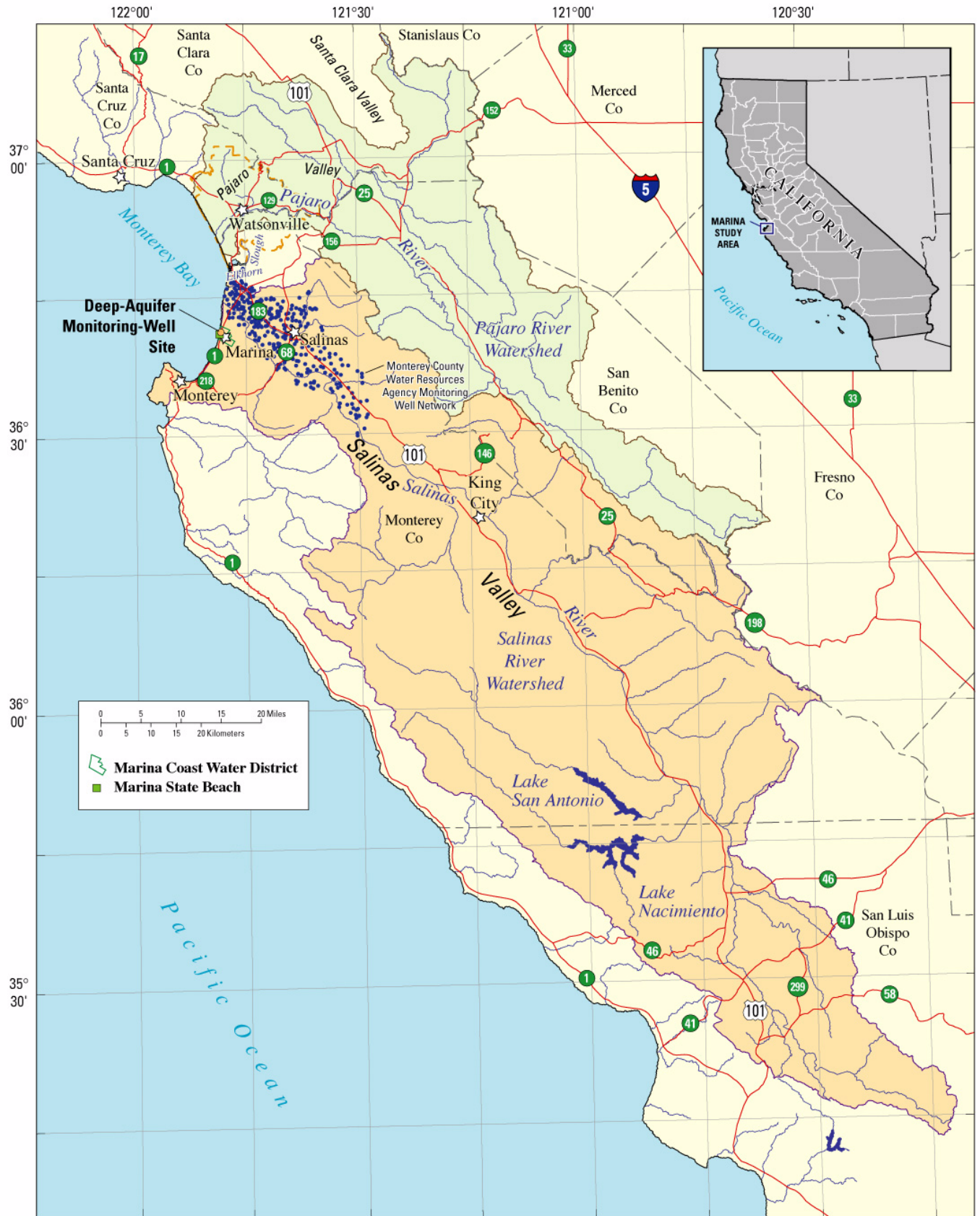


Figure 1. Location of deep-aquifer system monitoring-well site in the Salinas Valley at Marina, California.

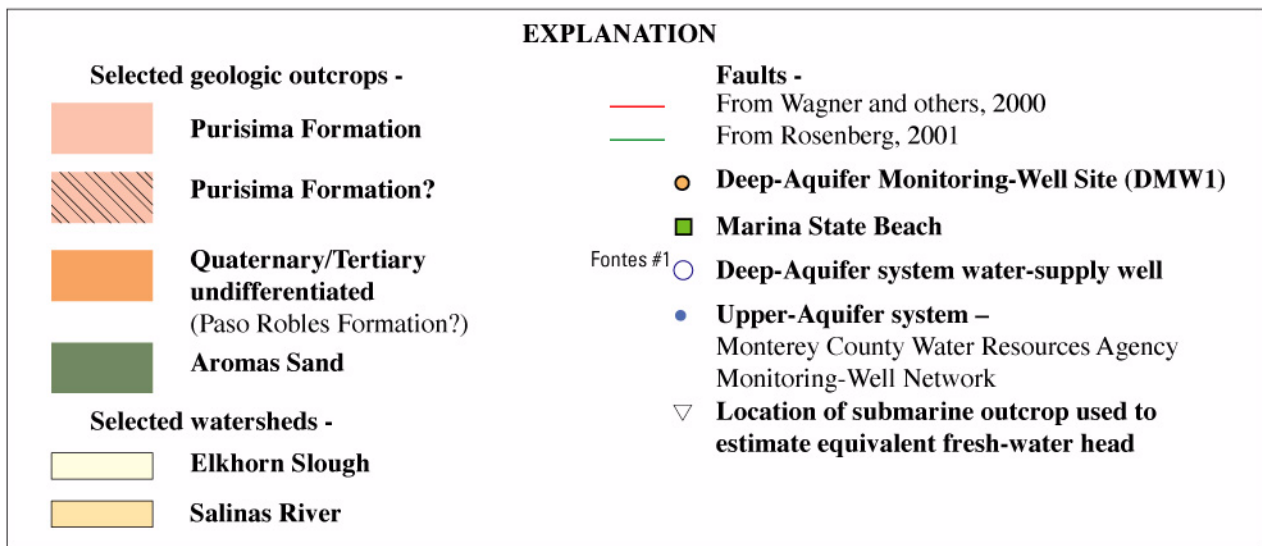
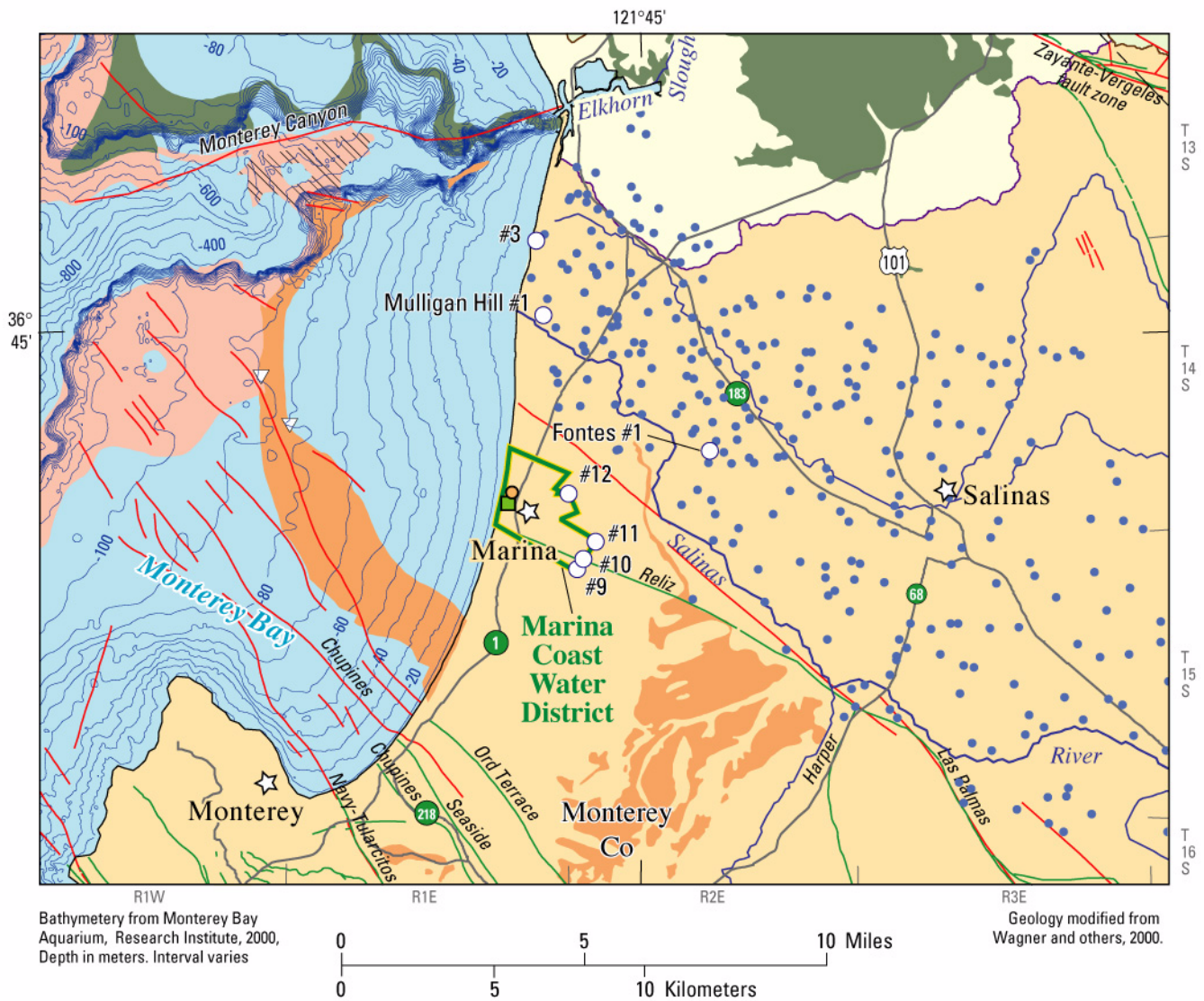


Figure 2. Location of deep-aquifer system monitoring-well site and selected water-supply wells, Marina, California.

such as at Marina, to include sediments to depths as great as 700 ft bls. The base of the “400-foot” aquifer was previously delineated as the base of the Aromas Sand (Green, 1970). The underlying sediments that compose the basal part of the upper-aquifer system contain parts of the Paso Robles Formation (Green, 1970) and may locally be designated as the “900-foot” aquifer (Geoconsultants, Inc., 1993).

The geohydrologic framework of the deep-aquifer system in the Marina area remains uncertain and may represent a transition between terrestrial Pleistocene-age sediments deposited in re-incised channels along the ancestral Salinas River and shallow marine-shelf sediments that were aligned with and bounded by the southwestern side of the Marina “Trough” (Geoconsultants, Inc., 1993; fig. 3). Previous investigators delineated the deep-aquifer system as the interval between 1,300 and more than 2,000 ft bls (Geoconsultants, Inc., 1993) of Pleistocene-age deposits based on data from the MCWD deep-aquifer system water-supply wells. Quaternary-Tertiary undifferentiated sediments, which may be the Paso Robles Formation (Green, 1970), outcrop west of the monitoring-well site about 25,500 ft (4.8 mi) offshore (Wagner and others, 2000) at a depth of about 262 ft below sea level (fig. 1). These deposits may be hydraulically connected to the Paso Robles Formation at the DMW1 site. The Purisima Formation crops out on the southwestern side of the Monterey submarine canyon about 30,500 ft (5.8 mi) offshore (Wagner and others, 2000) from the monitoring-well site at a depth of about 295 ft below sea level (fig. 2). Additional geologic investigations, beyond the completion of the DMW1 site, are needed to establish this stratigraphic relation.

Approach to Investigation

During the drilling of 2,012-foot-deep multiple-well monitoring site, DMW1 (tables 1 and A1.1), cuttings were collected at regular intervals and cores at selected depths (appendix 1). Geophysical logs were run after reaching final borehole depth. Fossils contained in the cuttings and cores were used to establish the age of the sediments (appendix 2). Water extracted from cores from depths below 800 ft and

water sampled from the four monitoring wells were analyzed for general water chemistry (appendix 3), as well as constituents that would help determine the source, age, and movement of ground water in the deep aquifers. Each of the wells within the DMW1 borehole also was hydraulically tested to determine selected aquifer properties (table 2). The specific methods of data collection and analysis are summarized, in addition to the presentation of the data and results, in later sections and the appendices of this report.

All of these data and estimates of physical properties were integrated into a preliminary interpretation of the geohydrology of the DMW1 site, based on interpretations of the geologic, hydrologic, and geochemical conditions of the aquifers at the DMW1 site and correlations to conditions at the nearby MCWD deep-aquifer system water-supply wells. Because this study is largely limited to data obtained from one monitoring-well site, no broader or more detailed interpretations of the regional geology and hydrology for the coastal regions of the Salinas Valley were made as part of this study.

Acknowledgments

This study could not have been accomplished without the assistance of personnel from the Monterey County Water Resources Agency (MCWRA) and Marina Coast Water District (MCWD). Analysis and processing of core data was with the help of Bradley Carkin, Daniel Ponti, and Brian Edwards, U.S. Geological Survey, Menlo Park, California (appendix 1). James Gibbs, U.S. Geological Survey, Menlo Park, California, provided down-hole shear wave log analyses. Collin Williams, U.S. Geological Survey, Menlo Park, California, provided detailed temperature-log analyses. Kevin Knudsen (U.S. Geological Survey, Portland Oregon), provided additional multi-spectral gamma and electromagnetic conductivity logs. Charles Powell and Kristin McDougall, U.S. Geological Survey, Menlo Park, California, provided fossil identification (appendix 2). Michael Land, U.S. Geological Survey, San Diego, California, performed sampling and sample analysis of pore waters from the cores (appendix 4).

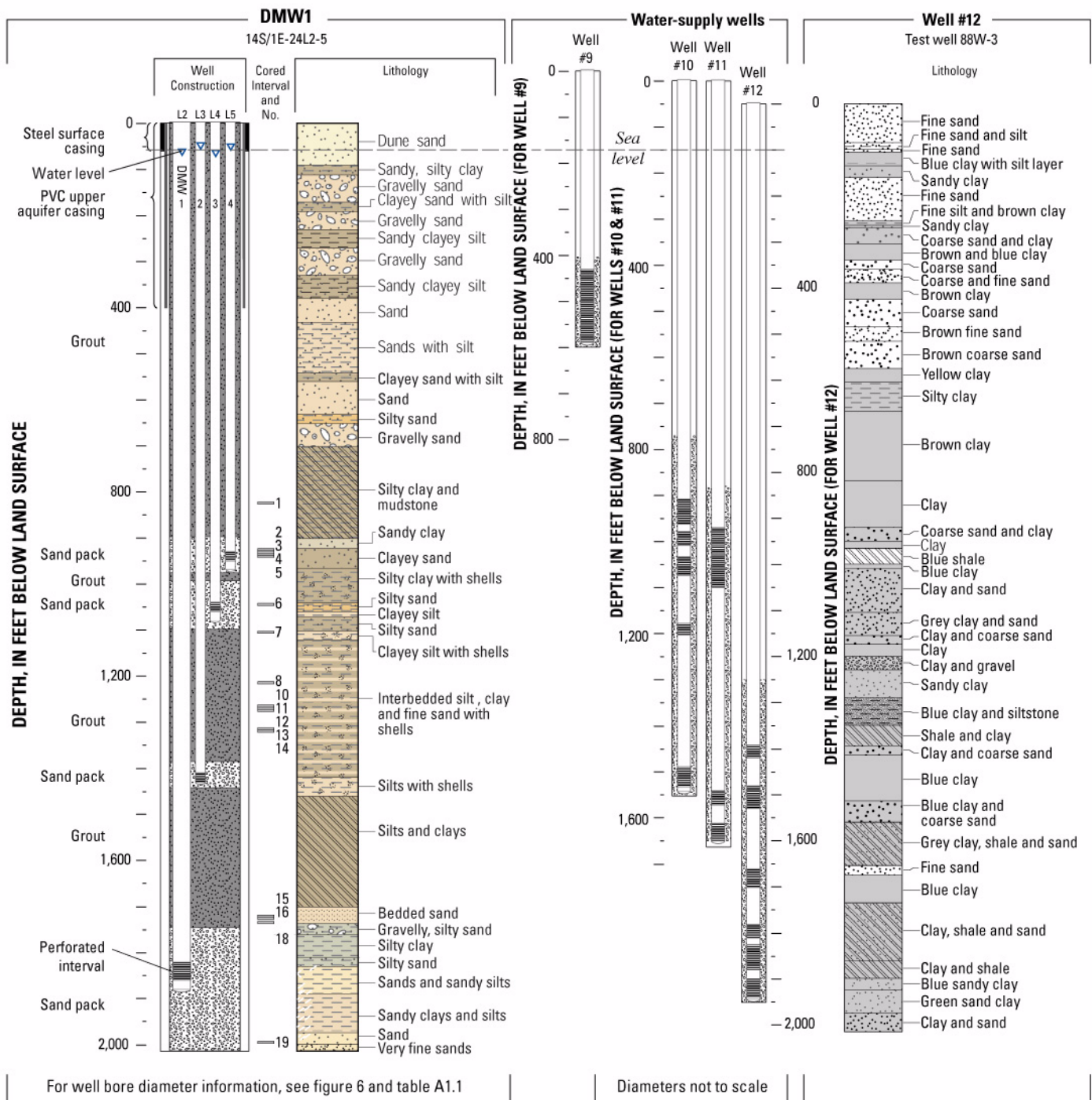


Figure 3. Well construction and lithology for the deep-aquifer monitoring well and selected nearby water-supply wells, Marina, California.

GEOHYDROLOGIC DESCRIPTION OF DMW1

The deep-aquifer system monitoring well (DMW1) site is located at the former wastewater-treatment facility and current (2000) offices of the Marina Water District at Marina State Beach (fig. 1), and is approximately 55.6 ft above sea level. The site contains four separate wells in a single borehole, each screened at a different depth below 800 ft and corresponding to the interval screened in a nearby MCWD deep-aquifer system water-supply wells. A schematic of the wells and the lithology of the DMW1 site are shown in figure 3, and general well construction information is provided in table 1. Water levels range from 58 to 73 ft bls. These water levels are all below sea level.

The DMW1 site includes a 14-inch-diameter steel casing installed to 98 ft bls in a 21-inch-diameter borehole and sealed from the bottom with cement as required by the well permit from the County of Monterey. A tightly fitting 10-inch-diameter polyvinyl chloride (PVC) casing was installed to a depth of 400 ft bls to help seal off the saline zones in the upper aquifer system. Within the screened interval of the monitoring wells, the borehole diameter varies from 9 7/8 to 7 7/8 inch, depending on the depth of the well. Monitoring wells DMW1-2, -3, and -4 are 2 inch inner diameter, schedule 80 PVC, each with a 20 foot, 1.2 x 0.02 inch slotted screen near the bottom. Well DMW1-1 is 3 inch diameter, schedule 80 PVC with a 40-foot screen near the bottom. The screened interval of each monitoring well is sand packed with a mixture

of coarse aquarium and number 3 Monterey sand, and bentonite pressure-grout seals separate the sand packs.

Geologic Data

The geologic data indicate multiple layers of coarse- and fine-grained sediments throughout the depth of the well (fig. 3). However, these layers are not homogeneous, as evidenced by the cores (fig. 4). Layers of fine-grained deposits increase in occurrence below a depth of 700 ft (fig. 3). Marine sediments, which are indicated by drill-cutting samples that contain shell fragments, start at about 1,005 ft bls and are present intermittently to 1,920 ft bls (table A1.1). Calcite crystals also are in the drill cuttings between 1,560 and 1,810 ft bls and may represent excess dissolved calcite that precipitated from pore water as the cuttings dried during storage.

A major change in color and type of sediments occur at 955 ft bls. In general, drill cuttings above 955 ft are a characteristic buff-to-tan color that contain no shell fragments, indicating that the sediments were deposited on land. Below 955 ft the deposits change to gray and contain shell fragments, indicating they were deposited in the ocean (table A1.1). The core photographs show that a major transition in color occurs between core 5 (937–942 ft bls) and core 7 (1,102–1,107 ft bls) (figs. 4, A3.1 in Appendix 1). Core 6 (1,042–1,046 ft bls) may represent a transition from land to ocean deposits; drill cuttings from 955 to 1,050 ft bls are characterized by tan-to-buff color and the presence of shell and wood fragments. The remaining cores represent sediments deposited in the ocean: The

Table 1. Summary of well completion for the deep-aquifer system multiple-well monitoring site, Marina, California

[ft., foot; bls, below land surface]

[Well site is located at latitude 36°41'57" and longitude 121°48'27", NAD 1927]

Local well name	State well number	Depth to top of perforations (ft bls)	Depth to bottom of perforations (ft bls)	Depth to water (ft bls) [6/13/00]	Altitude of water (ft above sea level) [6/13/00]
DMW1-4	14S/1E-24L5	930	950	58.6	-3.0
DMW1-3	14S/1E-24L4	1,040	1,060	73.0	-17.4
DMW1-2	14S/1E-24L3	1,410	1,430	56.4	-8
DMW1-1	14S/1E-24L2	1,820	1,860	72.5	-16.9

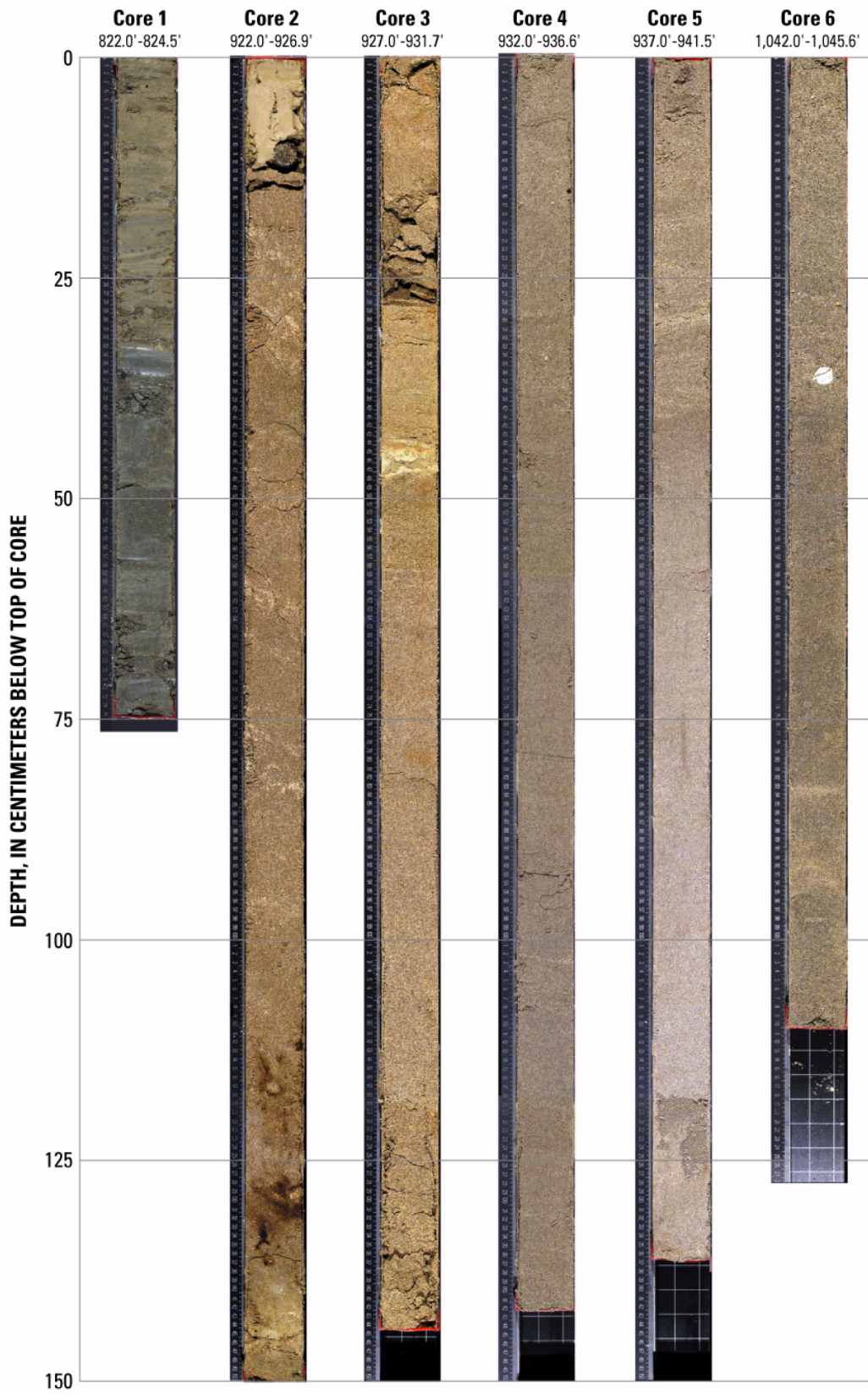


Figure 4. Cores 1 to 19 from the deep-aquifer system monitoring-well site, Marina, California.

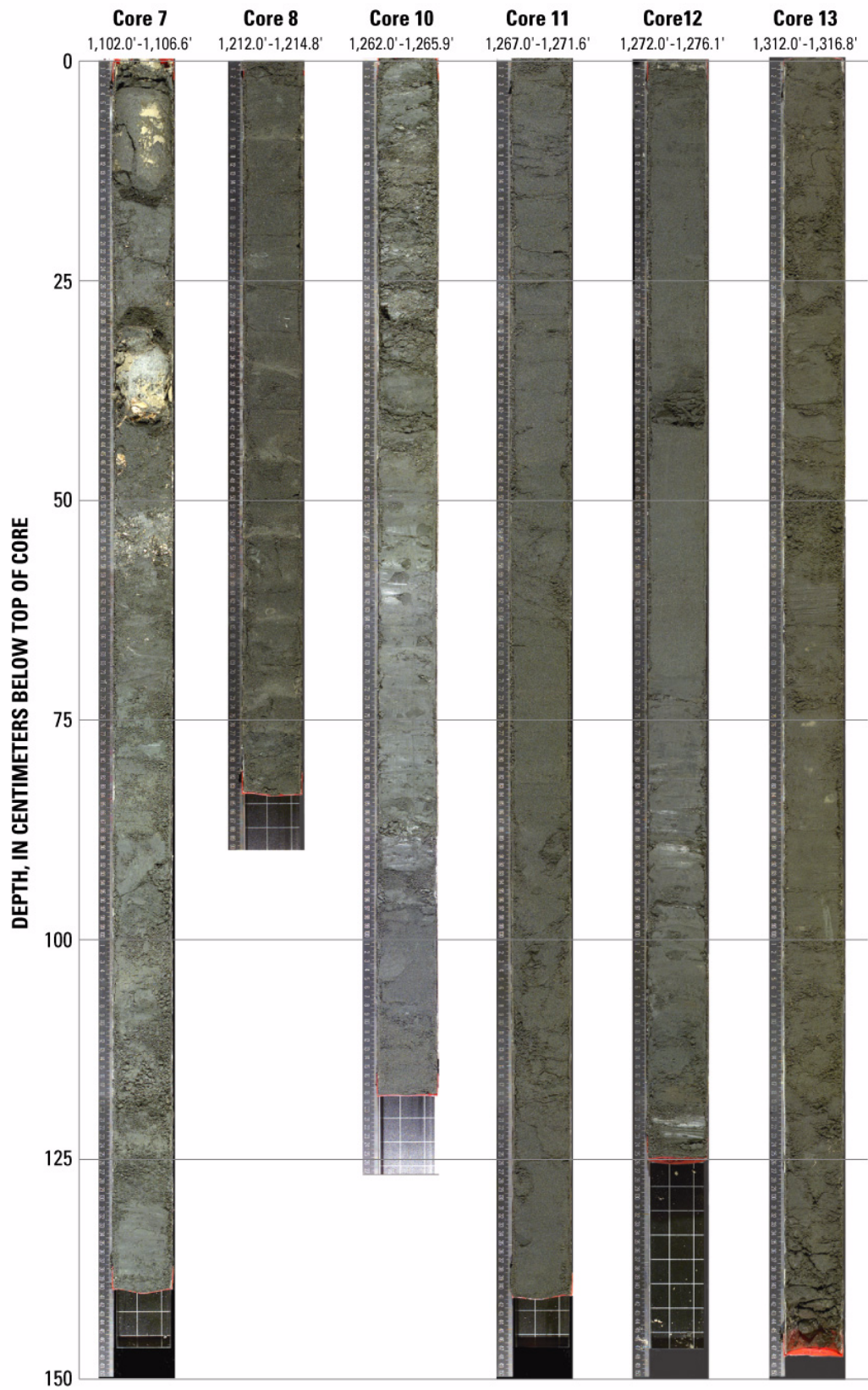


Figure 4.—Continued.

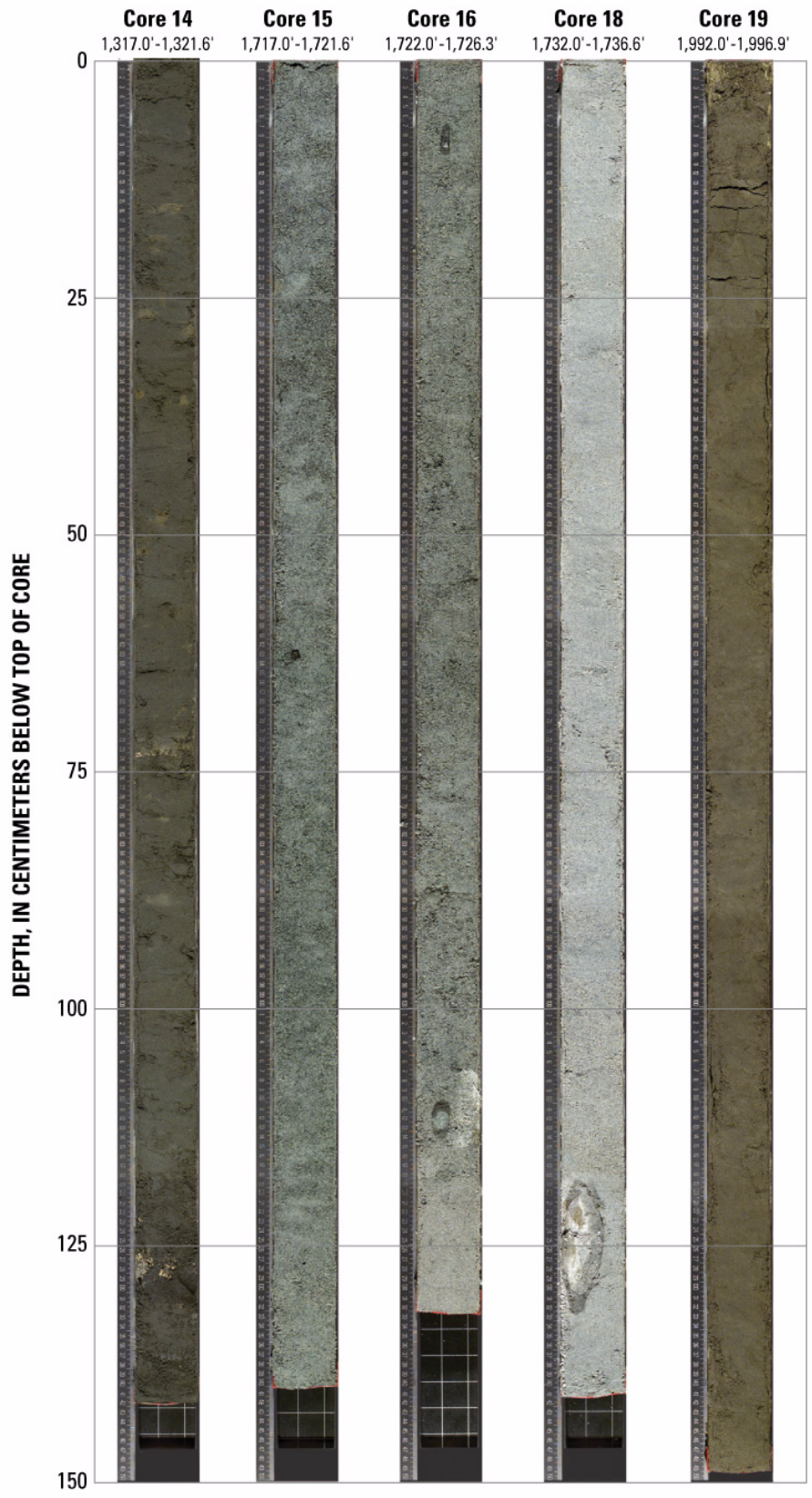


Figure 4.—Continued.

material of cores 7 (1,102–1,107 ft bls) through 18 (1,732–1,737 ft bls) have an olive-gray color; the deepest core, core 19 (1,992–1,997 ft bls), has a green-gray color suggesting sediment deposition in a chemically reducing marine environment. Although weathered fragments of the Monterey Formation were encountered in some drill-cutting samples, the shales of the Monterey Formation were not penetrated to the total drilled depth of 2,012 ft at the DMW1 site.

Geophysical Data

The geophysical logging yielded additional information about the distribution of aquifers, fine-grained interbeds and confining units between aquifers, the relation of water quality with respect to depth, and the nature of ground-water flow and seawater intrusion. The following summaries identify the geologic and hydrologic features determined from the geophysical data collected at the DMW1 site (figs. 5, 6, 7, 8). These data are summarized in figure 5 along with the related stratigraphic and aquifer-system layering that was determined from these data (see the “Hydrostratigraphy of DMW1 Site” section of this report).

Geophysical logging was completed in the open borehole after the site was drilled, and additional logs were completed after well completion. The logs completed after drilling include caliper, bulk-natural gamma ray, 16-inch and 64-inch resistivity, self-potential resistivity, electromagnetic conductivity (EM), borehole inclinometer, temperature, and acoustic (figs. 5 and 6). Additional logs completed after well completion include multi-spectral natural gamma ray (fig. 7), EM (fig. 8), downhole shear-wave velocity (James Gibbs, U.S. Geological Survey, written commun., 2000) and temperature (Collin Williams, U.S. Geological Survey, written commun., 2001).

The figures shown in this report represent the final set of geophysical logs completed after drilling in May 2000 (figs. 5 and 6). Additional logs were completed in November 2000 to help assess the stratigraphy and the potential for seawater intrusion (figs. 7 and 8). The borehole inclinometer log indicates that the final drill hole is relatively vertical with

maximum inclinations of less than 1 degree to a depth of about 1,400 ft bls and less than 2 degrees from 1,400 to 2,000 ft bls.

The bulk-natural gamma-ray logs are used to help locate low permeability silt and clay layers that may be difficult to determine from conventional electric logs where saline water is present. These silt and clay layers represent potential confining units between aquifers. The bulk-natural gamma ray and EM logs and drill cuttings (fig. 5) indicate that substantial confining units occur from 100 to 110 ft, 330 to 410 ft, 480 to 550 ft, 660 to 710 ft, 720 to 910 ft, 950 to 1,030 ft, 1,060 to 1,170 ft, 1,380 to 1,400 ft, 1,430 to 1,700 ft, and 1,900 to 1,980 ft. These confining units are commonly very thickly bedded; below 1,005 ft they are marine fine-grained deposits that are typically saline and contain shell fragments (table A1.1). The bulk-natural gamma-ray log also shows seven distinctive peaks that may represent beds that can be used for future stratigraphic analysis of the aquifer systems in the Salinas Valley. These beds potentially represent chronostratigraphic markers that may correspond to stratigraphic layers at other well locations. The seven gamma peaks occur from 100 to 110 ft, 958 to 962 ft, 990 to 997 ft, 1,010 to 1,020 ft, 1,060 to 1,070 ft, 1,240 to 1,245 ft, and 1,685 to 1,700 ft bls (fig. 5). In addition, the multi-spectral gamma logs indicate that the shallowest gamma spike, at about 100 ft bls, is relatively enriched in thorium, whereas the spikes at about 1,025 and 1,075 ft bls are relatively enriched in potassium and uranium (fig. 7). These differences suggest a different origin in the radiogenic constituents that may represent a different origin for the clay layers.

The combination of spontaneous-potential, short- and long-normal resistivity, bulk-natural gamma ray, and EM logs (figs. 5 and 8) were used to identify the relative quality of water within aquifer zones. Lower resistivity in sandy zones (from drill cuttings and cores), combined with lower gamma-ray activity and higher EM conductance (figs. 5 and 8), indicates saline water in most water-bearing zones shallower than 720 ft bls and from about 1,025 to 1,130 ft bls (fig. 8). Whereas, higher resistivity in sandy zones, combined with relatively lower gamma-ray activity and lower EM conductance, indicates fresher water from about 910 to 950 ft bls (DMW1-4), 1,130 to

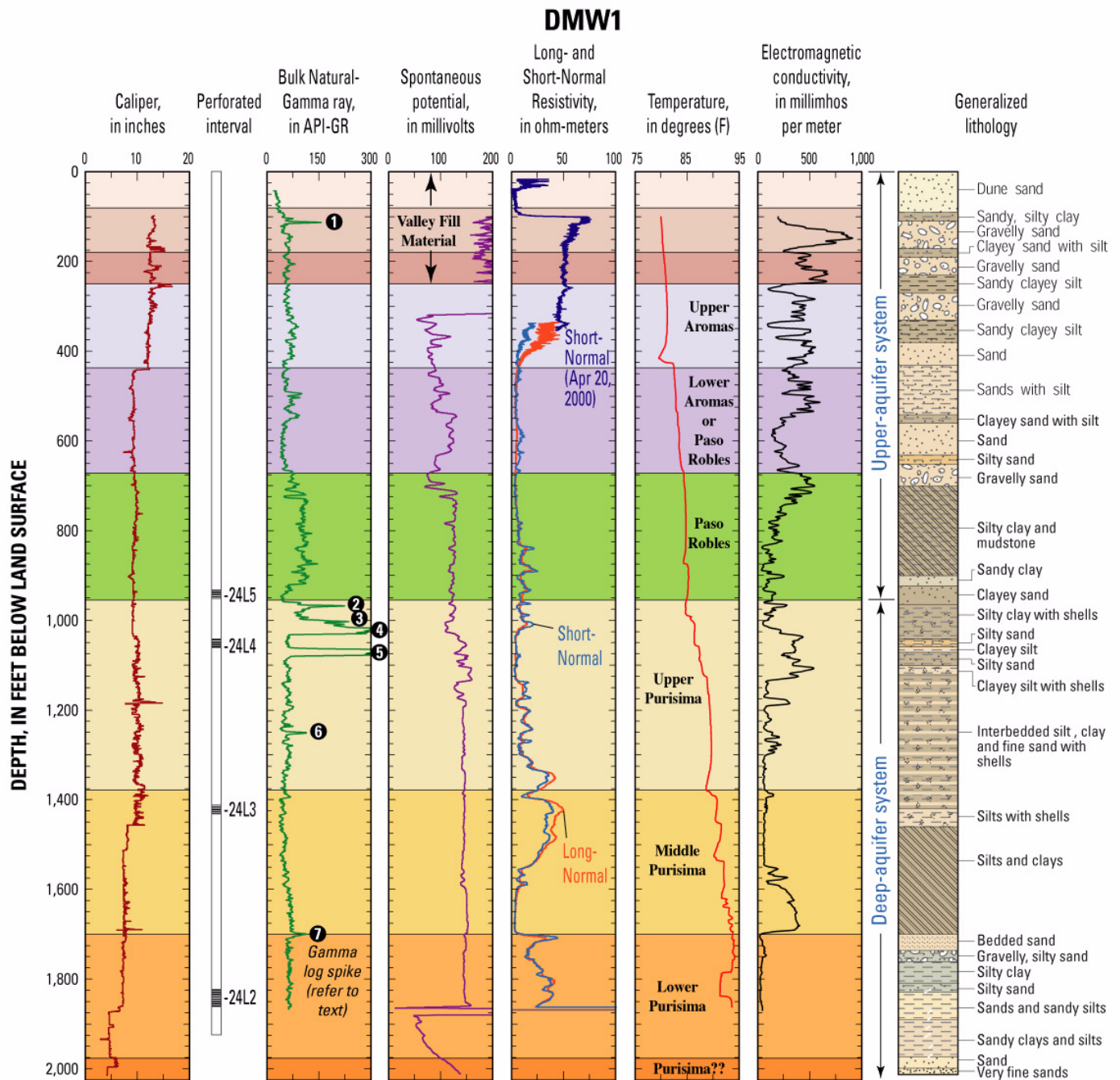


Figure 5. Lithology and geophysical logs for the deep-aquifer system monitoring-well site, Marina, California.

DMW1

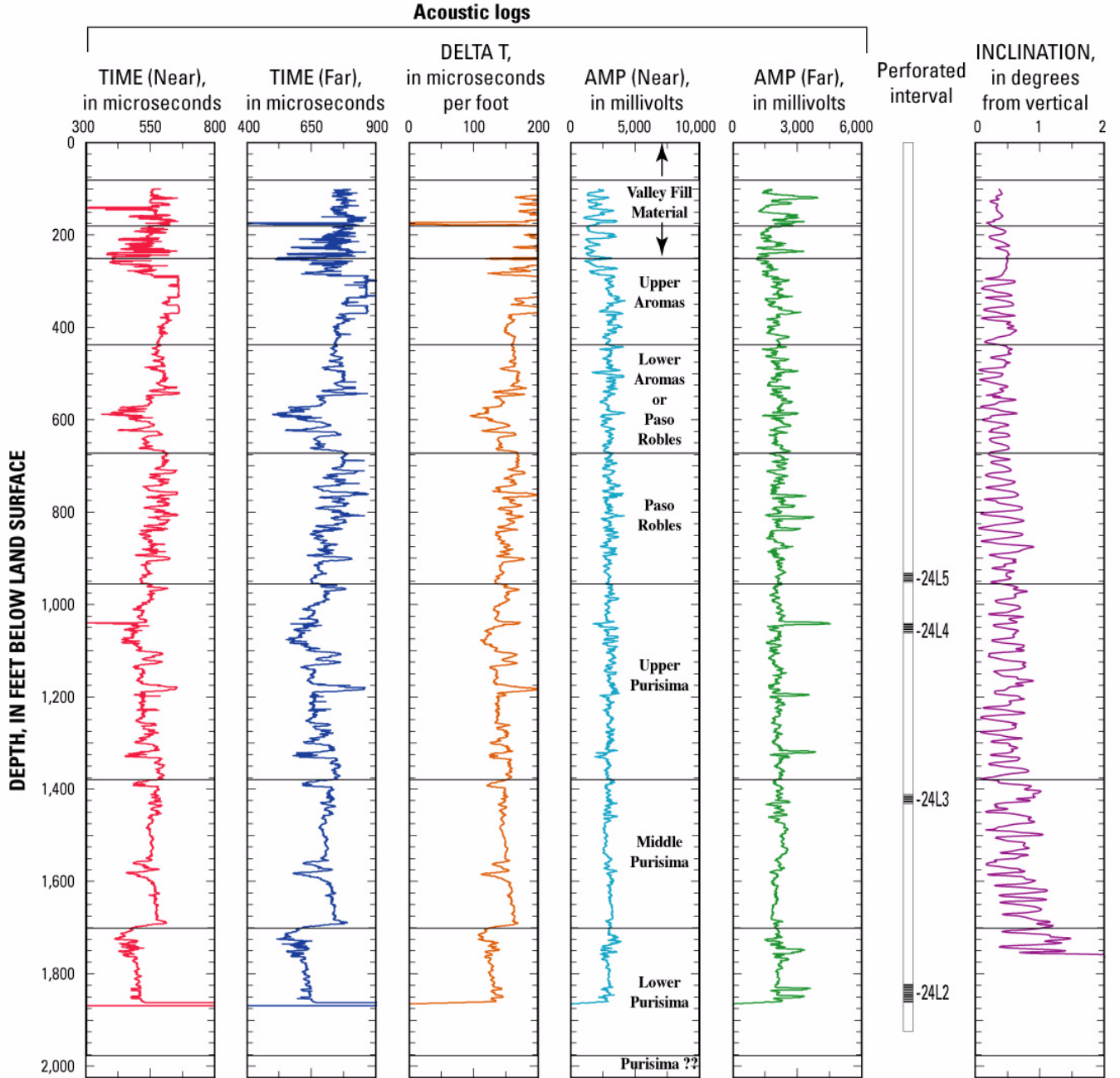


Figure 6. Acoustic and borehole inclinometer geophysical logs for the deep-aquifer system monitoring-well site, Marina, California.

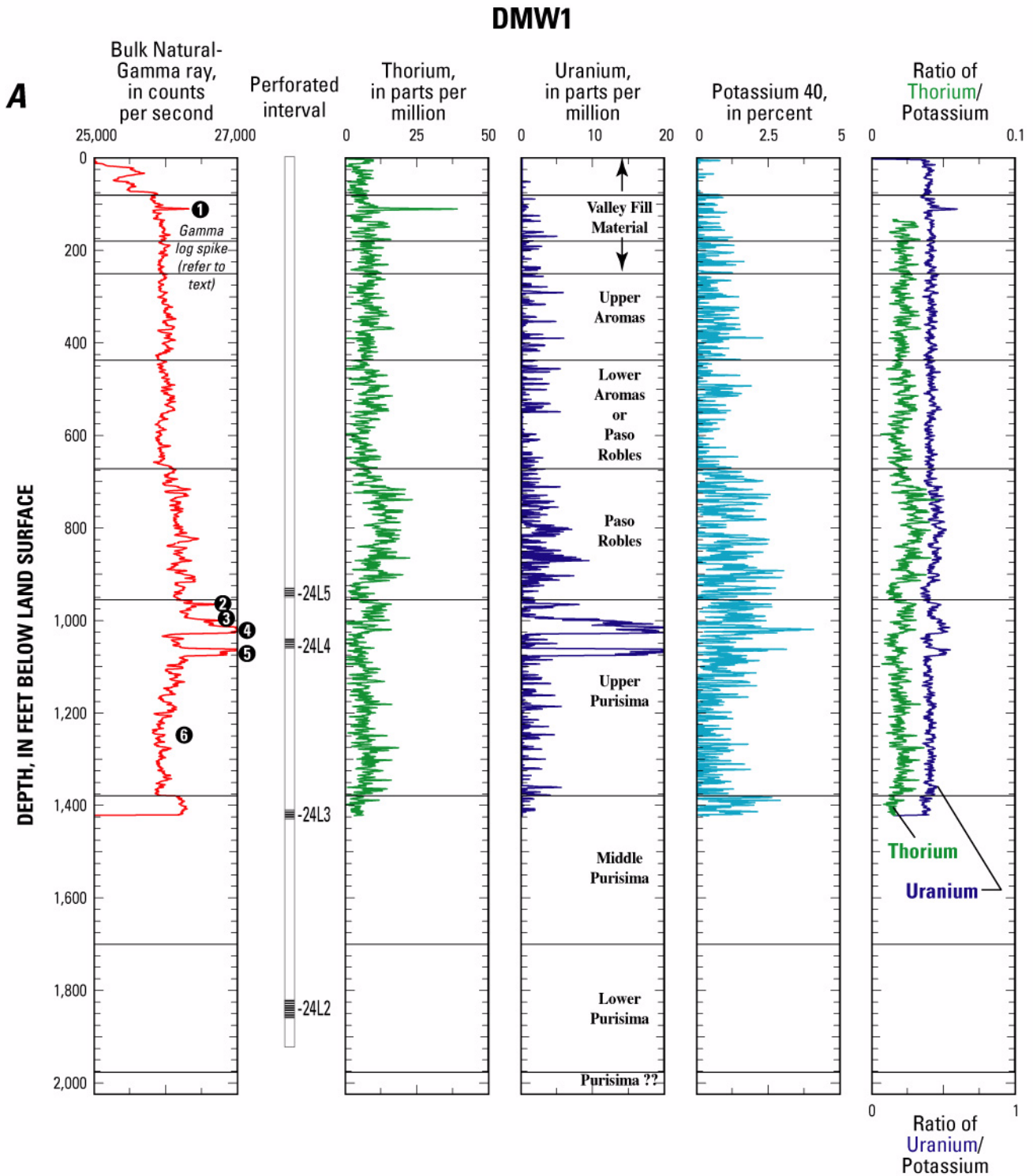


Figure 7. Multi-spectral natural gamma ray geophysical logs for the deep-aquifer system monitoring-well site, Marina, California.

DMW1

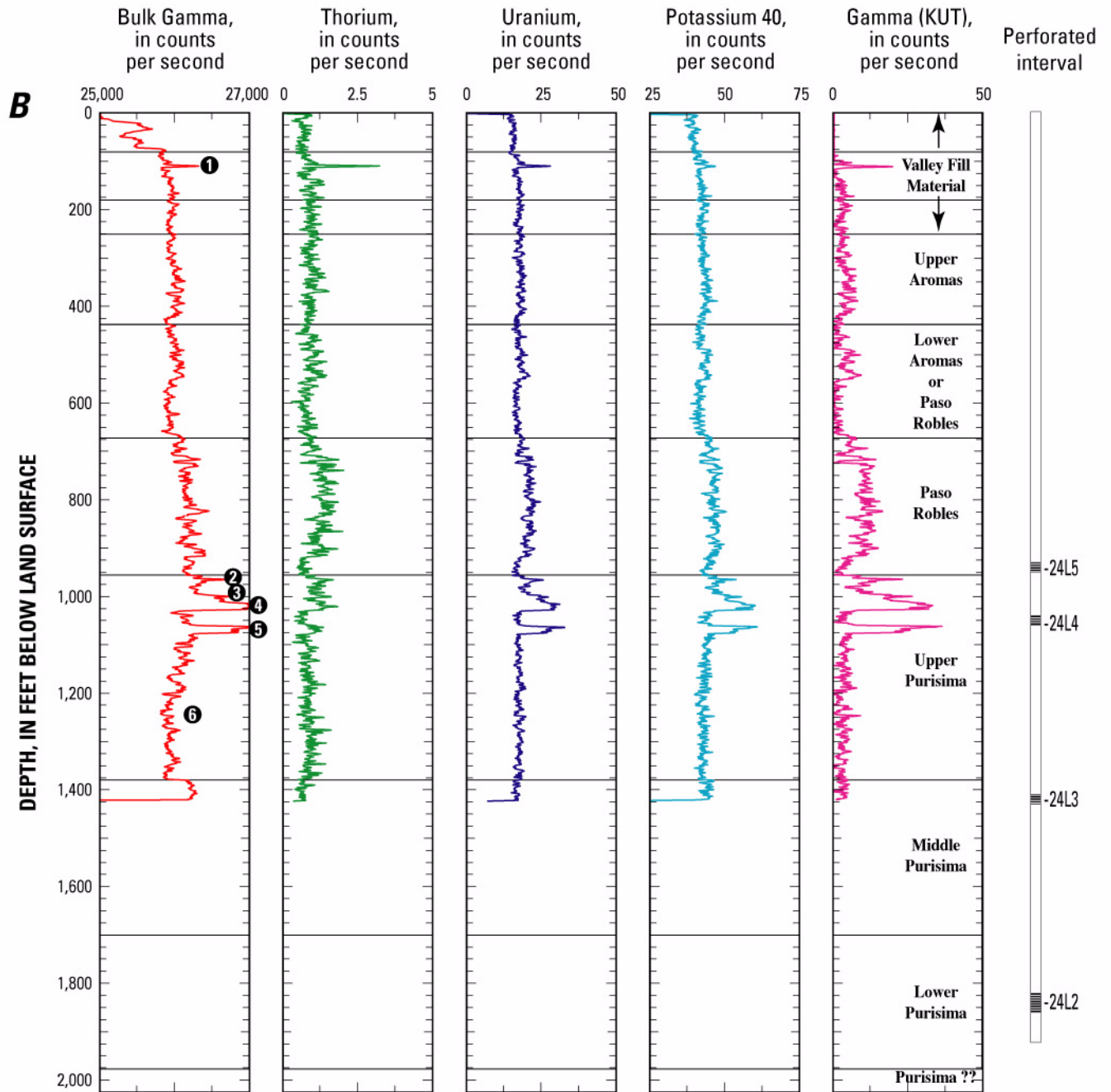


Figure 7.—Continued.

DMW1

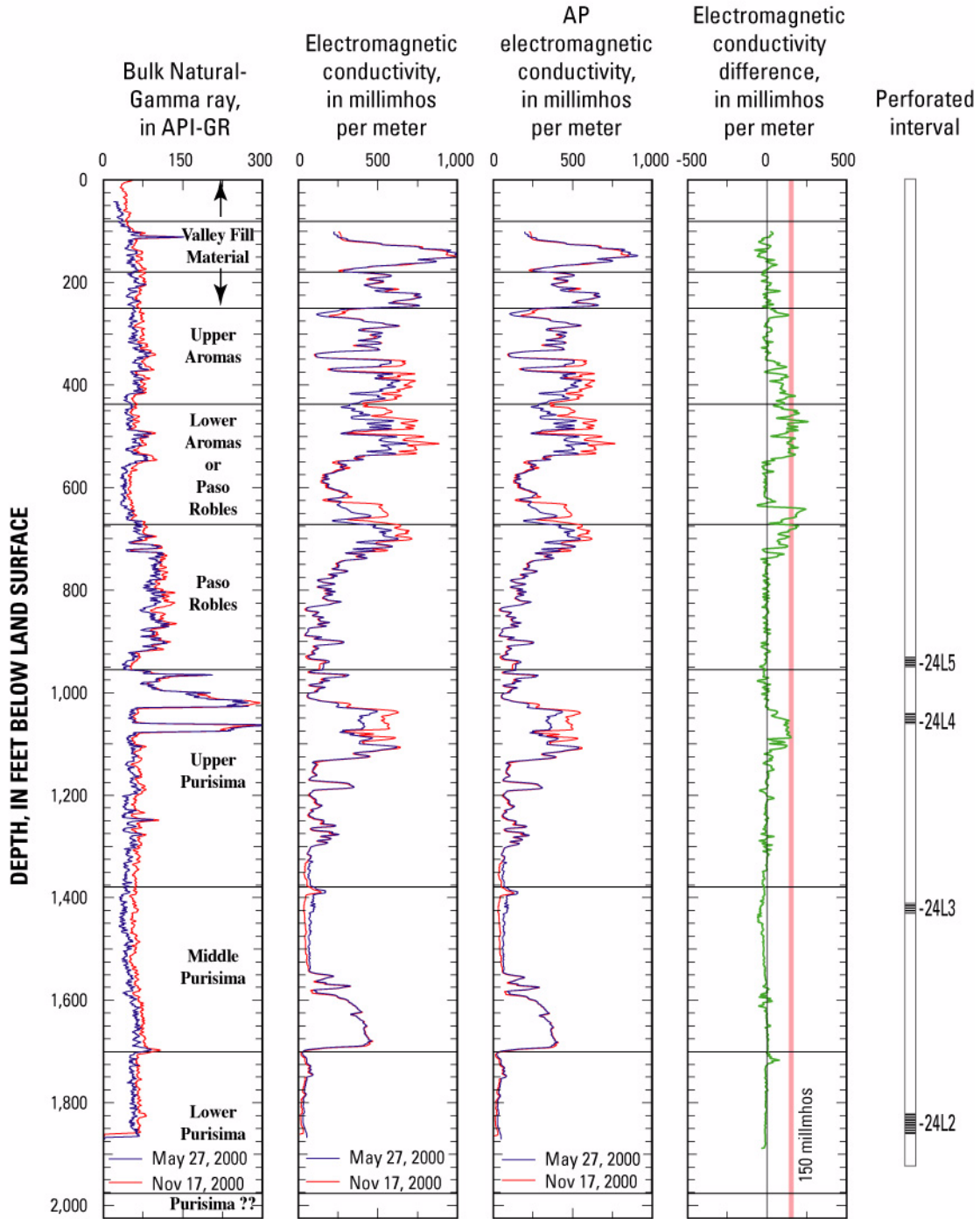


Figure 8. Geophysical logs for the deep-aquifer system monitoring-well site, Marina, California.

1550 ft bls, and below 1,650 ft bls. Potentially saline marine silt and clay layers occur at depths from about 1,025 to 1,130 ft bls and from 1,550 to 1,700 ft bls. (fig. 5).

Changes in water quality and especially seawater intrusion can be effectively monitored with the periodic acquisition of EM logs and water-quality samples. For example, the curvilinear relation (fig. 9) between log-chloride concentrations from pore-water samples and log-EM demonstrates that the EM appears to be more related to additional chloride concentration above a conductivity of about 150 mmho/m (millimhos per meter). The two sets of EM logs (fig. 8), May 27 and November 17, 2000, indicate ground water with some degree of salinity to about 1,180 ft bls. Based on differences in EM conductivity between the two logs, some changes in water quality probably occurred between May and November. In this report, peaks greater than 150 mmho/m in the EM-difference log were used to identify potential zones of increased salinity. As shown on figure 8, increases in salinity occur in five very narrow and discrete zones between 350 and 400 ft, at about 500 ft, and between 630 and 675 ft. The largest differences occur in the shallowest zone between 350 and 400 ft and may represent a small amount of seasonally driven seawater intrusion in the basal coarse-grained units of the “400-foot” aquifer. There are additional differences of less than 150 mmho/m in the EM-difference log from 675 to 700 ft and from 1,025 to 1,100 ft. However, synoptic water-chemistry samples combined with EM logs are needed to determine if these differences are increases in salinity due to chloride.

Paleontologic Data

Micro-fossil analyses of samples from cores and drill cuttings (appendix 2); (Kristin McDougall, U.S. Geological Survey, written commun., 2001) indicate that sediments from 1,152 to 1,660 ft bls are Pliocene in age and correspond to the Purisima Formation. These micro-fossils also indicate a marine shelfal environment on the deeper part of a submergence depth of 0 to 150 ft below sea level. The fine-grained mudstone of core 7 (1,102 to 1,107 ft bls) may represent the younger part of the upper Purisima Formation. These micro-fossils appear to be distinctly

different assemblages from the groups examined by Ingle (1985, 1986, 1989) from the MCWD water-supply wells 10, 11, and 12. These results suggest that the monitoring well and the water-supply wells penetrate sediments of different age and different depositional environment.

Mega-fossil identification (appendix 2; Charles Powell, U.S. Geological Survey, written commun., 2001) indicates that the sediments cored from DMW1 at a depth of about 1,317 ft bls are typical of the marine sediments of the Purisima Formation of Pliocene age (appendix 2). The identification of the two mega-fossil samples from cores 7 and 13 could not be used for a definitive geologic age or determination of the sedimentary environment. However, Powell (appendix 2) indicates that fossils from cores 7 and 13 are similar to those from the Purisima Formation. In addition, the identification of *Anadara trilineata* from core 14 (1,317 to 1,322 ft bls) indicates an age of late Miocene to late Pliocene and a marine environment of typical water depths of 0 to 150 ft below sea level. This fossil is common in the Purisima Formation.

Hydrostratigraphy of DMW1 Site

The hydrostratigraphy represents the geologic and hydrologic data collected at the DMW1 site. In addition, this hydrostratigraphy is part of the broader geohydrologic framework of the ground-water resources that represent the features of the Salinas Valley. The data from the DMW1 site has provided new information regarding the geologic and hydrologic relations of the aquifer systems in the Marina area of the Salinas Valley.

The upper-aquifer system at the DMW1 site was identified as the six depth-sequential aquifer-system units within the nonmarine sediments that extend to a depth of 955 ft bls, which is the base of the Paso Robles Formation (fig. 5). The upper-aquifer system constitutes the shallow perched aquifer in the dune sand, the “180-foot” and the “400-foot” aquifers within the older valley-fill alluvium and upper Aromas, and the “900-foot” aquifer in the lower Aromas and Paso Robles Formation (fig. 5). Though these depth-sequential aquifer-system units are referred to here as “aquifers,” they generally constitute heterogenous assemblages of fine- and coarse-grained deposits.

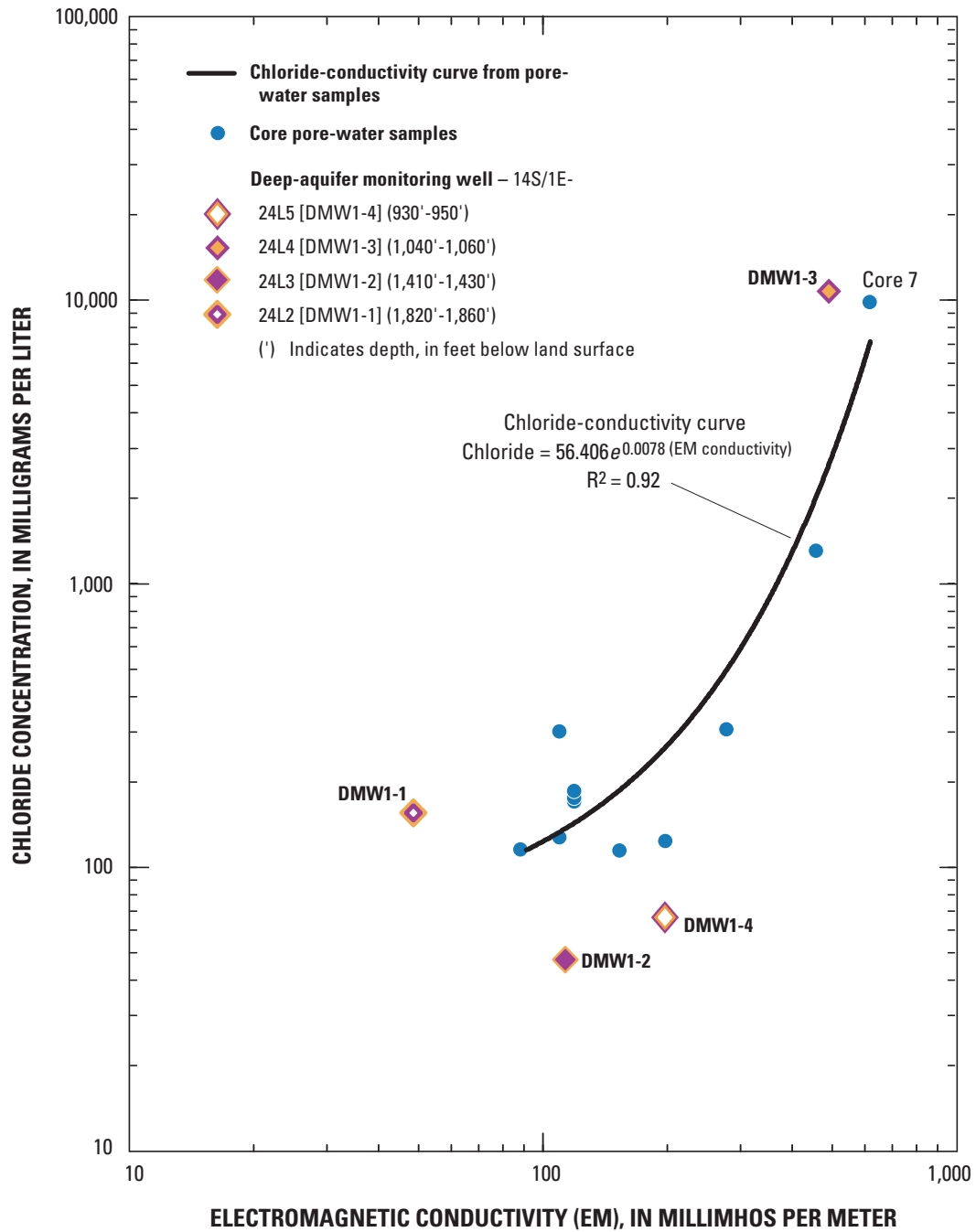


Figure 9. Relation between chloride concentration and electromagnetic conductivity for core pore-water and well-water samples from the deep-aquifer system monitoring-well site, Marina, California.

The deep-aquifer system at the DMW1 site is probably all within the Purisima Formation. The deep-aquifer system is identified in DMW1 as the aquifers within predominantly marine sediments that extend from the base of the Paso Robles Formation from a depth of 955 ft to more than 2,012 ft bls. Mega-fossil identification indicates that the sediments cored from DMW1 at a depth of about 1,317 ft bls are typical of the marine sediments of the Purisima Formation of Pliocene age (appendix 2). Micro-fossil identification also confirms that these deposits are from the Purisima Formation of Pliocene age (appendix 2). The geophysical logs from the DMW1 site indicate four groups of layers of sediment between 955 and 2,012 ft bls, which probably represent several erosional and depositional cycles within the Purisima Formation.

The geophysical and geologic data collected from this study has enabled the identification of 10 hydrostratigraphic units at the DMW1 site (fig. 5) that were modified from the preliminary classification by Green (1970).

UPPER-AQUIFER SYSTEM

- (1) **0 to 80 ft bls**—The dune sands of Holocene age may represent an extension of the Salinas Valley perched “A” aquifer that is bounded below by the Salinas Valley Aquiclude (Tinsley, 1975; Andrew Fisher, University of California at Santa Cruz, written commun., 2002)
- (2) **80 to 180 ft bls**—The “180-foot” aquifer composed of valley-fill alluvium of Holocene to Pleistocene age.
- (3) **180 to 250 ft bls**—The water-bearing units between the “180-foot” and the “400-foot” aquifers, which may be composed of additional valley-fill alluvium of Holocene to Pleistocene age.
- (4) **250 to 450 ft bls**—The upper part of the “400-foot” aquifers is composed of water-bearing sands and gravels, which may be equivalent to the upper Aromas Sand of Pleistocene age.
- (5) **450 to 670 ft bls**—The lower part of the “400-foot” aquifer is predominantly composed of water-bearing sands, includes a thin basal gravelly sand, and may represent the lower Aromas Sand of Pleistocene age.
- (6) **670 to 955 ft bls**—The basal part of the upper-aquifer system (also referred to as the “900-foot” aquifer in the Marina area) may

represent the terrestrial deposits of the Paso Robles Formation of late Pliocene to Pleistocene age. The shallowest monitoring well, DMW1-4, is screened at the bottom of this layer.

DEEP-AQUIFER SYSTEM

- (7) **955 to 1,380 ft bls**—The upper Purisima Formation of Pliocene age was identified by micro- and mega-fossils; the first shell fragments were encountered at 1,005 ft bls (appendix 2). The interval 1,030–1,045 ft bls is one of the few water-bearing units in this zone (bounded by silt and clay layers identified by natural gamma spikes 4 and 5 in figure 5); well DMW1-3 is screened in the zone bounded by the more radiogenic fine-grained layers. The interval 1,345–1,360 ft bls is another potential water-bearing zone in the upper Purisima Formation.
- (8) **1,380 to 1,700 ft bls**—The middle Purisima Formation is predominantly fine-grained marine deposits. On the basis of the resistivity log (fig. 5), the top of this unit is a regressive sequence (upward coarsening of sediment grain size) where the well DMW1-2 is screened in the water-bearing sediments near the top of this unit.
- (9) **1,700 to 1,975 ft bls**—The lower Purisima Formation is predominantly composed of sands. The deepest monitoring well, DMW1-1, is screened near the middle of this water-bearing unit.
- (10) **1,990 to 2,012 ft bls**—This interval is possibly part of the lower Purisima Formation. The unit is composed of silts and fine-grained sands of dark greenish gray to olive gray color that may be a water-bearing unit that is separate from unit 9.

HYDRAULICS

The DMW1 monitoring site provides information on water levels and aquifer properties of the deep aquifer system. The water levels, water-level differences between aquifers, and relation to offshore equivalent freshwater heads are all aspects of pressure within the aquifer system that help assess the potential for seawater intrusion and intraborehole flow in the

deep-aquifer system. Estimates of hydraulic conductivity from slug tests of monitoring wells and their relation to aquifer tests of the deep-aquifer system water supply wells provide some comparison of hydraulic transmission properties of the deep-aquifer system.

Water-Level Measurements

The water-level altitudes for the deep-aquifer system monitoring wells at DMW1 are 1 to 18 ft below sea level (table 1). Therefore, if these aquifers are connected to the submarine outcrops of the Paso Robles and Purisima Formations in Monterey Bay (fig. 2), then the potential exists for seawater intrusion. The water-level altitudes required to prevent landward flow of seawater (seawater intrusion) at the submarine outcrops were estimated by dividing the depth of seawater above the top of the submarine outcrop by 40 (density ratio between saltwater and freshwater). On the basis of this relationship, a water-level altitude of at least 6.6 ft above sea level is needed to prevent seawater intrusion in the aquifers of the Paso Robles Formation, and at least 7.4 ft above sea level is needed to prevent seawater intrusion in the aquifers of the Purisima Formation. Therefore, water levels at the DMW1 site are 10 ft below the level that would be needed to prevent seawater intrusion in DMW1-4 (screened in the Paso Robles Formation) and 8 to 27 ft below the level that would be needed to prevent seawater intrusion in DMW1-1,2,3 (screened in the Purisima Formation).

Water levels in the supply wells MCWD 9, 10, and 11 have been below sea level since they were completed and, except for initial water levels after installation, water levels in MCWD 12 also have been below sea level (Lauren Howard, MCWRA, oral commun., 2001). This suggests a landward hydraulic gradient from the offshore outcrop to the supply wells, which provides the potential for the landward flow of seawater and seawater intrusion. Additional water-level measurements are needed to determine the hydraulic connection between the supply and monitoring wells.

The depth-to-water measurements made in the four monitoring wells after completion of the

monitoring site range from 56 ft bls for well DMW1-2 to as much as 73 ft for the wells DMW1-1, -3 (table 1). This results in a water-level difference of as much as 16 ft between these monitoring wells. On the basis of the water-level differences measured in the wells at the DMW1 site, intraborehole flow could occur in water-supply wells for wells screened across these water-bearing units.

Hydraulic Properties

Estimates of hydraulic conductivity for the deep-aquifer system at the monitoring wells were obtained using pressure-pulse “slug tests.” This test is very useful in small diameter wells that have a small-screened interval. Unlike longer-term tests, the results are based on very small changes in water level measured over very short periods and, therefore, represent the hydraulic response from only a small volume of aquifer material adjacent to the well screen.

Between 24 and 30 slug tests were performed on each of the four monitoring wells. Slug test results were analyzed with Aqtesolv 2.01 computer software (Duffield and Rumbaugh, 1991) using the Cooper-Bredehoeft-Papadopulus (Cooper and others, 1967) method. The method was used to solve for values for transmissivity on the basis of an assumed value of specific storage. Two values of specific storage were used, 1×10^{-5} and 1×10^{-6} , that are typical of specific storage values estimated for other deep coastal aquifers (Hanson and Nishikawa, 1996). For each test, the lower specific-storage value results in a transmissivity of about 22 to 25 percent higher than the larger specific-storage value. Resulting estimates of transmissivity were divided by the screened interval to calculate hydraulic conductivities (table 2). The geometric mean of estimates for each well yields values of hydraulic conductivities that ranged from 2 ft/d (foot per day) at well DMW1-4 to 14.5 ft/d at well DMW1-1 (table 2).

The hydraulic conductivities of the monitoring wells are bounded by the estimates from aquifer tests and from tests of side-wall cores from the supply wells, even though the monitoring and supply wells are completed in different geologic formations. Aquifer tests of the supply wells yielded estimates of

Table 2. Summary of slug-test estimates of hydraulic properties for the deep-aquifer system monitoring-well site Marina, California.

[Geometric-mean values shown are based on an assumed range in specific-storage values of 1×10^{-5} to 1×10^{-6} ft⁻¹; ft bls, feet below land surface; ft²/d, foot squared per day; ft/d, foot per day]

Local well name	Depth to top of perforations (ft bls)	Depth to bottom of perforations (ft bls)	Transmissivity (ft ² /d)	Hydraulic conductivity (ft/d)	Number of tests
DMW1-4	930	950	48–40	2.4–2.0	24
DMW1-3	1,040	1,060	276–224	13.8–11.2	29
DMW1-2	1,410	1,430	152–124	7.6–6.2	28
DMW1-1	1,820	1,860	580–464	14.5–11.6	30

transmissivity and hydraulic conductivity (transmissivities divided by the total screened interval) of 4,070 ft²/d (foot squared per day) and 25.4 ft/d for MCWD 10, 3,280 ft²/d 2) and 16.4 ft/d for MCWD 11; and 3,970 ft²/d and 16.5 ft/d for MCWD 12 (Geoconsultants, Inc., 1983, 1986, 1989, 1993). Additional estimates of hydraulic conductivity were inferred from tests on the sidewall core collected during drilling of the supply wells (Geoconsultants, Inc., 1989). Estimates range from 4.6 ft/d at 842 ft bls to 0.6 ft/d at 1,460 ft bls in MCWD 10; and from 7 ft/d at 1,536 ft bls to 1 ft/d at 1,436 ft bls.

WATER CHEMISTRY

Water from the DMW1 site was compared with water from nearby upper-aquifer supply well MCWD 9 and deep-aquifer system supply wells MCWD 10, 11, and 12 to help identify the chemical characteristics, the source, age, and movement of ground water, and the potential for seawater intrusion in the deep aquifer in the Marina area. The sampling and analysis included physical attributes, major ions and nutrients, selected trace elements, and selected stable and unstable isotopes. The four wells at DMW1 were sampled June 23–25, 2000. Analytical results are summarized in appendix 3 (table A3.1). Comparisons are made with water from MCWD supply wells 9, 10, 11, and 12 sampled in 1995, 1997, and 2000 (C. Moss, Monterey County Water Resources Agency, written commun., 2000) and the average chemical composition of seawater (Hem, 1985). Selected chemical analyses of pore water extracted from selected cores at DMW1 also are summarized in Appendix 3 (table A3.2).

Chemical Characteristics of Water from Monitoring and Supply Wells

Chemical analyses of water samples from the DMW1 wells indicate potable water-bearing units in the deep-aquifer system, with the exception of the saline water from DMW1-3. The chloride concentrations in samples from DMW1-1, -2, and -4 and water-supply wells range from 45 to 180 mg/L and the total dissolved solids range from 304 to 610 mg/L. The dissolved solids concentration of water from DMW1-1 (610 mg/L) exceeds the secondary maximum contaminant level (SMCL) of 500 mg/L (U.S. Environmental Protection Agency, 2000). The water from well DMW1-3 contains chloride concentrations of 10,800 mg/L, dissolved solids concentration of 23,800 mg/L, sulfate concentrations of 1,510 mg/L, and manganese concentrations of 0.39 mg/L. This water exceeds the SMCL for chloride (250 mg/L), dissolved solids (500 mg/L), sulfate (250 mg/L), and manganese (0.05 mg/L).

Water from the DMW1 monitoring wells lacked dissolved oxygen and had a trace odor of hydrogen sulfide, noted during sample collection, indicating that the waters from these wells are under reduced conditions. If shallower ground waters are oxygenated, then mixing of these waters may result in the precipitation of minerals on well screens, within gravel packs and aquifer pore spaces, or within agricultural soils or water-supply transmission pipes.

Trilinear diagrams (Piper, 1944) were used to classify the major-ion chemistry of water from monitoring wells at DMW1 and water-supply wells MCWD 9, 10, 11, and 12. Such diagrams are useful for grouping major-ion data and for interpreting mixing and other chemical reactions that occur along flow paths through aquifers. The water samples from the

DMW1-4 and DMW1-2 wells are a sodium-bicarbonate water, water from the DMW1-1 well is a sodium-chloride water, and water from the DMW1-3 is a calcium/magnesium-chloride water. The sample from well DMW1-3 is relatively high in chloride, similar to seawater, but is proportionally higher in calcium and magnesium than is seawater (fig. 10).

The water samples from the nearby deep water-supply wells appear to be a mixture of the water types sampled from the three non-saline monitoring wells (DMW1-1, -2, and -4) (fig. 10), which form a “chemical triangle” surrounding the samples from water-supply wells. The sides of this chemical triangle represent the lines of simple mixing between the monitoring-well compositions. Assuming that the supply wells are a mixture of the water from the monitoring wells, figure 10 can be used to determine source(s) of water. As shown in figure 3, MCWD 9 is screened solely in the upper-aquifer system, MCWD 10 and 11 are screened in the lower part of the upper-aquifer system and parts of the deep-aquifer system, and MCWD 12 is screened solely in the deep-aquifer system.

Water from MCWD 9 in 1995 is similar to water sampled from monitoring well DMW1-4, which is screened in the base of the upper-aquifer system. The 1997 and 2000 samples from MCWD 9 (14S/2E-31K2) show a small increase in calcium, magnesium, and chloride that may represent mixing with another source of ground water (fig. 10). Water from MCWD 10 and 11 also plot near DMW1-4. Both of these wells have perforations in the upper-aquifer system at the same elevation as DMW1-4. MWCD 11 well also may be receiving a small percentage of water from the lower screen, which is at a similar elevation as the screen of well DMW1-2 (figs. 3 and 10).

Water from the deepest supply well (MCWD 12) appears to be a mixture of water sampled from the two deepest monitoring wells (DMW1-1 and DMW1-2) (fig. 10). The screened interval of MCWD 12 spans the screened intervals of DMW1-1 and -2, which may explain the similarity of water types. These results suggest that wells that are screened opposite both the upper- and deep-aquifer systems obtain most of their water from the upper-aquifer system.

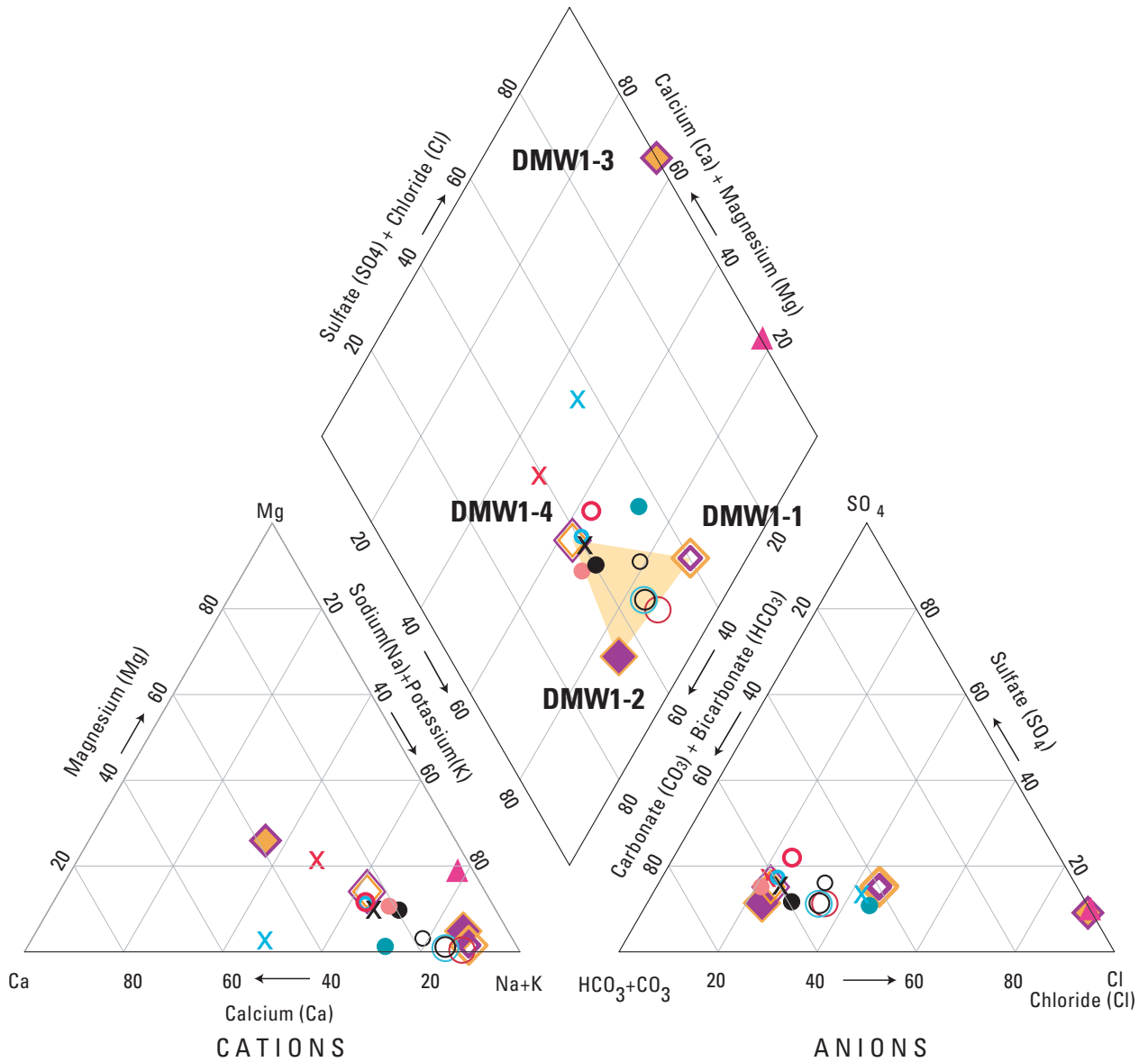
Comparison of 1995, 1997, and 2000 data from the supply wells show some changes in chemical characteristics. Water from supply wells MCWD 9 and 11 show increased chloride in 1997 compared to 1995

and 2000. This may indicate mixing with a more saline source other than that represented by the three non-saline monitoring wells (DMW1-1, -2, and -4). Samples from the deepest water-supply well, MCWD 12, show few to no changes in major chemistry for the 6-year period (1995 to 2000). Depth-dependent samples and wellbore flowmeter logs from the water-supply wells would be needed to apportion the amounts of inflow and related chemical loads from the major contributing water-bearing units (Izbicki and others, 1999; Gossell and others, 1999). Additional isotope and depth-dependent samples from water-supply wells and other monitoring wells also will help to further delineate the association, source, movement, and age of ground waters from the aquifer systems of the Salinas Valley.

Source, Age, and Movement of Ground Water

The source, age, and movement of ground water in the deep-aquifer system can be delineated, in part, from the chemical and isotopic characteristics of the deep-aquifer system and the potential “end-members” represented by waters from nearby surface-water sites and upper-aquifer-system wells in the Salinas Valley (Vengosh and others, 2002).

The anion ratio of chloride-to-boron was used to infer possible sources of ground water in the deep-aquifer system. Plots of chloride-to-boron ratios against chloride indicate that water in the deep-aquifer system at DMW1 are enriched in chloride, relative to boron with respect to surface water from the Salinas River, Lake Nacimiento, and Lake San Antonio in the Salinas Valley (labeled as surface water on fig. 11A). Additionally, the relation of chloride-to-boron ratios to boron in water from the shallowest well (DMW1-4) and the monitoring well DMW1-2 are similar to each other and to samples from some upper-aquifer system wells (fig. 11A) in the Salinas Valley. The chloride-to-boron ratios infer that ground water from some parts of the upper- and deep-aquifer systems in the Salinas Valley may have a similar source of recharge. The chloride-to-boron ratios for the deepest monitoring well, DMW1-1, and for DMW1-3 are enriched in chloride, relative to boron. These ratios bracket the range of upper-aquifer system wells that are identified as having some seawater intrusion (fig. 11A). Possible sources for higher chloride-to-boron ratios and chloride concentrations in these wells may be excess chloride from seawater intrusion or from dissolution of



EXPLANATION

Wells – Deep-aquifer monitoring

- 14S/1E–
- ◊ 24L5 [DMW1-4] (930'-950')
- ◊ 24L4 [DMW1-3] (1,040'-1,060')
- ◊ 24L3 [DMW1-2] (1,410'-1,430')
- ◊ 24L2 [DMW1-1] (1,820'-1,860')

(') Indicates depth, in feet below land surface

▲ **Seawater**

Wells – Water supply

	1995	1997	2000	MCWD well number
14S/2E–				
31K2M	X	X	X	9
32	○	●	●	10
32D1	●	●	●	11
30	○	○	○	12

Figure 10. Trilinear diagram of major-ion chemistry for selected ground-water samples from the deep-aquifer system in the Salinas Valley, 1995, 1997, and 2000 with samples from DMW1 wells, 2000.

chloride in sediments. While some boron can be removed from ground water through adsorption (Rai and Zachara, 1984), the high chloride concentrations of the pore waters from core 7 (appendix 3) suggests that increased chlorides from the dissolution of chloride from marine sediments is a likely cause of increased chloride-to-boron ratios.

Oxygen ($\delta^{18}\text{O}$) and deuterium ($\delta\text{-D}$) are stable isotopes also used to provide information on the source and mixing of the ground water (see Stable Isotopes in appendix 3). In the Salinas Valley, the range in isotopic composition of water from wells completed in the upper- and deep-aquifer systems indicates that there have been different sources or different climatic conditions during recharge of the aquifers underlying the Salinas Valley (fig. 12). The isotopic composition of water from the perched aquifer in Salinas Valley (Vengosh and others, 2002) (fig. 12) and water from wells in the upper-aquifer system (the "180-foot" and "400-foot" aquifers) of the Salinas Valley plots near the meteoric water line and close to the average isotopic composition of precipitation at Santa Maria, California. This suggests that the upper aquifer may be recharged by water that is similar to recent precipitation. The isotopic composition of all samples from the deep-aquifer system monitoring wells in the Salinas Valley plots below the meteoric water line and with the exception of DMW1-3, is lighter (more negative) than wells sampled from the upper aquifer system (fig. 12). This suggests that the deep-aquifer system in the Marina area was not recharged under current climatic conditions.

The strontium-87/86 stable isotope ratio can be used to determine the origins of strontium in a system and the related sediments of the aquifers (see Stable Isotopes in appendix 3). Strontium in selected ground-water samples from Salinas Valley, including deep-aquifer system monitoring wells DMW1-2 and DMW1-4 (fig. 13A), appear to be partitioned above the strontium ratio of 0.7082 for coastal California granitic rocks (Faure and Powell, 1972), indicating a source of sediments for the aquifer in the Salinas valley that is, in part, granitic—possibly derived from the granitic-bedrock mountains that bound parts of the alluvial basin. However, the strontium ratios for samples from DMW1-1 and DMW1-3 plot below the ratio for coastal California granite (fig. 13A, table A3.1), which may indicate a different source for the sediments for these aquifers. In contrast to all other water samples,

the sample from DMW1-3 exceeds the strontium concentration of recent seawater. The strontium isotopes, which indicate that the DMW1-1 and DMW1-3 wells are completed in different sediments than wells DMW1-2 and DMW1-4, are consistent with the differences in chloride-to-boron ratios (fig. 11).

On the basis of tritium and carbon-14 analyses, the water samples from the DMW1 monitoring wells represent old ground water. Ground-water samples from the deep-aquifer system monitoring-well site at DMW1 do not contain detectable amounts of tritium, indicating that these ground waters were recharged prior to 1952. Inorganic carbon-14 activities of water from the DMW1 wells in percent modern carbon are 4.0 percent for DMW1-1, 6.5 percent for DMW1-2, 2.8 percent for DMW1-3 and 2.1 percent for DMW1-4 (table A3.1). These percentages of modern carbon were adjusted for initial waters and represent corrected ages of about 25,000 years before present for DMW1-1, 21,000 years before present for DMW1-2, 28,000 years before present for DMW1-3, and 29,000 years before present for DMW1-4. These estimated ages are interpretive and subject to considerable uncertainty. Davis and Bentley (1982) estimated that errors in carbon-14 ages may be as much as 100 percent. Even considering this uncertainty, the results indicate that these ground waters were probably recharged thousands of years before present. Additional geologic and geochemical investigations are needed to determine whether the deep-aquifer system beneath the Salinas Valley is being actively recharged.

Seawater Intrusion and Saline Ground Water

Hydraulic data at the monitoring and supply wells indicate the potential for seawater intrusion. The deep monitoring well DMW1-3 contains high concentrations of chloride that may indicate seawater intrusion has already occurred. Seawater intrusion is the landward inflow of seawater from the ocean through the submarine outcrops of the aquifer systems. Seawater intrusion can include the inflow of both recent and older seawater. For the purposes of this study, intrusion of recent seawater is defined as seawater that has entered the aquifer within the last 50 years and typically contains some measurable tritium. Potential sources of chloride other than seawater can include high-chloride water from partly consolidated marine deposits, igneous rocks with high

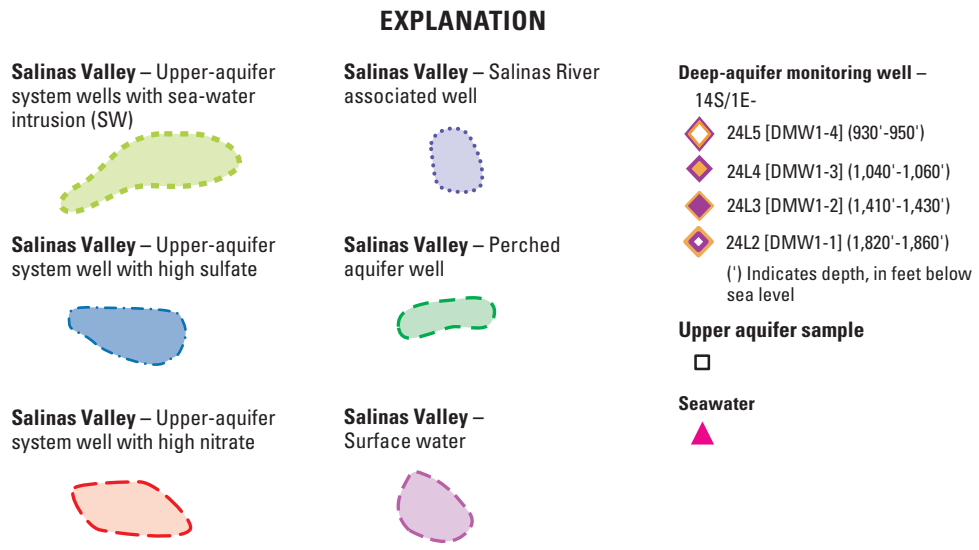
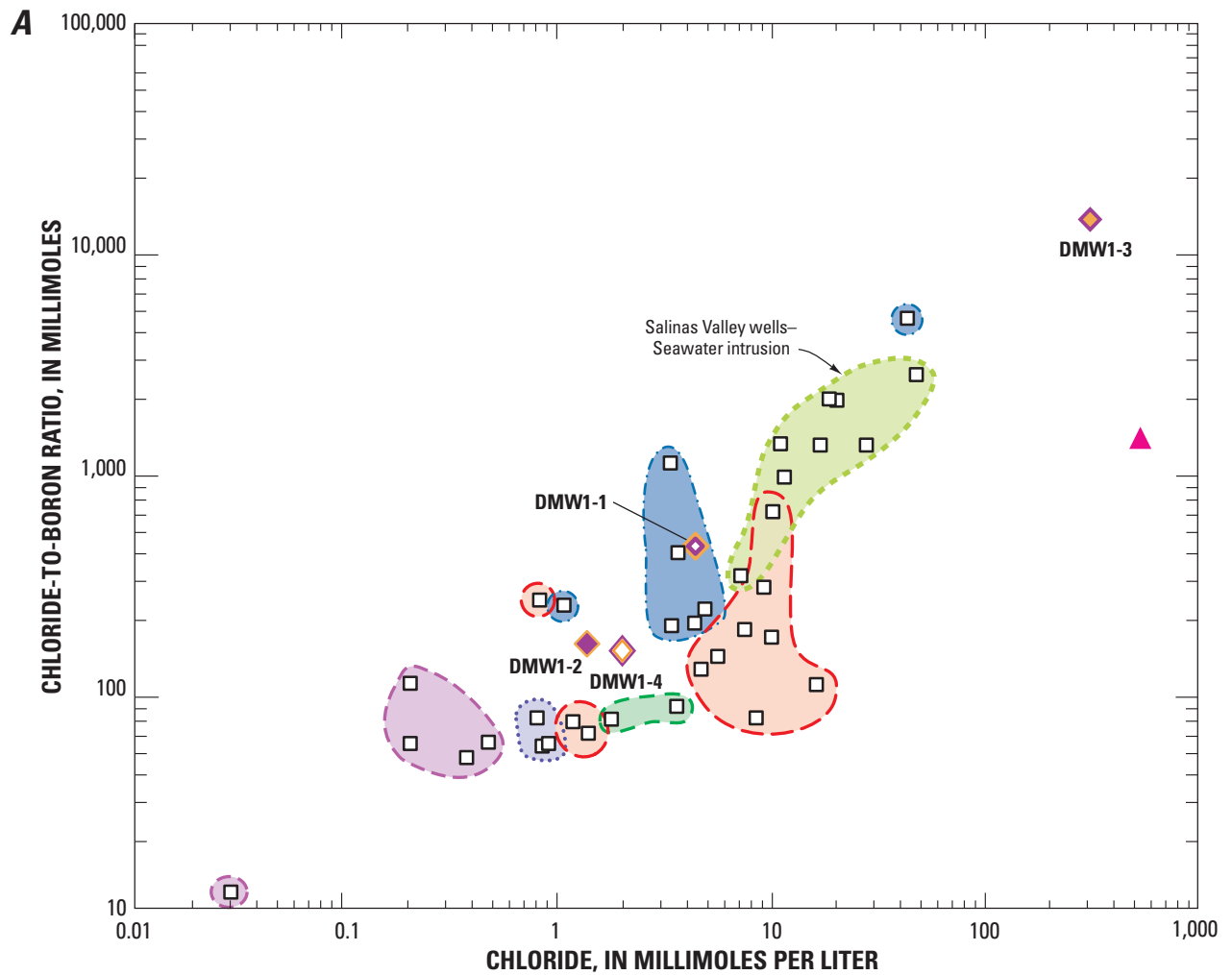


Figure 11. Ratios of chloride-to-boron (A), chloride-to-iodide (B), and chloride-to-bromide (C) plotted against chloride for ground-water and surface-water sites in the Salinas Valley, California.

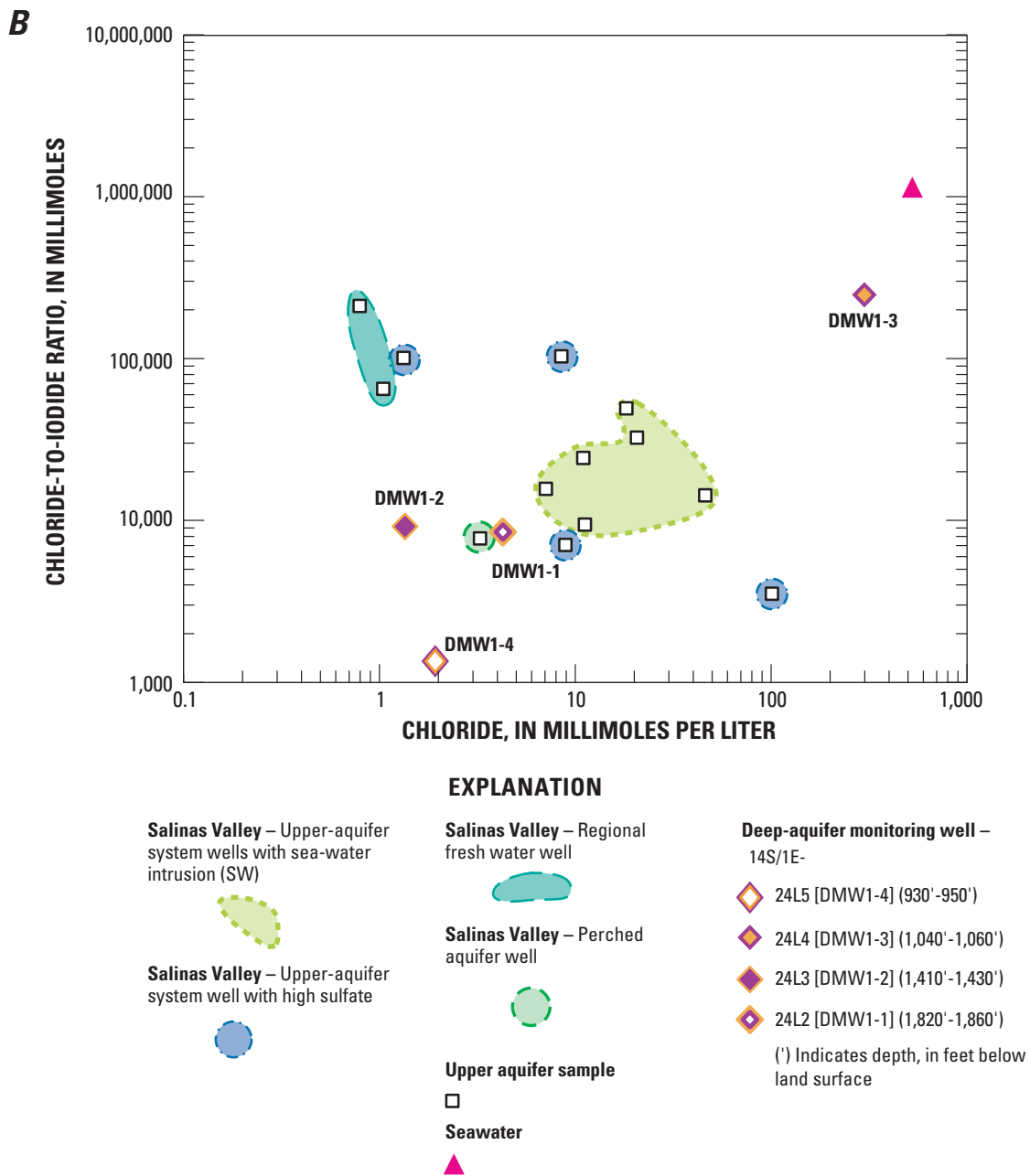


Figure 11.—Continued.

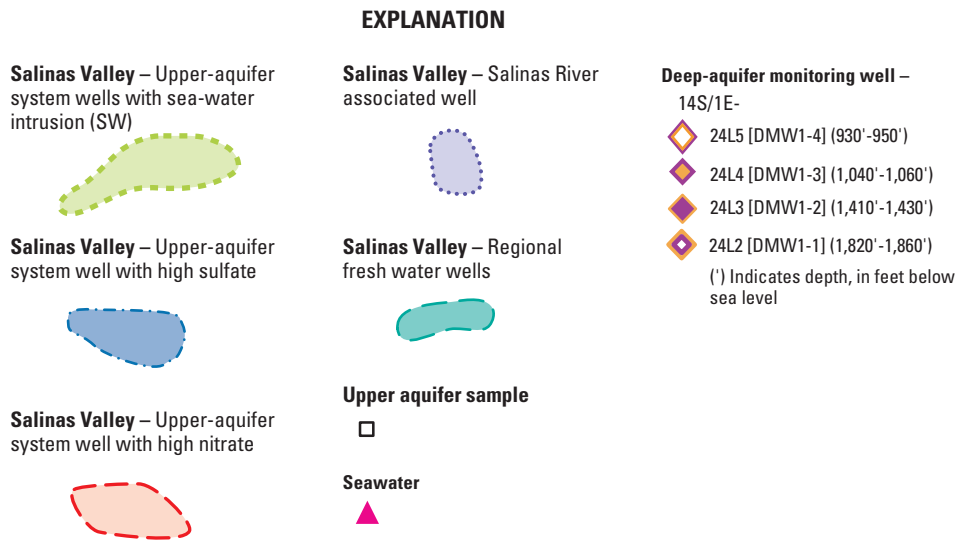
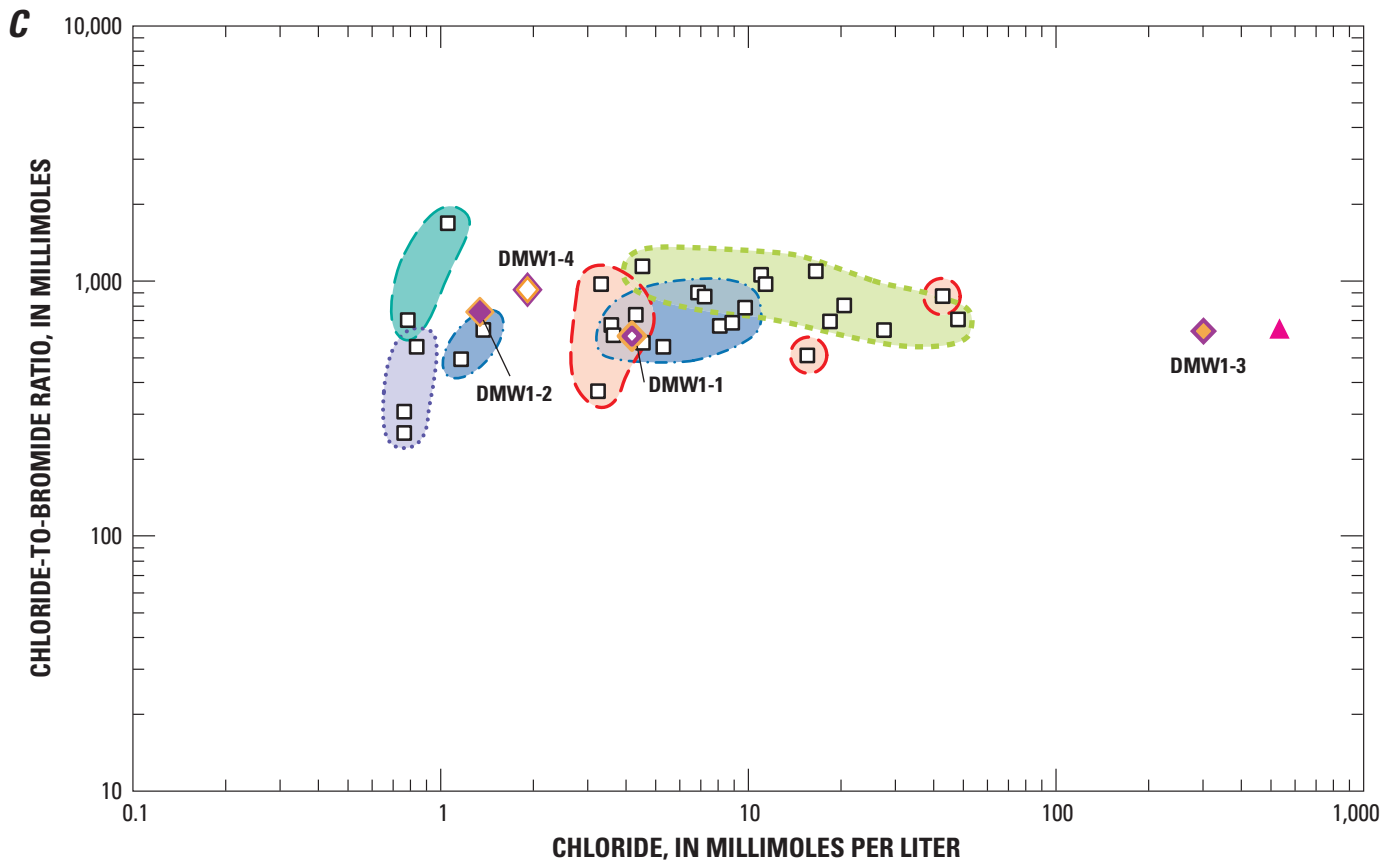
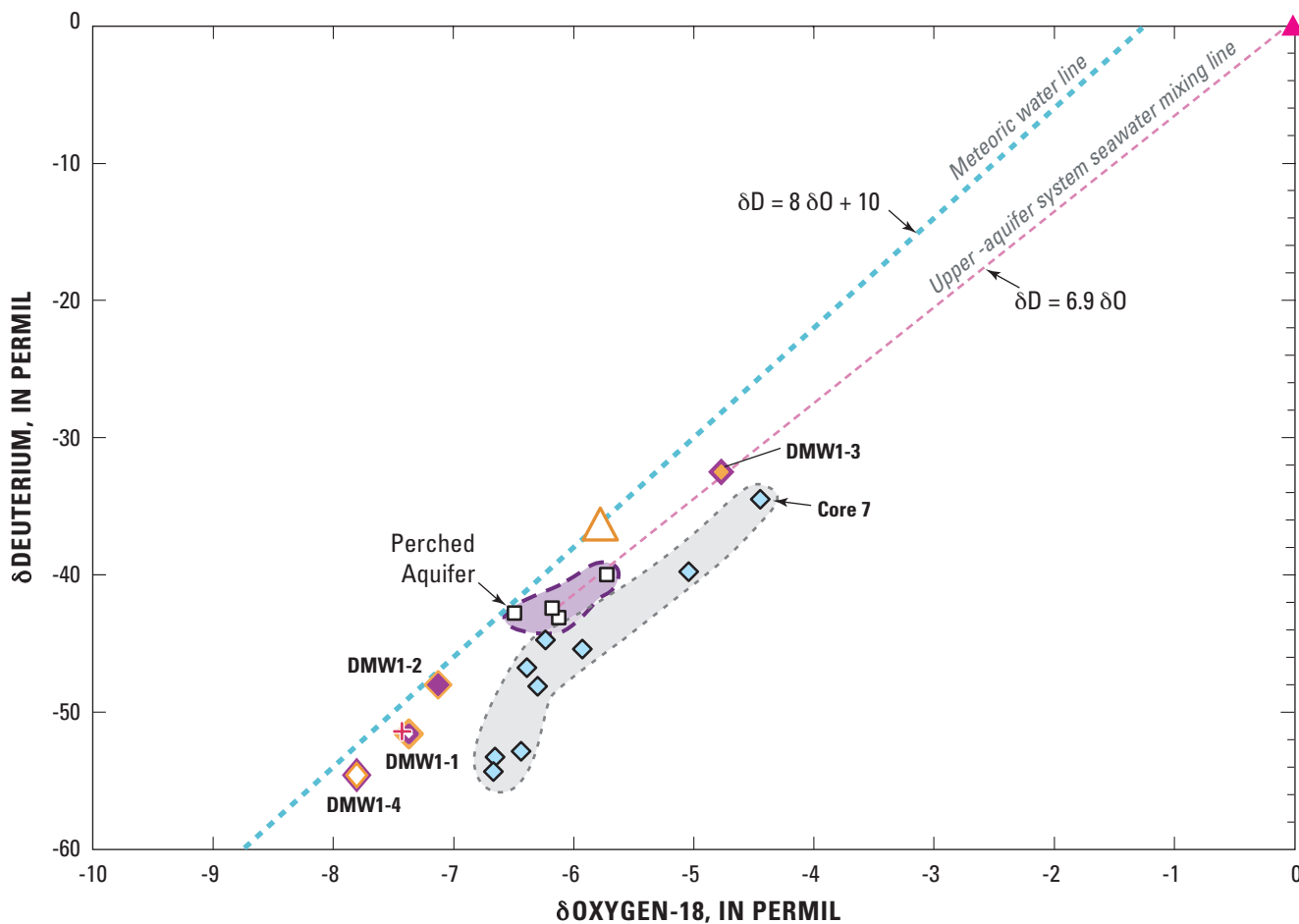


Figure 11.—Continued.



EXPLANATION












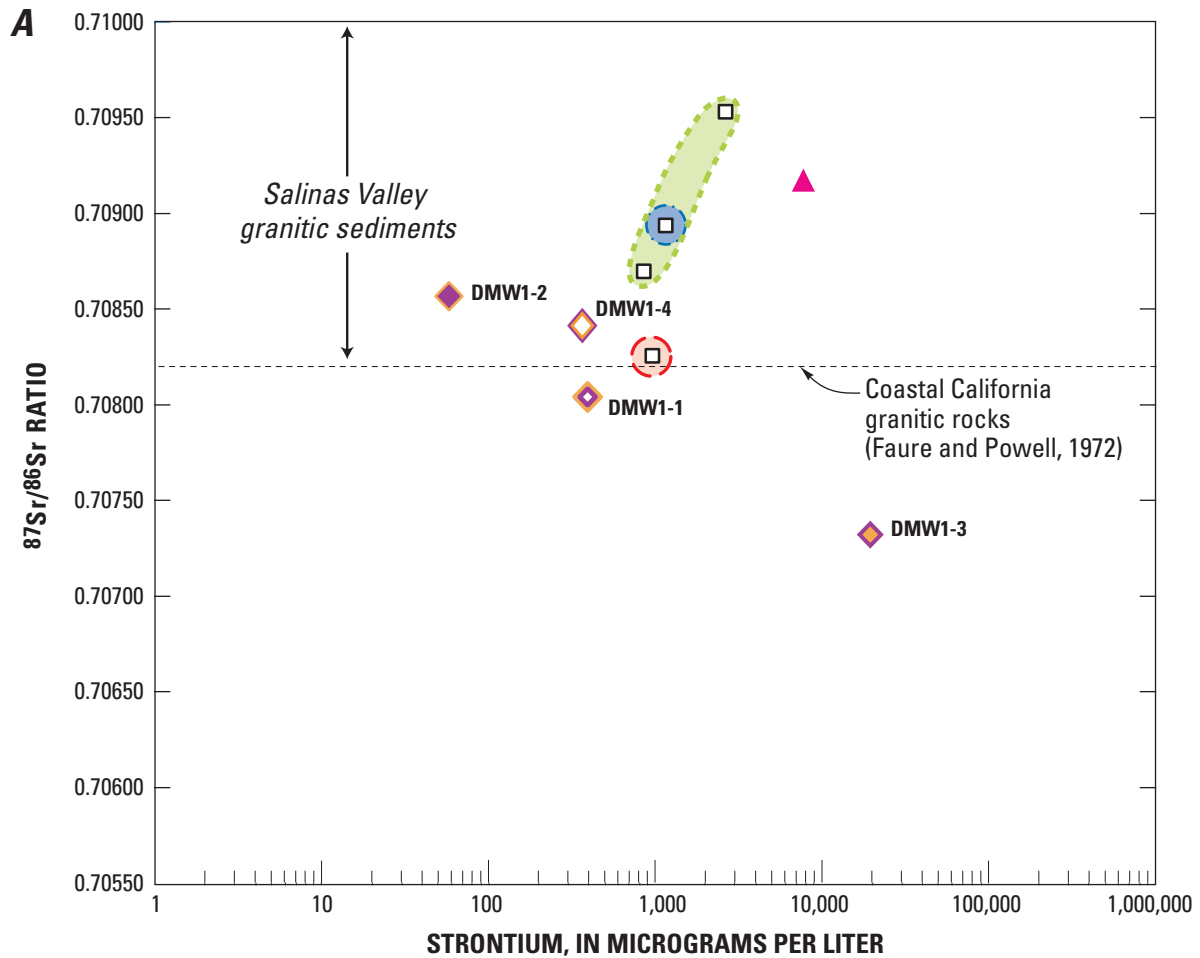
<p>Salinas Valley – Upper-aquifer system wells</p> 	<p>Precipitation – Santa Maria</p> 	<p>Deep-aquifer monitoring well – 14S/1E-</p>
<p>Core-pore water – Deep-aquifer monitoring well</p> 	<p>Upper aquifer sample</p> 	<p> 24L5 [DMW1-4] (930'-950')</p> <p> 24L4 [DMW1-3] (1,040'-1,060')</p> <p> 24L3 [DMW1-2] (1,410'-1,430')</p> <p> 24L2 [DMW1-1] (1,820'-1,860')</p> <p>(') Indicates depth, in feet below land surface</p>
	<p>Core-pore water sample</p> 	
	<p>Average value of DMW1-1,-2,-4</p> 	
	<p>Seawater</p> 	

Figure 12. Deuterium and oxygen isotope values for selected ground-water and surface-water samples from the Salinas Valley, California.



EXPLANATION

Salinas Valley – Upper-aquifer system wells with sea-water intrusion (SW)



Salinas Valley – Upper-aquifer system well with high sulfate



Salinas Valley – Upper-aquifer system well with high nitrate



Upper aquifer sample



Seawater



Deep-aquifer monitoring well – 14S/1E-

◊ 24L5 [DMW1-4] (930'-950')

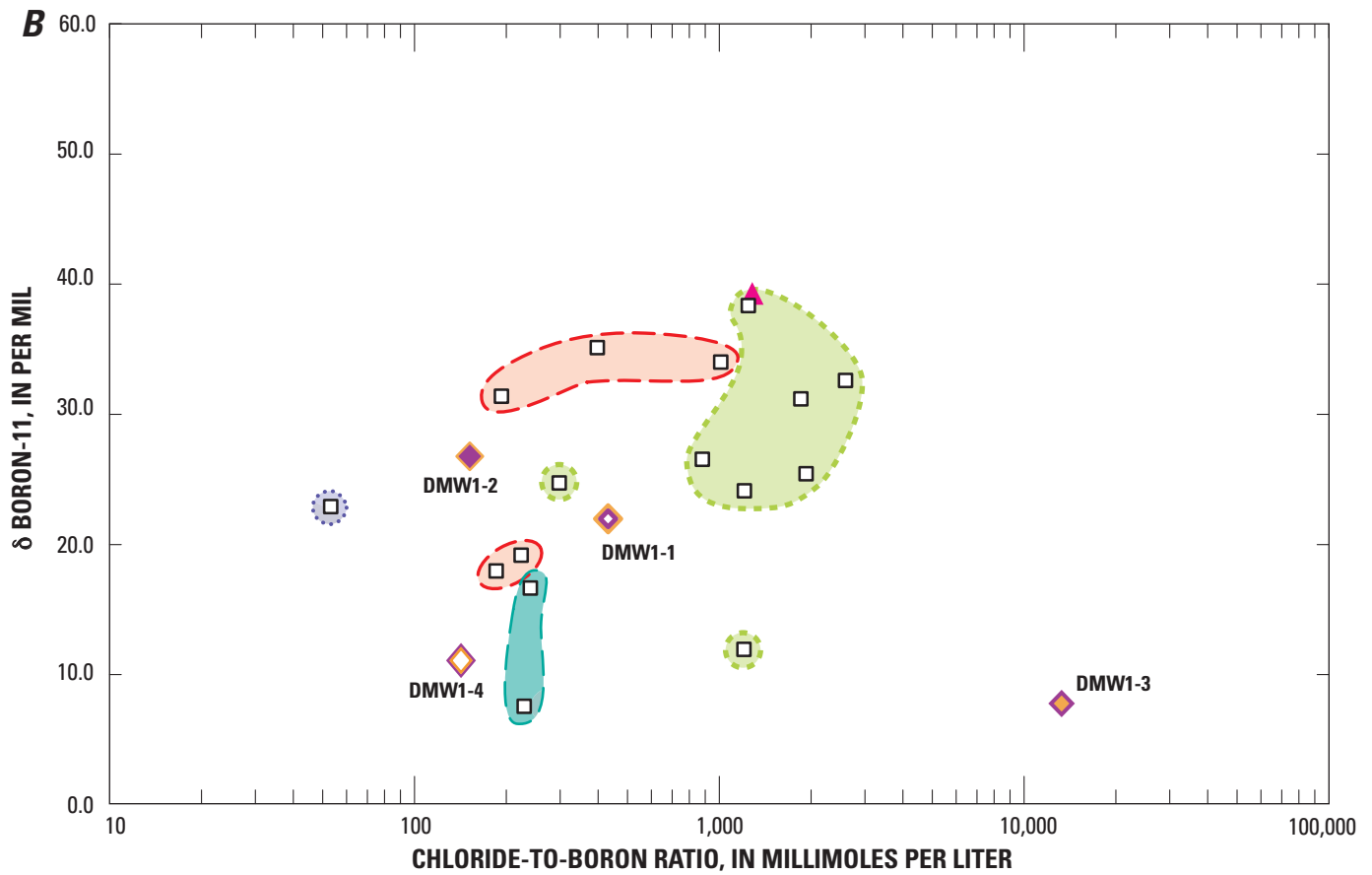
◊ 24L4 [DMW1-3] (1,040'-1,060')

◊ 24L3 [DMW1-2] (1,410'-1,430')

◊ 24L2 [DMW1-1] (1,820'-1,860')

(') Indicates depth, in feet below land surface

Figure 13. Strontium-87/86 ratios plotted against strontium (**A**), and delta boron-11 plotted against chloride-to-boron ratios (**B**) for selected wells in the Salinas Valley, California.



EXPLANATION

Salinas Valley – Upper-aquifer system wells with sea-water intrusion (SW)



Salinas Valley – Upper-aquifer system well with high nitrate



Salinas Valley – Regional fresh water well



Salinas Valley – Salinas River associated well



Upper aquifer sample



Seawater



Deep-aquifer monitoring well – 14S/1E-

◇ 24L5 [DMW1-4] (930'-950')

◇ 24L4 [DMW1-3] (1,040'-1,060')

◇ 24L3 [DMW1-2] (1,410'-1,430')

◇ 24L2 [DMW1-1] (1,820'-1,860')

(') Indicates depth, in feet below land surface

Figure 13.—Continued.

chloride concentrations, and irrigation-return water from shallow unconfined aquifers.

Geochemical indicators were used in this study to identify the possible sources of the high chloride in the ground water, including percentages of common major and minor constituents, anion ratios, and stable and unstable isotopes. These indicators infer the relation of ground-water samples to recent average seawater composition and, when combined with other data, help identify the source of high-chloride water. Iodide, boron, bromide, and barium have been used in previous studies to determine the origin of ground water in coastal areas where seawater, high-chloride water from partly consolidated marine deposits, and irrigation-return water from shallow unconfined aquifers may contribute to increasing chloride in wells (Piper, Garrett, and others, 1953). Graphical techniques that normalize changes in trace-element concentrations to changes in concentrations of conservative (nonreactive) tracers are useful in the interpretation of the source of the waters represented by these data.

Major and minor ions and trace elements in water from DMW1 (appendix 3) were compared to seawater. Chloride was 10,800 mg/L in DMW1-3, which is about 57 percent of the average concentration of seawater (Hem, 1985). Iodide, which averages about 0.06 mg/L in seawater, ranged from 0.06 mg/L in the deepest monitoring well (DMW1-1) to 0.19 mg/L in the shallowest (DMW1-4). DMW1-3 had the highest concentration of boron, about 0.25 mg/L, but is about 6 percent of the average concentration of seawater. Barium ranged from about 102 percent in DMW1-2 to about 1,200 percent of seawater in DMW1-3. Strontium was 1.9 mg/L and bromide was 39.1 mg/L in well DMW1-3, or about 250 percent and about 50 percent of the average concentrations in seawater, respectively. Therefore, the saline water from DMW1-3 is depleted in boron and bromide and enriched in iodide, barium, and strontium, relative to the average concentration of seawater. The enriched barium and depleted boron concentrations suggests that seawater is not the source of the high-chloride water from DMW1-3.

Core 6 (1,042–1,047 ft bls) samples (table A3.1) the upper sediments screened in monitoring-well DMW1-3 (1,040–1,060 ft bls), and its pore water has a chloride concentration of 1,300 mg/L (equivalent to 7 percent of the chloride concentration of seawater).

Core 7 (1,102–1,107 ft bls) samples (table A34.1) of the fine-grained marine sediments beneath the screened interval of DMW1-3, and its pore water has a chloride concentration of 9,800 mg/L (equivalent to 52 percent of the chloride concentration of seawater). This percentage is comparable to the 57 percent of chloride from the DMW1-3 sample. These results suggest that fine-grained marine sediments, like those sampled in core 7, may be the source of salinity-to-water in DMW1-3. Relative to seawater, the saline water in DMW1-3 has ratios of chloride-to-boron, chloride-to-iodide, and chloride-to-bromide (fig. 11A, B, C), collectively indicating that the water is enriched in iodide, depleted in boron, and similar in bromide to the ratios found in seawater. A plot of chloride-to-boron ratios against chloride indicates that the high chloride water from DMW1-3 has almost an order of magnitude higher chloride-to-boron ratio than seawater. A plot of chloride-to-iodide ratios against chloride shows that the sample from DMW1-3 is between seawater and the upper-aquifer system wells intruded with seawater, suggesting that seawater could be the source of the high chloride water. The chloride-to-bromide ratios indicate that all waters occur along a mixing between fresh ground water and seawater, which also suggests that seawater could be the source of the high chlorides for well DMW1-3.

The stable isotopes of water, deuterium, and oxygen indicate that the ground-water samples in the Salinas Valley and core pore waters from DMW1 (table A3.1) generally fall below the meteoric water line, with the more saline water trending toward the isotopic composition of recent average seawater (fig. 12). Assuming the average oxygen isotope composition (–7.43 per mil) for the three nonsaline monitoring wells represents the initial composition of the ground water in the water-bearing zone of DMW1-3, then the water in DMW1-3 is about 36 percent mixture with seawater. This estimate is significantly less than the 57 percent mixing estimate based on chloride. This suggests that the additional chloride encountered in this part of the aquifer (1,040 and 1,060 ft bls) has a source other than seawater.

Because boron is ubiquitous and is a soluble ion in water and because boron isotopes have fractionated through geologic time, boron isotopes provide a combined indicator of the potential for natural sources of water such as seawater intrusion as well as

anthropogenic sources of boron (Bassett, 1990; Vengosh and others, 1994; Vengosh and others, 2002) (see Stable Isotopes in appendix 3). Samples from the upper-aquifer system (“180-foot” and “400-foot” aquifers) that have been intruded by seawater in the Salinas Valley (fig. 13B) have boron isotopic compositions similar to recent seawater (Vengosh and others, 2002). In contrast, the samples from DMW1 (Appendix 3, table A3.1) are significantly below the isotopic composition of seawater (39.2 per mil). The sample from DMW1-3 has one of the lightest delta-boron-11 values and plots separately from the rest of the samples, relative to the chloride-to-boron ratio (fig. 13B). This suggests that the source of the high chloride in the sample from this well is not seawater intrusion. Instead, the source may be a mixture of old ground water and water from, in part, an igneous source (Tom Bullen, U.S. Geological Survey, written commun., 2001).

In summary, although the percentage of chloride and the chloride-to-iodide and chloride-to-bromide ratios indicate a possible seawater source for the high chloride water from well DMW1-3, the percentage of barium and boron, the chloride-to-boron ratio, the deuterium-oxygen isotopes in comparison to chloride concentrations, and the boron isotope data in the DMW1-3 sample, relative to seawater along with the estimated age of the ground water indicate that the saline water in deep-aquifer system monitoring well DMW1-3 is not recent seawater. In particular, the small percentage of boron in this well, relative to seawater tends to exclude a seawater origin. The high salinity of this ground water may be related to the dissolution of salts from the radiogenic saline marine clays (core 7) that surround the water-bearing zone screened by DMW1-3 (figs. 3, 4, 5, and 7).

SUMMARY AND CONCLUSIONS

A deep-aquifer system monitoring-well site (DMW1) completed at Marina, California, in 2000 has provided basic geologic and hydrologic information about the deep-aquifer system in the coastal region of the Salinas Valley. The monitoring-well site contains four wells: one from 930 to 950 feet below land surface (bls) in the Paso Robles Formation; one 1,040 to 1,060 feet bls in the upper Purisima Formation; one from 1,410 to 1,430 feet bls in the middle Purisima Formation; and one from 1,820 to 1,860 feet bls in the

lower Purisima Formation. The DMW1 site is installed between the coast and several deep-aquifer system supply wells in the Marina Coast Water District, and the completion depths are within the zones screened in those supply wells. The sediments below a depth of 955 feet are Pliocene age, whereas the sediments encountered at the water-supply wells just a few miles inland from the DMW1 site are Pleistocene age at an equivalent depth. This may suggest that the water-supply wells are completed in Pleistocene-age sediments deposited in the proposed Marina Trough. The deep monitoring wells occur in older sediments that may extend offshore to their submarine outcrops in Monterey Bay. However, additional geologic investigations would be needed to establish these geohydrologic relations.

Water levels are below sea level in DMW1 and the Marina Water District deep-aquifer system supply wells, which indicates that the potential for seawater intrusion exists in the deep-aquifer system. If the aquifers at DMW1 are in hydraulic connection with the submarine outcrops in Monterey Bay, then the water levels at the DMW1 site are 10 feet below the level that would be needed to prevent seawater intrusion in DMW1-4 (screened in the Paso Robles Formation) and 8 to 27 feet below the level that would be needed to prevent seawater intrusion in DMW1-1, 2, 3 (screened in the Purisima Formation). The numerous, thick, fine-grained interbeds and confining units in the upper- and lower-aquifer systems retard the vertical movement of ground water or seawater between aquifers. These fine-grained units also tend to restrict the movement of seawater to narrow water-bearing zones in the upper-aquifer system.

Hydraulic testing of the DMW1 and the Marina Water District supply wells indicates that the tested zones within the deep-aquifer system are transmissive water-bearing units with hydraulic conductivities ranging from 2 to 14.5 feet per day. The hydraulic properties of the supply wells and monitoring wells are similar, even though the wells were completed in different geologic formations.

Geophysical logs indicate saline water in most water-bearing zones shallower than 720 feet below land surface and from about 1,025 to 1,130 feet bls, and indicate fresher water from about 910 to 950 feet bls (DMW1-4), 1,130 to 1,550 feet bls, and below 1,650 feet bls. Potentially saline marine silt and clay layers occur at depths from about 1,025 to 1,130 feet

bls and from 1,550 to 1,700 feet bls. Temporal differences between EM logs indicate possible seasonal seawater intrusion in five water-bearing zones from 350 to 675 feet bls in the upper-aquifer system.

The water-chemistry analyses from the deep-aquifer system monitoring and supply wells indicate that these deep aquifers contain potable water, with the exception of the saline water in well DMW1-3. The major-ion water chemistry of the monitoring wells and the nearby MCWD water-supply wells are similar, which may indicate they are in hydraulic connection, even though the stratigraphic layers differ below 955 ft bls. The hydraulic connection could be better inferred by comparison of continuous water-level records from the monitoring and supply wells.

The waters from the deep-aquifer system are slightly basic (pH greater than 7.0), reduced, oxygen-depleted, and chemically different from surface waters and upper-aquifer system ground water. The chloride-to-boron ratios infer that ground water from some parts of the upper and deep-aquifer systems in the Salinas Valley may have a similar source of recharge. The deuterium-oxygen data suggest that the waters from the deep-aquifer system in the Marina area were not recharged under current climatic conditions. No tritium was detected in samples from the deep monitoring wells. The lack of tritium suggests that there is no recent recharge water (less than 50 years old) in the deep-aquifer system at the DMW1 site. The carbon-14 analyses of these samples indicate ground water was recharged thousands of years ago. The strontium isotopes indicate that the DMW1-1 and DMW1-3 wells were completed in different sediments than wells DMW1-2 and DMW1-4.

The saline water from well DMW1-3 contains chloride concentrations of 10,800 milligrams per liter and dissolved solids concentration of 23,800 milligrams per liter. The source of this water was determined not to be recent seawater on the basis of geochemical indicators and the estimated age of the ground water. In particular, the small percentage of boron in this well, relative to seawater tends to exclude a seawater origin. The high salinity of this ground water may be related to the dissolution of salts from the radiogenic saline marine clays that surround the water-bearing zone screened by DMW1-3.

Additional studies are needed to better characterize the geohydrologic framework of the aquifer systems in the Marina area. Geophysical

investigations such as seismic, regional gravity, aeromagnetic, and electromagnetic-resistivity surveys could help to identify the areal extent and thickness, and any potential boundaries, such as faults, of the regional aquifers. The presence of significant silt and clay deposits in the Marina area suggests that spatially detailed InSAR (interferometric synthetic aperture radar) derived ground-displacement maps from repeat synthetic aperture radar images also could be used to help identify hidden faults that may act as potential hydraulic barriers and assess the extent of potential aquifer-system compaction and land subsidence (Galloway and others, 1999). The potential utility of InSAR in the Salinas Valley depends, in part, on the susceptibility of silts and clays in the aquifer systems to deformation resulting from stresses imposed by changes in hydraulic head.

If the water resources of the deep-aquifer system are to be further developed, the extent and characteristics of these resources will need to be better defined. This may require the installation of a network of additional multiple-well monitoring sites as has been completed in many other coastal aquifer systems in California. This type of network would allow the collection of water-level and water-chemistry data through time to help assess the effects of development on the water resources of the coastal aquifer systems in the Salinas Valley.

REFERENCES CITED

- Bassett, R.L., 1990, A critical evaluation of the available measurements for the stable isotopes of boron: *Journal of Applied Geochemistry*, v. 5, p. 541–554.
- California Department of Water Resources, 1973, Seawater intrusion lowers Salinas Valley: California Department of Water Resources San Joaquin District Technical Report, 42 p.
- California State Water Resources Board (CWRCB), 1953, Santa Cruz–Monterey Counties Investigation: California State Water Resources Board Bulletin No. 5, 230 p.
- Cooper, H.H., Bredehoeft, J.D., and Papadopolus, S.S., 1967, Response of a finite diameter well to an instantaneous charge of water, *Water Resources Research*, v. 3, no.1, p. 263–269.
- Craig, H., 1961, Isotopic variation in meteoric waters: *Science*, v. 133, p. 1702–1703.
- Davis, S.N., and Bentley, H.W., 1982, Dating groundwater, a short review, *in* Currie, L.A., ed., *Nuclear and chemical dating techniques—Interpreting the environmental*

- record: American Chemical Society Symposium Series, v. 176, p. 187–222.
- Duffield G.M. and Rumbaugh, J.O., 1991, AQTESOLV Aquifer Test Solver version 2.01: Geraghty & Miller, Inc. Environmental Services, [variously paged].
- Faure, G., and Powell, J.L., 1972, Strontium isotope geology: New York, Springer-Verlag, 188 p.
- Folk, R.L., 1954, The distinction between grain size and mineral composition in sedimentary rock nomenclature: *Journal of Geology*, v. 62, no. 4, p. 344–359.
- Galloway, D., Jones, D.R., and Ingebritsen, S.E., 1999, Land subsidence in the United States: U.S. Geological Survey Circular 1182, 175 p.
- Geoconsultants, Inc., 1983, Summary report test drilling and well completion, well no. 10 Marina County Water District, Monterey County, California: Consultants report to Marina Coast Water District August, 1983, [variously paged].
- 1986, Summary report drilling and well completion, well no. 11 Marina County Water District, Monterey County, California: Consultants report to Marina Coast Water District February, 1986, [variously paged].
- 1989, Summary report test drilling and well completion, well no. 12 Marina County Water District, Monterey County, California: Consultants report to Marina Coast Water District June, 1989, [variously paged].
- 1993, Identifying potential sources of water supply: Consultants report to Monterey County Water Resources Agency Task 2.06.2.2 January, 1993, [variously paged].
- Gonfiantini, R., 1978, Standards for stable isotope measurements in natural compounds: *Nature*, v. 271, p. 534–536.
- Goodwin, J.C., and Thomson, J.N., 1954, Purisima Pliocene Foraminifera of the Halfmoon Bay area, San Mateo County, California, Contributions from the Cushman Foundation for Foraminiferal Research, v. 5, pt. 4, p. 170–178.
- Gossell, M.A., Nishikawa, T., Hanson, R.T., Izbicki, J.A., Tabidian, M.A., and Bertine, K., 1999, Application of flowmeter and depth-dependent water quality data for improved production well construction: *Ground Water*, v. 37, no. 5, p. 729–735.
- Green, H.G., 1970, Geology of the Southern Monterey Bay and its relationship to the ground water basin and salt water intrusion: U.S. Geological Survey Open-File Report 70-141, 50 p.
- Hanson, R.T., 2001, U.S. Geological Survey deep-aquifer monitoring-well site, Marina, California: U.S. Geological Survey Open-File Report 01-242, 2 p.
- Hanson, R.T., and Nishikawa, Tracy, 1996, Combined use of flowmeter and time-drawdown data to estimate hydraulic conductivities in layered aquifer systems: *Ground Water*, v. 34, no. 1, p. 84–94.
- Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254 (3d ed.), 206 p.
- Ingle, James C., 1985, Analysis of Foraminifera from the Marina No. 10 well and the Sand City MacDonald No. 1 well: Consultant's report prepared for Geoconsultants, Inc., July 8, 1985, 11 p.
- 1986, Analysis of Foraminifera from Marina County Water District – Well no. 11, Monterey County, California: Consultant's report prepared for Geoconsultants, Inc., February 24, 1986, 8 p.
- 1989, Analysis of Foraminifera from Marina County Water District – Well no. 12, Monterey County, California: Consultant's report prepared for Geoconsultants, Inc., April 18, 1989, 8 p.
- International Atomic Energy Agency, 1981, Statistical treatment of environmental isotope data in precipitation, Technical Report Series No. 206, 255 p.
- Izbicki, J.A., 1996, Source, movement, and age of ground water in a coastal California aquifer: U.S. Geological Survey Fact Sheet 126-96, 4 p.
- Izbicki, J.A., Christensen, A.H., and Hanson, R.T., 1999, U.S. Geological Survey combined well-bore flow and depth-dependent water sampler: U.S. Geological Survey Fact Sheet 196-99, 2 p.
- Izbicki, J.A., Michel, R.L., and Martin, Peter, 1993, 3H and 14C as tracers of ground water recharge, in Engman, Ted, Saving a threatened resource—In search of solutions: American Society of Civil Engineers, IR Div/ASCE, p. 122–127.
- Michel, R.L., 1976, Tritium inventories of the world's oceans and their implications: *Nature*, v. 263, p. 103-106.
- Monterey Bay Aquarium Research Institute, 2000, Internet URL <http://www.mbari.org/data/mapping/gis/>, accessed August 10, 2001.
- Moore, E.J., 1983, Tertiary marine pelecypods of California and Baja California: Nuculidae through Malleidae: U. S. Geological Survey Professional Paper 1228A, p. A1–A108.
- Munsell Color Chart, 1975, Munsell soil color charts: Baltimore, Maryland, Munsell Color, Macbeth Division of Kollmorgen Corporation.
- National Oceanic and Atmospheric Administration, 2001, Internet URL <http://www.ncdc.noaa.gov/>, accessed February 12, 2001.
- National Research Council, 1947, Report on the subcommittee on sediment terminology: American Geophysical Union Transactions, v. 28, no. 6, p. 936–938.
- Piper, A.M., 1944, A graphical procedure in the geochemical interpretations of water analyses: American Geophysical Union Transactions, v. 25, p. 914–923.

- Piper, A.M., Garrett, A. A., and others, 1953, Native and contaminated waters in the Long Beach-Santa Ana area, California: U.S. Geological Survey Water-Supply Paper 1136, 320 p.
- Rai, D., and Zachara, J.M., 1984, Chemical attenuation rates, coefficients, and constants in leachate migration, Volume 1: A critical review: U.S. Environmental Protection Agency EA-3356, Volume 1, [variously paged].
- Rosenberg, L.I., 2001, Geology resources and constraints, Monterey County, California: Consultants technical report for Monterey County 21st Century General Plan Update Program, April, 2001, CD Version 1.0.
- Roth, B., 1979, Late Neogene of northern California and southern Oregon. University of California, Berkeley, Calif., Ph.D. dissertation, 800 p.
- Templin, W.E., Smith, P.E., DeBertoli, M.L., and Schlater, R.C., 1996, Water-resource data network evaluation for Monterey County, California, phase 2: northern and coastal areas of Monterey County: U.S. Geological Survey Water-Resources Investigation Report 95-9210, 102 p.
- Tinsley, J.C., III, 1975, Quaternary geology of the northern Salinas Valley, Monterey County, California: Ph.D. dissertation, Stanford University, Stanford, Calif., 195 p.
- U.S. Census Bureau, 2001, Internet URL <http://www.census.gov/>, accessed February 12, 2001.
- U.S. Environmental Protection Agency, 1994, Drinking water standards and health advisories: U.S. Office of Water, EPA 822-B-00-001, 12 p.
- Vengosh, A., Gill, J., Davidson, M.L., and Hudson, G.B., 2002 (in press), A multi-isotope (B, Sr, O, H, C) and age dating (³H-³He, ¹⁴C) study of groundwater from Salinas Valley California: Hydrochemistry, dynamics, and contamination processes: Water Resources Research, August 13, 2001, 29 p.
- Vengosh, A., Heumann, K.G., Juraske, S., and Kasher, R., 1994, Boron isotope application for tracing sources of contamination in groundwater: Journal of Environmental Science and Technology, v. 28, no. 11, p. 1968–1974.
- Wagner, D.L., Green, G., Saucedo, G.J., and Pridmore, C.L., 2000, Geologic Map of the Monterey 30' × 60' Quadrangle and Adjacent Offshore Region, California: A Digital Database: California Department of Conservation, Division of Mines and Geology, DMG CD 2000-000.
- Wilde, F.D., Radtke, D.B., Gibs, J., and Iwatsubo, R.T., 1998, Preparations for water sampling, National Field Manual for the Collection of Water-Quality Data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A1, [variously paged].
- Yates, E.B., 1988, Simulated effects of ground-water management alternatives for the Salinas Valley, California: U.S. Geological Survey Water-Resources Investigations Report 87-4066, 79 p.