Ground-Water Quality of Coastal Aquifer Systems in the West Coast Basin, Los Angeles County, California, 1999–2002

By Michael Land, Eric G. Reichard, Steven M. Crawford, Rhett R. Everett, Mark W. Newhouse, and Colin F. Williams

In cooperation with the
Water Replenishment District of Southern California

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Contents

Abstract 1
Introduction 2
Purpose and Scope 2
Previous Investigations 2
Acknowledgments 4
Description of Study Area 4
Physiographic Setting 4
Geohydrologic Setting 4
Hydrostratigraphy 4
Recharge and Discharge 4
Ground-Water Movement and Levels 7
Methods of Investigation 8
Well Network 8
Water Quality 8
Core Pore-Water Extraction 8
Geophysical Logging 12
Electromagnetic Induction 12
Gamma-Ray Emission 12
Temperature 12
Specific Conductance 12
Quality Assurance 12
Ground-Water Chemistry 13
Major-Ion Composition 13
Dissolved Chloride 18
Dissolved Bromide 21
Dissolved Iodide 24
Dissolved Boron 24
Ground-Water Isotopes 27
Oxygen and Deuterium 27
Tritium 29
Carbon 33
Boron 33
Strontium 33
Summary of Ground-Water Chemistry and Isotope Data 36
Geophysical-Log Analysis 36
Evaluation of Log Data near the Dominguez Gap Barrier Project 36
Evaluation of Log Data near the Southern Part of West Coast Basin Barrier Project 38
Summary Analysis of Geophysical Log Data 39
Ground-Water-Quality Conditions along a Geohydrologic Section 39
Summary 39
References Cited 42
Appendixes 45

Figures

Figure 1. Map showing surface geology and other features of the study area, Los Angeles County, California . . . 3
Figure 2. Stratigraphic section showing geologic units and aquifers in the study area . . . 5
Figure 3. Schematic diagram showing generalized geologic, hydrologic, and other features of the study area . . . 6
Figure 4. Water-level hydrographs showing selected wells in the Upper and Lower aquifer systems near the West Coast Basin and Dominguez Gap Barrier Projects, 1970–2000 . . . 9
Figure 5. Map showing location of wells sampled for water chemistry in the study area . . . 10
Figure 6. Map showing location of wells logged for geophysical properties in the study area . . . 11
Figure 7. Trilinear diagram showing major-ion composition of ground water from wells sampled in the study area . . . 17
Figure 8. Map showing dissolved-chloride concentrations for wells sampled in the study area . . . 19
Figure 9. Graph showing dissolved-chloride concentration and water-level altitude as a function of time in the Upper and Lower aquifer systems in selected wells near the West Coast Basin and Dominguez Gap Barrier Projects . . . 20
Figure 10. Graphs showing dissolved chloride as a function of depth in pore water from continuously cored monitoring sites in the study area: Westchester-1, Long Beach-3, Long Beach-4, and Long Beach-5 . . . 22
Figure 11. Graph showing chloride-to-bromide ratio as a function of chloride in water from wells sampled in the study area . . . 23
Figure 12. Graph showing chloride-to-iodide ratio as a function of chloride in water from wells sampled in the study area . . . 25
Figure 13. Graph showing chloride-to-boron ratio as a function of chloride in water from wells sampled in the study area . . . 26
Figure 14. Graph showing delta deuterium as a function of delta oxygen-18 for selected wells in the study area . . . 28
Figure 15. Graph showing delta oxygen-18 as a function of depth in pore water from continuously cored monitoring sites in the study area: Westchester-1, Long Beach-3, Long Beach-4, and Long Beach-5 . . . 30
Figure 16. Estimated tritium concentration in precipitation, Los Angeles County, California . . . 31
Figure 17. Map showing tritium concentrations in water from selected wells sampled in the study area . . . 32
Figure 18. Graph showing chloride-to-boron ratio as a function of delta boron-11 in water from selected wells sampled in the study area . . . 34
Figure 19. Graph showing strontium-87/86 ratio as a function of dissolved strontium in water from selected wells sampled in the study area . . . 35
Figure 20. Graph showing chloride concentration as a function of electromagnetic-log conductivity in wells sampled in the study area . . . 37
Figure 21. Geohydrologic section *A′–A* showing ground-water-quality conditions from the Dominguez Gap to the San Pedro Bay . . . 40

Appendix C. Geophysical logs for selected well sites in the study area, Los Angeles County, California . . . . . .
Figure C1. 351-E. 56
Figure C2. 351-M 57
Figure C3. 360-N 58
Figure C4. 361-U 59
Figure C5. 714-H 60
Figure C6. 735-A 61
Figure C7. 736-D 62
Figure C8 738-D 63
Figure C9. 745-A 64
Figure C10. 868-HH 65
Figure C11. 898-AB 66
Figure C12. Hawthorne-1 67
Figure C13. Long Beach-2 68
Figure C14. Long Beach-3 69
Figure C15. Long Beach-4 70
Figure C16. Long Beach-5 71
Figure C17. PM-1 72
Figure C18. PM-3 73
Figure C19. PM-4 74
Figure C20. Westchester-1 75
Figure C21. Wilmington-1 76
Figure C22. Wilmington-2 77

Tables

Table 1. Averaged annual water use and replenishment in the West Coast Basin, Los Angeles County, California 7
Table 2. Summary of ground-water sources for wells sampled in the West Coast Basin 14

Appendixes

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California 46
Appendix B. Well construction information and index of well-log data collected in the study area, Los Angeles County, California 54
Appendix C. Geophysical logs for selected well sites in the study area, Los Angeles County, California
Figure C1. 351-E. 56
Figure C2. 351-M 57
Figure C3. 360-N 58
Figure C4. 361-U 59
Figure C5. 714-H 60
Figure C6. 725AB 61
Figure C7. 735-A 62
Figure C8. 736-D 63
Figure C9 738-D 64
Figure C10. 745-A 65
Figure C11. 868-HH 66
Figure C12. 898-AB 67
Figure C13. Hawthorne-1 68
Figure C14. Long Beach-2 69
Figure C15. Long Beach-3 70
Figure C16. Long Beach-4 71
Figure C17. Long Beach-5 72
Figure C18. PM-1 73
Figure C19. PM-3 74
Figure C20. PM-4 75
Figure C21. Westchester-1 76
Figure C22. Wilmington-1 77
Figure C23. Wilmington-2 78

Conversion Factors, Vertical Datum, Water-Quality Information, Abbreviations, and Acronyms

CONVERSION FACTORS

Multiply	By	To obtain
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot (ft)	0.3048	meter
inch (in.)	2.54	centimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
picocurie per liter (pCi/L)	0.037	becquerel per liter
pounds per square inch (psi)	0.068046	atmosphere
square mile (mi^2)	12.590	square kilometer

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

$$°F=1.8\ °C+32.$$

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 a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude: As used in this report, refers to distance above or below sea level

WATER-QUALITY INFORMATION

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is approximately equivalent to parts per million. Micrograms per liter is approximately equivalent to parts per billion. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Data for the isotopes oxygen-18, deuterium, boron-11, and carbon-13 are reported in delta (δ) notation as per mil (parts per thousand); tritium data are reported in tritium units (TU); carbon-14 data are reported as percent modern carbon (pmc).

ABBREVIATIONS AND ACRONYMS

δ11B	delta boron-11
DGBP	Dominguez Gap Barrier Project
EM	electromagnetic induction
g	gram
mL	milliliter
mmho/m	millimho per meter
NIU	Newport-Inglewood Uplift
µM	micrometer
PVC	poly vinyl chloride
psi	pound per inch
Sr-87/86	strontium 87 to strontium 86 ratio
VSMOW	Vienna Standard Mean Ocean Water
WCBBP	West Coast Basin Barrier Project

Organizations

API	American Petroleum Institute
LACDPW	Los Angeles County Department of Public Works
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WBMWD	West Basin Municipal Water District
WRDSC	Water Replenishment District of Southern California

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Abstract

The extensive use of ground water throughout the Central and West Coast Basins of Los Angeles County during the first half of the 20th century resulted in declining water levels, widespread seawater intrusion, and deterioration of water quality along most reaches of the coast. In order to control seawater intrusion in the West Coast Basin, freshwater is injected into a series of wells at two seawater barrier projects. In order to better understand the processes of seawater intrusion and the efficiency of current barrier operation, data were collected from multiple-well monitoring sites installed by the U.S. Geological Survey, from local observation wells, and from production wells. The occurrence and areal extent of native, saline, and recently injected ground water near the coast were defined through the collection and analysis of inorganic and isotopic water-quality data and geophysical logs.

Most water in the West Coast Basin with a dissolved-solids concentration less than 500 milligrams per liter generally has a sodium-bicarbonate to sodium/calcium-bicarbonate character. Water with a dissolved-solids concentration greater than 1,000 milligrams per liter also contains variable amounts of calcium and sodium, but chloride is predominant. Most of these high-dissolved-solids wells are perforated in the Upper aquifer systems; several have dissolved-chloride values near that of seawater. Elevated chloride concentrations were measured at many wells in both the Upper and Lower aquifer systems inland from the barrier projects. Although water levels have increased in many wells over the last 30 years, some of the wells do not show a corresponding decrease in dissolved chloride.

A detailed assessment of saline ground water was provided by examining the ratios of chloride to bromide, iodide, and boron. Seawater-freshwater mixing lines were constructed using all three ratios. These ion ratios also identify water affected by mixing with injected imported water and oil-field brine water.

Isotopic data—oxygen-18, deuterium, strontium-87, boron-11, tritium, and carbon-14—also were collected. The stable isotopes oxygen-18 and deuterium were used to distinguish between isotopically heavier water that originated in the Los Angeles Forebay, isotopically lighter water that originated in the Montebello Forebay, local recharge, and water containing a mixture of seawater and imported water. Tritium data were used to identify recent water (less than 50 years old) present in the Upper and Lower aquifer systems inland from the seawater barrier projects, and present locally near the Dominguez Gap. Carbon-14 data indicate that water with uncorrected ages ranging from about 4,000 years to more than 20,000 years before present occurs in the Lower aquifer systems and in the Pico unit.

Borehole electromagnetic conductivity logs, combined with gamma-ray logs, were used to identify potential saline zones throughout the entire well depth; this provides an indicator of intrusion in zones that are not being monitored by a piezometer. Temperature logging was used to track the thermal effects of the cooler water used for injection. Specific-conductance logs provided a screening-level indicator of poor-quality water in monitoring wells.

Introduction

The extensive use of ground water in the Central and West Coast Basins of Los Angeles County (fig. 1) during the first half of the 20th century dramatically altered the ground-water flow system. The resulting decline in water levels led to widespread seawater intrusion and deterioration of water quality along most reaches of the coast. To address this problem, injection of freshwater was begun in 1953 at nine experimental wells along a 1-mile line in Manhattan Beach (Callison and Roth, 1967). In 1959, the Water Replenishment District of Southern California (WRDSC) was formed for the purpose of replenishing and managing ground-water supplies in the two basins. By court order, the West Coast Basin was adjudicated in 1961 and a limit on pumpage was set at 64,468 acre-ft/yr (Water Replenishment District of Southern California, 2000). Injection along other lengths of the coast was expanded by the Los Angeles County Department of Public Works (LACDPW) in order to further control seawater intrusion. A series of injection wells, which constitute the West Coast Basin Barrier Project (WCBBP) and Dominguez Gap Barrier Project (DGBP), were completed in 1965 and 1971, respectively.

Despite the controls on pumping and the injection of freshwater, ground-water quality is an ongoing concern in the West Coast Basin. In several areas, water-level altitudes remain well below sea level. In aquifers along the coast, concentrations of chloride and dissolved solids commonly exceed the U.S. Environmental Protection Agency (USEPA) Secondary Maximum Contaminant Level (250 and 500 mg/L, respectively; U.S. Environmental Protection Agency, 1996). Intruding seawater, naturally occurring oil-field brines, industrial-age contaminants (Shelton and others, 2001), and artifacts from past land usage are problems that continue to threaten ground-water resources of the area.

The seawater-barrier projects play a dual role in the West Coast Basin: impeding seawater intrusion and providing freshwater replenishment to the ground-water system. An improved understanding of the water-quality differences that occur between and within the aquifer systems is essential for management of the West Coast Basin and long-term operation of the barrier projects.

Purpose and Scope

The purpose of this report is to present data that describe current ground-water quality conditions of the major aquifer systems in the West Coast Basin, with an emphasis on the Dominguez Gap area. Of particular interest is the occurrence of seawater intrusion and the effects of barrier operations. The scope of this study included (1) collecting and analyzing water samples for major- and minor-ion chemistry, trace elements, and various isotopes; (2) collecting and analyzing pore fluids at continuously cored monitoring sites; (3) characterizing lateral and vertical differences in ground-water chemistry; (4) interpreting the source, movement, and relative age of ground water, with a focus on discriminating between native ground water, seawater, injected water, and oil-field brine; and (5) collecting and analyzing a suite of geophysical logs.

The results of this study are presented in the following manner: the approach and application of various data-collection techniques are briefly described; the distribution and variation of chemical and isotopic species within the aquifer systems are presented; data from several geophysical logs are discussed; and, finally, the chemical and geophysical results are synthesized along a section line.

Previous Investigations

The first regional assessment of ground-water conditions in the Los Angeles coastal area was completed by Mendenhall (1905a,b,c). A series of reports by Poland and co-workers (Poland and others, 1956, 1959; Piper and Garrett, 1953) provided a detailed description of the geology, geohydrology, and ground-water chemistry of the area. The California Department of Water Resources (1961) presented an analysis of the regional geohydrology, including a lithostratigraphic delineation of aquifers. Overviews of the geology and tectonic history of the Los Angeles Basin were provided by Yerkes and others (1965) and Wright (1991). Recent studies that have addressed the hydrostratigraphic framework in the Dominguez Gap area include aminostratigraphic work by Ponti (1989) and the application of sequence stratigraphy by Ehman and Cramer (1997) and Ehman and others (2001).

Zielbauer and others (1957, 1962) presented results from the LACDPW exploratory drilling program for the West Coast Basin and Dominguez Gap Barrier Projects, which detailed the geology, hydrostratigraphy, and water quality of the study area. Other reports have dealt specifically with aspects of the barrier projects (Bookman, 1967). The LACDPW issues regular reports detailing hydrologic operations, annual costs, and improvements for the barrier projects, along with water-level altitudes and dissolved-chloride concentration contours (Rancilio and Cristiano, 1990; Bunker and Bernabe, 1998; Saunders and Bernabe, 1999). Ground-water conditions were studied to evaluate the use of highly treated wastewater along the WCBBP as a supplement for imported-water use (West Basin Municipal Water District, 1997).

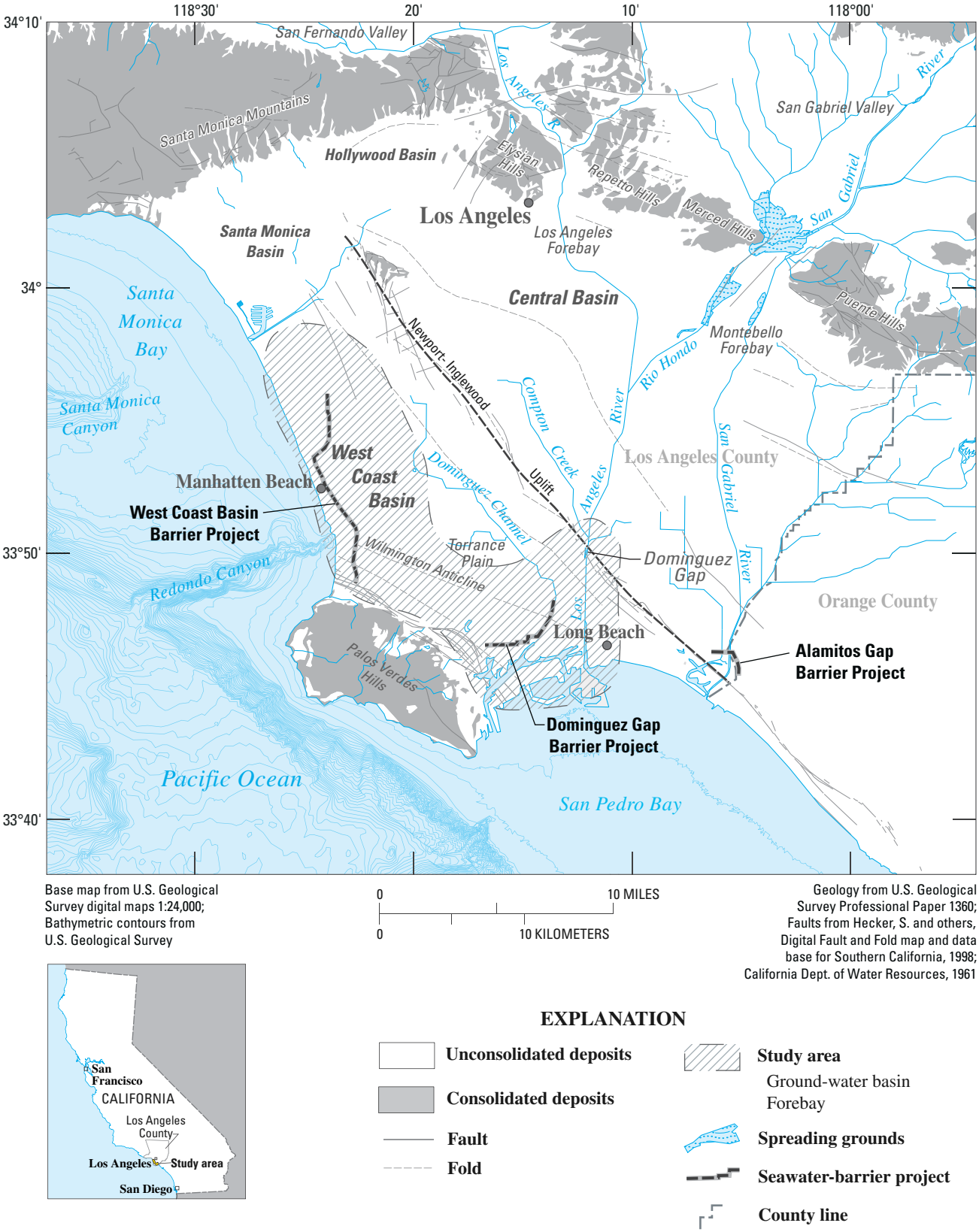


Figure 1. Surface geology and other features of the study area, Los Angeles County, California.

Several computer models have been developed that simulate ground-water flow in the study area. The USGS built a regional model of the Central and West Coast Basins (Reichard and others, 2003). Other models simulated flow in parts of the West Coast Basin (Chieh and others, 1988; P&D Technologies, 1998; Camp, Dresser & McKee, 1998). Kulshan (2002) developed a coupled density-dependant flow and solute-transport model to examine/simulate the saltwater-freshwater interface in the West Coast Basin and evaluate ground-water management alternatives.

Acknowledgments

This investigation was conducted by the U.S. Geological Survey in cooperation with the Water Replenishment District of Southern California as part of a regional study of the ground-water resources of the Central and West Coast Basins of Los Angeles, California. The LACDPW, Water Resources Department, provided historical water-level and chloride data, access to numerous barrier-project wells, and logistical support during the investigation. We thank the Tosco Corporation and the Southern California Water Company for access to their production wells.

Description of Study Area

Physiographic Setting

The West Coast Basin is bounded on the north by the Santa Monica Basin, on the west by the Santa Monica Bay and Palos Verdes Hills, on the south by San Pedro Bay, and on the east by the Newport-Inglewood Uplift (NIU). The NIU, a northwest-trending series of folds and discontinuous faults, acts as a partial barrier to ground-water flow between the Central and West Coast Basins (fig. 1). The Wilmington Anticline, located between the Palos Verdes Hills and NIU, appears to affect the hydrostratigraphy in the study area. The area has a Mediterranean-type climate marked by warm, dry summers, and cool, moist winters. Precipitation, which averages 14 in./yr, occurs predominantly during the winter months. The area is drained by Compton Creek, the Dominguez Channel, and the Los Angeles River.

The study area focused on the near-coastal areas of the West Coast Basin, generally within 4 miles inland of shore (see shaded areas in fig. 1). Also included is a portion of the Torrance Plain and the Dominguez Gap. The Dominguez Gap is described by Piper and Garrett (1953, p.167) as “the tongue of the Downey Plain incising the Newport-Inglewood Uplift, extending southward along the Los Angeles River to the coast.” Surrounded by several once-prolific oil-producing fields, the Dominguez Gap area is one of diverse land uses, including commercial and residential areas, industrial zones, and shipping ports.

Geohydrologic Setting

Hydrostratigraphy

The geohydrologic framework for the Central and West Coast Basins is summarized by Reichard and others (2003). They grouped aquifers into four systems: the Recent, Lakewood, Upper San Pedro, and Lower San Pedro aquifer systems (fig. 2). The aquifer systems were defined on the basis of “unconformities, lithology, depositional characteristics, geochemistry, and vertical water-level differences.”

The Recent aquifer system is predominantly composed of deposits of Holocene age and includes the Gaspur aquifer (California Department of Water Resources, 1961). The Lakewood aquifer system is composed of upper Pleistocene deposits and includes the Gage (also referred to as the 200-foot sand) and Gardena aquifers. The Upper San Pedro aquifer system is composed of lower Pleistocene deposits and includes the Lynwood (also referred to as the 400-foot gravel) and Silverado aquifers. The Lower San Pedro aquifer system is composed of lower Pleistocene deposits and includes the Sunnyside aquifer (also referred to as the Lower San Pedro aquifer). The Pico unit is considered as a low-transmissive zone that underlies the Lower San Pedro aquifer system. The Pico unit is composed primarily of upper Pliocene to lower Pleistocene deposits.

In the discussion of the geochemical and geophysical results in this report, the Recent and Lakewood aquifer systems are grouped together and referred to as the Upper aquifer systems. The Upper and Lower San Pedro aquifer systems are grouped together and referred to as the Lower aquifer systems. A generalized schematic of important hydrologic features in the study area is shown in figure 3.

Recharge and Discharge

Recharge to the West Coast Basin ground-water system is composed of artificial and natural sources. These occur through (1) injection of water in the seawater-barrier wells, (2) local infiltration, (3) intrusion of seawater, and (4) underflow from adjacent basins.

Injection at the WCBBP and DGBP (1996–2000), which averages about 17,000 and 5,000 acre-feet per year (acre-ft/yr), respectively, is a key source of recharge to the West Coast Basin. Since 1995, the WCBBP has made partial use of highly treated recycled water as an alternative source for injection (West Basin Municipal Water District, 1997). Injection of recycled water at the DGBP is scheduled to begin in 2004.

AGE	FORMATION	AQUIFER	AQUIFER SYSTEM	
HOLOCENE	ACTIVE SAND DUNE	SEMIPERCHED	RECENT AQUIFER SYSTEM	UPPER AQUIFER SYSTEMS
UPPER PLEISTOCENE	OLDER SAND DUNE	GASPUR BALLONA	LAKEWOOD AQUIFER SYSTEM	
	LAKEWOOD FORMATION (California Dept. of Water Resources, 1961) *(UNNAMED UPPER PLEISTOCENE* Poland and others 1956, 1959)	EXPOSITION ARTESIA GARDENA GAGE (200-FOOT SAND)		
LOWER PLEISTOCENE	*SAN PEDRO FORMATION*	HOLLYDALE JEFFERSON LYNWOOD (400-FOOT GRAVEL) SILVERADO	UPPER SAN PEDRO AQUIFER SYSTEM	LOWER AQUIFER SYSTEMS
		SUNNYSIDE LOWER SAN PEDRO	LOWER SAN PEDRO AQUIFER SYSTEM	
UPPER PLIOCENE	*PICO FORMATION, UPPER DIVISION*			PICO UNIT

Modified from California Department of Water Resources, 1961; Ponti, 1989

Figure 2. Geologic units and aquifers in the study area.

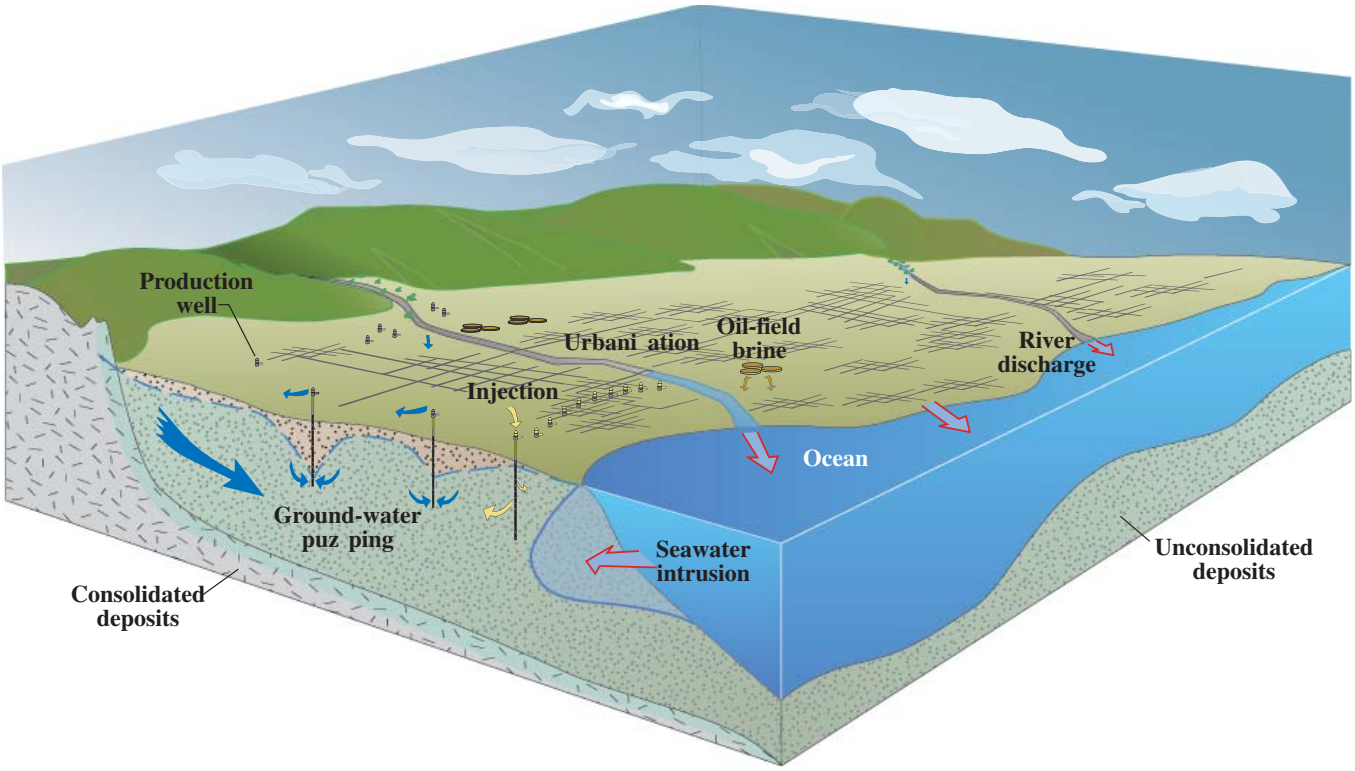


Figure 3. Generalized geologic, hydrologic, and other features of the study area.

Local infiltration—through direct precipitation, stream recharge, irrigation return, and runoff from the surrounding uplands—is estimated to be about 15,000 acre-ft/yr (Reichard and others, 2003). Recharge from precipitation is limited by urbanization. Recharge from streams and rivers is also limited because most are lined throughout the study area for flood control purposes.

Simulation modeling by the USGS estimated average flow (1996–2000) from seawater and adjacent basins to the West Coast Basin to be about 8,000 and 7,000 acre-ft/yr, respectively (Reichard and others, 2003).

Prior to the development of the Los Angeles basin, approximately 30 percent of the area was under flowing artesian conditions (Mendenhall, 1905c). Discharge from the ground-water flow system occurred offshore, at some fault zones, or in wetlands. Since then, discharge has been dominated by pumping from wells. Demands for water exceed natural replenishment in the West Coast Basin (table 1). About 146,000 acre-ft/yr of State Project and Colorado River water are imported for direct use (West Basin Municipal Water District, 2003). Current ground-water extractions average 52,000 acre-ft/yr (Water Replenishment District of Southern California, 2000), most of which are focused in the Silverado aquifer of the Lower aquifer systems in the Dominguez Gap area.

Ground-Water Movement and Levels

Before the 20th century, ground water moved from the Central Basin south and westward, toward the Santa Monica and San Pedro Bays. By the 1920s, owing to development of ground-water resources, water levels were below sea level throughout much of the West Coast Basin. Seawater began moving inland in aquifers from both Santa Monica Bay and San Pedro Bay. By the 1940s, elevated concentrations of chloride owing to seawater intrusion were noted in all coastal areas (Poland and others, 1959, plate 16).

Injection at what is now the WCBBP began in the 1950s on an experimental basis. The success of this program led to the expanded construction of the DGBP in the West Coast Basin and the Alamitos Gap Barrier Project in the Central Basin near Orange County (fig. 1). Imported State Project and Colorado River water is delivered to the project facilities. Recycled water began being used for injection at the West Coast Barrier Project in the 1990s. There is injection into both the Upper and Lower aquifer systems at the WCBBP and DGBP; however there is no direct injection of water into the Silverado aquifer at the DGBP.

Table 1. Averaged annual water use and replenishment in the West Coast Basin, Los Angeles County, California

[Values in acre-feet per year]

Water use: 1997–2001		
Imported water[a]		146,000
Recycled water[a]		22,000
Ground water[a]		52,000
	Total	220,000
Basin replenishment: 1996–2000		
Injection[b]		22,000
Precipitation/irrigation[c]		15,000
Seawater[c]		8,000
Adjacent basins[c]		7,000
	Total	52,000

[a]Data courtesy of U. Daniel, West Basin Municipal Water District.
[b]Water Replenishment District of Southern California, 2002, Engineer and Survey Report.
[c]Reichard and others, 2003, table 7, page 117, 1996–2000

Recent hydrographs of selected West Coast Basin wells monitored by Los Angeles County are shown in figure 4. The hydrographs show a pattern of rising water levels following construction of the barrier projects. Water-level altitudes are above, or close to sea level near the WCBBP, in part because of the higher land-surface altitudes and favorable geology. In contrast, water-level altitudes remain well below sea level near the DGBP. This is likely due to extensive ground-water pumping in the area, in combination with the land-surface altitudes that are near sea level, and the complex hydrostratigraphy.

Methods of Investigation

Well Network

Water-chemistry and geophysical data for this study were collected from a network of multiple-well monitoring sites, production wells, and observation wells (figs. 5, 6). Most water-quality samples were collected during February 1999–May 2002. Reference and construction information for the well network is provided in Appendixes A and B.

For this study, the USGS installed eight multiple-well monitoring sites, each containing four to six nested wells (see Land and others, 2002) for a description of a typical monitoring site). Four of these eight monitoring sites—Long Beach-3, -4, -5, and Westchester-1—were continuously cored, allowing for the collection of pore fluids and other detailed geologic information. The Long Beach-3, -4, and -5, sites are located east of the DGBP; Westchester-1 is located north of the WCBBP figs. 1, 5). The Wilmington-1 and Wilmington-2 monitoring sites, located north and south of Wilmington Anticline, respectively, are both less than 1 mi inland from the DGBP. The Hawthorne-1 site is located about 2 mi inland from the northern section of the WCBBP. The Long Beach-2 site, located in the Central Basin, just north of the Newport-Inglewood Uplift and Dominguez Gap, serves as a background or reference location for other wells in the study area.

Numerous observation wells have been installed by the LACDPW near the WCBBP and DGBP to assess barrier operations. Several of these wells were incorporated into the well network for this study. Some wells are constructed of galvanized 2-inch steel pipe with a perforated length of 10 ft. Other more recent wells are constructed of 4-inch PVC pipe with a perforated length of 40 to 140 ft, or more. A set of observation wells, constructed by the WRDSC to monitor a plume of seawater beneath the Torrance Plain (fig. 1), were also included in the network (PM-1, PM-3, and PM-4, fig. 5).

Water Quality

Most samples for water quality were collected from February 1999 through May 2002. Samples for major ions, selected trace elements, deuterium, and oxygen-18 were collected for all wells; tritium, boron-11, strontium-87, and carbon-14 isotope samples were collected for selected wells. The methods used to collect and analyze these samples are presented by Land and others (2002).

Field measurement of specific-conductance, pH, temperature, alkalinity, and dissolved-oxygen followed procedures outlined by Wilde and Radtke (1998). Conductivity and pH meters were calibrated daily; thermometers were calibrated at the beginning of the study. Because of the expected chemical instability of ground water in the study area, alkalinity was determined, immediately following collection, by titration to a fixed end-point of pH 4.5. When the presence of dissolved sulfide, an unstable constituent commonly occurring near the coast, was noted or suspected during well purging, a sample was also analyzed by titration in the field to determine the sulfide concentration (Fishman and Friedman, 1989). On the basis of replicate determinations, the reporting limit for dissolved sulfide was set at 1 mg/L.

Imported water was collected from a distribution pipeline and analyzed for most parameters listed above. The pipeline, referred to as West Basin Cross Connection #37 (WB #37), is the main distribution line providing water to the DGBP. Field measurements of pH, specific conductance, and temperature from a spigot on the pipeline remained virtually constant for 1 hour prior to sample collection.

Additional inorganic chemical and field data for wells PM-1; PM-4; 331-A,-B; 340-L,-M,-N were provided by the WRDSC (Anthony Kirk, Water Replenishment District of Southern California, unpub. data, 2002). Water-chemistry data for all wells are presented in Appendix A.

Core Pore-Water Extraction

At four continuously cored monitoring-well locations, pore water was extracted from numerous fresh core samples using a hydraulic press and stainless steel capsule system described by Manheim and others (1994). Approximately 50 g of sediment was first collected from finer grained sections of selected cores. Pore water was extracted by gradually applying 4,000–6,000 psi to the capsule system. Squeezing for a period of 15 to 45 minutes yielded between 3 and 15 mL of fluid, depending on the type of core material. Pore water was collected in a plastic syringe, and filtered through a 0.45 mm polyethersulfone disk. Salinity (as percent NaCl) and pH were measured onsite. Pore-water samples were then prepared for the analysis of major ions, total carbon, stable isotopes, and organic acids.

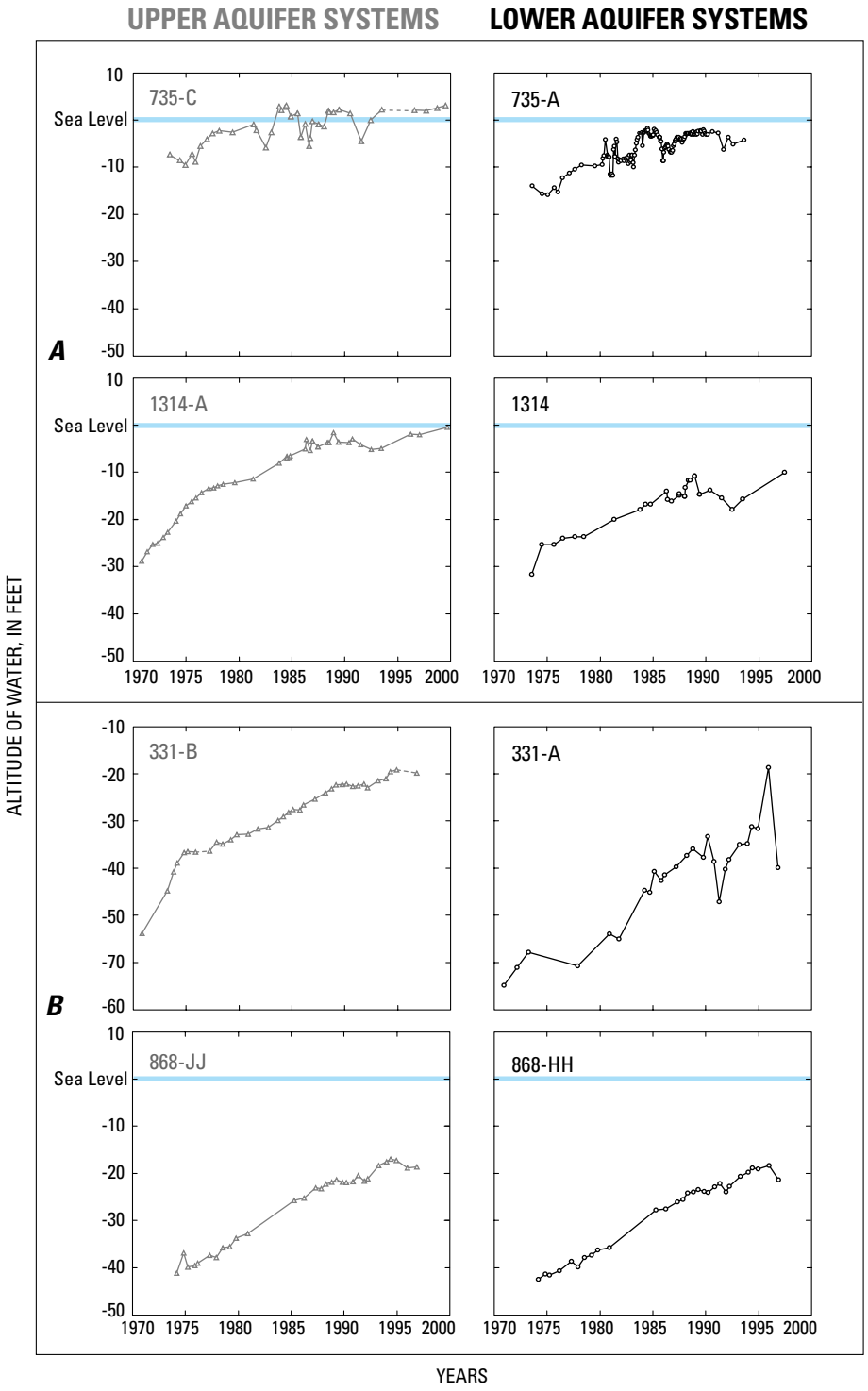
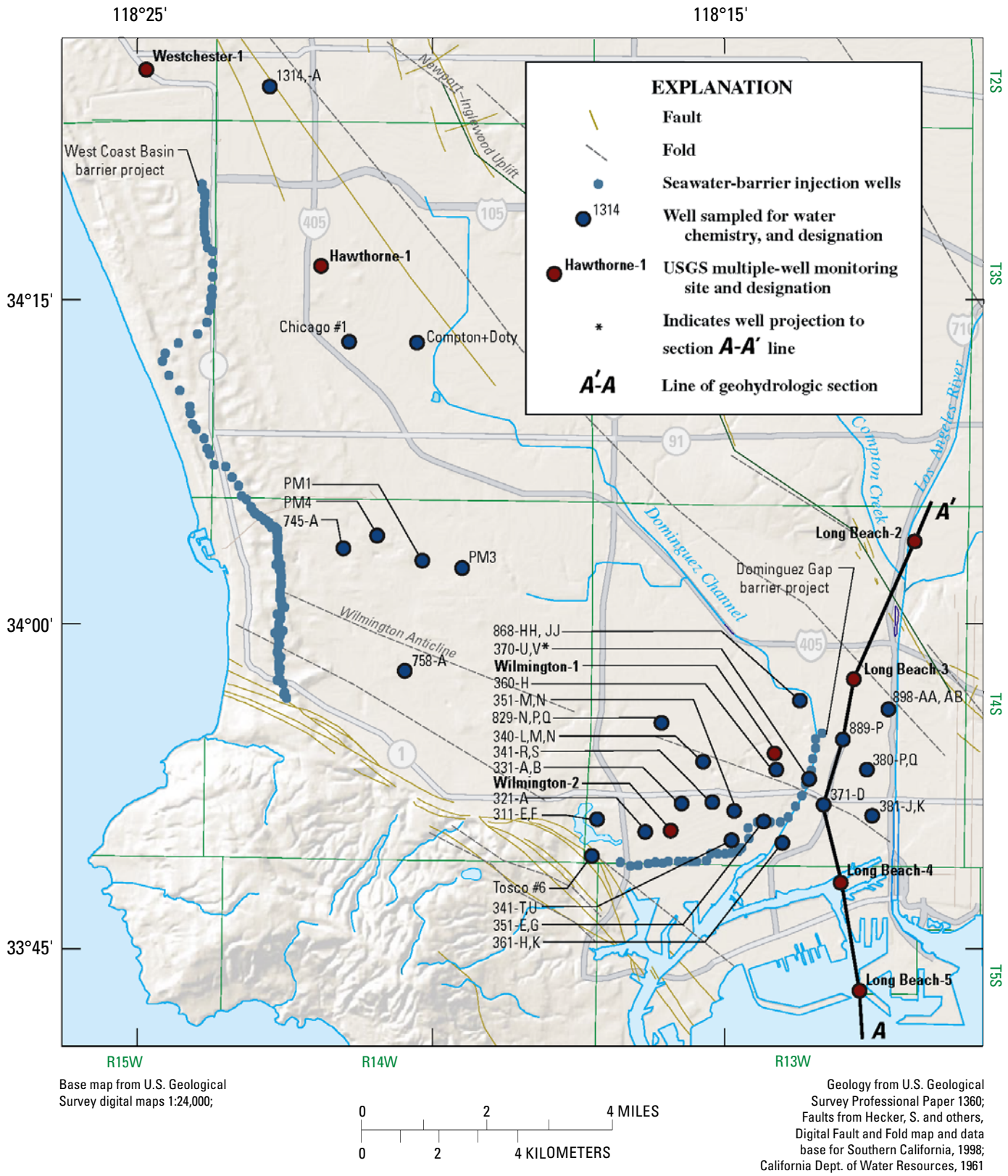


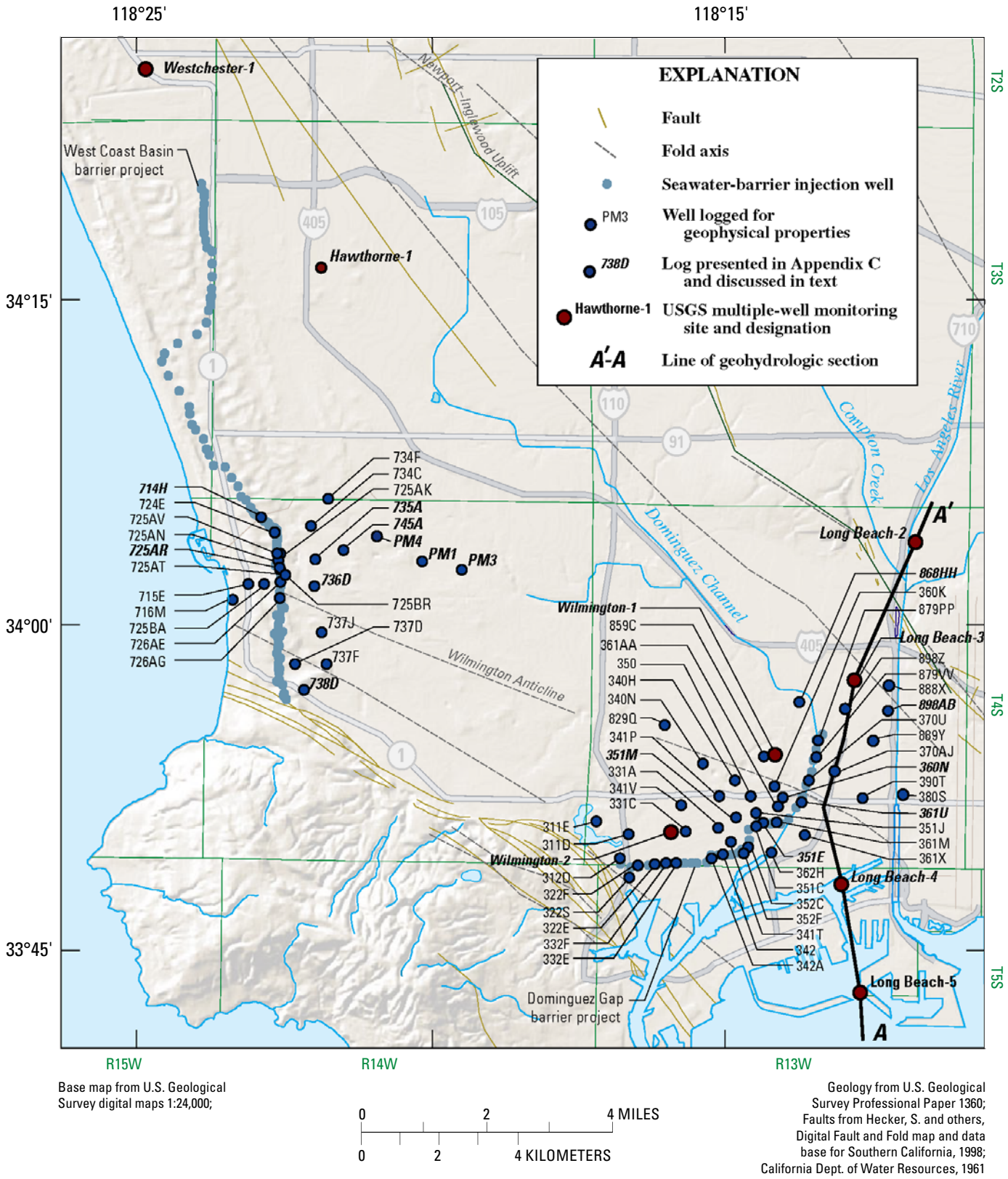
Figure 4. Selected wells in the Upper and Lower aquifer systems near the (*A*) West Coast Basin and (*B*) Dominguez Gap Barrier Projects, 1970–2000. (Location of wells shown in figures 5, 6.)



Base map from U.S. Geological Survey digital maps 1:24,000;

Geology from U.S. Geological Survey Professional Paper 1360; Faults from Hecker, S. and others, Digital Fault and Fold map and data base for Southern California, 1998; California Dept. of Water Resources, 1961

Figure 5. Location of wells sampled for water chemistry in the study area.



Base map from U.S. Geological Survey digital maps 1:24,000;

Geology from U.S. Geological Survey Professional Paper 1360; Faults from Hecker, S. and others, Digital Fault and Fold map and data base for Southern California, 1998; California Dept. of Water Resources, 1961

Figure 6. Location of wells logged for geophysical properties in the study area.

Geophysical Logging

Electromagnetic Induction

The electromagnetic induction (EM) tool is used to construct a continuous profile of electrical conductivity of the geologic formation penetrated by a borehole. The radius of material investigated ranges from 10 to 50 in. The EM tool, which can be run inside PVC pipe, is relatively insensitive to any borehole fill and is virtually blind to any medium properties at a radius less than 10 in.

The EM tool induces eddy currents that produce secondary magnetic and electrical fields. The receiver coil on the tool senses both secondary fields. The magnitude of the fields sensed is proportional to the conductivity of the surrounding media or bulk electrical and magnetic conductivity (McNeill and others, 1990).

Natural variability in the EM-log conductivity is caused by physical properties of the geologic deposits. Coarser deposits are much more resistive than are the finer grained deposits when the pore water is not saline. Clay and silt material is intrinsically conductive. In addition, finer grained layers have the ability to retain chloride from evaporative salts long after seawater and salts have been flushed from adjacent coarser grained layers. This retention can cause EM-log conductivity in the finer-grained layers to remain high. When combined with other data, such as gamma-ray logs, the EM data can be used to identify and monitor zones of poor-quality water through both blank and perforated PVC casing. EM logs therefore may reveal the relation between seawater intrusion and stratigraphy at depths at which a well is not perforated.

Gamma-Ray Emission

A natural-gamma-ray tool measures the intensities of gamma-ray emissions resulting from the natural decay of potassium-40 and of the daughter products of uranium and thorium. In general, the natural gamma activity of clay-rich sediments is much higher than that of quartz sands (Keys and MacCary, 1971). Gamma logs are used primarily to define lithology indicators (for example, finer-grained sequences) and for geologic correlation (Norris, 1972; Strom, 1997).

Temperature

Ground-water temperature is related to factors such as lithology, geothermal gradient, recharge source, and residence time of water within the sediments. Temperature in the subsurface is subject to a geothermal gradient, which normally increases with increasing depth (approximately 0.6^{o}C per 100 ft). As such, temperature logs can provide useful information on lithology changes as well as horizontal and vertical ground-water flow patterns (Keys and MacCary, 1971; Beck, 1976; Michalski, 1989; Williams and others, 1994). A lithology change in a thickly bedded sequence may appear as a distinct temperature shift. Horizontal flow in the aquifer may appear as a deflection or an interval of constant temperature in the temperature log. In this study, the data are especially useful because of the temperature differences between injection water, seawater, and the surrounding formations. Imported water is cooler (see WB #37, Appendix A) throughout the year in comparison with subsurface temperatures. Injection into the ground-water flow system along the barrier project disturbs the natural geothermal gradient. Temperature anomalies also result from seawater intrusion and can vary depending on the depth of water from which the intrusion originated.

Specific Conductance

Specific-conductance logs provide an indication of the dissolved-solids concentration of the water contained in the well at a particular depth; they are not always indicative of water-quality conditions in the formation adjacent to a well. Density stratification makes it difficult to locate discrete zones of poor-quality water using only the specific-conductance log. However, specific-conductance logs can provide an indicator that poor-quality water is present within the perforated interval or in a zone in hydraulicly connected to the perforated interval. In some cases specific-conductance logs can provide evidence of a compromised well casing (Michalski, 1989).

Quality Assurance

Quality-control samples were collected to qualify bias and precision associated with obtaining water-quality data for this study. Samples include a source solution blank, equipment blank, field blank, and sequential field replicate. Blanks were analyzed to identify contamination of routine ground-water samples by field personnel, sampling equipment, sample bottles, or any other source of contamination during transportation of field equipment, during shipment to the laboratory, or during analysis at the laboratory. Blank samples were analyzed under a custom schedule having slightly lower reporting limits for many analytes. Data from the analysis of blanks indicate detectable concentrations of dissolved calcium, magnesium, and boron. However, these values were below the reporting limit of routine ground-water sample schedules in this study; therefore no adjustments to the environmental data were made. Replicates were collected to assess variability of the sample-collection process and analysis. Samples with a relative error less than 15 percent were considered acceptable. The relative error was less than 10 percent for 18 of 19 constituents; one measurement of sulfate had a relative error of 12 percent. Repeated titration of a prepared “zero-DO” solution yielded concentrations less than the reporting limit of 0.1 mg/L. Precision of deuterium and oxygen-18 are better than $\pm$2.0 and 0.2 per mil, respectively.

Quality-control procedures for the collection of geophysical well-bore data incorporated tool calibration and replicate logging runs. The zero-depth starting point at each well was land surface. A two-point calibration check was performed on the EM-gamma tool using free air as a zero value and a calibration-ring sleeve manufactured to read 750 millimhos per meter (mmho/m). Sequential EM-gamma log data were collected using two different Century tools at well 311-D with acceptable response between each tool. Natural gamma-ray emission was measured using a passive gamma tool (where bombardment of an inset crystal generates a measurable electrical charge). Size and surface area of the crystal affect the raw gamma count; therefore, output was correlated to American Petroleum Institute (API) units. This standard unit of measurement is close to 98 percent of counts per second, and facilitates comparison of other gamma-ray logs employing different crystal sizes. The fluid conductivity tool was calibrated using two specific-conductance standards prepared by the USGS Ocala Quality of Water Unit. Fluid log measurements are auto-corrected for differences in temperature to a standard reference of 25 degrees Celsius. Temperature output was verified against a calibrated thermometer over a range of values ($r^2 = 0.99$).

Ground-Water Chemistry

Increasing chloride concentrations can be an indicator of seawater intrusion in a freshwater aquifer. However, there are other potential sources of high-chloride water in coastal areas (Piper, 1953; Martin, 1984, Izbicki, 1991; Rosenthal, 1992; Hanson and others, 2002). Other major ions, and especially trace-element ratios, often impart a distinct chemical signature that can be used to identify and distinguish between different sources of high-chloride water to wells and to evaluate the geochemical processes affecting water quality within the aquifer systems.

In the study area, the following types of water were considered: native ground water, imported water, seawater from Santa Monica or San Pedro Bays, and an oil-field brine. The occurrence of these water types for wells sampled in the well network is summarized in table 2. Mixing lines (Kaehler and Belitz, 2003) were constructed between these 'end-member' sources to help distinguish the most likely water type.

Native ground water in this report refers to freshwater as described by Poland and others (1959, p. 167), that is, water generally having less than 600 mg/L of dissolved solids and a sodium/calcium-bicarbonate composition. Most of this water is recharged in the forebay areas of Central Basin (fig. 1) (Reichard and others, 2003). Water collected at the Long Beach-2 monitoring site (fig. 5) was used as the end member for native water.

Imported State Project water and Colorado River water are injected at the seawater-barrier projects. Amounts delivered to each project vary throughout the year, although the proportion of Colorado River water delivered to the DGBP is generally larger than that delivered to the WCBBP. The sample collected at WB-#37 serves as this end member.

Recently intruded seawater enters the study area from Santa Monica and San Pedro Bays along estuary environments or where aquifers crop out offshore. Outcrops can be very close to shore along features such as the Redondo Canyon (fig. 1). Older seawater may also be trapped in finer grained sediments within or adjacent to the study area (van der Kamp and others, 2000).

During the early development of oil fields in the West Coast Basin, unregulated disposal practices commonly resulted in contamination of ground water by oil-field brine waste. Although some waste was piped directly to the ocean, other waste was discharged into sumps, natural channels, or onto the land surface (Piper and Garrett, 1953). The potential for contamination of deeper ground water (fig. 3) also exists through abandoned wells or failed well casings . Not all brine fluid is related to oil-field development waste. Fresh meteoric water that has been chemically altered as a result of deep circulation in the basin (Collins, 1975) may also contain similar trace-element ratios.

Major-Ion Composition

The major-ion data for ground-water samples collected in the study area are summarized in figure 7. The plot presents the relative contribution of major cations and anions by expressing each concentration (on a charge-equivalent basis) as a percentage of the total ion content of the water (Piper, 1944). Of the 86 samples considered, 82 had an ion balance difference (cations to anions) of less than 4 percent; 4 samples were between 4 and 8 percent. A trilinear diagram is useful for screening a large number of chemical analyses (data points), identifying simple ground-water mixing between chemically distinct sources, and distinguishing water-mineral interactions along a ground-water flow path.

Table 2. Summary of ground-water sources for wells sampled in the West Coast Basin, 1999–2002

[Aquifer systems —see figure 2 for explanation; mg/L, milligrams per liter; chloride range—low = less than 250 mg/L, medium = between 250 and 2,500 mg/L, and high = greater than 2,500 mg/L; N, native water; S, seawater; I, imported water; B, oil-field brine; —, no data; ft, feet below land surface; *, no interpretation due to color interference; relative age—see section on "Tritium" for explanation; EM, electromagnetic induction]

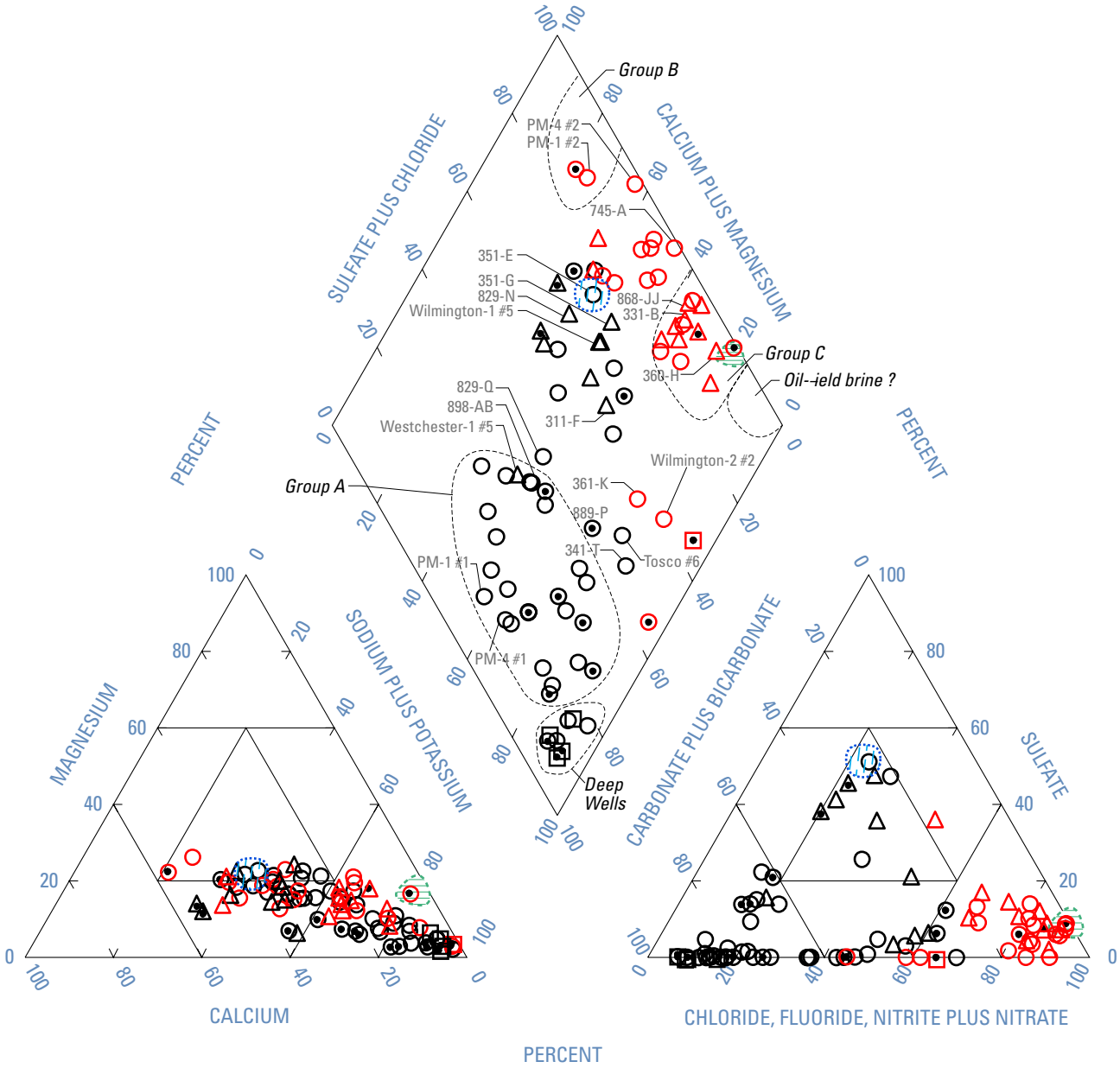
Common name	Aquifer systems	Chloride range	Chloride-to-bromide	Chloride-to-iodide	Chloide-to-boron	Stable isotope	Relative age of water	Comment
311-E	Lower	Low	B-N	N	N	N	—	Native, fresh water recharged locally from Palos Verdes Hills
311-F	Upper	Low	S-N	N	N	N	—	Native, fresh water recharged locally from Palos Verdes Hills
321-A	Lower	Medium	S	B-S-N	S	S-N	Old	Likely intrusion of older seawater
331-A	Lower	Medium	S	B-S-N	S	I-S-N	Recent	Mix of native, imported and seawater
331-B	Upper	Medium	S	B-S-N	S	I	Recent	Mix of native, imported and seawater
340-L	Upper	Medium	B	—	B	S-N	Recent	EM log shows localized saline unit from 125–190 ft
340-M	Lower	Medium	B	—	B-S-N	S-N	Recent	Poorer quality water attributed to vertical movement from overlying saline unit
340-N	Lower	Low	B-N	—	S-N	N	Old	
341-R	Lower	Medium	S	S	S	I	—	Occurence of substantial imported water masked by seawater
341-S	Upper	Medium	B	B	B	N-I	—	
341-T	Lower	Low	B-N	B-N	B-N	N	—	No change in historic chloride concentration, but major-ion composition and trace-element ratios suggest incipient mixing with an oil-field brine
341-U	Upper	Medium	S	N-S	S	I	—	Occurence of substantial imported water masked by seawater
351-E	Lower	Low	I	I	N	I	—	Substantial imported water present
351-G	Upper	Low	I	I	N	I	—	Substantial imported water present, although EM log shows saline unit above and below well perforation
351-M	Lower	Medium	S	B-S-N	S	I	—	Historic data show increasing chloride concentrations
351-N	Upper	Medium	S	B-S-N	B	I	—	
360-H	Upper	High	S	S	S	I	Recent	Occurrence of substantial imported water masked by seawater
361-H	Lower	Low	N	N	N	N	Old	
361-K	Lower	Medium	B	B	B	N	Old	Native water mixed with an oil-field brine (source unknown)
370-U	Lower	Low	B-N	B-N	S-N	N	—	
370-V	Upper	Medium	S	S	S	I	—	Occurrence of substantial imported water masked by seawater; EM log shows saline units above and below well perforation
371-D	Lower	Low	N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
380-P	Lower	Low	N	N	N	N	Old	Native, fresh, sodium-bicarbonate water
380-Q	Lower	Low	N	N	N	N	—	Native, fresh, sodium-bocarbonate water
381-J	Lower	Low	*	*	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene; sample outgassed during collection
381-K	Lower	High	S	B-S-N	S	S-N	Old	Likely intrustion of old seawater
745-A	Lower	High	S	S	S	S	Recent	EM log indicates relatively fresh water is present to a depth of 520 ft
758-A	Lower	Low	N	N	N	N	Old	
829-N	Upper	Low	B-N	B-N	S-N	N	Old	
829-P	Lower	Low	B-N	B-N	N	N	—	
829-Q	Lower	Low	N	N	N	N	—	Native, fresh, sodium-bicarbonate water for the West Coast Basin
868-HH	Lower	Medium	B	B	B	S	—	Persistent high-chloride water; oil-field brine source probable
868-JJ	Upper	High	S	B-S-N	B	S	—	

Table 2. Summary of ground-water sources for wells sampled in the West Coast Basin, 1999–2002—Continued

Common name	Aquifer systems	Chloride range	Chloride-to-bromide	Chloride-to-iodide	Chloide-to-boron	Stable isotope	Relative age of water	Comment
889-P	Lower	Low	B-N	B-N	B-N	N	—	Native water; incipient mixing with an oil-field brine suspected
898-AA	Upper	Medium	B	B	B	N	—	Native water mixed with an oil-field brine source
898-AB	Lower	Low	N	N	N	N	—	
1314	Lower	Low	N	N	N	N	—	Native, fresh, calcium/sodium-bicarbonate water
Chicago-1	Lower	Low	N	N	N	N	Old	
Compton+Doty	Lower	Low	N	N	N	N	—	
Hawthorne-1 #1	Pico	Low	N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
Hawthorne-1 #2	Lower	Low	N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
Hawthorne-1 #3	Lower	Low	N	N	N	N	Old	
Hawthorne-1 #4	Lower	Low	N	N	N	N	Old	
Hawthorne-1 #5	Upper	Low	I-N	S-N	S-N	N	Recent	
Hawthorne-1 #6	Upper	Medium	S-I-N	B-S-N	S	N-I	Recent	Some imported water present; source of high chloride water is probably seawater
Long Beach-2 #1	Pico	Low	N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene; distinct chloride-to-bromide ratio attributed to hyperfiltration
Long Beach-2 #2	Lower	Low	N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
Long Beach-2 #3	Lower	Low	N	N	N	N	Old	Native, fresh, sodium-bicarbonate water
Long Beach-2 #4	Lower	Low	N	N	N	N	Old	Native, fresh, sodium-bicarbonate water
Long Beach-2 #5	Upper	Low	B-N	S-N	B-N	N	Recent	Recharge derived from local Central Basin precipitation
Long Beach-2 #6	Upper	Low	B-N	S-N	B-N	N	Recent	Recharge derived from local Central Basin precipitation
Long Beach-3 #1	Lower	Low	N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
Long Beach-3 #2	Lower	Low	N	N	N	N	Old	
Long Beach-3 #3	Lower	Low	N	N	N	N	Old	
Long Beach-3 #4	Lower	Low	B-N	B-N	S-N	N	Old	
Long Beach-3 #5	Lower	Medium	B	B	S	S-N	Old	Calcium-chloride water
Long Beach-4 #1	Pico	Low	N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
Long Beach-4 #2	Lower	Medium	B	B	B	N	Old	
Long Beach-5 #1	Pico	Medium	S	B-S-N	B	N	Old	Old seawater with distinct major-ion composition and trace-element ratios; likely recharged during the Pleistocene
Long Beach-5 #2	Lower	High	S	S	S	S	Old	Ground water composed mostly of seawater
PM-3 #1	Lower	Low	*	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
PM-3 #2	Lower	Low	N	N	N	N	Old	Native, fresh, calcium/sodium-bicarbonate water
PM-3 #3	Lower	Low	B-N	B-N	S-N	N	Old	
PM-3 #4	Upper	Low	B-N	B-N	S-N	N	Recent	
Tosco #6	Lower	Low	S-N	S-N	B-N	N	—	Native water; chloride-to-bromide and chloride-to-iodide ratio suggest incipient seawater intrusion
Westchester-1 #1	Pico	Low	S-N	B-N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
Westchester-1 #2	Lower	Low	*	N	N	N	Old	
Westchester-1 #3	Lower	Low	*	N	N	N	Old	
Westchester-1 #4	Lower	Low	N	N	N	N	Old	Recharge derived from local West Coast Basin precipitation
Westchester-1 #5	Upper	Low	N	N	N	N	Old	Recharge derived from local West Coast Basin precipitation
Wilmington-1 #1	Lower	Low	B-N	B-N	S-N	N	Old	
Wilmington-1 #2	Lower	Medium	S	B-S	S	N	Old	

Table 2. Summary of ground-water sources for wells sampled in the West Coast Basin, 1999–2002—Continued

Common name	Aquifer systems	Chloride range	Chloride-to-bromide	Chloride-to-iodide	Chloide-to-boron	Stable isotope	Relative age of water	Comment
Wilmington-1 #3	Lower	Medium	S	B-S-N	S	I-S-N	Recent	Native water mixed with seawater and from imported water from the overlying unit
Wilmington-1 #4	Lower	Medium	S	B-S-N	S	I	Recent	Likely mixture of imported and seawater
Wilmington-1 #5	Upper	Low	S-N	B-N	S-N	I	Recent	Likely mixture of imported and seawater
Wilmington-2 #1	Lower	Low	S-N	N	N	N	Old	Isotopically light water attributed to recharge during the Pleistocene
Wilmington-2 #2	Lower	Medium	B	B	B	S	Old	Isotopically light water attributed to recharge during the Pleistocene; localized saline unit attributed to an oil-field brine
Wilmington-2 #3	Lower	Low	N	N	N	N	Old	Native, fresh, sodium-bicarbonate water
Wilmington-2 #4	Lower	Medium	S	B-S-N	S	I-S-N	Recent	
Wilmington-2 #5	Upper	High	S	S	S	S-I	Recent	Some imported water is present, though masked by seawater; EM log shows extensive intrusion from 85–185 ft



EXPLANATION

Dissolved chloride greater than or equal to 250 milligrams per liter

- Upper aquifer systems
- Lower aquifer systems
- Pico unit

Dissolved chloride less than 250 milligrams per liter

- Upper aquifer systems
- Lower aquifer systems
- Pico unit

- Seawater
- Imported water

- **Well along geohydrologic section *A-A′* section *(see fig. 5)***

Figure 7. Major-ion composition of ground water from wells sampled in the study area.

Most native freshwater in the study area has a calcium/sodium-bicarbonate to sodium-bicarbonate composition, resulting from extensive cation-exchange and sulfate-reduction reactions, typical of coastal aquifers (Back and others, 1993). The composition of this water is shown as Group A in fig. 7. All wells in this group (except Westchester-1 #5) are perforated in the Lower aquifer systems. Other fresh sodium-bicarbonate water occurring in deep portions of the Lower aquifer systems (and the Pico unit) is further distinguished by the near absence of sulfate, an orange-yellow color (from higher amounts of dissolved organic carbon), and the occurrence of hydrogen sulfide gas. The composition of this water plots below Group A (fig. 7). Native fresh ground water in the Upper aquifer systems was described by Poland (1959) as a calcium-bicarbonate type; however, this composition was not found in any wells sampled as part of this study. Instead, most water was commonly of the sodium-chloride to calcium-chloride type.

Imported water (from WB-#37) has a calcium/sodium-sulfate composition that is often not easily distinguished from other high-dissolved solids, mixed composition, water in the study area (fig. 7). Similar major-ion compositions were observed for water from wells 351-E, 351-G, and Wilmington-1 #5.

Seawater and other wells yielding water with a sodium-chloride composition plot within Group C in figure 7. These data show that part of the Upper (wells 331-B and 360-H) and Lower (wells 321-A, 381-K, Long Beach-5 #2) aquifer systems are intruded with seawater.

Many oil-field wastes or brine fluids from Tertiary rocks are also dominated by sodium and chloride ions (Piper and Garrett, 1953) but generally plot to the lower right of Group C. Discerning between these sources and seawater on the basis of major-ion composition alone may not be possible. For example, the mixing of water from Group A and [an oil-field brine] either of these high-chloride sources (without reaction) could result in a composition shown in water from well 341-T, 361-K, 889-P, Tosco #6, or Wilmington-2 #2 (fig. 7). Trace element ratios (discussed in the following sections Dissolved Bromide, Dissolved Iodide, or Dissolved Boron) often provide a more discriminating means as to the probable source.

Changes in major-ion composition that occur between the water and aquifer matrix during seawater intrusion are represented by a few wells in figure 7. A known plume of seawater originating from Santa Monica Bay extends several miles inland (Chieh and others, 1988; Johnson, 1992). Initially, excess sodium ions from the intruding seawater displace calcium ions on clay minerals in the fresh-water aquifer. This is first seen as a shift from Group A (wells PM-1 #1 and PM-4 #1) to a calcium-chloride composition (shown by wells PM-1 #2 and PM-4 #2, labeled as Group B). As seawater continues to intrude, and the exchange sites are exhausted, the composition will begin to shift toward seawater (shown by well 745-A).

Dissolved Chloride

Chloride concentrations in native water ranged from 10 to 65 mg/L in the Upper aquifer systems and 10 to 35 mg/L in the Lower aquifer systems; near the coast, portions of the Lower aquifer systems may have contained as much as 90 mg/L of chloride (Poland and others, 1959; Reichard and others, 2003). Dissolved-chloride concentrations collected as part of this study are shown in figure 8. Features of note in figure 8 include elevated chloride concentrations measured at several Upper and Lower aquifer systems wells inland from the barrier projects (331-A, -B; Wilmington-1 #2), and relatively low chloride concentrations measured at several Lower aquifer system wells in the northwestern part of the study area (Hawthorne-1, Westchester-1) and east of the DGBP (371-D, 380-Q, 381-J, 898-AB, Long Beach-3 #3, Long Beach-4 #1).

For most wells, water levels along the coast have been rising since the early 1970s in response to injection of freshwater at the barrier projects and reduced pumping (Reichard and others, 2003). However, not all wells with increased water levels show a corresponding decrease in dissolved chloride. A comprehensive accounting of chloride changes with time is beyond the scope of this report. However, several time-series plots showing chloride concentration and water level at a few selected wells are presented in figure 9. These plots were constructed from historical water-level and depth-dependant chloride-concentration data collected by the LACDPW (Rancilio and Cristiano, 1990; Bunker and Bernabe, 1998; Saunders and Bernabe, 1999).

Inland from the WCBBP wells 735-C and 1314-A (Upper aquifer system) and wells 735-A and 1314 (Lower aquifer systems) show relatively small changes in chloride concentration with time. Well 735-A contains relatively saline water, whereas well 1314 contains relatively freshwater. Inland from the DGBP well 331-B, 340-L, and 351-G indicate relatively saline water is present in the Upper aquifer systems. Well 331-B shows generally increasing concentrations through the early 1990s after which concentrations decease; well 340-L shows generally constant concentrations from the early 1980s onward; well 351-G (located directly on the barrier) shows an initial decrease in concentration, along with periods of increased concentration occurring in the early 1980s and the mid-1990s. A similar increase in chloride concentration in the Lower aquifer systems is also seen at well 331-A.

Along with the depth-dependent chloride concentrations collected by the LACDPW, chloride concentrations from bulk sampling by the USGS are plotted in figure 9. In comparison with concentrations measured at discrete depths (under nonpumped conditions) within a well, concentrations obtained through bulk sampling can be similar (1314 and 331-B), higher (321-A), or lower (340-L and 351-G).

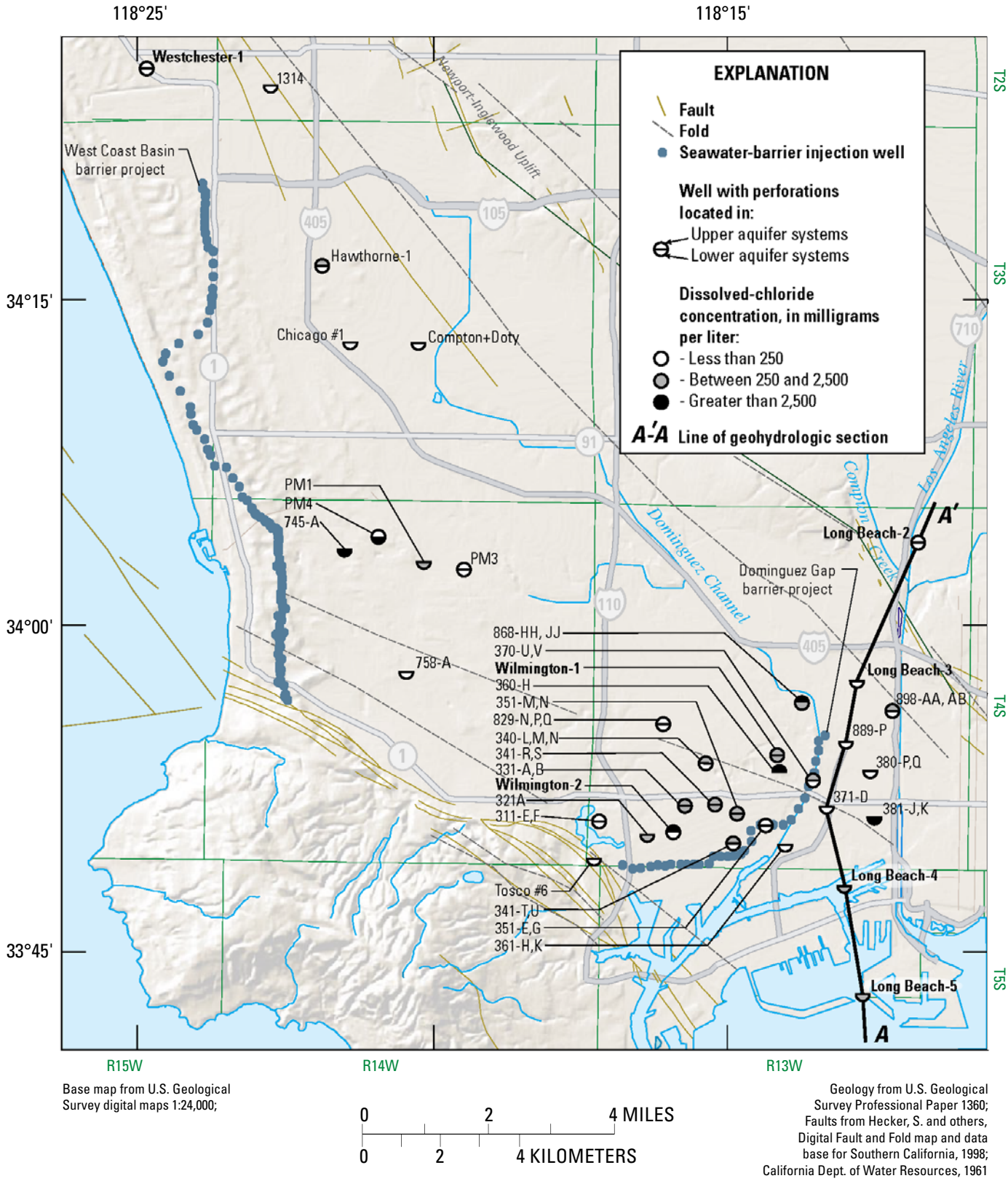


Figure 8. Dissolved-chloride concentrations for wells sampled in the study area.

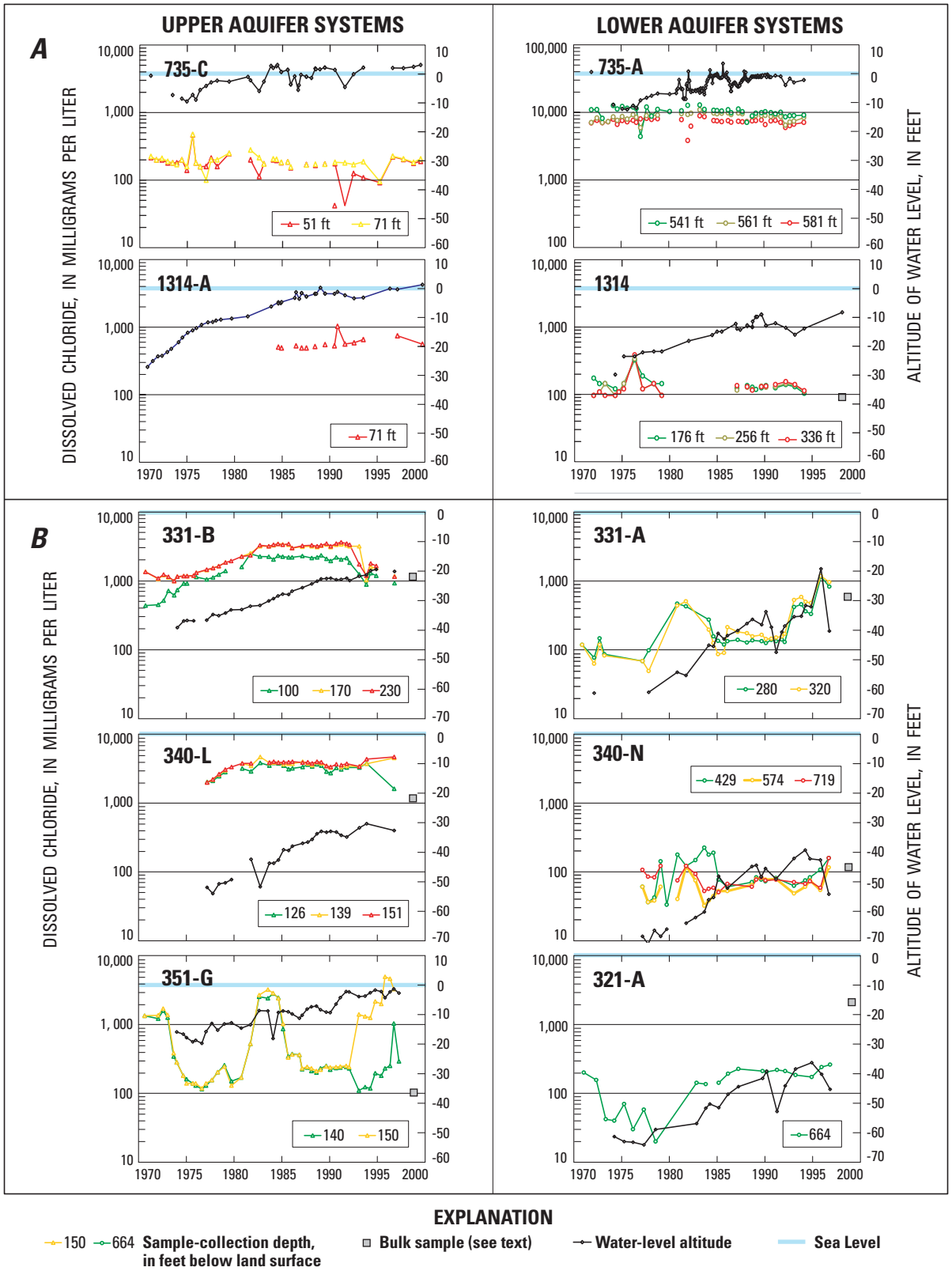


Figure 9. Dissolved-chloride concentration and water-level altitude as a function of time in the Upper and Lower aquifer systems in selected wells near the West Coast Basin (*A*) and Dominguez Gap Barrier Projects (*B*).

Many factors related, but not limited, to well construction and sampling technique can influence the representativeness of ground-water samples from an aquifer. Density stratification between saline and fresh ground water in a coastal environment may result in chemically stratified water composition within the casing of a well (Gossell and others, 1999). Several observation wells in this study have 4-inch-diameter casings with perforations typically spanning 40 to 140 ft (or more) and, as a result, are more likely to show these effects. The chemical composition resulting from bulk purging of a well typically reflects the most productive water-bearing zone within the perforated interval. Inadequate purging of a well prior to sampling can allow stagnant, density-stratified, and therefore chemically stratified, water to be sampled. Variable pumping rates, particularly low flow rates, can cause skimming from the top of the perforated interval, resulting in a sample that does not represent the entire interval.

Shown in figure 10 are dissolved-chloride concentrations of pore water extracted from cores collected at the Westchester-1, Long Beach-3, Long Beach-4, and Long Beach-5 monitoring sites (note that concentrations are plotted at different logarithmic scales for the different sites). There are clear differences in chloride concentrations among the four sites. There also are differing magnitudes and patterns of chloride concentrations associated with the different hydrologic units at each site. Data from Westchester-1 show low chloride concentrations throughout the Upper and Lower aquifer systems, with a shift to slightly higher concentrations in the Pico unit. The data from the Long Beach sites show increasing chloride as one moves south (seaward) from Long Beach-3 to Long Beach-5. At Long Beach-3, several zones within the Upper aquifer system have elevated chloride concentrations (for example, 2,900 mg/L at about 275 ft; fig. 10). At Long Beach-4, most of the Upper aquifer system has chloride concentrations greater than 10,000 mg/L, and elevated chloride concentrations extend about 200 ft into the Lower aquifer systems. At Long Beach-5, the Upper and much of the Lower aquifer systems have chloride concentrations near that of seawater.

Dissolved Bromide

Bromide is a generally nonreactive dissolved species, and like chloride, it behaves conservatively in ground-water environments (Hem, 1992). Bromide is also considerably less abundant and more soluble than is chloride (Davis and others, 1998). Bromide concentrations in water from wells in this study area ranged from 0.07 mg/L (Long Beach-2 #2) to 36 mg/L (Long Beach-5 #2). Seawater has a bromide concentration of 67 mg/L. Higher concentrations were reported in oil-field brines (Collins, 1975), including those from the Los Angeles basin (Piper and Garrett, 1953), and in water from estuarine deposits of a nearby coastal basin (Izbicki and others, 1995).

Bromide data for wells in the study area are presented in figure 11. Because small changes in the concentration of bromide, relative to chloride, may be significant, values are plotted on a mole per mole basis as a ratio of chloride to bromide. In the study area, the chloride-to-bromide ratio of seawater, about 640, is similar to that of low-chloride native water from several wells in the Lower aquifer systems (for example, Long Beach-2 #3). This is labeled as native freshwater in figure 11. Mixing between these two sources will yield a value proportional to each that plots along the freshwater/seawater mixing line (fig. 11). For example, higher-chloride water from wells 331-B, 360-H, 370-V, 868-JJ, and Wilmington-2 #5 in the Upper aquifer systems and 321-A, 381-K, and 745-A in the Lower aquifer systems appears to reflect mixing with seawater.

Imported Colorado River water collected at WB #37 contains a relatively small amount of dissolved bromide (0.04 mg/L), resulting in a large chloride-to-bromide ratio (about 4,100). This is labeled as imported water in figure 11. In the study area, water from a few wells has a chloride-to-bromide ratio greater than native freshwater or seawater (351-E, 351-G, Hawthorne-1 #5, #6). These data show that some of the water is derived from the injection of imported water. However, the apparently high chloride-to-bromide ratios for deep wells 381-J, Westchester-1 #2 and #3, and PM-3 #1 (labeled colored water in fig. 11) are the result of colormetric interferences in the determination of bromide. Tritium data (see “Tritium” section) further preclude the presence of significant recently injected water at these locations.

Most water from wells sampled in the study area has a chloride-to-bromide ratio below that of seawater, indicating substantial bromide enrichment relative to chloride. Of these samples, some have a chloride-to-bromide ratio less than 290 (fig. 11), a value which Piper and Garrett (1953) used as presumptive evidence for mixing with a brine source. Piper and Garrett (1953) reported chloride-to-bromide ratios as low as 70 in water associated with oil-field waste in the Los Angeles area, although the concentration of bromide in these sources varies (White, 1965; Davis and others, 1998). Low chloride-to-bromide ratios indicate that the source of higher chloride water in the Upper aquifer systems wells 340-L, 341-S, and 898-AA (inland from the DGBP) is an oil-field brine. In the Lower aquifer systems, low chloride-to-bromide ratios in water from wells 340-M, 868-HH, and Long Beach-3 #5 also indicate mixing with an oil-field brine.

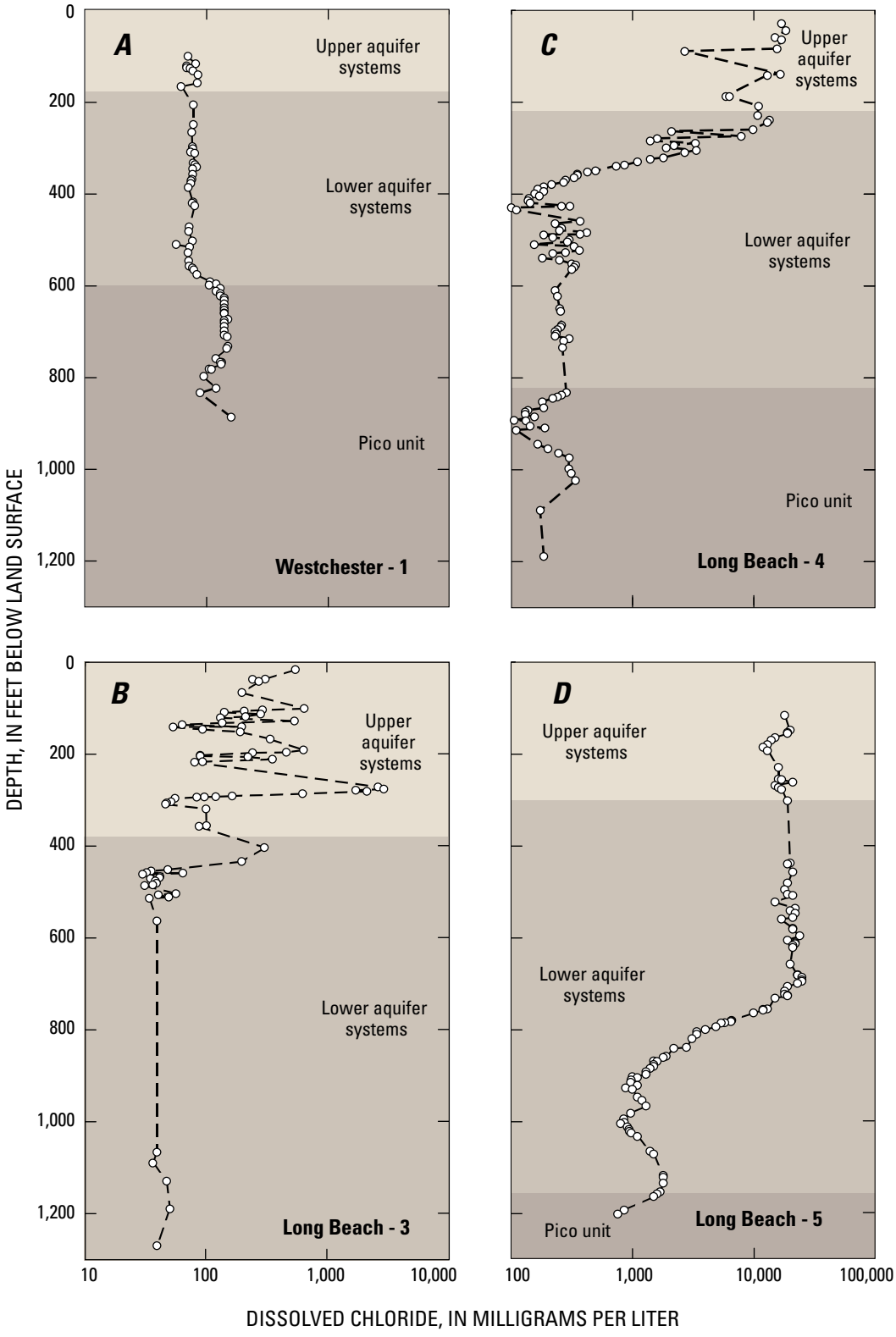


Figure 10. Dissolved chloride as a function of depth in pore water from continuously cored monitoring sites in the study area: (*A*) Westchester-1, (*B*) Long Beach-3, (*C*) Long Beach-4, (*D*) Long Beach-5. (The concentration of dissolved-chloride in seawater is approximately 19,000 milligrams per liter.)

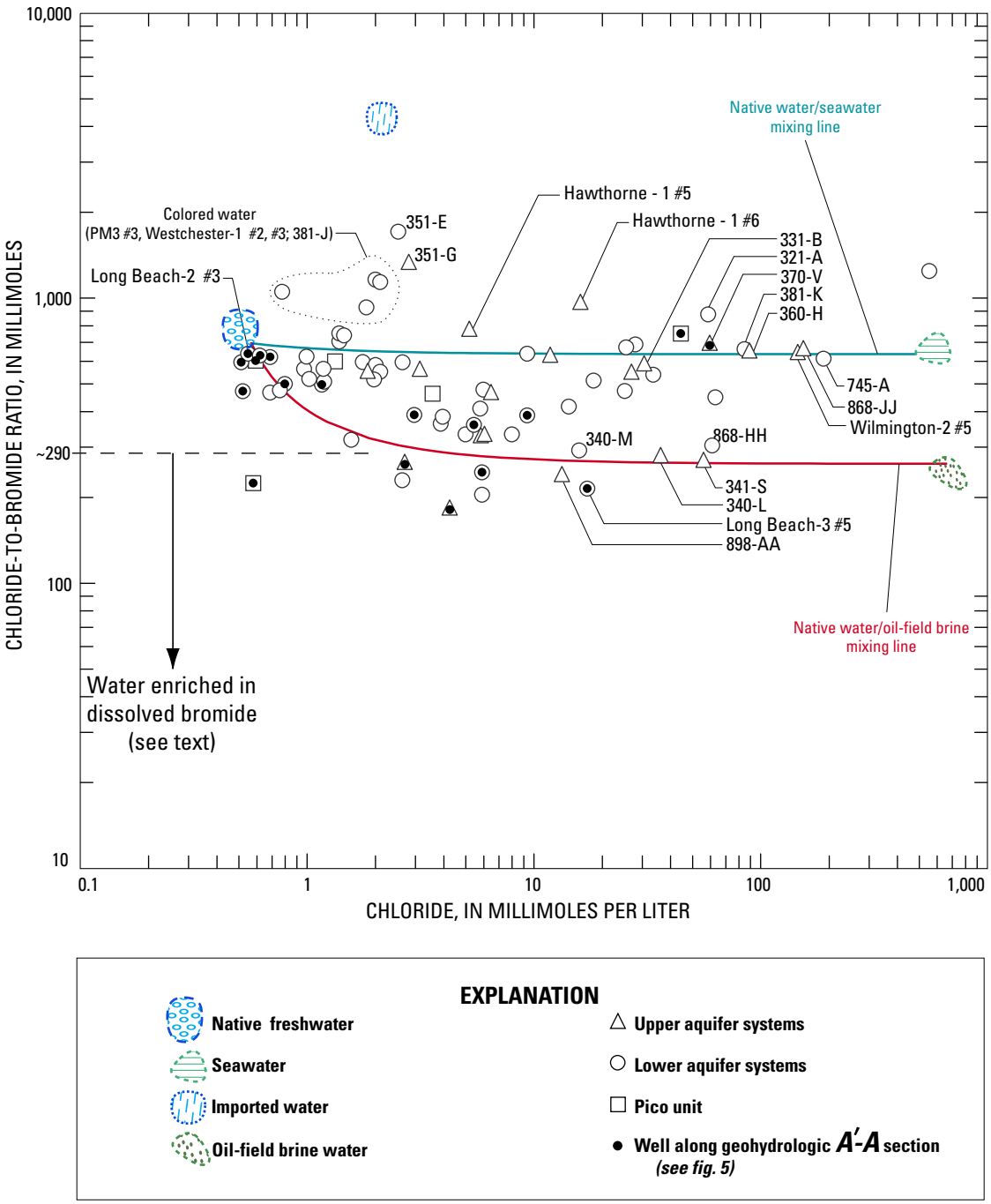


Figure 11. Chloride-to-bromide ratio as a function of chloride in water from wells sampled in the study area.

Dissolved Iodide

Unlike bromide or chloride, iodide is reactive under certain geochemical environments. In this study, concentrations of iodide ranged from 0.016 mg/L (351-E) to 5.7 mg/L (341-S). The concentration of iodide in native water from the Central Basin (0.03 mg/L; Land and others, 2002) and in imported water (0.001 mg/L) is relatively low. Iodide also is low in seawater (0.06 mg/L; Hem, 1992), but it is concentrated by near-shore marine vegetation, especially kelp. When this material is incorporated into marine sediments, iodide may dissolve and enrich the ground water; thus higher concentrations provide an indication of contact with marine sediments. Piper and Garrett (1953) reported oil-field brines containing 30 to 80 mg/L of iodide near the coast of San Pedro Bay.

Iodide data are plotted in figure 12 as a ratio of chloride to iodide (in millimoles per liter).

Native freshwater, imported water (WB #37), seawater, and oil-field brine are distinguished from each other by their chloride-to-iodide ratio and concentration of chloride. Also shown in figure 12 are mixing lines between native freshwater and seawater, and between native freshwater and an oil-field brine.

The ratio of chloride-to-iodide in high-chloride water from wells 341-R, 370-V, 360-H, Wilmington-2 #5, 745-A, and Long Beach-5 #2 plot along (or near) the native/seawater mixing line in figure 12. This indicates that seawater is the contributing source of salinity in these areas (note that, because iodide is reactive, some two-part mixtures may not plot strictly along the seawater line). In contrast, high-chloride water from other wells has a chloride-to-iodide ratio less than that of native water and plots slightly below the native/brine mixing line. Values for wells 898-AA and 341-S (Upper aquifer systems) and Wilmington-2 #2, Long Beach-3 #5, and 868-HH (Lower aquifer systems) provide presumptive evidence for mixing with an oil-field brine (fig. 12). Other water in the Lower aquifer systems (for example, Long Beach-4 #1, 371-D, 361-H) also has a chloride-to-iodide ratio less than that of native water; however, this is low-chloride water. These values probably reflect a naturally evolving brine water rather than mixing with an oil-field brine.

For other wells, the chloride-to-iodide ratio is less conclusive. Interpretation of some values may be complicated by colormetric interferences in the water (381-J), reactivity of iodide, or uncertainty in the concentration of iodide in native water and oil-field brine compositions. For example, several wells yield high-chloride water with a chloride-to-iodide ratio between that of seawater and native water (labeled as possible 3-member mixing in fig. 12). This composition could result from mixing of native water, seawater, and oil-field brine. A similar composition could also result if a low-chloride water, with a low chloride-to-iodide ratio (for example, water from 341-T or Wilmington-1 #1), was mixed with seawater (resulting in water like that found in 341-U or Wilmington-1 #2, respectively).

Dissolved Boron

Boron is generally soluble and unaffected by evaporation, oxidation/reduction reactions, and precipitation or dissolution reactions (Bassett and others, 1995). Dissolved boron, present predominantly as $B(OH)_3$, may be affected by adsorption onto the surface of minerals, especially clay, in the aquifer system (Hem, 1992). This process is dependent on the concentration of boron, pH, and salinity, as well as on aquifer mineralogy. Boron concentrations in water from wells sampled ranged from 100 mg/L (829-N) to 8,400 µg/L (Long Beach-5 #1). Seawater contains about 4,500 µg/L of boron. Oil-field brine water in the Dominguez Gap area may contain as much as 70,000 µg/L dissolved boron (Piper and Garrett, 1953). Boron data are presented in figure 13 as the ratio of chloride to boron (on a millimole basis).

For sampled wells in the study area, the chloride-to-boron ratio generally increases with increasing chloride concentration. In simple mixtures of native water and seawater, boron should plot along the mixing line (fig. 13). Boron data suggest that seawater is the source of high chloride in water from several wells in the Upper and Lower aquifer systems (PM-3 #3, Wilmington-1 #2, 331-A, 370-V, 360-H), A few wells yielded higher-chloride water, with a chloride-to-boron ratio that plots substantially above the native/seawater mixing line (Long Beach-3 #5, 381-K, Wilmington-2 #5, 745-A). This depletion, relative to chloride, shows that boron is not entirely conservative in the study area.

Piper and Garrett (1953) stated that high-chloride water with a chloride-to-boron ratio less than 140 may be presumptive evidence for mixing with a brine source. For sampled wells in this study, high-chloride water from wells 898-AA, Wilmington-2 #2, 868-HH, and 868-JJ plot near the seawater mixing line and seem to approach the composition of an oil-field brine (fig. 13). Water from several other wells has a low chloride-to-boron ratio but, on the basis of the relatively low concentration of chloride, could not have resulted from significant mixing with an oil-field brine (for example, Long Beach-2, Hawthorne-1, and Westchester-1 in fig. 13). At these monitoring sites, the chloride-to-boron ratio decreases with increasing depth as a result of extensive water-aquifer interaction along deep parallel flowpaths (see connecting lines; fig. 13).

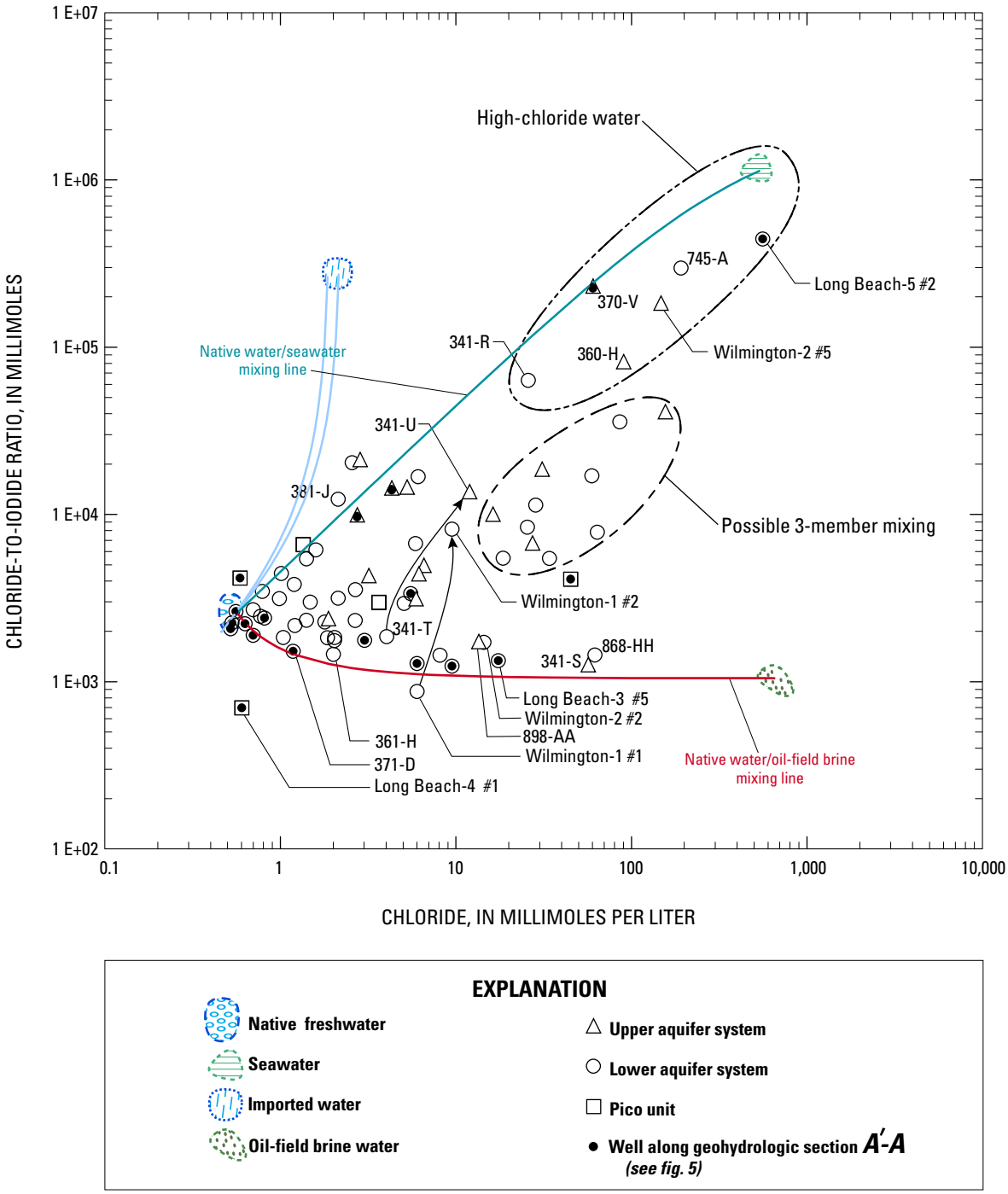


Figure 12. Chloride-to-iodide ratio as a function of chloride in water from wells sampled in the study area.

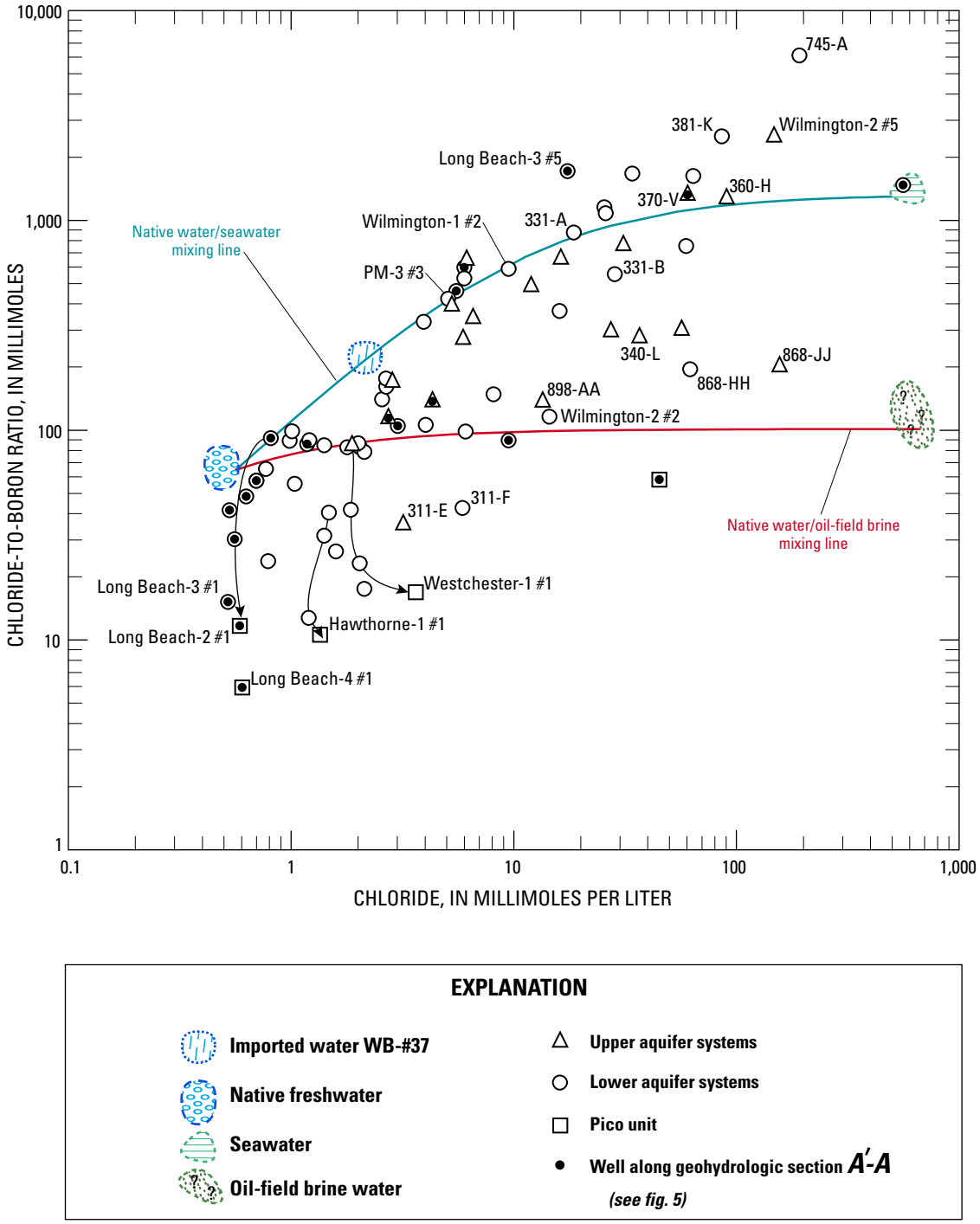


Figure 13. Chloride-to-boron ratio as a function of chloride in water from wells sampled in the study area

Ground-Water Isotopes

Oxygen and Deuterium

To distinguish between waters of similar chemical character and to understand the source and movement of ground water in the study area, samples were analyzed for oxygen-18 and deuterium. Oxygen-18 and deuterium are stable isotopes of oxygen and hydrogen. These isotopes are heavier than the common oxygen and hydrogen isotopes (oxygen-16 and hydrogen, respectively). The isotopic composition of water is expressed in terms of relative difference in parts per thousand (denoted as per mil) from the international standard composition of ocean water known as Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1984). For example, water that has less deuterium than ocean water will have a negative per mil value and is "isotopically light" relative to seawater. Stable isotope data for seawater, for imported water, and for water from wells sampled in the study area are shown in figure 14.

Most precipitation originating as evaporation from seawater is linearly correlated along a line referred to as the meteoric water line (Craig, 1961). The isotopic composition of one ground water relative to another, and to the global meteoric water line, may provide information about a common source of recharge for that water (Mazor, 1991). Precipitation recharging a low-temperature ground-water system retains its isotopic composition after reaching the water table. Stable isotopes, because they are part of the water molecule and do not react like other tracers, are conservative in mixing relations. Graphically, mixing between two distinct sources of ground water will plot on a line connecting the two end members. The isotopic composition of ground water in the study area commonly is the result of mixing processes between multiple sources.

Regional work by the USGS (Reichard and others, 2003) indicates that isotopically heavy water (–6.7 to –7.5 per mil oxygen-18) originates in the Los Angeles Forebay (fig. 1). In this study, a similar range of values, which plot along or above the meteoric water line, was observed for water from wells in the western part of the study area. Other wells located in the northern and eastern parts of the Dominguez Gap area, including deeper zones at the Wilmington-1 site, yielded water that also plots within a narrow range (–7.0 to –7.4 per mil oxygen-18; fig. 14). Isotopic data show that native water, similar to ground water recharged in the Los Angeles Forebay, is present at these locations.

Regional work by the USGS also indicates that isotopically light water (–8.0 t o –9.5 per mil oxygen-18) originates in the Montebello Forebay (fig. 1). In the study area, a similar range of values, which plot along or above the meteoric water line, was observed for water from the Lower aquifer systems. This includes water from Wilmington-2 #1, 2, and 3 and from well 381-J, 371-D, 361-H, 361-K located east of the DGBP. This isotopically light, native water was generally not observed in the Upper aquifer systems in the study area.

Many Upper aquifer system wells located near injection wells yield water that plots below and nearly parallel to the meteoric water line. In the study area, this isotopic composition is consistent with two-member mixing of seawater and imported water (sampled at WB-#37). Low-chloride water from wells 351-E and 351-G (fig. 14), at the isotopically light left end of this group, is composed of at least 90 percent imported Colorado River water (on the basis of oxygen-18 data). In contrast, water from 351-M, 360-H, and Wilmington-2 #5, which plot at the isotopically heavy right end of this group, have a comparably larger seawater component and significantly higher chloride (2,200 to 5,200 mg/L). Other locations in the Upper aquifer systems that yield water predominantly composed of seawater and imported water include Wilmington-1 #4, 341-R, 341-U, 351-N, 370-V, and 331-B. A seawater-imported water isotope composition was not observed for wells perforating the deeper part of the Lower aquifer systems near the DGBP, indicating that injected water does not readily reach these units.

As described earlier, a few wells in the interior of the Dominguez Gap area yielded high-chloride water (fig. 8). These wells also yielded water with relatively heavy isotopic values. Stable isotope data are not sufficient alone to distinguish between high-chloride water from seawater and from an oil-field brine. Since the isotopic composition of native oil-field brine in the study area is not well defined, combining trace-element and isotopic data is often useful in clarifying this uncertainty. For example, isotopic data for well 340-L suggest intruding seawater (less than 10 percent on the basis of oxygen-18 data); however, trace-element ratios show that the source of salinity is attributable to an oil-field brine (table 2). A more pronounced mixing trend is evident for high-chloride water in well 868-HH (oil-field brine), as well as well 868-JJ and 745-A (both seawater).

In contrast, wells 311-F and 311-E yielded water with notably heavier isotopic ratios but with relatively low chloride concentrations. Chemical and stable isotope data suggest that the source of this water is related to local recharge from the Palos Verdes Hills and not to imported injected water from the DGBP. Isotopically heavy water (–5.2 to –6.2 per mil oxygen-18), present in several shallow monitoring wells on the upgradient section of the Palos Verdes Hills (Ted Johnson, Water Replenishment District of Southern California, unpub. data, 1999), and the relatively heavy isotopic values noted at a nearby monitoring site (Land and others, 2002) support this argument.

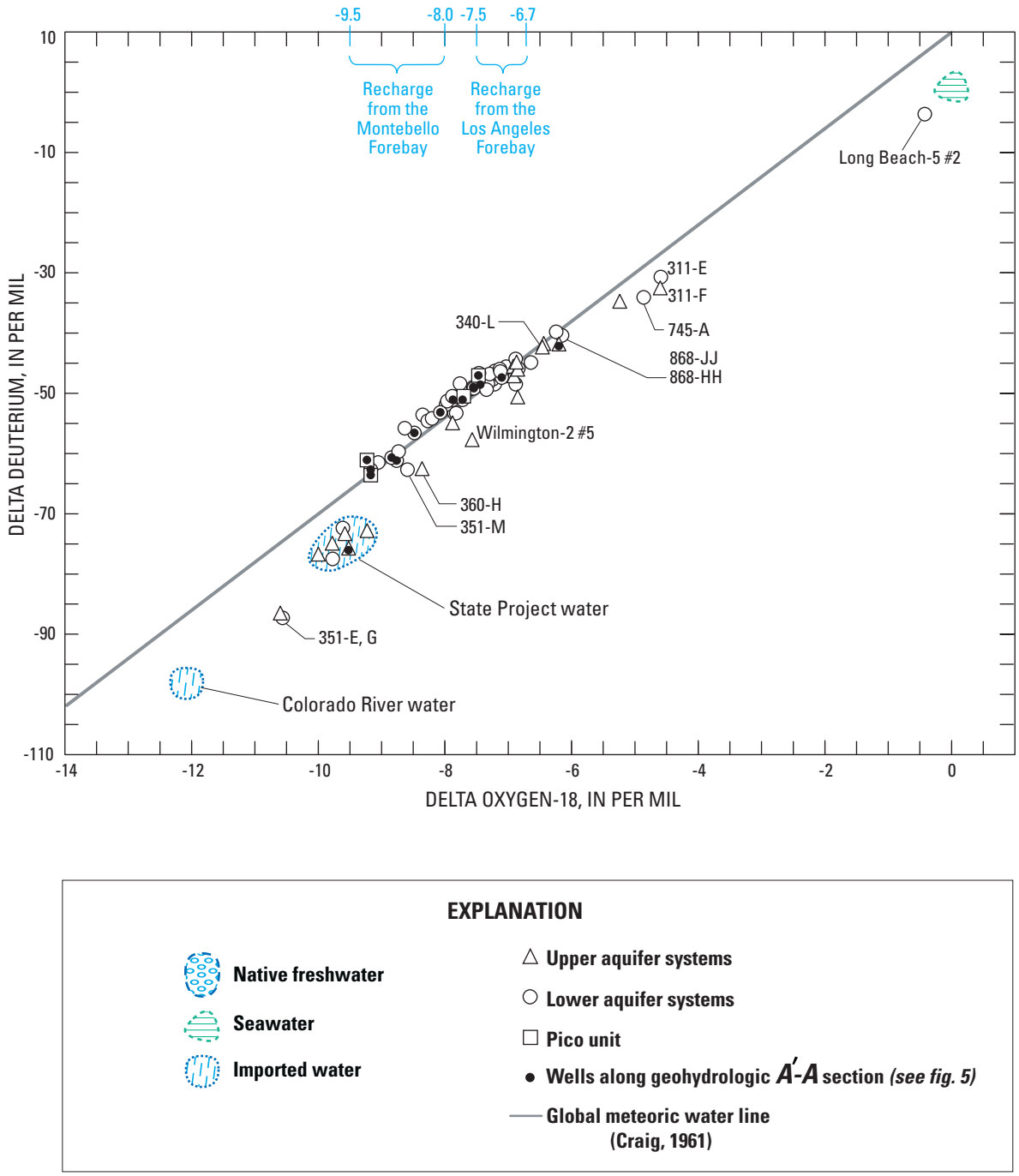


Figure 14. Delta deuterium as a function of delta oxygen-18 for selected wells in the study area.

Shown in figure 15 are delta oxygen-18 values of pore water extracted from cores collected at the Westchester-1, Long Beach-3, Long Beach-4, and Long Beach-5 monitoring sites. As shown in the plots, there are distinct isotopic signatures in the different aquifer systems at each of the sites, indicating different sources of water. The delta oxygen-18 value is close to that of seawater in the Upper aquifer systems at Long Beach-4 and in the Upper and much of the Lower aquifer systems at Long Beach-5. At Long Beach 4, there are differences in the delta oxygen-18 value within the Lower aquifer systems (isotoptically heavier water in the depth interval between about 400 and 700 ft). There are not comparable differences in chloride concentrations in this interval (fig. 10). Oxygen-18 data (fig. 15) are consistent with chloride data (fig. 10) and indicate that seawater is not present at Westchester-1 site. Isotopically lighter water is found in the Pico unit at Westchester-1, Long Beach-4 and Long Beach-5 and is consistent with recharge during the late Pleistocene (Clark and Fritz, 1997; Reichard and others, 2003). Isotopically light water is also found at the deepest part of the Long Beach-3 monitoring site. However, sequence stratigraphic analysis indicates that this zone is within the Lower aquifer systems (Daniel Ponti, U.S. Geological Survey, unpub. data, 2002).

Tritium

To distinguish water that was recharged relatively recently from older water, samples were analyzed for tritium content. The concentration of tritium is presented in tritium units (TU); 1 TU equals 3.2 picocuries per liter (pCi/L); one pCi is equivalent to about 2.2 disintegrations of tritium per minute or about one tritium atom in 3.1×1019 atoms of hydrogen. Tritium is a naturally occurring radioisotope of hydrogen that decays by beta-particle emission into helium-3 (half-life of 12.4 years). Because tritium is part of the water molecule and is not affected by reactions other than radioactive decay, it serves as a useful natural tracer for identifying recently recharged water (Michel, 1989). Prior to 1952, the tritium concentration of precipitation in coastal southern California was about 2 TU (Izbicki, 1996). Beginning in 1952, significant quantities of tritium were released into the atmosphere from the testing of hydrogen bombs, reaching a maximum in 1963 (fig. 16).

Tritium concentrations in water from wells sampled as part of this study ranged from less than 0.1 TU to 22 TU. These values are summarized in figure 17. Water with a tritium content less than 1 TU is interpreted as “older” water recharged prior to 1952. Water with tritium content greater than or equal to 1 TU is interpreted as “recent” water recharged after 1952. Imported water collected at cross-connection WB#37 contained 11 TU. Along the coast, seawater is another possible source of tritium. Interpretation of tritium analyses is complicated by the potential mixing of older water and recent water and the potential leakage of recent water into deep wells through well bores (Izbicki, 1996; Mazor, 1991).

Except near the seawater-barrier projects, most water in the Lower aquifer systems in the West Coast Basin is older water (Reichard and others, 2003). Wells that yielded older water in this study generally are perforated in the Lower aquifer systems. Among these are wells located north of the WCBBP (Westchester-1 #4); several miles inland from the WCBBP (Hawthorne-1 #4, Chicago #1, PM-3 #2, 758-A); inland from the DGBP (340-N); and east and north of the DGBP (Long Beach-2 #3, Long Beach-3 #3, 371-D, 380-P). Older water was also noted in the Upper aquifer systems, much farther from the barrier projects (Westchester-1 #5 and 829-N).

Less-than-measurable tritium concentrations in water from wells 361-K (seaward of the DGBP) and Wilmington-2 #3—both are perforated below the main zones of injection—show the vertical limitation on movement of injected water at locations less than 1 mi from the DGBP. Less-than-measurable tritium concentrations also occur in water from Long Beach-3 #5, Wilmington-1 #2, 321-A, and 381-K. However, the latter group of wells is distinguished by higher chloride concentrations (table 1), suggesting intrusion of older saline water.

Wells that yielded recent water in this study are commonly associated with recharge originating from the seawater-barrier projects. The extent of this recharge is apparent in many wells perforated in the Upper aquifer systems (for example, Hawthorne-1 #5, 340-L, Wilmington-1 #5). Significant tritium concentrations—greater than water measured at WB #37—occur in water from wells 331-B, 360-H, Hawthorne-1 #6, and Wilmington-2 #5 (fig. 17), indicating a portion of recharge during the peak period of weapons testing (fig. 16). As discussed, stable isotope data show a substantial source of imported-water replenishment to these wells; however, water quality at these locations remain questionable (table 2). Tritium data also illustrate the presence of recent water in a few wells perforating the Lower aquifer systems (340-M, 331-A, 745-A, Wilmington-1 #3, Wilmington-1 #4, and Wilmington-2 #4).

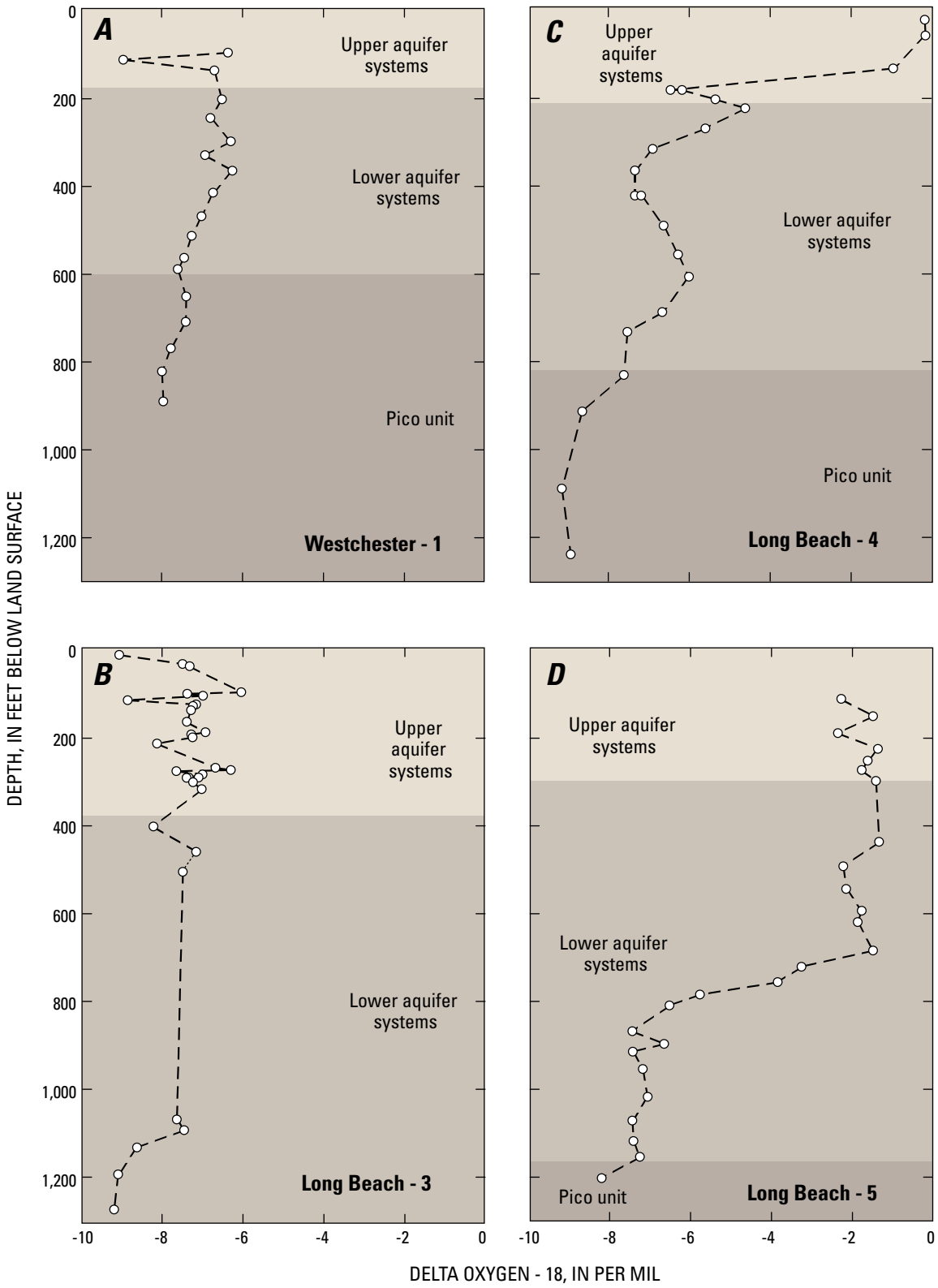


Figure 15. Delta oxygen-18 as a function of depth in pore water from continuously cored monitoring sites in the study area: (*A*) Westchester-1, (*B*) Long Beach-3, (*C*) Long Beach-4, and (*D*) Long Beach-5.

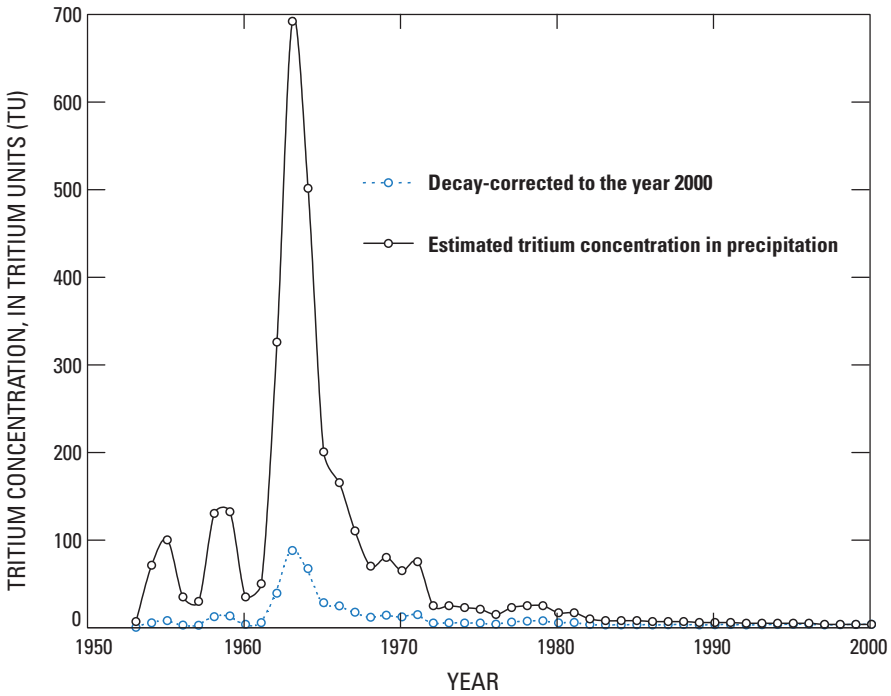
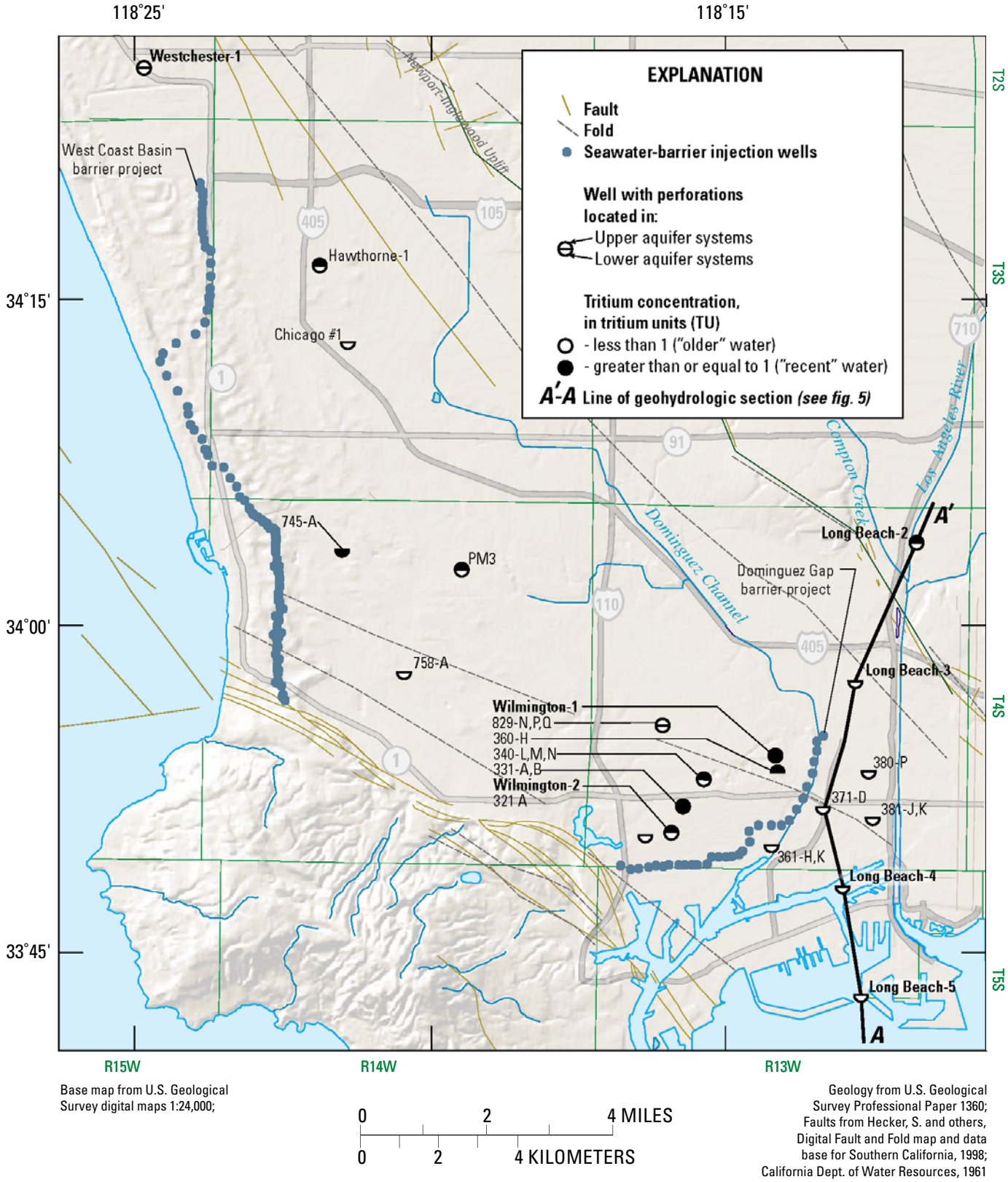


Figure 16. Estimated tritium concentration in precipitation, Los Angeles County, California.



Base map from U.S. Geological Survey digital maps 1:24,000;

Geology from U.S. Geological Survey Professional Paper 1360; Faults from Hecker, S. and others, Digital Fault and Fold map and data base for Southern California, 1998; California Dept. of Water Resources, 1961

Figure 17. Tritium concentrations in water from selected wells sampled in the study area

Carbon

Samples from selected wells were analyzed for carbon-14 to assess the relative age of older water in the study area. Carbon-14 is a naturally occurring unstable isotope of carbon with a half-life of 5,730 years that can be used to estimate ground-water age (since time of recharge) up to about 25,000 years (Gat and Gonfiantini, 1981).

Carbon is introduced into the ground-water system during recharge, through plant respiration, decay of organic matter in soils, and dissolution of minerals and, as such, is subject to reactions that occur between dissolved constituents and the aquifer matrix (Fontes, 1985). Reactions that add carbon that does not contain carbon-14 or that remove carbon-14 from the ground water can result in misleading carbon-14 ages. Carbon-14 data are reported as percent modern carbon (pmc) by comparing carbon-14 activities with the specific activity of an oxalic acid standard prepared by the National Bureau of Standards (Mook and van der Plicht, 1999).

Carbon-14 values ranged from approximately 1 to 55 pmc. Corresponding estimates of ground-water age range from about 4,000 years to more than 20,000 years before present, respectively (Reichard and others, 2003). An initial carbon-14 value of 90 pmc was assumed. These estimates are not corrected for potential exchange of carbon within the aquifer, and therefore they may not reflect the true age of the water.

In the Lower aquifer systems, carbon-14 values decreased with increasing depth. These data highlight the deep circulation of native water through multiple aquifer units of the West Coast Basin (Reichard and others, 2003). Some of the lowest values were observed in water from the Pico unit (Hawthorne-1 #1, Long Beach-2 #1, Long Beach-4 #1, Long Beach-5 #1) and are consistent with very light oxygen-18 values (fig. 14), indicating recharge during the Pleistocene (Gat and Gonfiantini, 1981). At a few inland locations (Long Beach-3 #5, Wilmington-1 #2), relatively high chloride and carbon-14 values could be an indication of intruding 'older' seawater.

In the Upper aquifer systems, inland from the WCBBP, water from well PM-3 #4 contained 40 pmc. However, water from this well also had ~4 TU, indicating that a mixture of older and recent water occurs, likely as a result of the recent plume of intruding seawater (Chieh and others, 1988; Johnson, 1992) and (or) injection from the barrier.

Boron

Dissolved-boron concentrations in the adjacent Central Basin suggest that boron may be useful for identify mixing processes between native and other ground-water sources (Anders and Schroeder, 1998). In other coastal plain studies, delta boron-11 (δ11B) has been used to distinguish anthropogenic sources of boron in ground water, especially wastewater (Vengosh and others, 1994). Isotopic fractionation of boron results primarily from clay adsorption, which preferentially enriches the ground water with heavy δ11B (Vengosh and others, 1994). Sewage effluent is enriched in boron owing to the presence of various detergents and is commonly characterized by an isotopic signature different from that of native ground water (Anders and Schroeder, 2003).

To evaluate the behavior of boron and its usefulness as a tracer in the study area, selected samples were analyzed for the δ11B isotope (fig. 18). Total δ11B values ranged from +1.5 to +45.5 per mil. Poor-quality, high-chloride waters from 381-K, Wilmington-1 #4, and Wilmington-2 #5 have outlying chloride-to-boron ratios and heavier δ11B values that indicate mixing with seawater. Isotopically light δ11B values for 321-A and Wilmington-2 #4 do not support mixing with seawater (counter to other chemical and isotopic data, table 2). This result may be explained, in part, by the colored, outgassing, and reducing nature of the water noted during collection.

Imported injection water collected from WB #37 had a δ11B value of +7.7 per mil. Stable isotope data indicate (Appendix A) that substantial imported water is present in Wilmington-1 #4 and #5; however, δ11B data do not reflect this composition. This discrepancy may be attributable to non-equilibrium conditions between dissolved boron and the aquifer matrix locally in the Upper aquifer systems.

Strontium

The concentration of dissolved strontium and the strontium-87/strontium-86 isotope ratio (Sr-87/86) in ground water can be useful in tracing ground-water movement and the origin of salinity in a coastal environment (Woods and others, 2000). Under normal geothermal conditions, strontium behaves much like calcium, and leaching from the aquifer matrix is typically quite rapid (Izbicki and others, 1994). Thus, given sufficient time, ground-water will adopt a strontium isotope-ratio signature reminiscent of the composition and age of the aquifer material specific to its flow path. Unlike the lighter isotopes, Sr-87 and Sr-86 do not fractionate owing to mass differences (similar to kinetic processes affecting deuterium or oxygen-18) or as a result of adsorption onto clay surfaces (similar to the behavior of boron-11). The use of the Sr-87/86 ratio is made possible by the high precision of the analysis, typically better than 0.005 percent. The ratio of modern seawater is 0.70925 (8,000 µg/L Sr); the ratio of imported water at WB #37 is 0.71040 (918 µg /L Sr). (fig. 19)

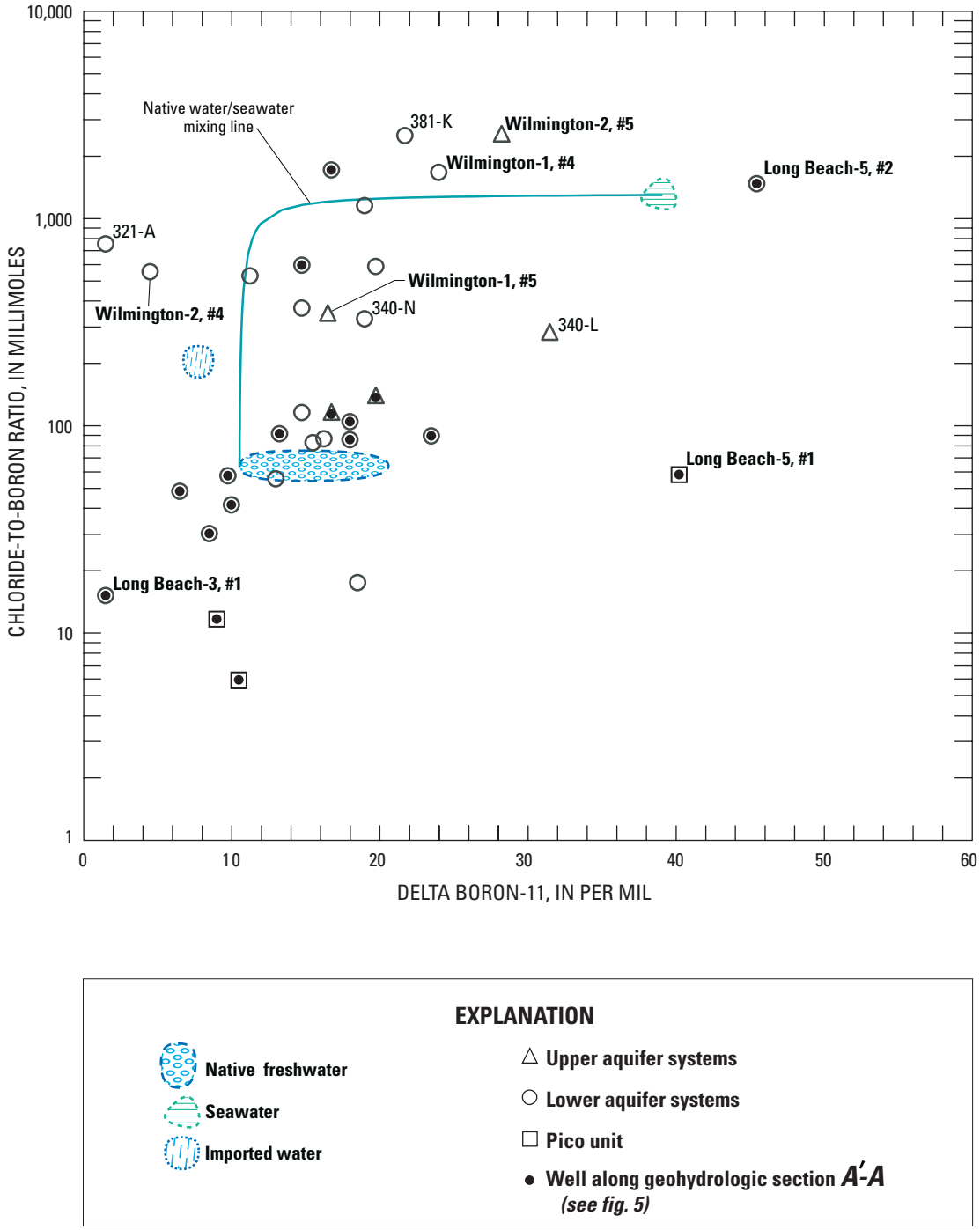


Figure 18. Chloride-to-boron ratio as a function of delta boron-11 in water from selected wells sampled in the study area.

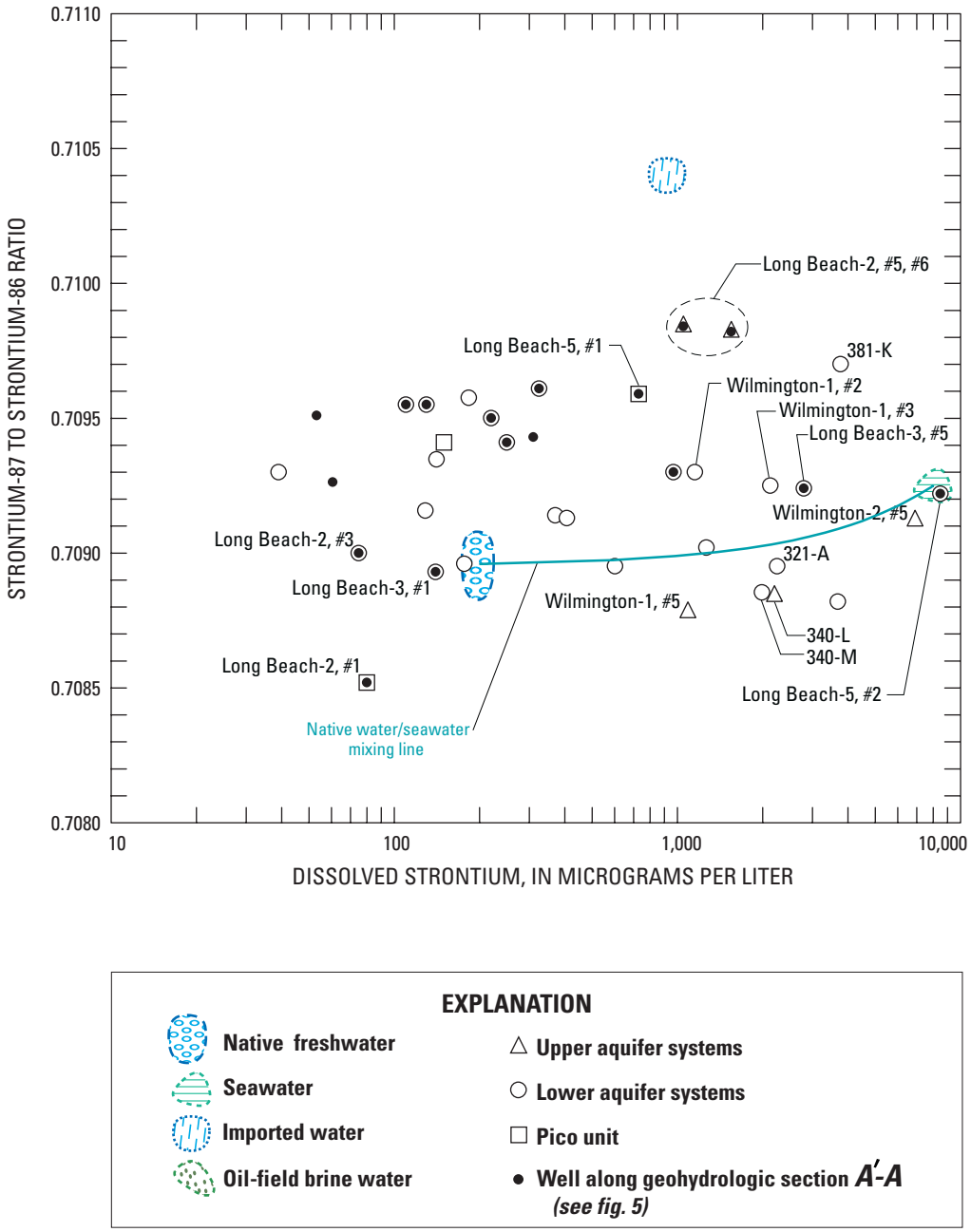


Figure 19. Strontium-87/86 ratio as a function of dissolved strontium in water from selected wells sampled in the study area.

Sr-87/86 ratios ranged from 0.70879 to 0.70985 in water in the Upper aquifer systems (fig. 19). The highest ratios were observed in water from two shallow wells at the Long Beach-2 monitoring site. However, these values reflect local recharge from the Los Angeles River and are not (on the basis of stable isotope data) an indication of mixing with imported water. Although imported water is present in Wilmington-1 #5 (table 2), it is not reflected in the Sr-87/86 ratio for this well (0.70879). This suggests that, chemically, ground water at this location has reached a steady state with the aquifer unit. Likewise, water from well 340-L, believed to have been affected by mixing with an oil-field brine (table 2), shows a similar Sr-87/86 ratio (0.70885) for the Upper aquifer system (fig. 19). In contrast, high strontium concentrations (6,900 µg/L) and a Sr-87/86 ratio of 0.70913 in water from Wilmington-2 #5 are consistent with other chemical data indicating that ground water at this location is intruded with seawater and not in equilibrium with the aquifer matrix.

In the Lower aquifer systems, water from wells sampled had a Sr-87/86 ratio from 0.70852 to 0.70970 (fig. 19). Relatively low strontium concentrations and Sr-87/86 ratios slightly higher that seawater (0.70935 to 0.70961) characterize freshwater yielded by most deep wells east of the DGBP. Within this range, data for wells 381-K and Long Beach-5 #1 show that relatively saline water—presumably from seawater (table2)—retains a similar Sr-87/86 ratio. One possible explanation is that the intruding saline water is older seawater. In contrast, relatively saline water from wells Wilmington-1 #2 and #3, Long Beach-3 #5, and Long Beach-5 #2 has a Sr-87/86 ratio close to seawater, possibly as a result of rapid or recent intrusion. Another group of wells yielded fresh water (Long Beach-2 #3, Long Beach-3 #1) with a Sr-87/86 ratio slightly lower than seawater (0.70879 to 0.70914) that is similar to native water found elsewhere in the West Coast Basin (Land and others, 2002). Within this range, other wells which yielded relatively saline water inland of the DGBP (321-A, 340-M) retain this Sr-87/86 ratio.

Summary of Ground-Water Chemistry and Isotope Data

By combining the interpreted results of different chemical and isotopic analyses, a joint assessment of water sources in the study area was developed. The results for individual constituents—each providing a slightly different constraint on the interpretation of the hydrologic system—are summarized in table 2. Together, in most cases, the conclusions drawn are concordant as to the most probable source(s) of water. In several cases (for example, wells 351-N, Long Beach-3 #5, and Wilmington-1 #2) the results yield conflicting interpretations. This illustrates the complexity of the ground-water flow system and indicates the limitations on conclusions and need for additional data collection.

Geophysical-Log Analysis

Electromagnetic (EM)-induction, gamma-ray, specific-conductance, and temperature logs were used together to provide additional insight into water quality and the presence of injection water in existing wells in the study area. Wells where geophysical data were collected are shown in figure 6 and listed in Appendix B. Geophysical-log plots for selected wells are presented in Appendix C.

As described earlier in the “Methods of Investigation” section, the conductivity measured by the EM tool is affected by both lithology and water chemistry. High EM conductivity can indicate poor-quality water or fine-grained sediments (Williams and others, 1993). To decouple these influences, EM logs were paired with gamma-ray logs. Zones with high EM values and low gamma values are likely to contain poor-quality water; zones with high EM values and high gamma values are likely to be fine-grained zones. For wells logged in the study area (see Appendix B), it was found that baseline EM-log conductivity of native freshwater was much less than 100 millimhos per meter (mmho/m). Therefore, 100 mmho/m was used as a screening value to identify potential zones of poor water quality.

To evaluate the relation between dissolved chloride and EM conductivity, chloride concentrations obtained from bulk sampling were plotted against the average EM-log conductivity observed within the perforated interval for the well. As shown in figure 20, chloride concentrations are positively correlated with peak EM-log conductivity. However, there is considerable spread to the data that likely reflects the influence of lithology and chemical composition of the water (that is, constituents other than chloride also affect conductivity).

Evaluation of Log Data near the Dominguez Gap Barrier Project

Wells 351-E and 361-U are located along the center part of the DGBP (fig. 6 and App. C). Water-level altitudes have steadily increased at both locations since about 1970. The EM log for well 351-E indicates high conductivity values at depths from about 110 to 125 ft and from about 160 to 240 ft. The conductivity in the shallower zone is consistent with that of saline water. The gamma-ray log and the driller's log indicate that the conductivity values in the lower zone likely result from the finer-grained lithology. The lower conductivity values below 250 ft show the occurrence of freshwater that presumably results from injection. Stable isotope and trace-element data from well 351-E confirm the predominance of imported water. The EM log from well 361-U, located along the DGBP northeast of 351-E, also indicates intruded zones above and between the individual wells (for example, at depths from 40 to 70 ft and 150 to 170 ft). The effect of the relatively cold injection water can be seen from the deflection of the temperature log from 235 to 265 ft below land surface at 361-U.

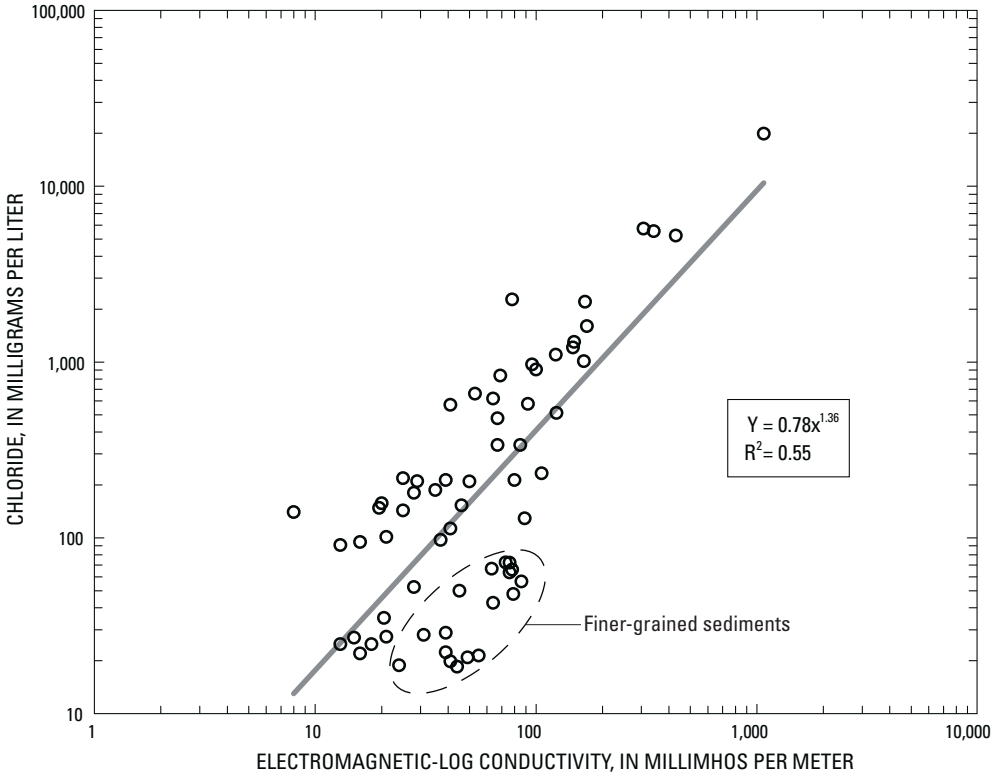


Figure 20. Chloride concentration as a function of electromagnetic-log conductivity in wells sampled in the study area, 1999–2002.

Wells 351-M and 360-N are located just inland from wells 351-E and 361-U (fig. 6). The EM log for 351-M indicates that the zone of highest salinity is from about 210 to 240 ft below land surface, between two monitoring wells. The EM log at 360-N shows elevated conductivity at depth intervals of 100 to 120, 140 to 160, 170 to 190, and 200 to 220 ft below land surface. Although there is generally consistency between concentrations of chloride measured in a well and the EM conductivity, elevated concentrations of chloride reported for well 360-N and high-fluid conductance values (App. C) are not consistent with the very low EM-conductivity values for that interval. A possible explanation for this contradiction may be that a zone of higher density saline water is present, just above, and hydraulically connected to, the perforated zone of well 360-N.

Monitoring sites Wilmington-2 and Wilmington-1, along with well 868-HH, are all located inland from the DGBP (fig. 6). At all these locations, the geophysical data show zones of high salinity. Wilmington-2 is inland (north) of the southwestern part of the DGBP; high-conductivity zones shown in the EM log (80–200 and 390–460 ft below land surface) are consistent with the elevated chloride concentrations measured in wells Wilmington-2 #4 and #5 (App. C). Of particular note are the high conductivity values extending above and below Wilmington-2 #5. Chemical and isotopic data indicate that this is attributable to seawater (at least 25 percent on the basis of chloride mass balance), even though some recently injected water also is present. High-chloride water in Wilmington-2 #4 also results from intruding seawater.

Wilmington-1 is inland (west) of the northern part of the DGBP. The EM log indicates elevated salinity from about 150 to 390 ft below land surface at this location (App. C). Chemical and stable isotope data (table 2) collected near this interval (Wilmington-1 #4 and #5) indicate a likely mixture of seawater and imported water. Although the relatively high chloride concentrations measured in Wilmington-1 # 3 are not reflected in the EM conductivity, chemical and isotopic data suggest that some water (550–570 ft below land surface) is probably drawn from the overlying aquifer systems. The temperature log at this site shows a negative deflection from about 200 to 400 ft and about 450 to 780 ft below land surface that are attributed to pumping from the Lower aquifer systems.

Wells 868-HH and 868-JJ are located northwest of the northern end of DGBP (fig.6). The EM log shows relatively high conductivity below a depth of about 70 ft. This is consistent with chemical data showing chloride concentrations higher than native fresh water in both wells (table 2). Seawater (as much as 30 percent on the basis of oxygen-18 and chloride data) is the source of salinity in water from well 868-JJ. However, ion ratios for well 868-HH (perforated in the Lower aquifer systems) clearly distinguish the source as an oil-field brine. Furthermore, data indicate that no imported water is present in either monitored zone at this location (table 2). The negative deflection of the temperature log below about 140 ft is likely the result of the intensive pumping that occurs in this area, rather than evidence of injected water.

Well 898-AB is located northeast of the DGBP (fig. 6). The EM log indicates intervals of elevated conductivity from about 50 to 90 and about 140 to 160 ft below land surface at this site (App. C). Bromide and iodide concentrations measured at well 898-AA indicates that the elevated chloride within the lower interval is likely the result of mixing with an oil-field brine (table 2). EM conductivity is quite low at depths below about 160 ft and, coupled with chemical and isotopic data from well 898-AB, indicates the occurrence of fresh native water.

Evaluation of Log Data near the Southern Part of West Coast Basin Barrier Project

Wells 714-H and 725-AR are both located along the WCBBP. At both locations, the EM log indicates relatively low salinity except in the interval just above 400 ft (360 to 390 ft in 714-H and 350 to 375 in 725-AR). The high fluid conductance in well 714-H, perforated from 395 to 495 ft below land surface, likely results from high salinity in the overlying zone.

Wells 735-A, 736-D, and 745-A are all located inland from the WCBBP (fig. 6). The EM logs show elevated conductivity in the lower parts of each well [below about 520 ft at 735-A and 745-A, and below about 560 ft at 736-D (App. C)]. Chemical and isotopic data indicate that the source of water to well 745-A (perforated from 547 to 627 ft) is approximately one-third recent seawater (table 2). Additionally, temperature-log data at these sites show that the intrusion is occurring below the main zones of injection.

A set of multiple-well monitoring sites completed by the WRDSC are located farther inland from the WCBBP to monitor the migration of an inland plume of salt water. The PM-4 site has elevated EM-log conductivities at 15 to 55 ft, 110 to 115 ft, 165 to 175 ft, and 445 to 565 ft (App. C). Well PM-4 # 2, which has chloride concentrations about one-third that of seawater, is perforated from 500 to 545 ft below land surface. The EM log at the PM-3 site, located inland from PM-4, indicates low salinity water is present below a depth of about 60 ft [except a fine-grained unit at ~295 ft (App. C)]. This is consistent with the chemistry data collected from all four wells at PM-3 (table 2).

Well 738-D is located just inland (east) of the southernmost end of the WCBBP (fig. 6). With the exception of the interval from about 485 to 550 ft below land surface, the EM log indicates very low conductivity between about 200 and 680 ft (App. C). The deflection of the temperature log indicates the effect of injection water within this interval. The increase in the EM-log conductivity and temperature below about 700 ft (similar to conditions in deep zones in wells 735-A, 736-D, and 745-A) suggest the inland movement of seawater at depth.

Summary Analysis of Geophysical Log Data

The foregoing analyses of selected geophysical logs, together with geochemical data, highlight several features of seawater intrusion and barrier operation in and around the DGBP and the southern part of the WCBBP. Along the DGBP, shallow zones of high-salinity water are present. The presence of substantial injected water at depths below about 250 ft is inferred from low EM conductivity and deflected temperature profiles. Zones of high salinity are present inland from the DGBP. In particular, the EM logs indicate that there are relatively thick zones of seawater at both the Wilmington-1 and Wilmington-2 monitoring sites. Along the southern part of the WCBBP, a zone of high-salinity water is present just above a depth of 400 ft below land surface. Inland from the WCBBP, EM logs help define the vertical extent of the known inland plume. At the very southern end of the WCBBP, EM and temperature log data (and chloride data) indicate high salinity water continues to intrude the deeper part of the Lower aquifer systems (below ~700 ft).

Ground-Water-Quality Conditions along a Geohydrologic Section

To evaluate current ground-water-quality conditions from the Dominguez Gap to the San Pedro Bay, geohydrologic cross section *A′–A* was constructed along the approximate predevelopment ground-water flow line (Mendenhall, 1905c; Piper and Garrett, 1953) (figs. 5, 21). Section *A′–A* was modified from the work of Ehman and Cramer (1997) and Ehman and others (2001) to include recent geohydrologic information from the regional work of Reichard and others (2003) and from several continuously cored monitoring sites (Daniel Ponti, U.S. Geological Survey, unpub. data, 2002). Changes in water chemistry between well locations along this section were studied with respect to the major aquifer systems and the regional flow system.

Data presented in this report indicate that most water along this section originates from the San Gabriel Valley (via Montebello Forebay)(fig. 1) and generally is fresh. Seawater is present at the far end of the flowpath (Long Beach-5). The transition between these end members varies with depth and distance from the coast and—prior to the development of the basin—was controlled largely by (1) eustatic water-level gradients and (2) deposition of thick, fine-grained units which protect the Lower aquifer systems from overlying intrusion. Freshwater is still present in aquifers that extend offshore as evidenced by low chloride concentrations (21 mg/L; App. A) in water from Long Beach-4 #1 (see also fig. 10).

Further inland, and locally, along the section, high-chloride water also results from seawater intrusion wells (370-V and 370-U, projected) and from mixing with a local oil-field brine source (Long Beach-3 #5). In the Lower aquifer systems and in the Pico unit, data show the presence of older water that increases in chloride concentrations from north to south along section *A′–A*. This is consistent with an increase in oxygen-18 values (isotopically heavy) resulting from mixing with older seawater.

The chemical character of water along section *A′–A* changes with increasing depth and distance downgradient. Available data show a sodium-carbonate composition of water for inland freshwater wells (denoted as A, fig. 21) and sodium chloride composition (denoted as C) at far end of the flow path (Long Beach-4 and -5, fig. 21). Transitions between these two zones show varied compositions (for example, calcium-chloride type water at Long Beach-3 #4 and #5 (labeled as B, fig. 21).

Recently-recharged water along section *A′–A* in the Upper aquifer systems is generally limited to the Dominguez Gap area, near the Los Angeles River at the north end of the section (Long Beach-2). On the basis of the ion ratios discussed earlier, some recent water is inferred to be present in the vicinity of wells 370-V and 370-U, near the DGBP. Recent water is not present in the Lower aquifer systems along this section.

Summary

Geochemical and geophysical data were collected from a network of multiple-well monitoring sites, production wells, and observation wells. Included in the network were four continuously cored sites. The data were analyzed to provide an improved geochemical characterization of the coastal West Coast Basin, with a focus on the area surrounding the Dominguez Gap Barrier Project (DGBP). Major sources of water in the study area include native ground water originating in the Central Basin, imported water (State Water Project or Colorado River Water), seawater, and oil-field brine fluids.

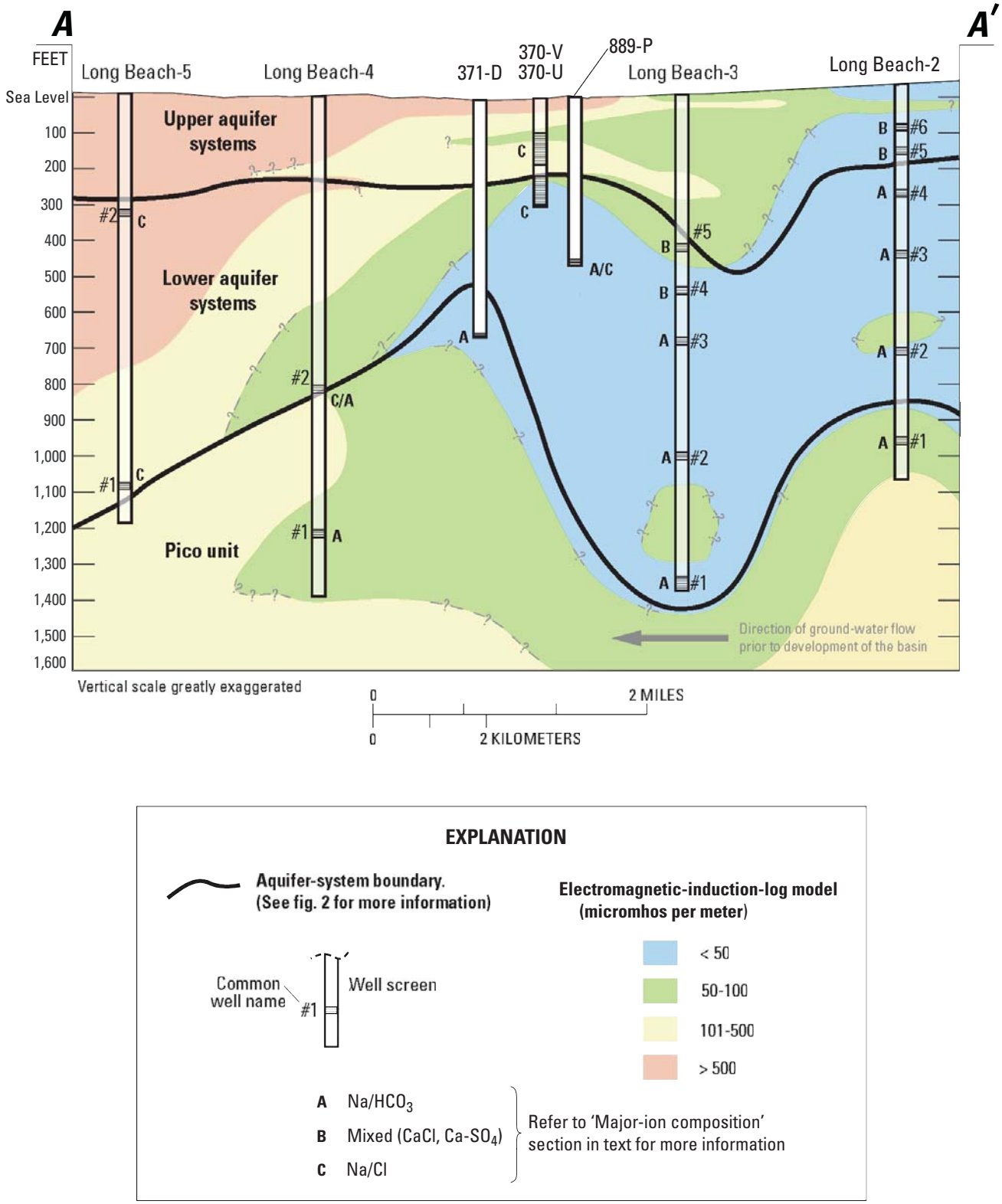


Figure 21. Geohydrologic section *A′–A* showing ground-water-quality conditions from the Dominguez Gap to the San Pedro Bay. Line of section is shown on figure 5. (Modified from Ehman, 1997, and Ehman and others, 2001)

Most water with less than 500 mg/L dissolved solids generally has a sodium-bicarbonate to sodium/calcium-bicarbonate character. Water with a dissolved-solids concentration greater than 1,000 mg/L also contains variable amounts of calcium and sodium, but chloride is predominant. Most of these latter wells are perforated in the Upper aquifer systems; several have a composition which plot near that of seawater. The chemical character of water with a dissolved-solids concentration between 500 and 1,000 mg/L varies considerably from sodium-bicarbonate to calcium/sodium-chloride/bicarbonate.

Elevated chloride concentrations were measured at many of the wells (in both the Upper and Lower aquifer systems) inland from the DGBP. Relatively low chloride concentrations were measured at several Lower aquifer system wells east of the DGBP. A review of historic data indicates that although many wells have had increasing water levels resulting from injection and decreased pumpage over the last 30 years, some of them do not show a corresponding decrease in dissolved chloride.

A more detailed assessment of high-salinity water was provided by examining the ratios of chloride to bromide, iodide, and boron. Water containing a mixture of freshwater and seawater plot along a mixing line. The chloride-to-bromide ratio of seawater (about 640) is similar to that of low-chloride native water from several wells in the Lower aquifer systems. Water affected by injection of imported water has a large chloride-to-bromide ratio. Some wells have water with chloride-to-bromide ratios less than 290, indicating likely mixing with brines. Chloride-to-iodide ratios and dissolved-chloride concentrations helped discriminate between the various water sources. Complex mixing of ground-water sources, dissolved interferences from highly colored water, and potential reactivity occasionally lead to inconclusive chloride-iodide interpretations. Analysis of chloride-to-boron ratios also identified wells with water that appeared to be a mixture of freshwater and seawater. In some cases (wells 340-L and 898-AA, for example), the interpretations using the boron data differed from those using bromide and iodide data. With some qualifications, a chloride-boron ratio less than 140 (for example, high-chloride water from Long Beach-5 #1) was considered indicative of mixing with a brine source.

Isotopic data provided additional tools to assess the source and movement of ground water in the study area. The stable isotopes oxygen-18 and deuterium were used to distinguish between heavier (less negative isotopic value) water that originated in the Los Angeles Forebay and lighter (more negative) water that originated in the Montebello Forebay. Many Upper aquifer system wells located near the injection wells yield water that plots along a line below and nearly parallel to the meteoric water line. This isotopic composition is consistent with two-member mixing of seawater and imported water.

Pore-water data from the continuously-cored sites indicate that there are distinct isotopic signatures in the different aquifer systems at each of the cored sites, thus indicating different sources of water. Isotopically heavy delta oxygen-18 values, close to that of seawater, were measured in saline water from the Upper aquifer systems at Long Beach-4 and in the Upper and much of the Lower aquifer systems at Long Beach-5. Isotopically heavy, low-chloride water also may be an indication of local recharge from the Palos Verdes Hills (for example, wells 311-E and 311-F) and an indication that the native water is not mixing with seawater.

Age-dating information was provided by tritium and carbon-14. Tritium data were used to identify the occurrence of relatively recent water. Wells that yielded water containing less than 1 TU of tritium (older water that recharged prior to 1952) generally are perforated in the Lower aquifer systems. Recent water is present in the Upper and Lower aquifer systems inland from the seawater-barrier projects, and locally near the Dominguez Gap. Carbon-14 provided a relative age for older ground water. Carbon-14 values ranged from 55 to 1 pmc, which yielded uncorrected age estimates for time of recharge from about 4,000 years to more than 20,000 years before present. The lowest carbon-14 values were for water from the Pico unit.

Two other isotopes used in the analyses were boron-11 and strontium-87/86. Heavier delta boron-11 values are indicative of mixing with seawater. In the future, boron-11 may be useful for tracking recycled water used for injection at the barrier projects. Strontium-87/86 ratios provide information on the source of sediments that comprise the aquifer matrix and help characterize regional flow system. In this study, strontium isotopes were not able to distinguish the occurrence of recently injected imported water. In general, strontium-87/86 ratios were slightly higher than seawater in water from wells east of the Dominguez Gap Barrier Project and slightly lower for inland wells. High strontium values along with a Sr-87/86 ratio of near that of seawater (for example, Wilmington-2 #5) are indicative of seawater intrusion.

Geophysical data, including EM-conductivity, temperature, and specific-conductance logs, provide an independent means for identifying high-salinity water and injection water. EM conductivity, combined with gamma-ray logs, can identify likely saline zones along the entire well depth. In the study area, this is especially valuable for identifying intruded zones that are not being monitored. EM logs from most wells in the Upper aquifer systems show zones of elevated EM log conductivities; data are variable within the Lower aquifer systems. Several wells show elevated EM conductivity in the uppermost part of the Lower aquifer systems. Because of the temperature differences between injection water, seawater, and the surrounding formations, temperature profiles provide additional information on zones affected by both injection water and intruding seawater. Although limited by the effects of density stratification, specific-conductance logs do provide an indicator that poor-quality water is present within or in hydraulic connection with the perforated interval of a well.

The multiple types of geochemical and geophysical data presented in this report provide the means for characterizing the three-dimensional distribution of native, injected, and saline (seawater, oil-field brine, and other sources) water in the West Coast Basin beyond simply considering chloride concentrations. In some cases, the ion ratios and isotope data yield conflicting results and indicate a need for additional data collection and analyses.

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Appendixes

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California

[Location of sites is shown in figure 5; residue (sum of constituents) values shown in italics estimated by regression from specific conductance (Reichard and others, 2003); number below the compound is the data parameter code, which is a 5-digit number used in the USGS computerized data system, National Water Information System (NWIS), to uniquely identify a specific constituent or property; USGS, U.S. Geological Survey; WRDSC, Water Replenishment District of Southern California; ft, feet; mg/L, milligrams per liter; µg/L, micrograms per liter; TU, tritium units; °C, degrees Celsius; µS/cm at 25°C, microsiemens at 25 degrees Celsius; <, actual value is less than value shown; —, no data]

Common name	State well No.	Source	Date	Depth to bottom of casing (ft)	Depth to bottom of perforation (ft)	Depth to top of perforation (ft)	Water level (ft below land surface)	Altitude of land surface (ft)
311-E	4S/13W-31F1S	USGS	03/07/1999	225	215	155	79.69	39
311-F	4S/13W-31F2S	USGS	03/07/1999	105	95	85	66.45	39
321-A	4S/13W-31J1S	USGS	02/06/1999	670	669	659	65.20	21.6
331-A	4S/13W-32B1S	WRDSC	02/03/1999	375	365	275	78.32	39.1
331-B	4S/13W-32B2S	WRDSC	02/03/1999	245	235	95	60.24	39.1
340-L	4S/13W-29H5S	WRDSC	02/03/1999	166	156	121	74.85	40.8
340-M	4S/13W-29H6S	WRDSC	02/03/1999	391	381	201	86.85	40.8
340-N	4S/13W-29H7S	WRDSC	02/03/1999	734	724	424	91.45	40.8
341-R	4S/13W-28N5S	USGS	02/05/1999	372	371	361	73.16	37.3
341-S	4S/13W-28N6S	USGS	02/05/1999	216	215	205	71.26	37.7
341-T	4S/13W-33L1S	USGS	03/06/1999	475	465	345	43.95	10
341-U	4S/13W-33L2S	USGS	03/06/1999	200	190	70	13.88	10
351-E	4S/13W-33H2S	USGS	02/25/1999	440	430	370	44.10	17.7
351-G	4S/13W-33H4S	USGS	02/25/1999	165	155	135	22.71	17.7
351-M	4S/13W-33C2S	USGS	02/26/1999	470	460	250	54.03	22.2
351-N	4S/13W-33C1S	USGS	03/09/1999	165	155	115	43.70	22.2
360-H	4S/13W-27E2S	USGS	08/31/1995	210	191	181	61.29	39
361-H	4S/13W-34M1S	USGS	02/10/1999	735	734	724	59.76	3.4
361-K	4S/13W-34M3S	USGS	02/10/1999	348	347	337	26.99	4.6
370-U	4S/13W-27K4S	USGS	02/25/1999	300	290	215	37.36	14.2
370-V	4S/13W-27K5S	USGS	02/25/1999	190	180	95	28.08	14.2
371-D	4S/13W-34A1S	USGS	02/11/1999	650	650	640	78.45	6.7
380-P	4S/13W-26F5S	USGS	02/04/1999	500	493	483	84.05	12.5
380-Q	4S/13W-26F6S	USGS	02/04/1999	262	262	252	30.43	12.9
381-J	4S/13W-35B2S	USGS	03/18/1999	713	703	693	78.83	6.7
381-K	4S/13W-35B3S	USGS	03/19/1999	398	388	378	23.00	6.7
745-A	4S/14W-9D1S	USGS	09/01/1995	655	645	565	114.21	113
758-A	4S/14W-15N1S	USGS	12/01/1995	380	370	360	89	78.2
829-N	4S/13W-20N3S	USGS	03/08/1999	177	167	117	72.05	38
829-P	4S/13W-20N2S	USGS	03/08/1999	577	577	202	81.53	38
829-Q	4S/13W-20N1S	USGS	03/08/1999	935	925	600	82.45	38
868-HH	4S/13W-22F5S	USGS	03/09/1999	290	270	200	40.41	16.3
868-JJ	4S/13W-22F6S	USGS	03/09/1999	160	150	50	37.68	16.3
889-P	4S/13W-23N3S	USGS	02/11/1999	471	470	460	81.00	17.4
898-AA	4S/13W-23H2S	USGS	03/09/1999	150	145	130	32.18	21
898-AB	4S/13W-23H1S	USGS	03/09/1999	410	405	370	36.25	21
1314	2S/14W-31H1S	USGS	06/12/1997	450	440	270	109.22	99.1
Chicago #1	3S/14W-21M1S	USGS	11/28/1995	438	399	378	75	60
Compton-Doty	3S/14W-22L1S	USGS	06/05/1997	502	416	352	—	—
Hawthorne-1 #1	3S/14W-17G3S	USGS	08/17/1999	990	950	910	167.35[1]	84
Hawthorne-1 #2	3S/14W-17G4S	USGS	08/07/1999	730	730	710	110.92	84
Hawthorne-1 #3	3S/14W-17G5S	USGS	08/07/1999	540	540	520	109.30	84
Hawthorne-1 #4	3S/14W-17G6S	USGS	08/07/1999	420	420	400	108.93	84
Hawthorne-1 #5	3S/14W-17G7S	USGS	08/07/1999	260	260	240	102.77	84
Hawthorne-1 #6	3S/14W-17G8S	USGS	08/17/1999	130	130	110	88.92[1]	84

See footnotes at end of table.

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California—Continued

Common name	Date	Dissolved oxygen, mg/L as O_2 (00300)	pH, field (00400)	Specific conductance, field, µS/cm at 25°C (00095)	Water temperature, °C (00010)	Calcium, mg/L (00915)	Magnesium, mg/L (00925)	Potassium, mg/L (00935)	Sodium, mg/L (00930)
311-E	03/07/1999	0.1	7.8	1,670	22.0	74.4	33.4	10.5	258
311-F	03/07/1999		7.6	1,480	22.6	101	12.3	14.2	186
321-A	02/06/1999		7.8	6,600	26.0	202	155	20.1	957
331-A	02/03/1999	.9	8.0	2,200	24.1	75	30	9.5	313
331-B	02/03/1999	1.4	7.4	4,240	24.0	210	53	16	583
340-L	02/03/1999	1.3	7.5	4,400	25.0	180	61	13	614
340-M	02/03/1999	<.1	7.4	2,390	21.4	170	53	7.8	231
340-N	02/03/1999	.8	8.0	813	25.0	57	16	3.4	81
341-R	02/05/1999		7.8	3,250	23.6	208	77.3	14.1	320
341-S	02/05/1999	<.1	7.4	6,290	22.4	265	104	19.9	905
341-T	03/06/1999	.1	8.2	905	22.6	16.0	6.99	6.29	161
341-U	03/06/1999	<.1	8.0	1,930	20.4	68.7	38.7	8.90	243
351-E	02/25/1999	.2	8.1	1,020	19.1	72.1	27.6	4.24	93.5
351-G	02/25/1999	.2	7.9	1,050	20.3	53.8	30.5	5.78	110
351-M	02/26/1999	.1	7.6	7,270	21.3	431	205	21.2	786
351-N	03/09/1999	<.1	7.8	3,580	23.0	88.1	33.4	11.9	593
360-H	08/31/1995	—	7.5	10,600	23.9	240	160	—	1,800
361-H	02/10/1999	.2	8.3	555	24.5	17.6	4.38	3.03	95.3
361-K	02/10/1999	.2	8.0	1,450	22.5	33.4	16.6	8.96	230
370-U	02/25/1999	<.1	8.2	936	20.6	52.6	10.9	4.10	127
370-V	02/25/1999	<.1	7.6	7,030	19.4	168	142	23.8	1,020
371-D	02/11/1999	<.1	8.7	440	23.9	6.42	1.41	3.41	89.3
380-P	02/04/1999	<.1	8.9	443	22.4	9.37	2.00	2.91	86.2
380-Q	02/04/1999	.6	8.3	458	20.8	14.5	4.08	3.84	76.4
381-J	03/18/1999	—	8.4	1,430	22.4	12.1	8.16	1.68	298
381-K	03/19/1999	<.1	8.2	9,710	21.8	293	251	42.2	1,410
745-A	09/01/1995	—	7.1	20,700	24.8	1,300	470	—	2,700
758-A	12/01/1995	.4	7.6	768	22.6	39.0	14.0	—	99.0
829-N	03/08/1999	.1	7.8	1,090	23.4	89.3	20.3	6.37	83.8
829-P	03/08/1999	.1	8.1	667	24.5	41.2	12.8	5.58	72.5
829-Q	03/08/1999	<.1	8.3	426	25.4	25.9	7.96	4.00	51.5
868-HH	03/09/1999	<.1	7.2	7,310	21.4	477	139	23.2	912
868-JJ	03/09/1999	<.1	6.9	17,200	21.8	757	338	26.0	2,590
889-P	02/11/1999	<.1	8.3	701	23.4	29.2	5.59	3.53	109
898-AA	03/09/1999	2.1	7.8	2,090	20.6	202	34.7	9.08	176
898-AB	03/09/1999	.2	8.4	532	22.1	29.0	13.4	6.73	60.4
1314	06/12/1997	<.1	7.9	949	24.0	47.1	25.0	9.88	103
Chicago #1	11/28/1995	.8	7.8	644	23.6	43.0	15.0	—	67.0
Compton-Doty	06/05/1997	.1	7.9	567	23.6	43.9	14.6	4.86	47.1
Hawthorne-1 #1	08/17/1999	730	.18	47.9	.026	46.1	<.1	—	—
Hawthorne-1 #2	08/07/1999	620	.17	42.6	.040	28.7	.7	—	765
Hawthorne-1 #3	08/07/1999	440	.15	50.0	.077	34.4	1.1	—	564
Hawthorne-1 #4	08/07/1999	350	.16	52.5	.063	37.4	.7	—	484
Hawthorne-1 #5	08/07/1999	210	.54	187	.046	32.7	18.8	<1	558
Hawthorne-1 #6	08/17/1999	290	1.34	577	.206	19.7	602	—	2,060

See footnotes at end of table.

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California—Continued

Common name	Date	Alkalinity, field, $CaCO_3$, mg/L (39036)	Bromide, mg/L (71870)	Chloride, mg/L (00940)	Iodide, mg/L (71865)	Silica, mg/L (00955)	Sulfate, mg/L (00945)	Sulfide, field, mg/L (99118)	Residue, sum of constituents, mg/L (70301)	Barium, µg/L (01005)
311-E	03/07/1999	320	1.15	209	0.112	26.7	201	<1	1,010	40.8
311-F	03/07/1999	270	.45	113	.094	26.4	296	<1	912	41.0
321-A	02/06/1999	300	5.43	2,110	.445	23.8	<.1	<1	*3,900*	83.7
331-A	02/03/1999	160	2.9	660	.432	—	<.1	<1	1,260	27
331-B	02/03/1999	230	4.2	1,100	.211	—	295[2]	<1	2,500	150
340-L	02/03/1999	260	10.4	1,300	—	—	98		2,560	290
340-M	02/03/1999	220	4.4	570	—	—	150	6	1,480	23
340-N	02/03/1999	180	.87	140	—	—	18	<1	480	9
341-R	02/05/1999	140	3.08	918	.052	21.8	155	<1	1,800	59.7
341-S	02/05/1999	250	16.7	2,010	5.70	28.0	69.3	<1	3,580	138
341-T	03/06/1999	230	.84	143	.276	24.9	.6	<1	501	7.9
341-U	03/06/1999	140	1.51	424	.111	22.9	147	<1	1,040	70.4
351-E	02/25/1999	130	.12	90.9	.016	13.6	248	<1	627	18.9
351-G	02/25/1999	130	.17	101	.017	18.0	242	<1	641	18.8
351-M	02/26/1999	170	11.4	2,270	1.04	21.9	208	<1	4,060	157
351-N	03/09/1999	180	3.95	968	.513	24.8	183	—	2,020	105
360-H	08/31/1995	260	11.0	3,200	.140	20.0	460	—	*6,380*	<100
361-H	02/10/1999	180	.31	71.2	.175	20.5	<.1	1	*329*	6.3
361-K	02/10/1999	290	1.95	288	.717	24.8	<.1	4	*858*	11.3
370-U	02/25/1999	140	1.23	196	.209	19.6	26.5	<1	525	13.1
370-V	02/25/1999	230	6.92	2,140	.033	13.1	250	1	3,900	238
371-D	02/11/1999	170	.19	41.9	.099	14.5	<.1	<1	*262*	3.2
380-P	02/04/1999	170	.16	36.9	.072	21.3	<.1	—	*263*	139
380-Q	02/04/1999	160	.19	42.9	.071	22.2	.2	<1	264	12.7
381-J	03/18/1999	660	.15	75.7	.022	16.3	.5	—	812	37.9
381-K	03/19/1999	190	10.4	3,050	.306	19.3	259	<1	5,450	273
745-A	09/01/1995	140	25.0	6,800	.082	23.0	870	—	*12,600*	<100
758-A	12/01/1995	230	.36	95.0	.096	36.0	.4	—	*448*	<100
829-N	03/08/1999	170	1.47	218	.177	24.3	34.4	<1	583	205
829-P	03/08/1999	180	.93	94.7	.146	25.6	<.1	<1	*396*	57.5
829-Q	03/08/1999	180	.12	24.8	.033	23.9	<.1	<1	*253*	23.1
868-HH	03/09/1999	320	16.3	2,200	5.47	29.1	301	<1	4,310	346
868-JJ	03/09/1999	470	18.7	5,540	.482	21.6	1,120	<1	10,700	82.4
889-P	02/11/1999	190	.62	107	.217	23.3	.2	1	394	6.1
898-AA	03/09/1999	220	4.46	478	.985	35.9	102	1	1,180	140
898-AB	03/09/1999	170	.13	27.4	.040	25.3	57.1	<1	320	63.8
1314	06/12/1997	300	.31	75.8	.086	38.6	62.7	—	544	62.8
Chicago #1	11/28/1995	250	.16	50.0	.033	31.0	5.0	—	*373*	<100
Compton-Doty	06/05/1997	200	.13	35.9	.029	30.8	24.8	—	325	51.2
Hawthorne-1 #1	08/17/1999	730	.18	47.9	.026	46.1	<.1	—	890	29.8
Hawthorne-1 #2	08/07/1999	620	.17	42.6	.040	28.7	.7	—	765	23.7
Hawthorne-1 #3	08/07/1999	440	.15	50.0	.077	34.4	1.1	—	564	33.6
Hawthorne-1 #4	08/07/1999	350	.16	52.5	.063	37.4	.7	—	484	28.1
Hawthorne-1 #5	08/07/1999	210	.54	187	.046	32.7	18.8	<1	558	83.9
Hawthorne-1 #6	08/17/1999	290	1.34	577	.206	19.7	602	—	2,060	74.4

See footnotes at end of table.

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California—Continued

Common name	Date	Boron, µg/L (01020)	Strontium, µg/L (01080)	Boron-11/10, per mil (62648)	Carbon-13/12, ratio, per mil (82081)	Carbon-14, percent modern (49933)	Hydrogen-2/1, per mil (82082)	Oxygen-18/16, per mil (82085)	Strontium-87/86, ratio (75985)	Tritium, in water molecules, TU (07000)
311-E	03/07/1999	1,500	735	—	—	—	−30.7	−4.59	—	—
311-F	03/07/1999	950	849	—	—	—	−32.5	−4.60	—	—
321-A	02/06/1999	850	2,240	1.50	—	—	−50.5	−7.88	0.70895	<0.1
331-A	02/03/1999	230	820	—	—	—	−53.3	−7.82	—	2.6
331-B	02/03/1999	430	1,700	—	—	—	−72.8	−9.23	—	22.0
340-L	02/03/1999	1,400	2,200	31.5	—	—	−42.3	−6.46	.70885	3.1
340-M	02/03/1999	470	2,000	14.7	—	—	−45.9	−6.84	.70885	1.0
340-N	02/03/1999	130	600	19.0	—	—	−46.3	−7.21	.70895	.1
341-R	02/05/1999	260	2,180	—	—	—	−72.4	−9.61	—	—
341-S	02/05/1999	1,990	3,080	—	—	—	−54.9	−7.88	—	—
341-T	03/06/1999	410	138	—	—	—	−53.6	−8.35	—	—
341-U	03/06/1999	260	732	—	—	—	−76.7	−10.00	—	—
351-E	02/25/1999	200	796	—	—	—	−87.3	−10.56	—	—
351-G	02/25/1999	180	546	—	—	—	−86.5	−10.60	—	—
351-M	02/26/1999	430	4,320	—	—	—	−62.7	−8.59	—	—
351-N	03/09/1999	970	941	—	—	—	−74.9	−9.78	—	—
360-H	08/31/1995	750	—	—	—	—	−62.5	−8.36	—	21.9
361-H	02/10/1999	250	129	16.2	—	—	−54.6	−8.27	.70916	<.1
361-K	02/10/1999	590	310	—	—	—	−54.2	−8.20	—	<.1
370-U	02/25/1999	130	441	—	—	—	−48.6	−7.44	—	—
370-V	02/25/1999	480	2,270	—	—	—	−75.7	−9.52	—	—
371-D	02/11/1999	150	53.2	18.0	—	—	−61.2	−8.76	.70951	<.1
380-P	02/04/1999	200	142	13.0	—	—	−53.3	−7.85	.70935	<.1
380-Q	02/04/1999	150	132	—	—	—	−51.9	−7.98	—	—
381-J	03/18/1999	1,320	184	18.5	—	—	−61.5	−9.05	.70958	.1
381-K	03/19/1999	370	3,760	21.7	—	—	−44.9	−6.64	.70970	<.1
745-A	09/01/1995	340	—	—	—	—	−34.1	−4.86	—	1.7
758-A	12/01/1995	180	—	—	—	—	−48.0	−7.41	—	<.1
829-N	03/08/1999	100	763	—	—	—	−46.0	−6.85	—	.2[3]
829-P	03/08/1999	160	463	—	—	—	−48.5	−7.21	—	—
829-Q	03/08/1999	130	288	—	—	—	−47.7	−7.24	—	—
868-HH	03/09/1999	3,440	4,300	—	—	—	−40.4	−6.15	—	—
868-JJ	03/09/1999	8,190	7,360	—	—	—	−34.7	−5.24	—	—
889-P	02/11/1999	310	310	18.0	—	—	−56.6	−8.48	.70943	—
898-AA	03/09/1999	1,040	2,020	—	—	—	−44.8	−6.87	—	—
898-AB	03/09/1999	130	460	—	—	—	−48.4	−7.37	—	—
1314	06/12/1997	290	402	—	—	—	−39.8	−6.24	—	—
Chicago #1	11/28/1995	180	—	—	—	—	−46.9	−7.15	—	<.1
Compton-Doty	06/05/1997	110	470	—	—	—	−46.4	−7.12	—	—
Hawthorne-1 #1	08/17/1999	1,380	248	—	−13.5	2.8	−50.5	−7.70	—	<.1
Hawthorne-1 #2	08/07/1999	1,020	153	—	−11.4	7.6	−49.3	−7.59	—	<.1
Hawthorne-1 #3	08/07/1999	490	415	—	−18.4	10.1	−46.1	−7.06	—	<.1
Hawthorne-1 #4	08/07/1999	400	420	—	−16.5[4]	15.6[4]	−45.6	−7.03	—	<.1
Hawthorne-1 #5	08/07/1999	140	808	—	—	—	−45.5	−6.92	—	1.0
Hawthorne-1 #6	08/17/1999	260	2,780	—	—	—	−50.6	−6.85	—	17.7

See footnotes at end of table.

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California—Continued

Common name	State well No.	Source	Date	Depth to bottom of casing (ft)	Depth to bottom of perforation (ft)	Depth to top of perforation (ft)	Water level (ft below land surface)	Altitude of land surface (ft)
Long Beach-2 #1	4S/13W-1N3S	USGS	03/09/2000	1,090	990	970	62.50	42
Long Beach-2 #2	4S/13W-1N4S	USGS	03/30/2001	740	740	720	72.82	42
Long Beach-2 #3	4S/13W-1N5S	USGS	03/09/2000	470	470	450	105.09	42
Long Beach-2 #4	4S/13W-1N6S	USGS	03/08/2000	300	300	280	51.13	42
Long Beach-2 #5	4S/13W-1N7S	USGS	03/07/2000	180	180	160	42.80	42
Long Beach-2 #6	4S/13W-1N8S	USGS	03/08/2000	115	115	95	41.42	42
Long Beach-3 #1	4S/13W-23D3S	USGS	03/29/2001	1,390	1,390	1,350	71.72	23
Long Beach-3 #2	4S/13W-23D4S	USGS	03/29/2001	1,017	1,017	997	99.56	23
Long Beach-3 #3	4S/13W-23D5S	USGS	03/28/2001	690	690	670	99.41	23
Long Beach-3 #4	4S/13W-23D6S	USGS	03/27/2001	550	550	530	93.18	23
Long Beach-3 #5	4S/13W-23D7S	USGS	03/26/2001	430	430	410	37.10	23
Long Beach-4 #1	5S/13W-2E1S	USGS	04/03/2001	1,380	1,220	1,200	58.04	5
Long Beach-4 #2	5S/13W-2E2S	USGS	04/04/2001	820	820	800	21.88	5
Long Beach-5 #1	5S/13W-11P1S	USGS	04/24/2002	1,110	1,110	1,090	37.65	10
Long Beach-5 #2	5S/13W-11P2S	USGS	04/24/2002	355	355	335	12.95	10
PM-1 #1		WRDSC	05/11/2001	600	595	555	—	78.4
PM-1 #2		WRDSC	05/21/2001	505	500	460	—	78.4
PM-3 #1	4S/14W-2N1S	USGS	08/29/1995	685	680	640	93.46	65
PM-3 #2	4S/14W-2N2S	USGS	08/28/1995	525	520	480	89.20	65
PM-3 #3	4S/14W-2N3S	USGS	08/29/1995	285	280	240	89.03	65
PM-3 #4	4S/14W-2N4S	USGS	08/28/1995	190	185	145	88.97	65
PM-4 #1		WRDSC	06/10/2001	715	710	670	—	97.7
PM-4 #2		WRDSC	06/10/2001	545	540	500	—	97.7
PM-4 #3		WRDSC	06/10/2001	385	380	340	—	97.7
PM-4 #4		WRDSC	06/10/2001	245	280	240	—	97.7
Tosco #6	4S/13W-1N4S	USGS	03/19/1999	800	800	630	—	80
Westchester-1 #1	2S/15W-35A1S	USGS	05/22/2002	860	760	740	129.18	125
Westchester-1 #2	2S/15W-35A2S	USGS	05/22/2002	580	580	560	118.01	125
Westchester-1 #3	2S/15W-35A3S	USGS	05/20/2002	475	475	455	117.66	125
Westchester-1 #4	2S/15W-35A4S	USGS	05/21/2002	330	330	310	117.54	125
Westchester-1 #5	2S/15W-35A5S	USGS	05/21/2002	235	235	215	117.36	125
Wilmington-1 #1	4S/13W-28A3S	USGS	04/24/1999	1,035	935	915	108.38	30
Wilmington-1 #2	4S/13W-28A4S	USGS	04/25/1999	800	800	780	108.34	30
Wilmington-1 #3	4S/13W-28A5S	USGS	04/25/1999	570	570	550	108.76	30
Wilmington-1 #4	4S/13W-28A6S	USGS	04/25/1999	245	245	225	70.51	30
Wilmington-1 #5	4S/13W-28A7S	USGS	04/24/1999	140	140	120	66.59	30
Wilmington-2 #1	4S/13W-32F1S	USGS	04/21/1999	1,030	970	950	82.43	29
Wilmington-2 #2	4S/13W-32F2S	USGS	02/18/1999	775	775	755	75.83	29
Wilmington-2 #3	4S/13W-32F3S	USGS	02/18/1999	560	560	540	70.25	29
Wilmington-2 #4	4S/13W-32F4S	USGS	04/21/1999	410	410	390	69.93	29
Wilmington-2 #5	4S/13W-32F5S	USGS	02/18/1999	140	140	120	42.20	29
WB-#37(imported)	4S/13W-15G	USGS	03/17/1999	—	—	—	—	—
Seawater	—	(Hem, 1992)	—	—	—	—	—	—
Oil-field brine	—	(Piper, 1953)	—	—	—	—	—	—

See footnotes at end of table.

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California—Continued

Common name	Date	Dissolved oxygen, mg/L as O_2 (00300)	pH, field (00400)	Specific conductance, field, µS/cm at 25°C (00095)	Water temperature, °C (00010)	Calcium, mg/L (00915)	Magnesium, mg/L (00925)	Potassium, mg/L (00935)	Sodium, mg/L (00930)
Long Beach-2 #1	03/09/2000	<0.1	8.4	659	27.5	6.75	1.47	2.42	143
Long Beach-2 #2	03/30/2001	.2	8.2	450	24.5	12.9	1.62	2.13	89.7
Long Beach-2 #3	03/09/2000	<.1	8.4	402	24.0	12.4	1.27	1.56	73.5
Long Beach-2 #4	03/08/2000	.8	8.1	480	23.0	35.1	3.99	2.97	60.1
Long Beach-2 #5	03/07/2000	.6	7.5	1,300	21.0	149	21.4	5.05	107
Long Beach-2 #6	03/08/2000	.4	7.4	1,810	21.0	209	34.5	6.85	138
Long Beach-3 #1	03/29/2001	.1	8.4	740	22.0	11.0	3.47	3.81	156
Long Beach-3 #2	03/29/2001	.2	8.4	380	23.0	15.9	2.73	2.50	61.5
Long Beach-3 #3	03/28/2001	.4	8.3	375	23.0	17.9	3.24	2.71	55.8
Long Beach-3 #4	03/27/2001	2.6	7.8	1,080	22.5	88.8	24.0	6.24	72.9
Long Beach-3 #5	03/26/2001	.2	7.6	2,370	22.0	238	57.3	7.84	98.6
Long Beach-4 #1	04/03/2001	<.1	8.2	1,250	23.0	9.57	4.63	5.78	259
Long Beach-4 #2	04/04/2001	<.1	8.2	2,150	24.0	6.55	7.18	10.8	422
Long Beach-5 #1	04/24/2002	<.1	7.8	6,950	22.8	17.8	30.5	25.8	1,500
Long Beach-5 #2	04/24/2002	<.1	7.1	52,000	21.5	519	1,220	272	10,800
PM-1 #1	05/11/2001	—	8.2	484	—	26	15	9.5	70
PM-1 #2	05/21/2001	—	7.7	2,550	—	270	88	13	150
PM-3 #1	08/29/1995	—	8.0	737	24.4	16.0	10.0	—	130
PM-3 #2	08/28/1995	—	7.7	494[5]	23.4	32.0	10.0	—	57.0
PM-3 #3	08/29/1995	—	7.4	954	22.5	70.0	22.0	—	81.0
PM-3 #4	08/28/1995	—	7.4	1,080[5]	21.8	70.0	20.0	—	120
PM-4 #1	06/10/2001	—	8.2	508	—	27	11	8.5	88
PM-4 #2	06/10/2001	—	7.5	14,730	—	1,500	410	39	1,400
PM-4 #3	06/10/2001	—	8.0	1,240	—	120	31	7.6	120
PM-4 #4	06/10/2001	—	8.1	1,090	—	88	22	7.2	130
Tosco #6	03/19/1999	<.1	7.9	1,310	25.4	29.4	13.2	8.45	218
Westchester-1 #1	05/22/2002	<.1	7.8	2,090	26.8	15.8	13.8	17.7	468
Westchester-1 #2	05/22/2002	<.1	7.8	1,260	24.3	24.1	14.1	14.9	258
Westchester-1 #3	05/20/2002	.2	7.6	1,040	27.4	40.0	18.6	12.9	168
Westchester-1 #4	05/21/2002	.2	7.6	966	22.9	68.3	26.8	9.82	103
Westchester-1 #5	05/21/2002	.2	7.4	947	22.4	65.1	25.3	8.50	106
Wilmington-1 #1	04/24/1999	.1	8.1	960	24.4	50.0	16.1	7.14	106
Wilmington-1 #2	04/25/1999	.3	7.8	1,580	24.3	124	26.9	5.61	130
Wilmington-1 #3	04/25/1999	—	7.6	3,240	23.8	214	46.5	9.42	346
Wilmington-1 #4	04/25/1999	.1	7.6	4,430	21.6	282	95.9	12.9	457
Wilmington-1 #5	04/24/1999	—	7.6	1,390	22.1	85.2	30.6	7.37	145
Wilmington-2 #1	04/21/1999	<.1	8.6	890	28.7	3.31	2.24	5.46	195
Wilmington-2 #2	02/18/1999	<.1	8.0	2,420	26.4	29.8	21.6	12.7	437
Wilmington-2 #3	02/18/1999	<.1	8.2	589	27.2	19.8	7.47	4.34	102
Wilmington-2 #4	04/21/1999	<.1	7.6	3,730	27.7	143	66.7	16.4	492
Wilmington-2 #5	02/18/1999	<.1	7.3	15,600	22.8	640	310	30.9	2,600
WB-#37(imported)	03/17/1999	10.0	8.0	940	13.9	67.4	24.9	4.04	79.3
Seawater		—	—	—	—	410	1,350	390	10,500
Oil-field brine		—	—	—	—	1,680	710	—	13,300

See footnotes at end of table.

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California—Continued

Common name	Date	Alkalinity, field, $CaCO_3$, mg/L (39036)	Bromide, mg/L (71870)	Chloride, mg/L (00940)	Iodide, mg/L (71865)	Silica, mg/L (00955)	Sulfate, mg/L (00945)	Sulfide, field, mg/L (99118)	Residue, sum of constituents, mg/L (70301)	Barium, µg/L (01005)
Long Beach-2 #1	03/09/2000	320	0.21	20.9	0.018	22.6	0.3	4	*417*	6.0
Long Beach-2 #2	03/30/2001	200	.07	19.8	.027	23.6	2.2	—	280	7.1
Long Beach-2 #3	03/09/2000	140	.08	22.3	.036	21.2	27.2	<1	248	3.8
Long Beach-2 #4	03/08/2000	140	.13	28.8	.043	23.8	46.3	<1	294	18.1
Long Beach-2 #5	03/07/2000	290	.82	97.1	.035	27.4	257	<1	840	82.9
Long Beach-2 #6	03/08/2000	310	1.87	153	.038	28.1	430	—	1,190	117
Long Beach-3 #1	03/29/2001	380	.07	18.5	.032	20.2	1.0	—	448	8.7
Long Beach-3 #2	03/29/2001		.09	18.8	.030	22.6	25.3	—	234	10.1
Long Beach-3 #3	03/28/2001	150	.09	24.8	.047	23.8	.2	—	221	12.8
Long Beach-3 #4	03/27/2001	130	1.96	213	.594	28.6	57.9	—	577	31.3
Long Beach-3 #5	03/26/2001	140	6.50	619	1.66	23.7	62.7	—	1,210	109
Long Beach-4 #1	04/03/2001	480	.08	21.4	.110	28.1	3.6	—	630	14.9
Long Beach-4 #2	04/04/2001	580	1.96	337	.976	35.3	1.4	—	1,180	17.2
Long Beach-5 #1	04/24/2002	1,200	4.81	1,650	1.40	40.7	.7	—	*4,100*	127
Long Beach-5 #2	04/24/2002	290	36.1	19,900	.161	14.5	2,640	—	35,600	82.0
PM-1 #1	05/11/2001	240	—	22	—	—	<.1	—	310	—
PM-1 #2	05/21/2001	150	—	836	—	—	56.6	—	1,910	—
PM-3 #1	08/29/1995	320	.06	28.0	.029	19.0	17.0	—	*437*	<100
PM-3 #2	08/28/1995	190	.14	35.0	.040	27.0	3.3	—	*293*	<100
PM-3 #3	08/29/1995	180	1.22	180	.220	29.0	13.0	—	*565*	<100
PM-3 #4	08/28/1995	190	1.43	210	.240	23.0	31.0	—	*639*	<100
PM-4 #1	06/10/2001	260	—	27	—	—	<.1	—	330	—
PM-4 #2	06/10/2001	160	—	5,740	—	—	645	—	11,700	—
PM-4 #3	06/10/2001	150	—	157	—	—	318	—	890	—
PM-4 #4	06/10/2001	190	—	148	—	—	216	—	730	—
Tosco #6	03/19/1999	310	1.02	216	.046	32.6	5.0	—	709	32.5
Westchester-1 #1	05/22/2002	980	.63	129	.155	39.7	1.2	—	1,290	35.8
Westchester-1 #2	05/22/2002	590	.14	72.1	.147	36.4	2.7	—	781	77.7
Westchester-1 #3	05/20/2002	450	.16	65.8	.129	39.0	13.2	—	631	55.7
Westchester-1 #4	05/21/2002	360	.24	63.5	.100	38.0	75.8	—	603	68.2
Westchester-1 #5	05/21/2002	330	.27	66.6	.100	33.3	79.0	—	586	56.9
Wilmington-1 #1	04/24/1999	130	2.35	213	.873	21.8	<.1	—	*490*	11.5
Wilmington-1 #2	04/25/1999	140	1.19	337	.148	21.3	58.6	—	787	10.6
Wilmington-1 #3	04/25/1999	170	4.33	907	.387	24.0	49.5	11	1,720	27.4
Wilmington-1 #4	04/25/1999	140	5.07	1,210	.794	26.1	288	<1	2,470	121
Wilmington-1 #5	04/24/1999	200	1.12	233	.168	26.2	140	1	789	103
Wilmington-2 #1	04/21/1999	380	.40	56.5	.033	24.2	<.1	<1	*527*	7.0
Wilmington-2 #2	02/18/1999	450	2.78	513	1.07	20.3	<.1	<1	*1,430*	50.4
Wilmington-2 #3	02/18/1999	180	.28	72.3	.141	20.8	<.1	<1	*350*	22.6
Wilmington-2 #4	04/21/1999	310	3.31	1,010	.318	29.0	29.4	13	1,990	117
Wilmington-2 #5	02/18/1999	200	18.2	5,230	.102	24.3	595	<1	7,200	140
WB-#37(imported)	03/17/1999	120	.04	76.2	.001	8.3	231	<1	566	93.3
Seawater		116	67	19,000	0.060	6.4	2,700	—	—	20
Oil-field brine		—	200	23,400	80	—	165	—	38,800	142

See footnotes at end of table.

Appendix A. Construction, water level, and water-quality data for wells sampled in the study area, Los Angeles County, California—Continued

Common name	Date	Boron, µg/L (01020)	Strontium, µg/L (01080)	Boron-11/10, per mil (62648)	Carbon-13/12 ratio, per mil (82081)	Carbon-14, percent modern (49933)	Hydrogen-2/1, per mil (82082)	Oxygen-18/16, per mil (82085)	Strontium-87/86, per mil (75985)	Tritium, in water molecules, TU (07000)
Long Beach-2 #1	03/09/2000	550	66.8	9.0	−8.3	1.3	−63.6	−9.17	0.70852	<0.1
Long Beach-2 #2	03/30/2001	200	129	8.5	−10.7	4.3	−60.7	−8.84	.70955	<.1
Long Beach-2 #3	03/09/2000	140	74.3	6.5	−16.7	22.3	−51.1	−7.87	.70900	<.1
Long Beach-2 #4	03/08/2000	100	318	13.2	—	—	−49.0	−7.55	.70961	<.1
Long Beach-2 #5	03/07/2000	250	1,120	16.7	—	—	−41.7	−6.44	.70985	5.2
Long Beach-2 #6	03/08/2000	330	1,600	19.7	—	—	−41.8	−6.20	.70983	3.6
Long Beach-3 #1	03/29/2001	370	120	1.5	6.3	1.8	−62.7	−9.17	.70893	<.1
Long Beach-3 #2	03/29/2001	140	191	10.0	−15.8	24.1	−51.1	−7.72	.70950	.1
Long Beach-3 #3	03/28/2001	130	226	9.7	−18.9	14.1	−53.2	−8.07	.70941	<.1
Long Beach-3 #4	03/27/2001	110	962	14.7	−14.3	42.8	−48.4	−7.32	.70930	<.1
Long Beach-3 #5	03/26/2001	110	2,530	16.7	−13.8	55.1	−47.4	−7.10	.70924	<.1
Long Beach-4 #1	04/03/2001	1,100	134	10.5	3.1	2.4	−61.1	−9.23	.70941	.2
Long Beach-4 #2	04/04/2001	1,150	97.5	23.5	−12.7	4.3	−49.2	−7.54	.70955	<.1
Long Beach-5 #1	04/24/2002	8,400	734	40.2	−6.4	.8	−47.1	−7.47	.70959	<.1
Long Beach-5 #2	04/24/2002	4,130	8,500	45.5	−12.3	48.5	−3.65	−0.42	.70922	<.1
PM-1 #1	05/11/2001	—	—	—	—	—	—	—	—	—
PM-1 #2	05/21/2001	—	—	—	—	—	—	—	—	—
PM-3 #1	08/29/1995	360	—	—	−13.2	9.8	−48.4	−7.76	—	.8
PM-3 #2	08/28/1995	120	—	—	−17.3	38.5	−48.5	−6.88	—	<.1
PM-3 #3	08/29/1995	130	—	—	−19.7	37.8	−44.3	−6.88	—	.9
PM-3 #4	08/28/1995	230	—	—	−19.3	39.7	−47.1	−6.91	—	4.4
PM-4 #1	06/10/2001	—	—	—	—	—	—	—	—	—
PM-4 #2	06/10/2001	—	—	—	—	—	—	—	—	—
PM-4 #3	06/10/2001	—	—	—	—	—	—	—	—	—
PM-4 #4	06/10/2001	—	—	—	—	—	—	—	—	—
Tosco #6	03/19/1999	670	241	—	—	—	−46.7	−7.46	—	—
Westchester-1 #1	05/22/2002	2,330	249	—	−6.4	2.2	−50.4	−7.54	—	<.1
Westchester-1 #2	05/22/2002	950	305	—	−12.3	6.4	−45.0	−6.83	—	<.1
Westchester-1 #3	05/20/2002	480	406	—	—	—	−44.5	−6.69	—	.2
Westchester-1 #4	05/21/2002	230	575	—	−17.4	30.2	−40.1	−6.18	—	<.1
Westchester-1 #5	05/21/2002	230	506	—	—	—	−40.8	−6.18	—	<.1
Wilmington-1 #1	04/24/1999	120	371	11.2	−15.8	29.6	−46.8	−7.29	.70914	<.1
Wilmington-1 #2	04/25/1999	180	1,150	19.7	−18.4	44.5	−46.0	−7.13	.70930	<.1
Wilmington-1 #3	04/25/1999	240	2,130	19.0	—	—	−49.4	−7.34	.70925	1.6
Wilmington-1 #4	04/25/1999	220	3,690	24.0	—	—	−77.5	−9.77	.70882	19.1
Wilmington-1 #5	04/24/1999	200	1,090	16.5	—	—	−73.3	−9.58	.70879	11.9
Wilmington-2 #1	04/21/1999	650	39.1	—	−.27	2.4	−59.7	−8.73	.70930	<.1
Wilmington-2 #2	02/18/1999	1,350	360	14.7	−.32	5.2	−55.8	−8.63	.70913	<.1
Wilmington-2 #3	02/18/1999	270	177	15.5	−15.0	14.4	−50.6	−7.84	.70896	<.1
Wilmington-2 #4	04/21/1999	560	1,270	4.5	—	—	−51.3	−7.96	.70090	1.4[6]
Wilmington-2 #5	02/18/1999	620	5,990	28.2	—	—	−57.7	−7.57	.70913	17.0[7]
WB-#37(imported)	03/17/1999	110	918	7.7	—	—	−98.2	−12.08	.71040	11.2
Seawater		4,500	8,000	39	—	—	0	0	.70925	—
Oil-field brine		70,950	—	—	—	—	—	—	—	—

[1]Water level measured 08/07/1999.
[2]Averaged value.
[3]Sample collected 10/12/1995.
[4]Sample collected 10/05/2001.
[5]Laboratory measured value.
[6]Sample collected 01/13/1998.
[7]Sample collected 01/12/1998.

Appendix B. Well construction information and index of well-log data collected in the study area, Los Angeles County, California

[Location of sites shown in figure 6; ft, feet]

Common name	Date logged	Depth to bottom of casing (ft)	Depth to top perforation (ft)	Depth to bottom perforation (ft)	Altitude of land surface (ft)	Logs collected				Logs presented in Appendix C
						Natural gamma	Electro-magnetic conductivity	Fluid conductivity	Temperature	
311-D	02/22/1999	155	85	145	22	Yes	Yes	No	No	No
311-E	02/09/1999	225	155	215	39	Yes	Yes	Yes	Yes	No
312-D	02/18/1999	185	100	175	27	Yes	Yes	Yes	Yes	No
322-E	02/12/1999	190	90	180	18	Yes	Yes	No	No	No
322-F	02/11/1999	285	235	275	23	Yes	Yes	No	No	No
322-S	02/07/1999	204	85	195	17	Yes	Yes	Yes	Yes	No
331-A	02/16/1999	375	275	365	39	Yes	Yes	No	No	No
331-C	04/22/1999	162	92	152	27	Yes	Yes	No	No	No
332-E	02/23/1999	170	90	160	14	Yes	Yes	No	No	No
332-F	02/10/1999	185	85	175	14	Yes	Yes	Yes	Yes	No
340-H	02/18/1999	370	240	360	43	Yes	Yes	No	No	No
340-N	02/16/1999	734	424	724	41	Yes	Yes	No	No	No
341-P	02/16/1999	682	672	682	37	Yes	Yes	No	No	No
341-T	02/12/1999	475	345	465	10	Yes	Yes	Yes	Yes	No
341-V	04/22/1999	175	115	165	22	Yes	Yes	No	No	No
342	02/10/1999	215	85	205	11	Yes	Yes	Yes	Yes	No
342-A	02/10/1999	220	90	210	13	Yes	Yes	Yes	Yes	No
350	04/22/1999	180	70	170	29	Yes	Yes	No	No	No
351-C	02/17/1999	180	135	170	13	Yes	Yes	No	No	No
351-E	02/17/1999	440	370	430	18	Yes	Yes	No	No	Yes
351-J	02/12/1999	450	270	440	24	Yes	Yes	No	No	No
351-M	02/12/1999	470	250	460	22	Yes	Yes	No	No	Yes
352-C	02/12/1999	180	130	170	8	Yes	Yes	No	No	No
352-F	02/12/1999	320	260	310	11	Yes	Yes	No	No	No
360-K	02/17/1999	305	245	295	33	Yes	Yes	No	No	No
360-N	02/11/1999	290	234	279	28	Yes	Yes	Yes	Yes	Yes
361-AA	02/17/1999	160	80	150	24	Yes	Yes	No	No	No
361-M	02/17/1999	420	370	410	17	Yes	Yes	Yes	Yes	No
361-U	02/18/1999	385	270	375	14	Yes	Yes	Yes	Yes	Yes
361-X	02/18/1999	390	305	380	6	Yes	Yes	No	No	No
362-H	02/17/1999	190	110	180	11	Yes	Yes	No	No	No
370-AJ	04/22/1999	340	216	331	11	Yes	Yes	No	No	No
370-U	02/17/1999	300	215	290	14	Yes	Yes	No	No	No
380-S	02/17/1999	340	230	330	8	Yes	Yes	No	No	No
390-T	02/22/1999	325	205	315	10	Yes	Yes	Yes	Yes	No
714-H	02/04/2000	505	395	495	139	Yes	Yes	Yes	Yes	Yes
715-E	02/02/2000	440	130	430	87	Yes	Yes	Yes	Yes	No
716-M	02/01/2000	630	550	620	52	Yes	Yes	Yes	Yes	No
724-E	02/04/2000	545	355	535	146	Yes	Yes	Yes	Yes	No
725-AK	02/04/2000	632	402	622	140	Yes	Yes	Yes	Yes	No
725-AN	02/09/2000	585	395	575	145	Yes	Yes	Yes	Yes	No
725-AR	02/04/2000	608	408	598	143	Yes	Yes	Yes	Yes	Yes
725-AT	02/02/2000	352	197	347	155	Yes	Yes	Yes	No	No
725-AV	02/09/2000	338	208	328	135	Yes	Yes	Yes	Yes	No
725-BA	02/03/2000	560	530	550	143	Yes	Yes	Yes	Yes	No
725-BR	02/03/2000	820	780	810	114	Yes	Yes	Yes	No	No

Appendix B. Well construction information and index of well-log data collected in the study area, Los Angeles County, California—Continued

Common name	Date logged	Depth to bottom of casing (ft)	Depth to top perforation (ft)	Depth to bottom perforation (ft)	Altitude of land surface (ft)	Logs collected				Logs presented in Appendix C
						Natural gamma	Electro-magnetic conductivity	Fluid conductivity	Temperature	
726-AE	02/04/2000	650	440	640	137	Yes	Yes	Yes	Yes	No
726-AG	02/04/2000	482	212	472	158	Yes	Yes	Yes	Yes	No
734-C	02/03/2000	490	370	480	98	Yes	Yes	Yes	Yes	No
734-F	02/03/2000	700	210	690	99	Yes	Yes	Yes	Yes	No
735-A	02/02/2000	690	630	680	94	Yes	Yes	Yes	Yes	Yes
736-D	02/02/2000	760	665	750	99	Yes	Yes	Yes	Yes	Yes
737-D	02/10/2000	630	420	620	75	Yes	Yes	Yes	Yes	No
737-F	01/31/2000	600	500	590	77	Yes	Yes	Yes	Yes	No
737-J	02/02/2000	655	230	645	89	Yes	Yes	No	No	No
738-D	02/10/2000	835	560	825	105	Yes	Yes	Yes	Yes	Yes
745-A	02/03/2000	655	547	627	113	Yes	Yes	No	No	Yes
829-Q	02/09/1999	935	600	925	35	Yes	Yes	Yes	Yes	No
859-C	02/08/1999	270	205	265	36	Yes	Yes	Yes	Yes	No
868-HH	02/08/1999	290	200	270	16	Yes	Yes	Yes	Yes	Yes
879-PP	02/17/1999	442	422	432	17	Yes	Yes	No	No	No
879-VV	09/16/1999	322	205	240	15	Yes	Yes	No	No	No
888-X	02/19/1999	318	288	308	20	Yes	Yes	No	No	No
889-Y	02/08/1999	333	273	323	18	Yes	Yes	Yes	Yes	No
898-AB	02/17/1999	415	370	405	20	Yes	Yes	No	No	Yes
898-Z	02/19/1999	493	458	483	24	Yes	Yes	No	No	No
Hawthorne-1	04/30/1999	990	910	950	84	Yes	Yes	No	Yes	Yes
Long Beach-2	11/22/1999	1,090	970	990	42	Yes	Yes	No	Yes	Yes
Long Beach-3	08/04/2000	1,390	1,350	1,390	23	Yes	Yes	No	Yes	Yes
Long Beach-4	12/21/2000	1,380	1,200	1,220	5	Yes	Yes	No	Yes	Yes
Long Beach-5	10/06/2001	1,110	1,090	1,110	10	Yes	Yes	No	Yes	Yes
PM-1	02/17/2000	600	555	595	78	Yes	Yes	No	No	Yes
PM-3	02/17/2000	683	640	680	71	Yes	Yes	Yes	Yes	Yes
PM-4	02/11/2000	715	670	710	98	Yes	Yes	No	No	Yes
Westchester-1	11/04/2001	860	740	760	125	Yes	Yes	No	Yes	Yes
Wilmington-1	11/20/1997	1,035	915	935	30	Yes	Yes	No	Yes	Yes
Wilmington-2	12/05/1997	1,030	950	970	29	Yes	Yes	No	Yes	Yes

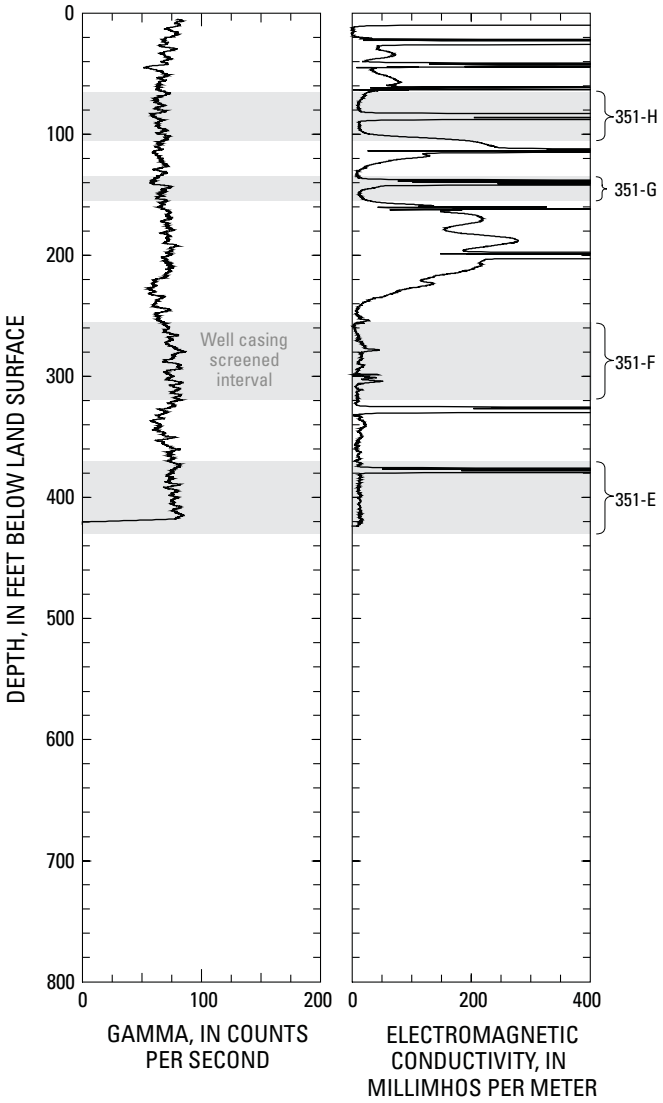

Figure C1. 351-E.

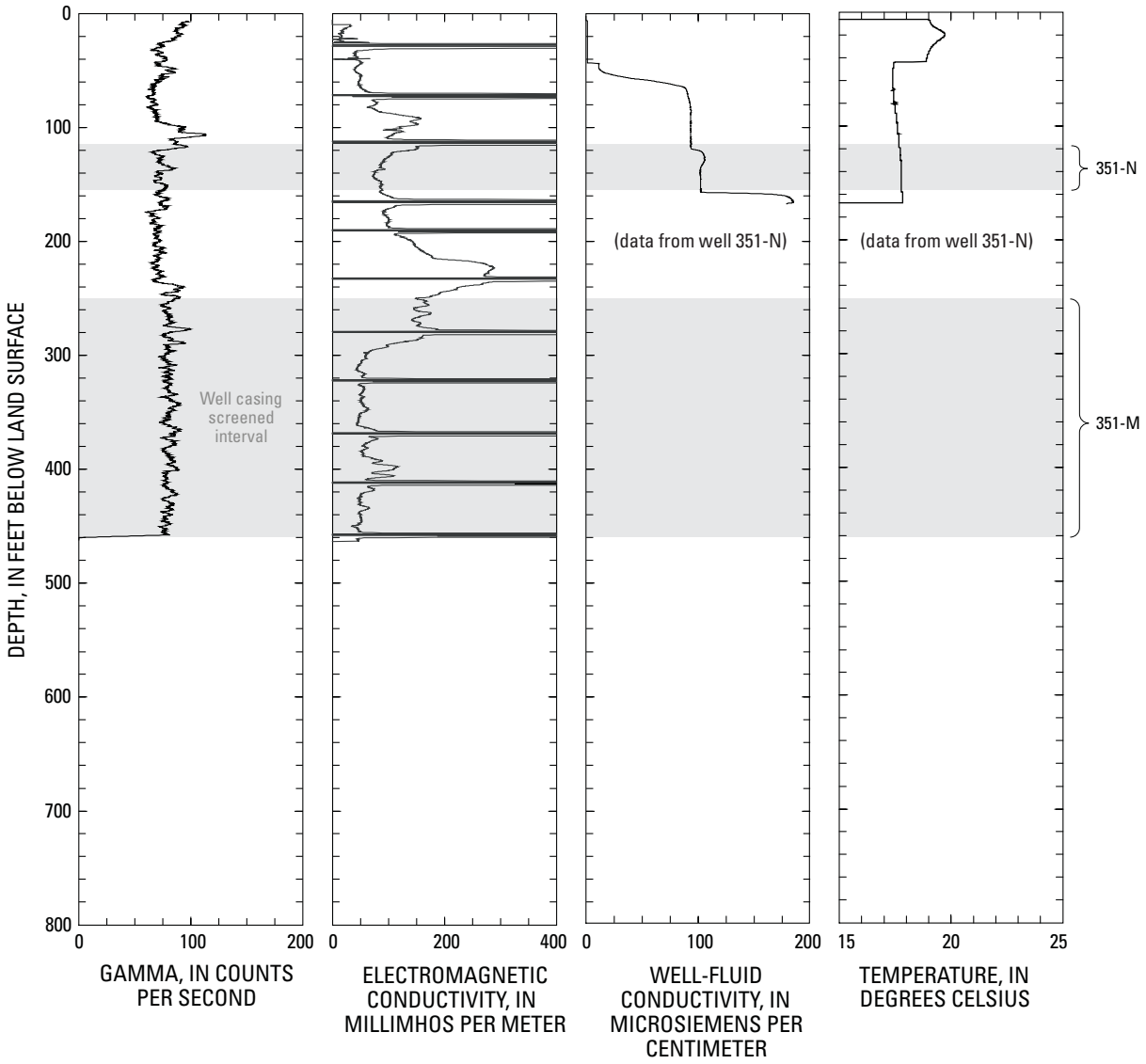

Figure C2. 355-M.

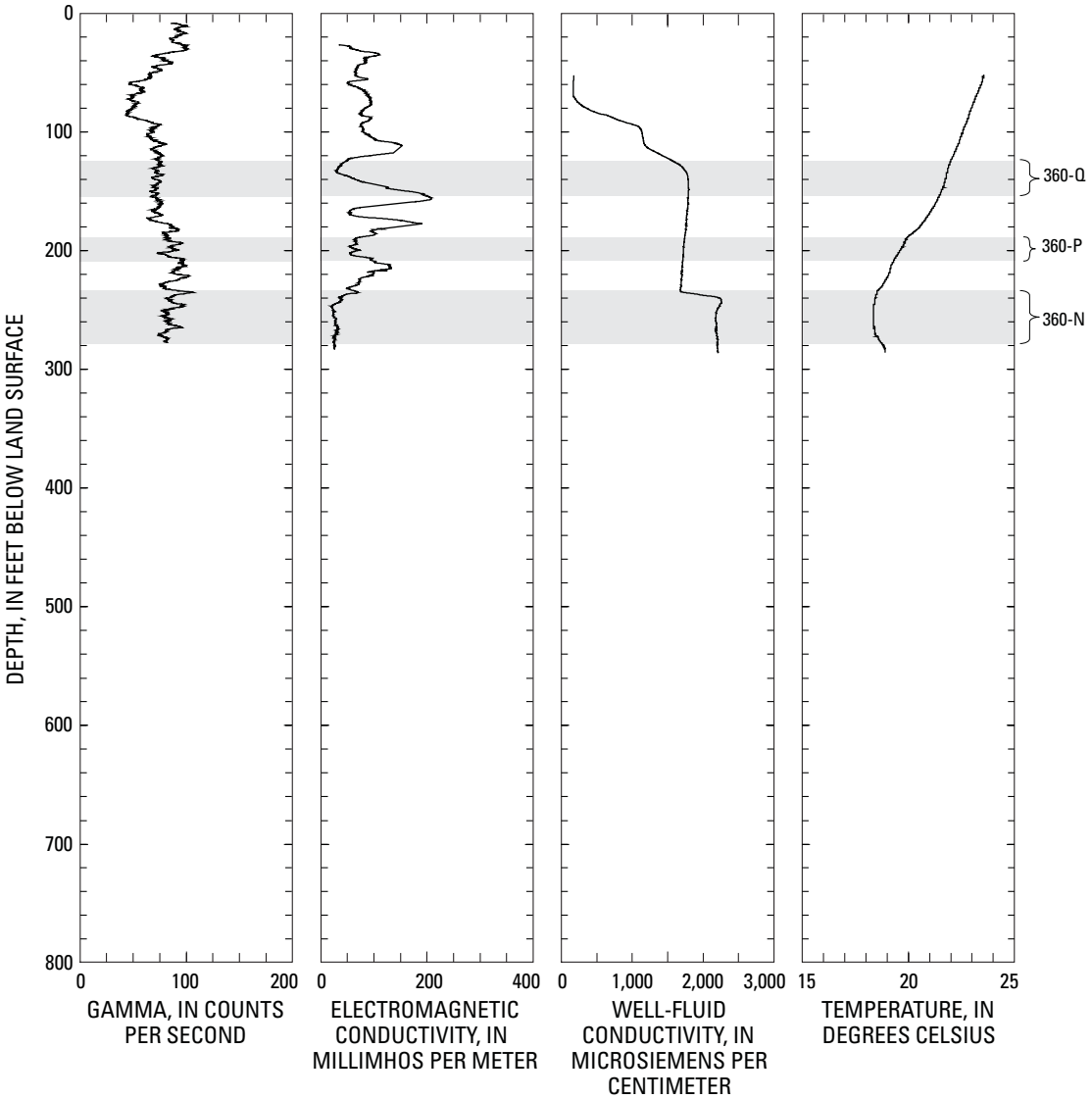

Figure C3. 360-N.

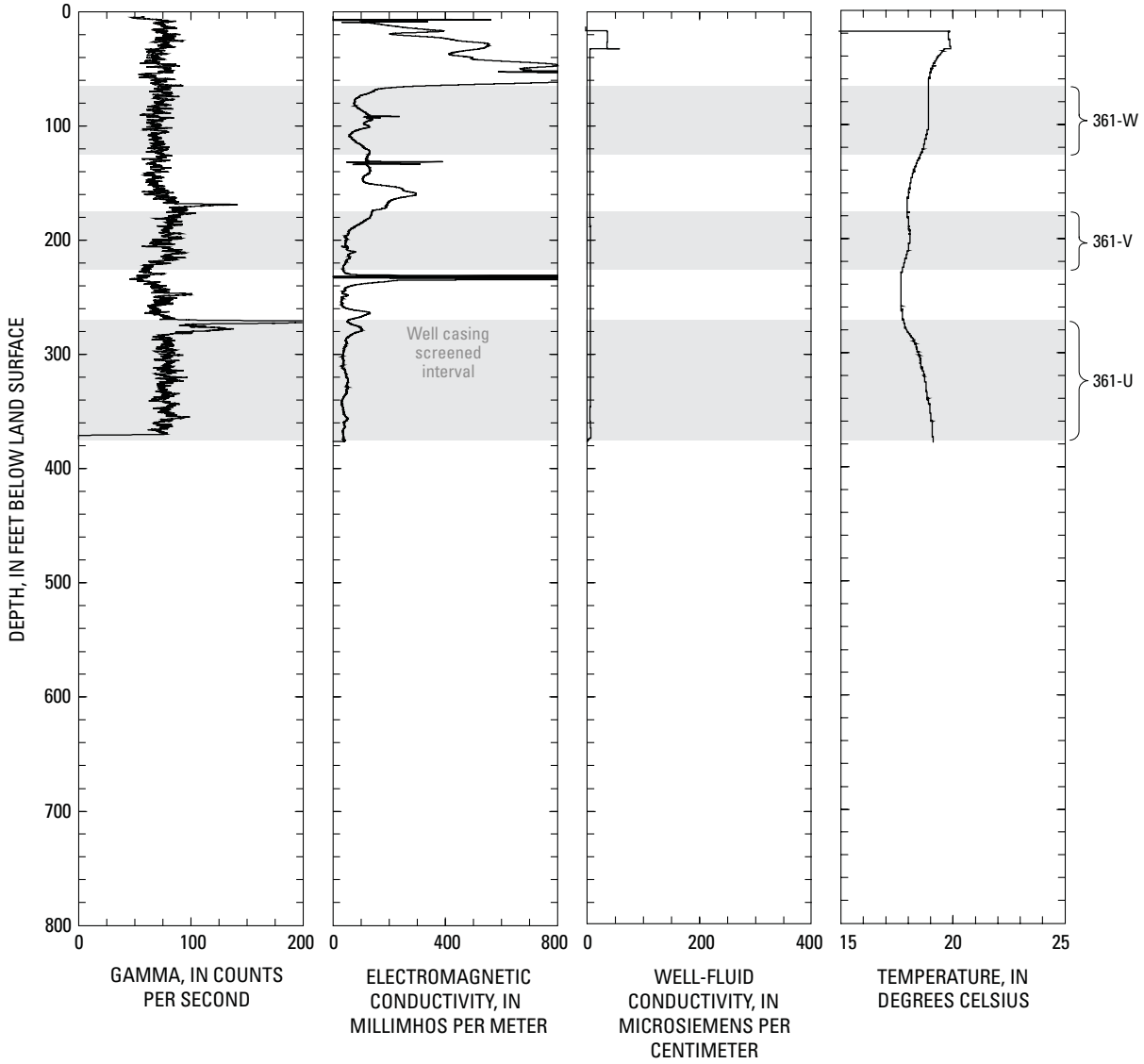

Figure C4. 361-U.

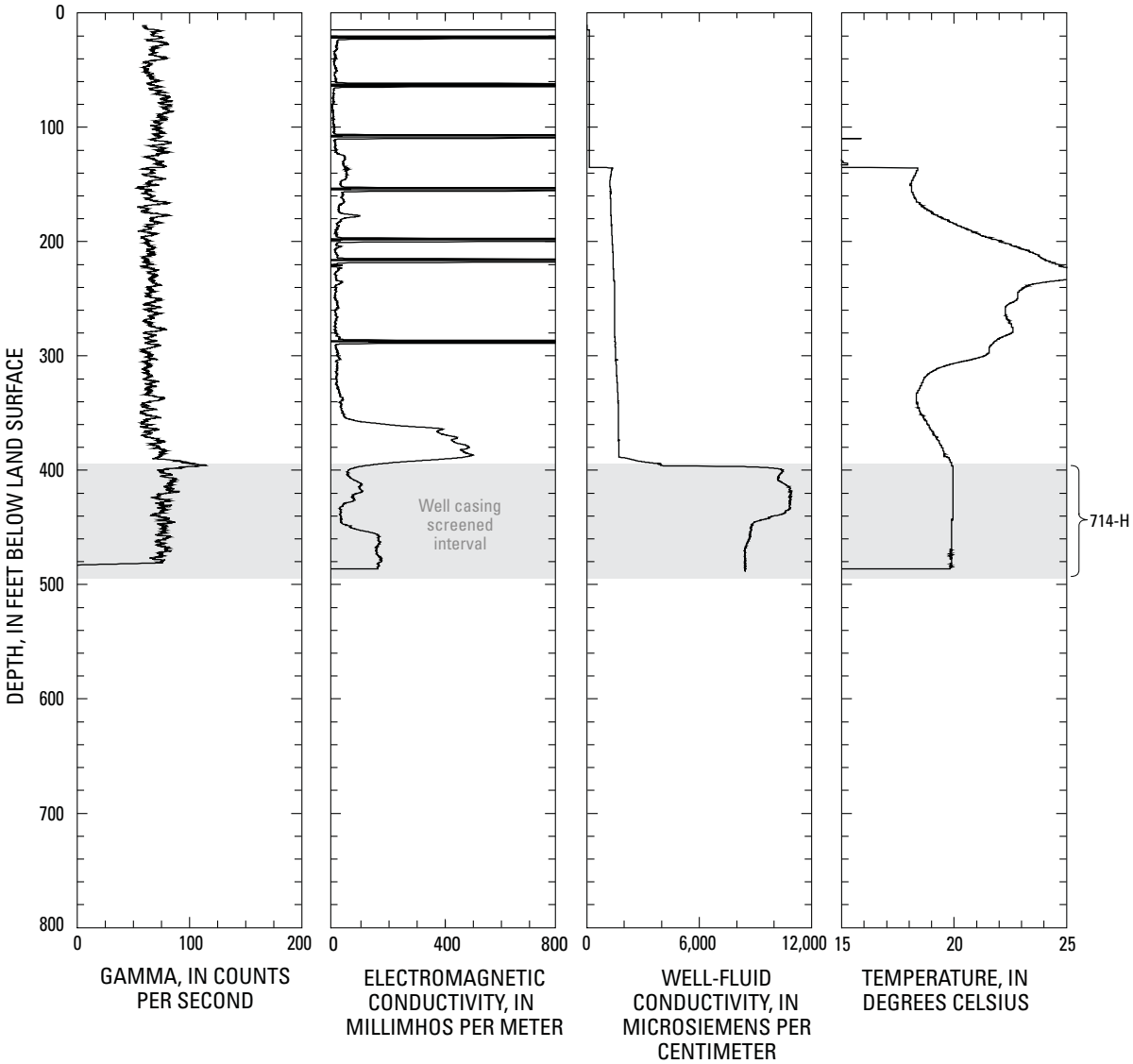

Figure C5. 714-H.

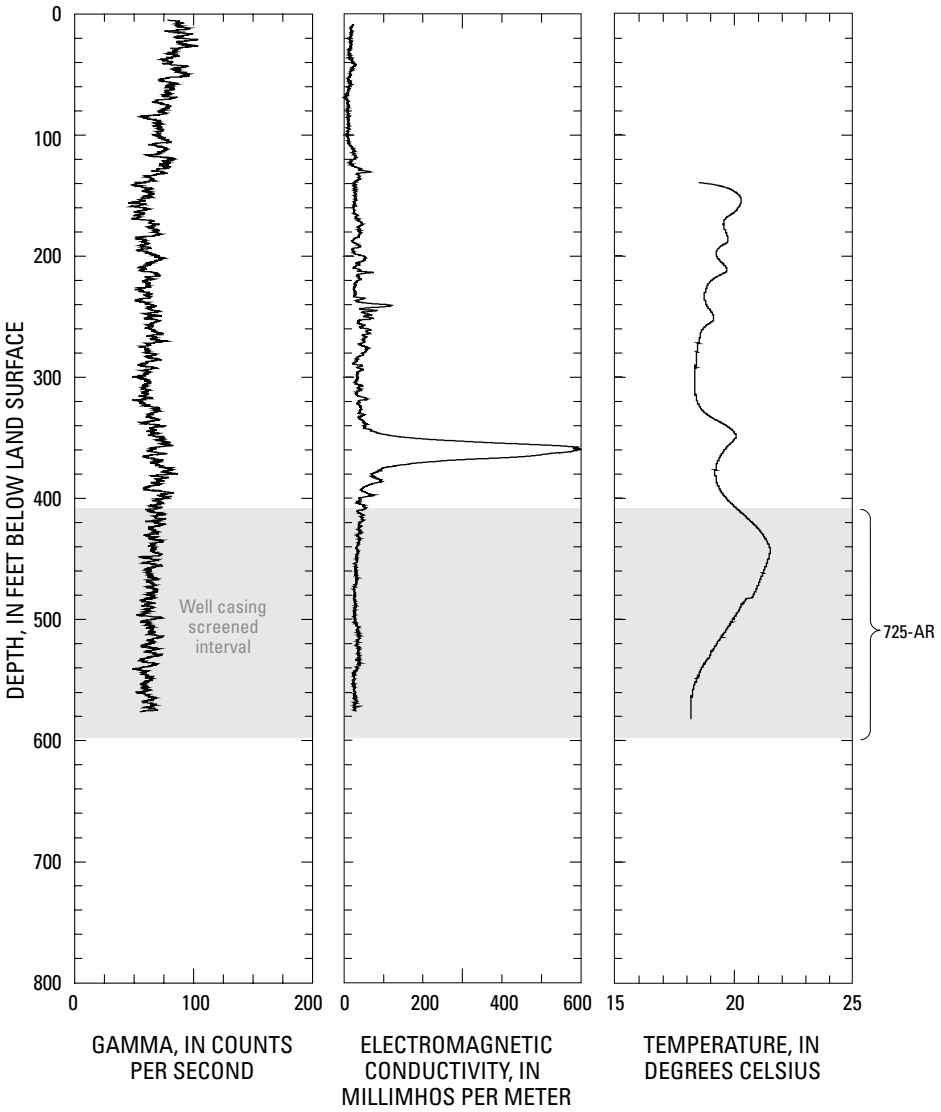

Figure C6. 725-AR.

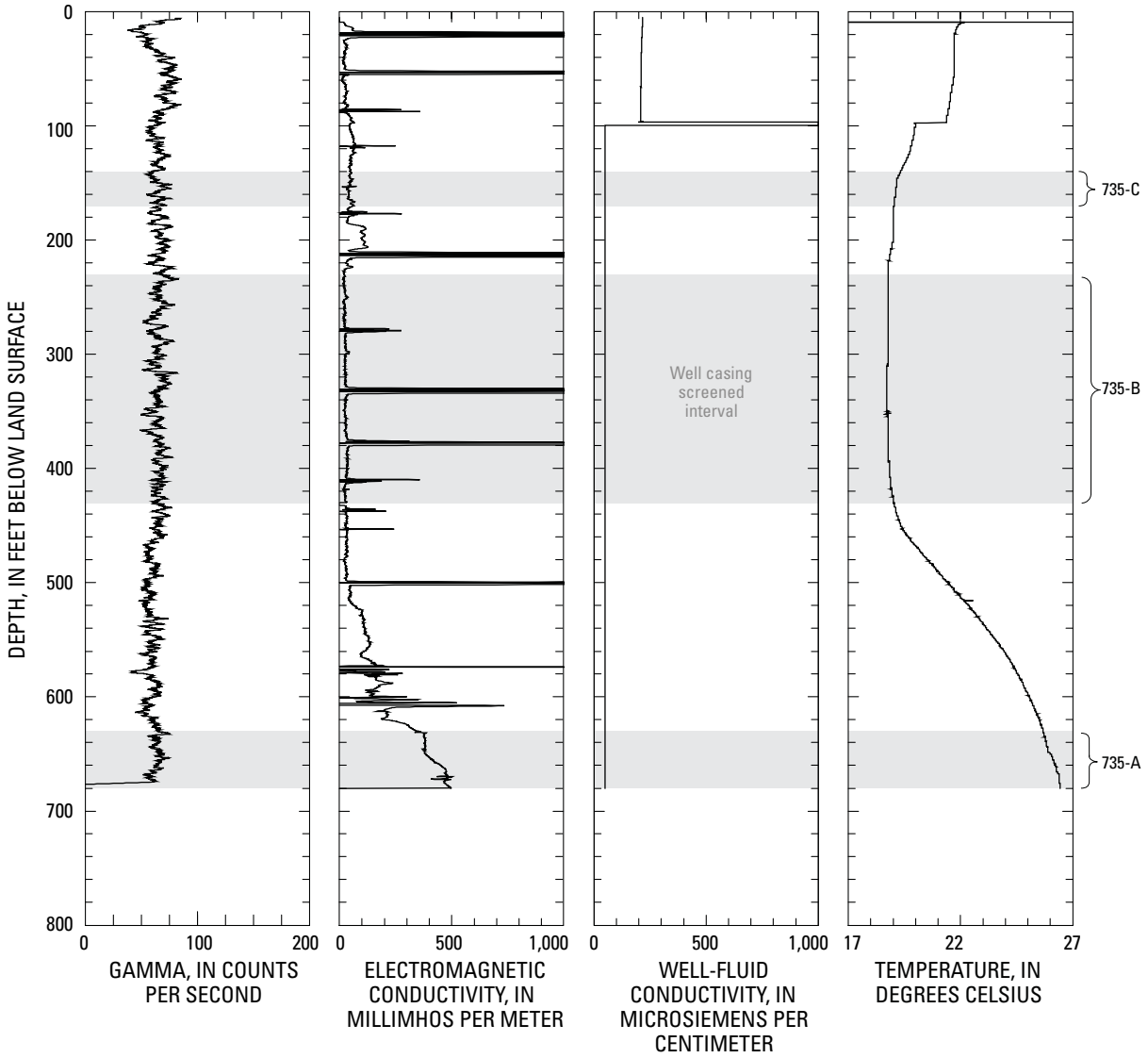

Figure C7. 735-A.

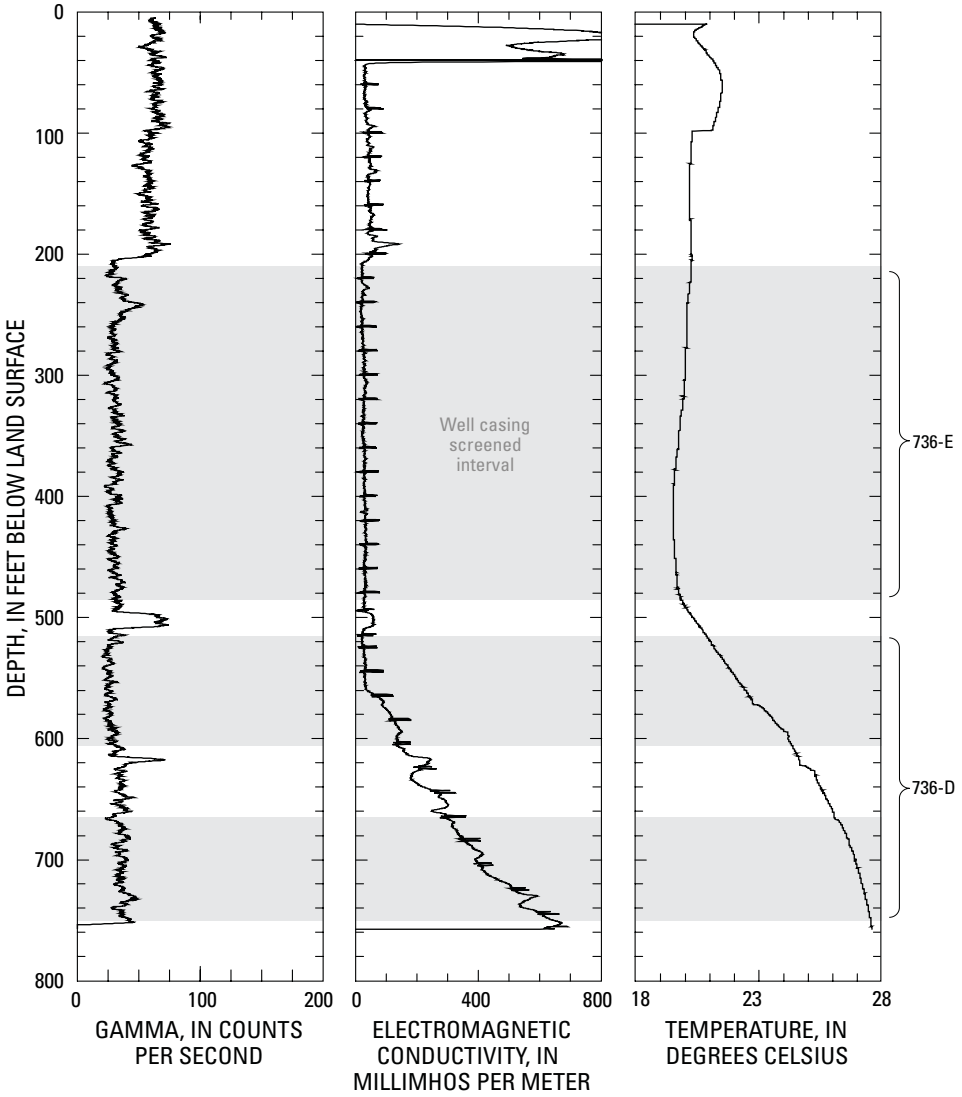

Figure C8. 736-D.

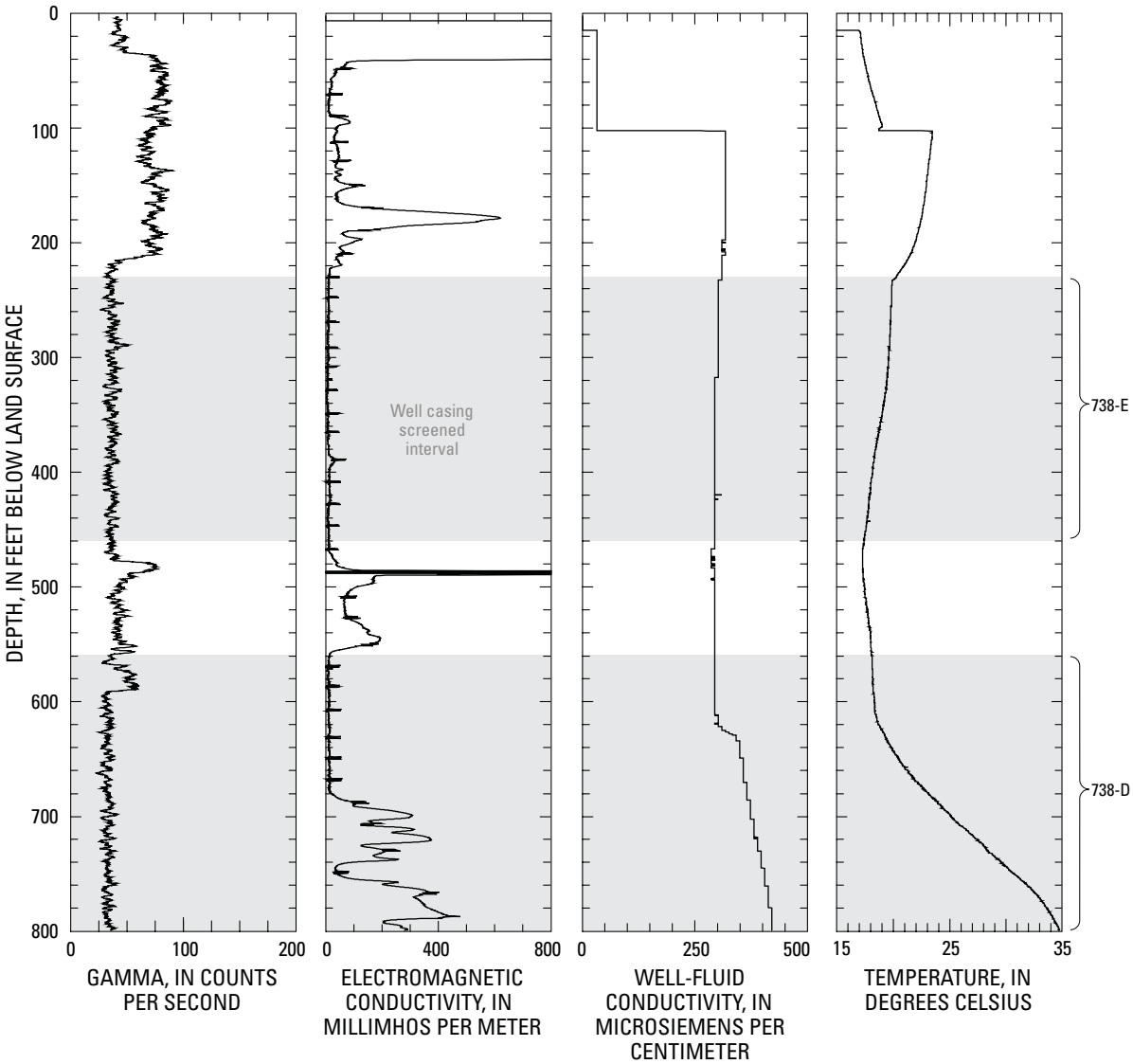

Figure C9. 738-D.

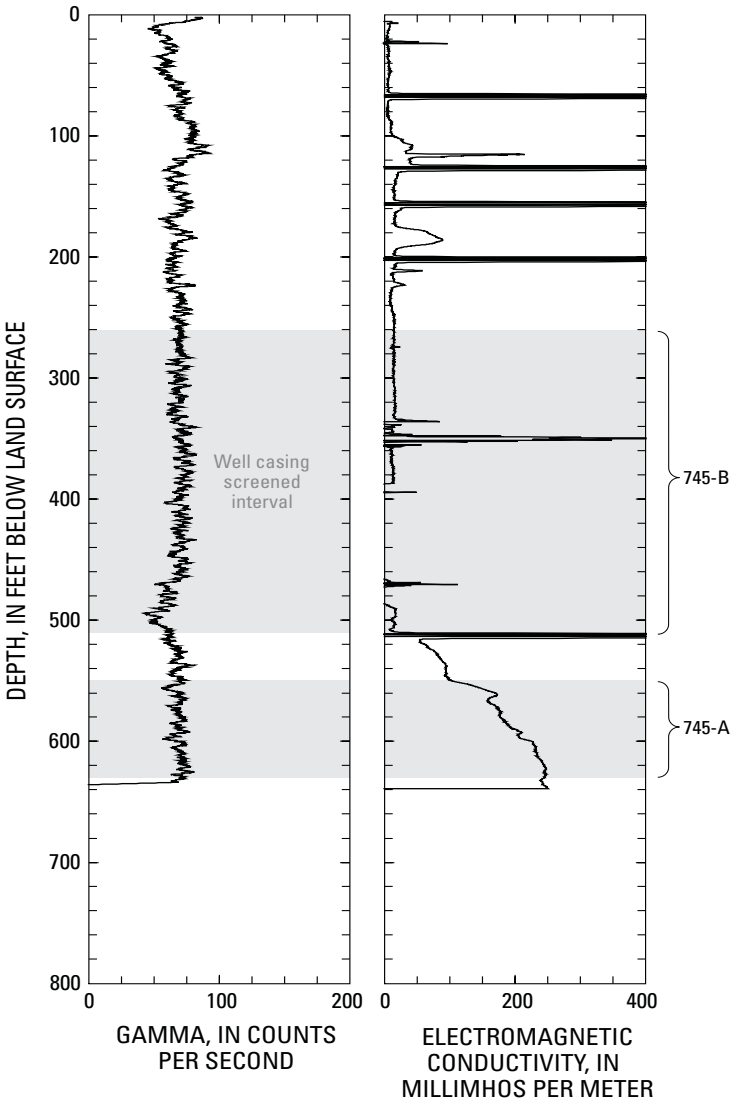

Figure C10. 745-A.

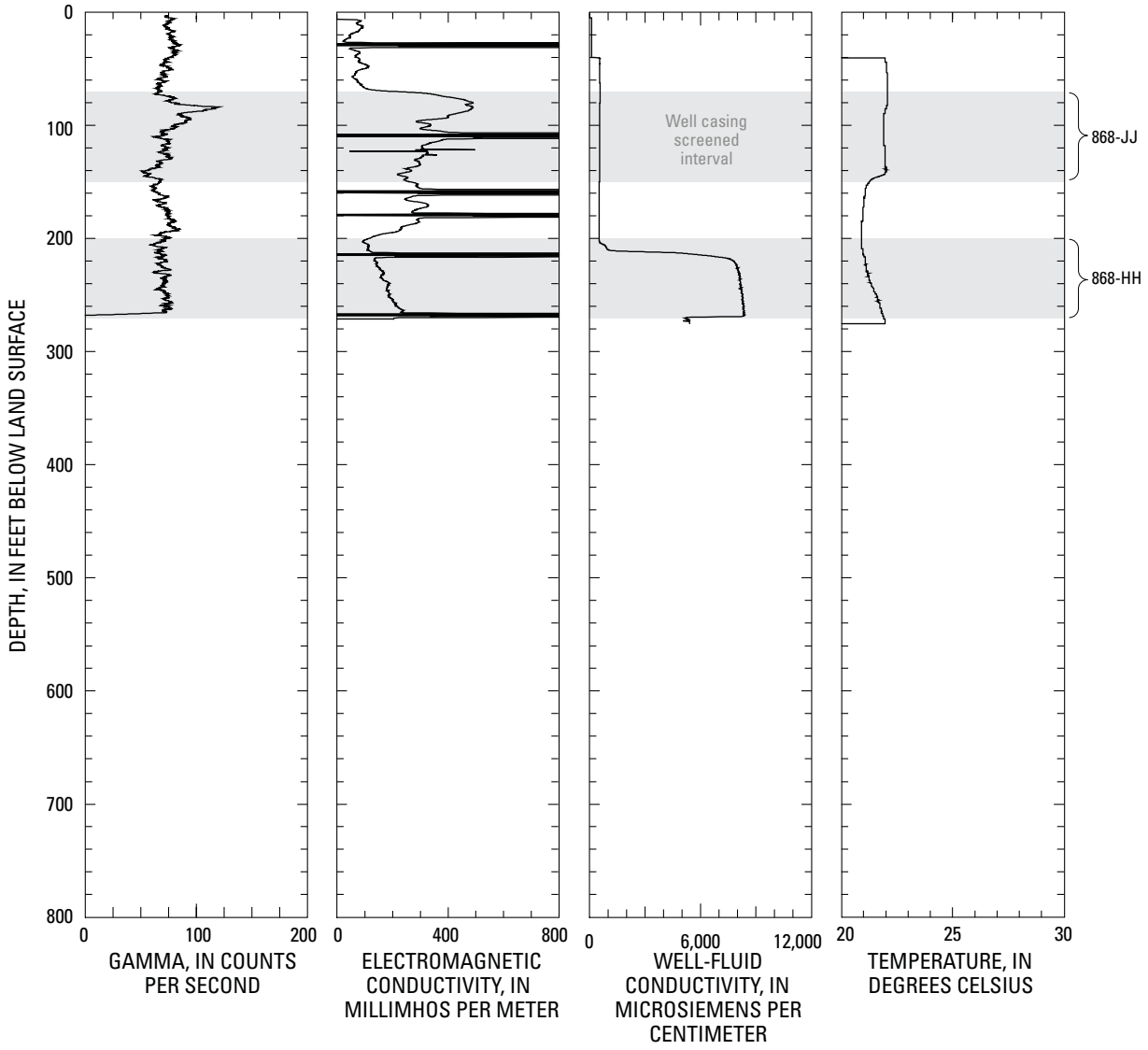

Figure C11. 868-HH.

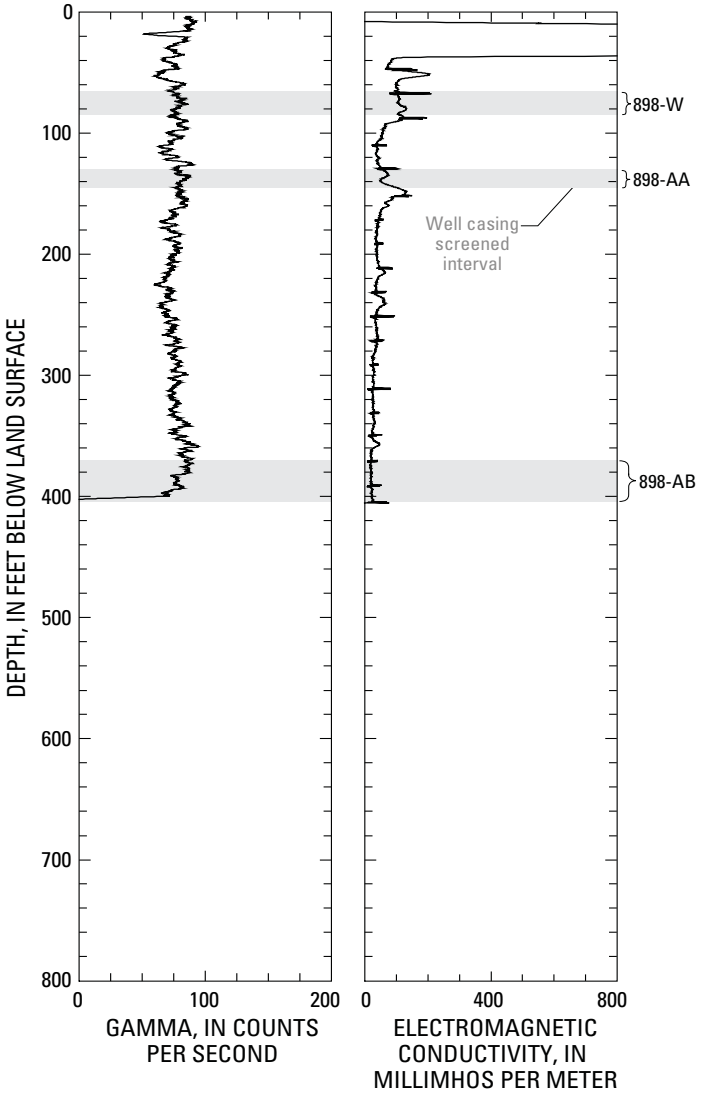

Figure C12. 898-AB.

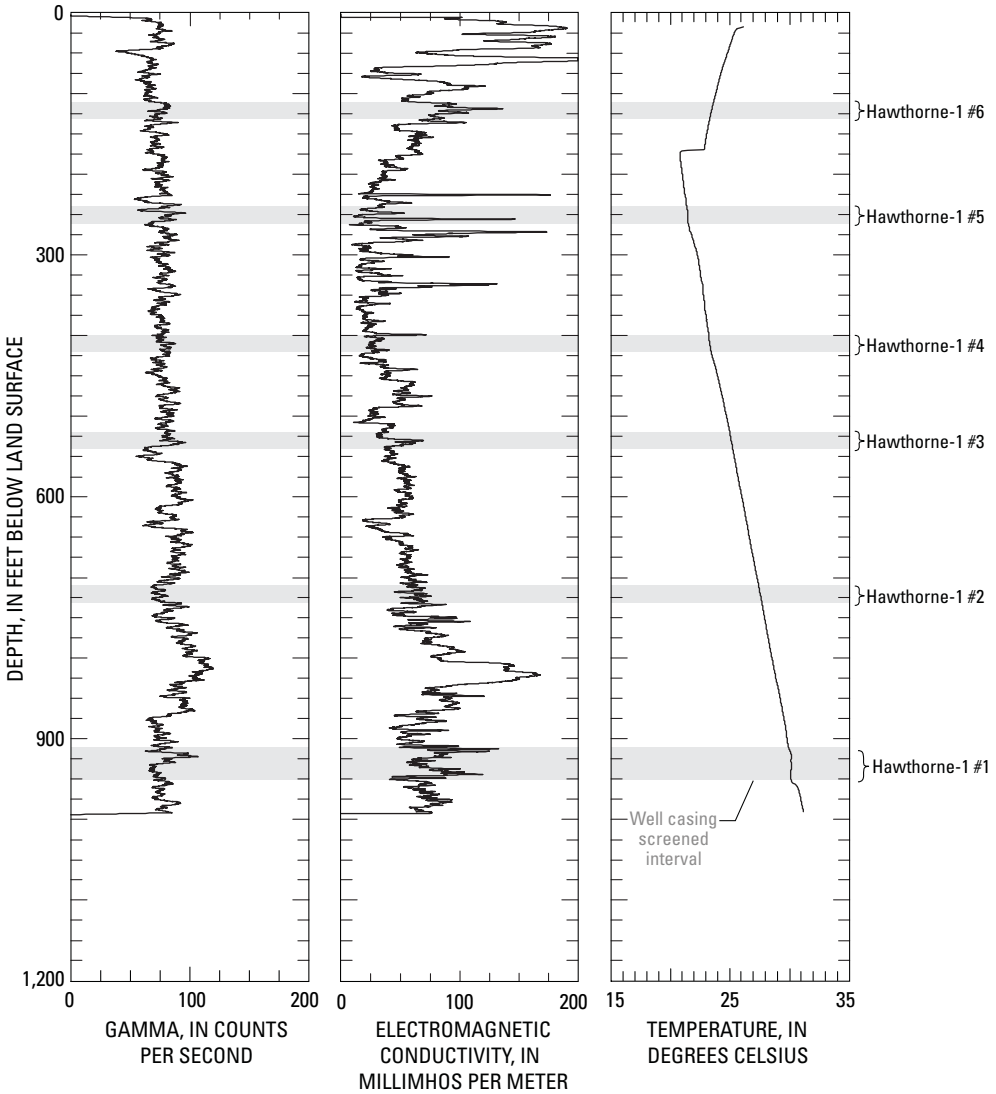

Figure C13. Hawthorne-1.

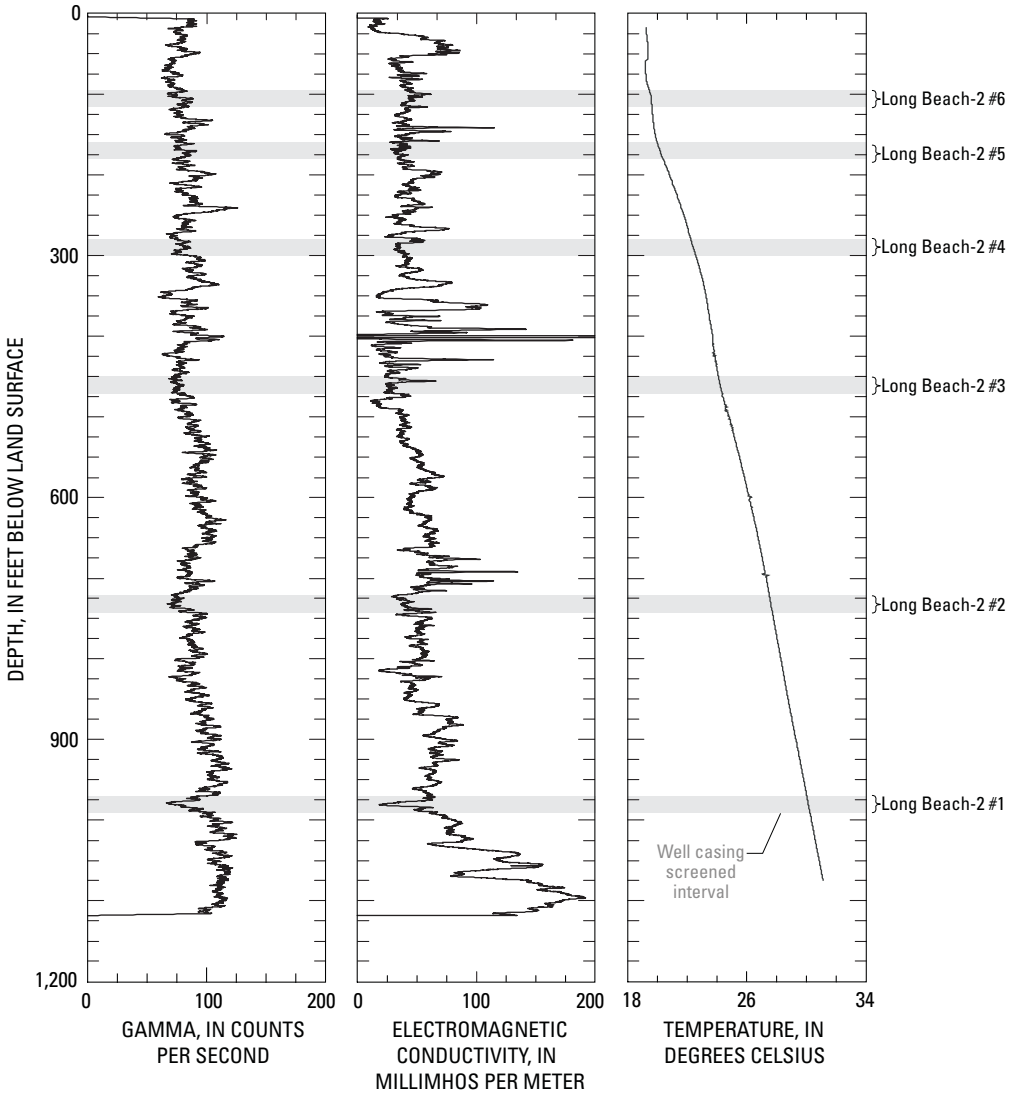

Figure C14. Long Beach-2.

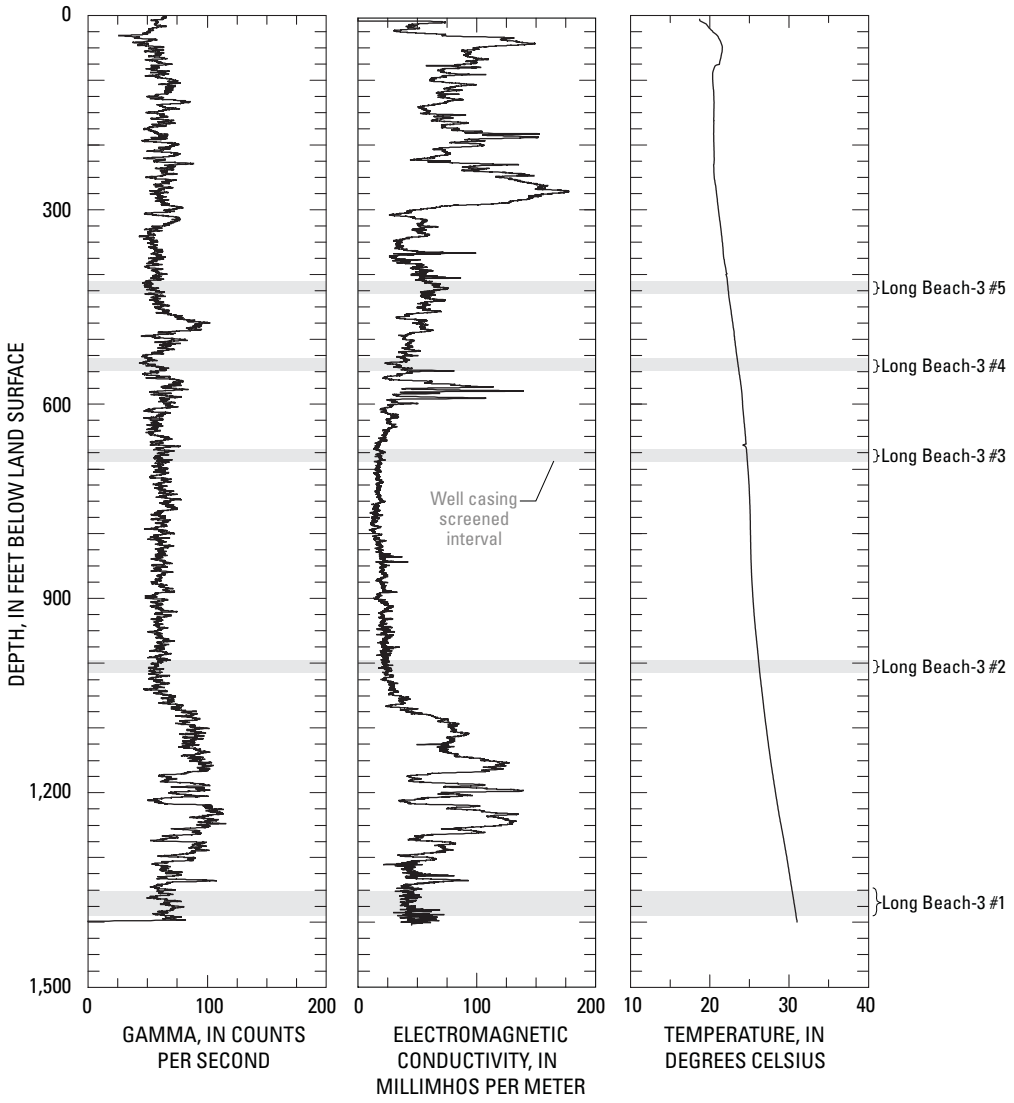

Figure C15. Long Beach-3.

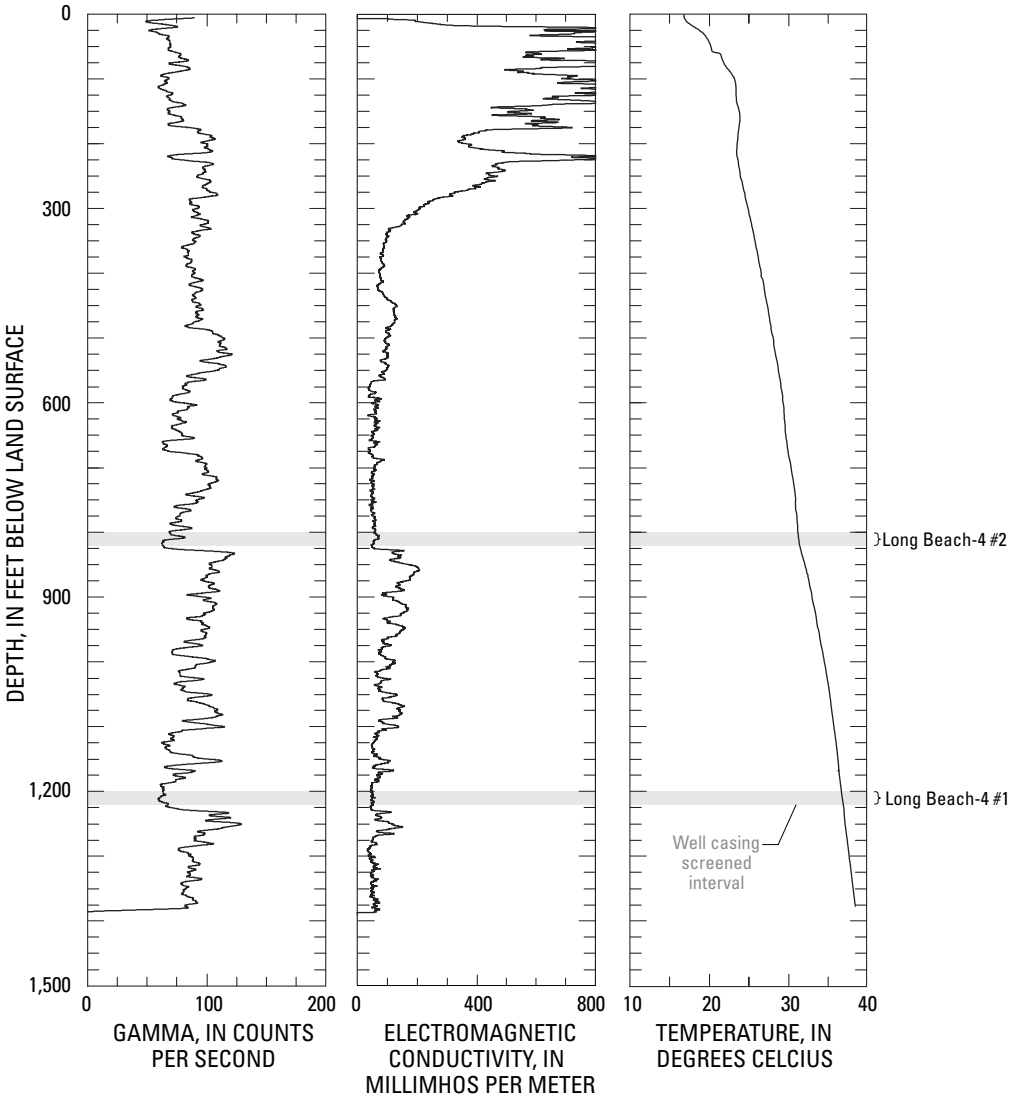

Figure C16. Long Beach-4.

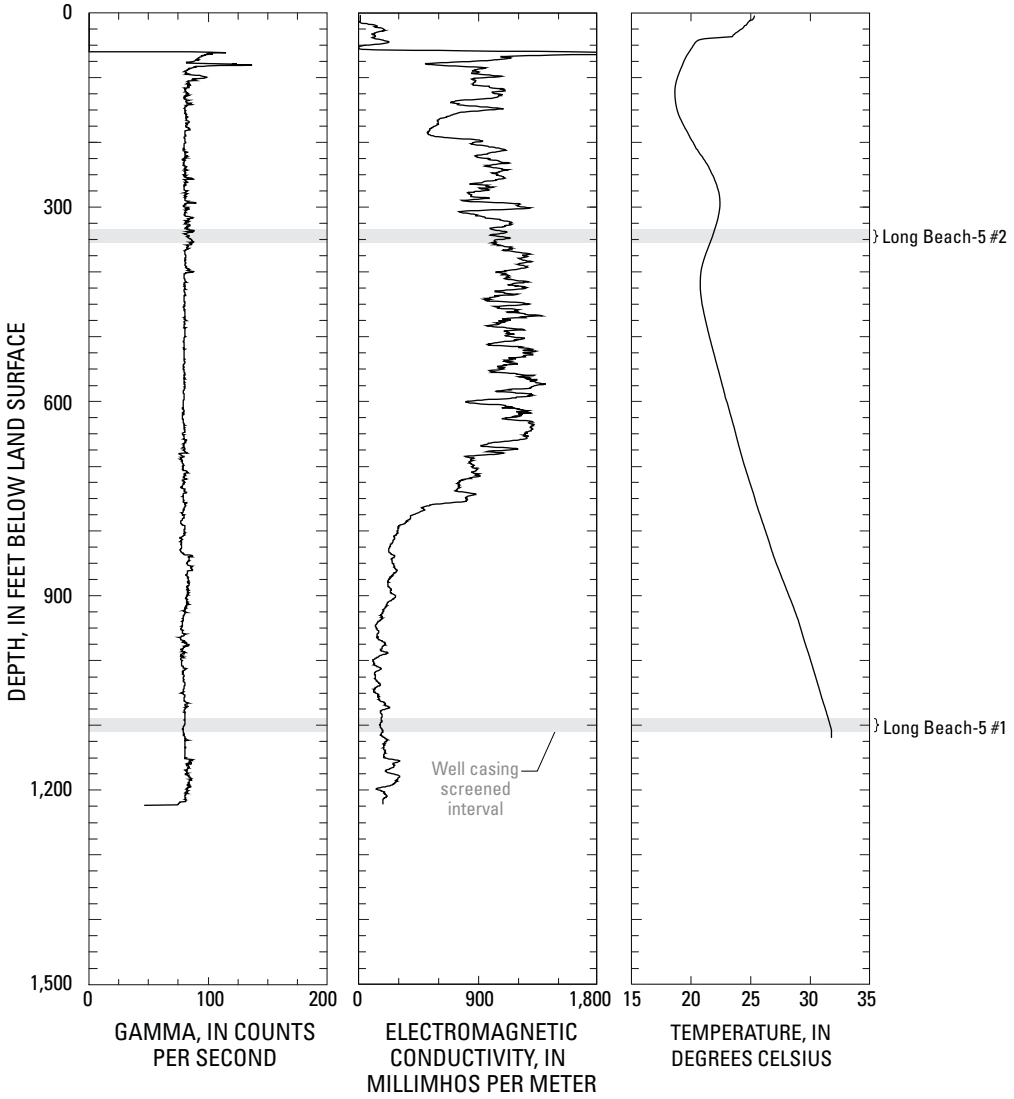

Figure C17. Long Beach-5.

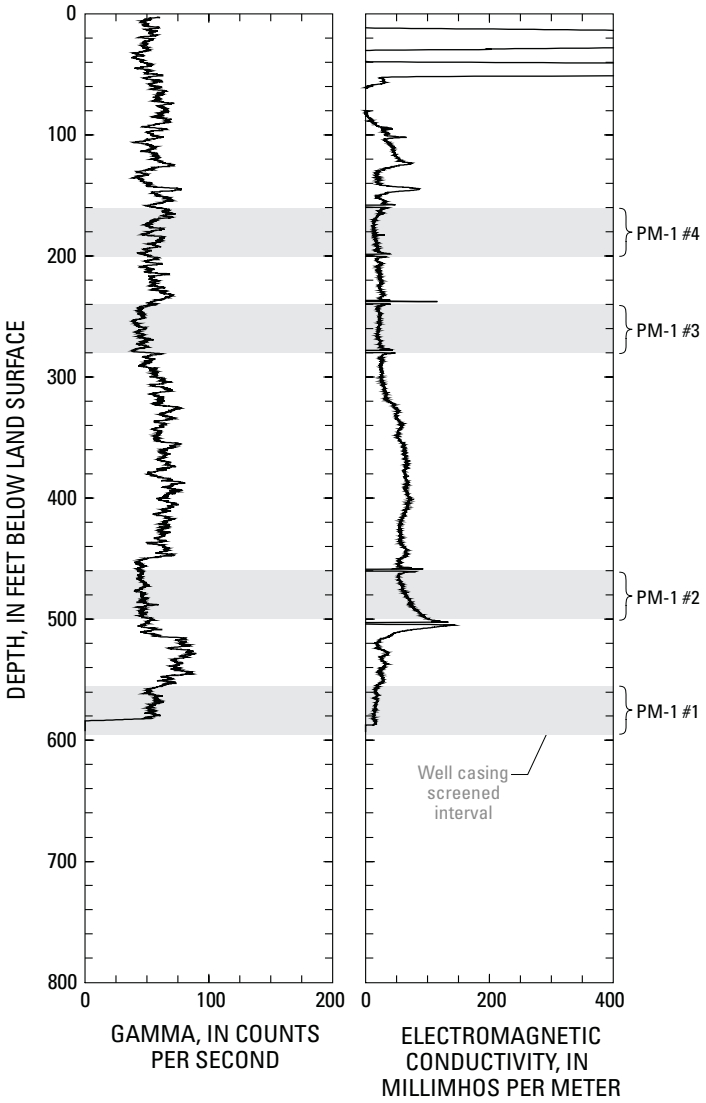

Figure C18. PM-1.

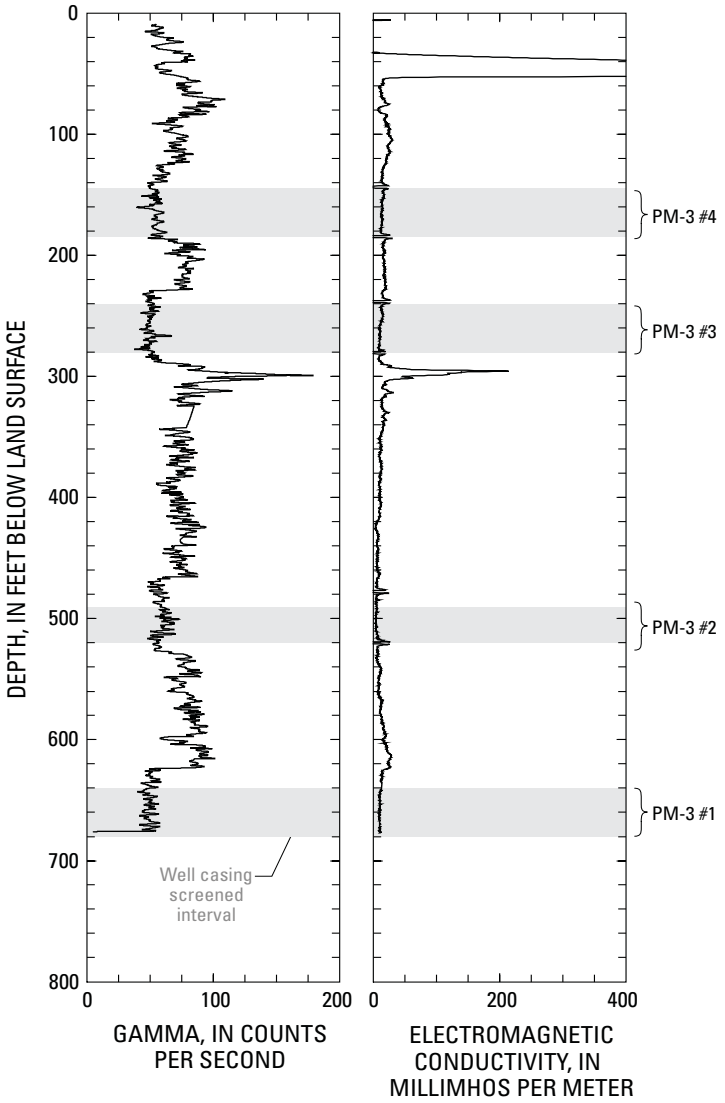

Figure C19. PM-3.

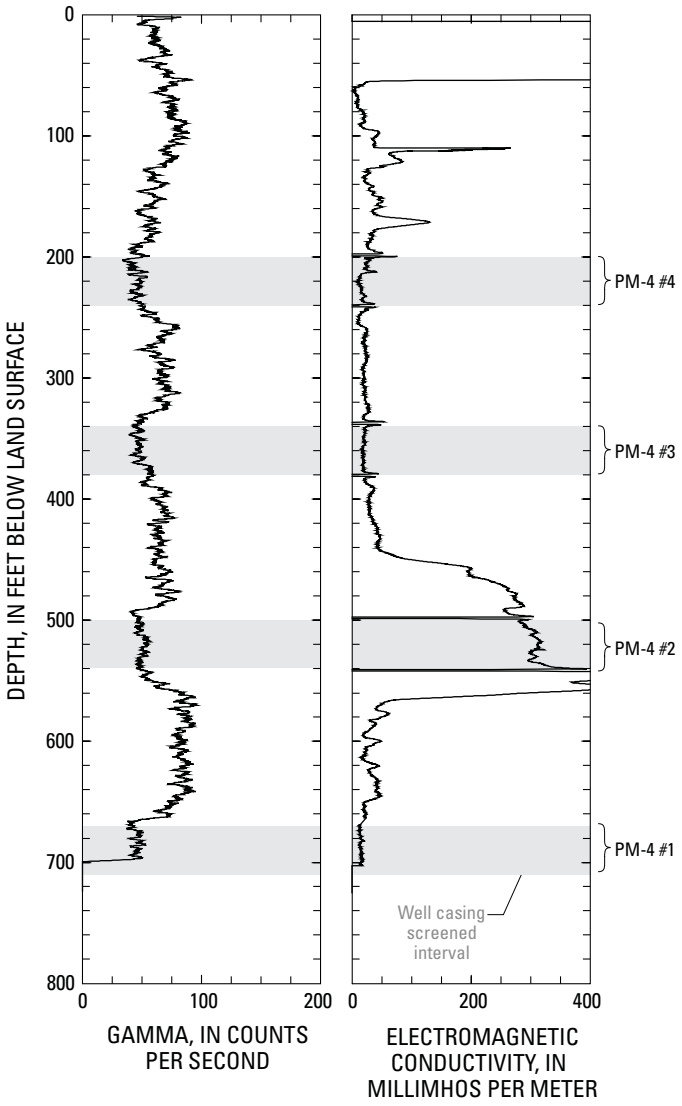

Figure C20. PM-4.

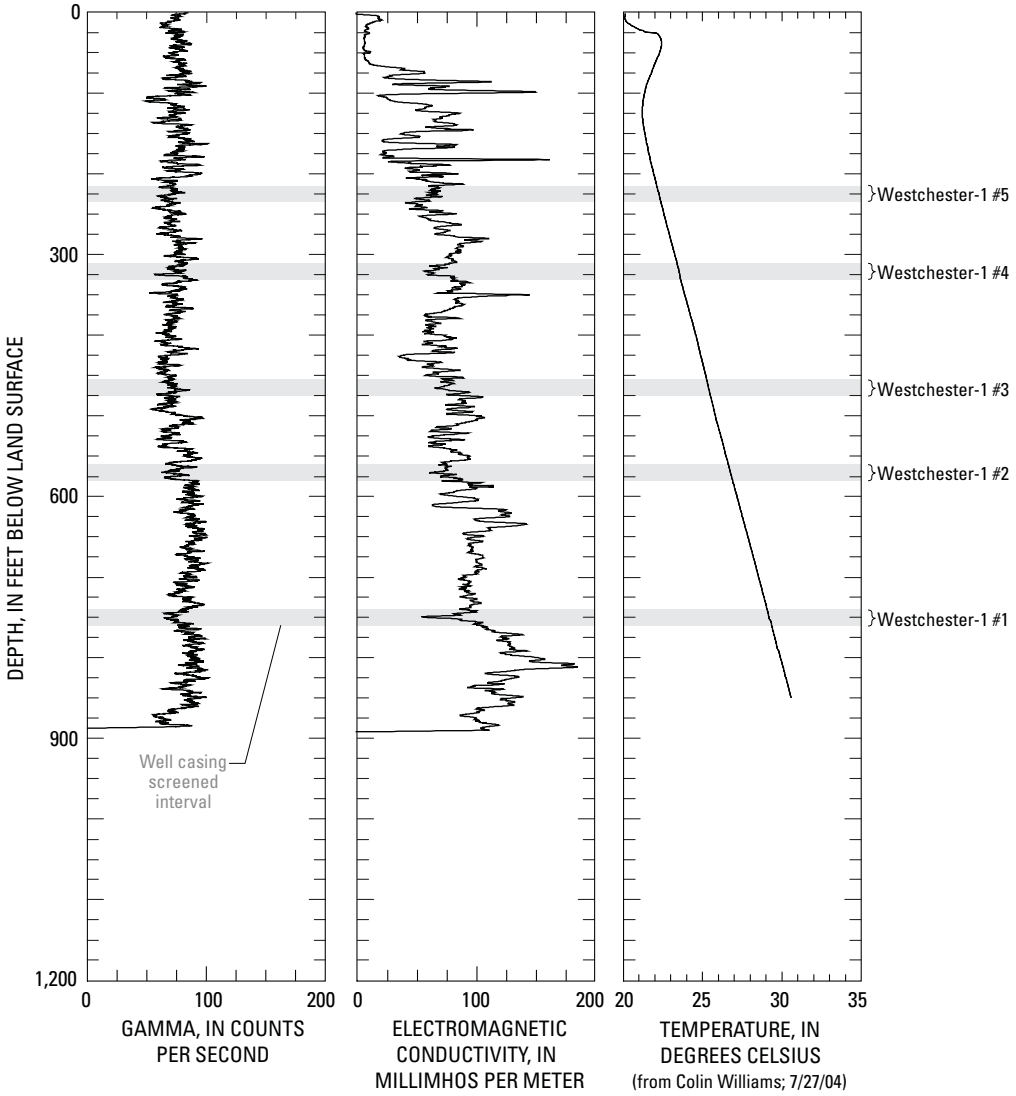

Figure C21. Westchester-1.

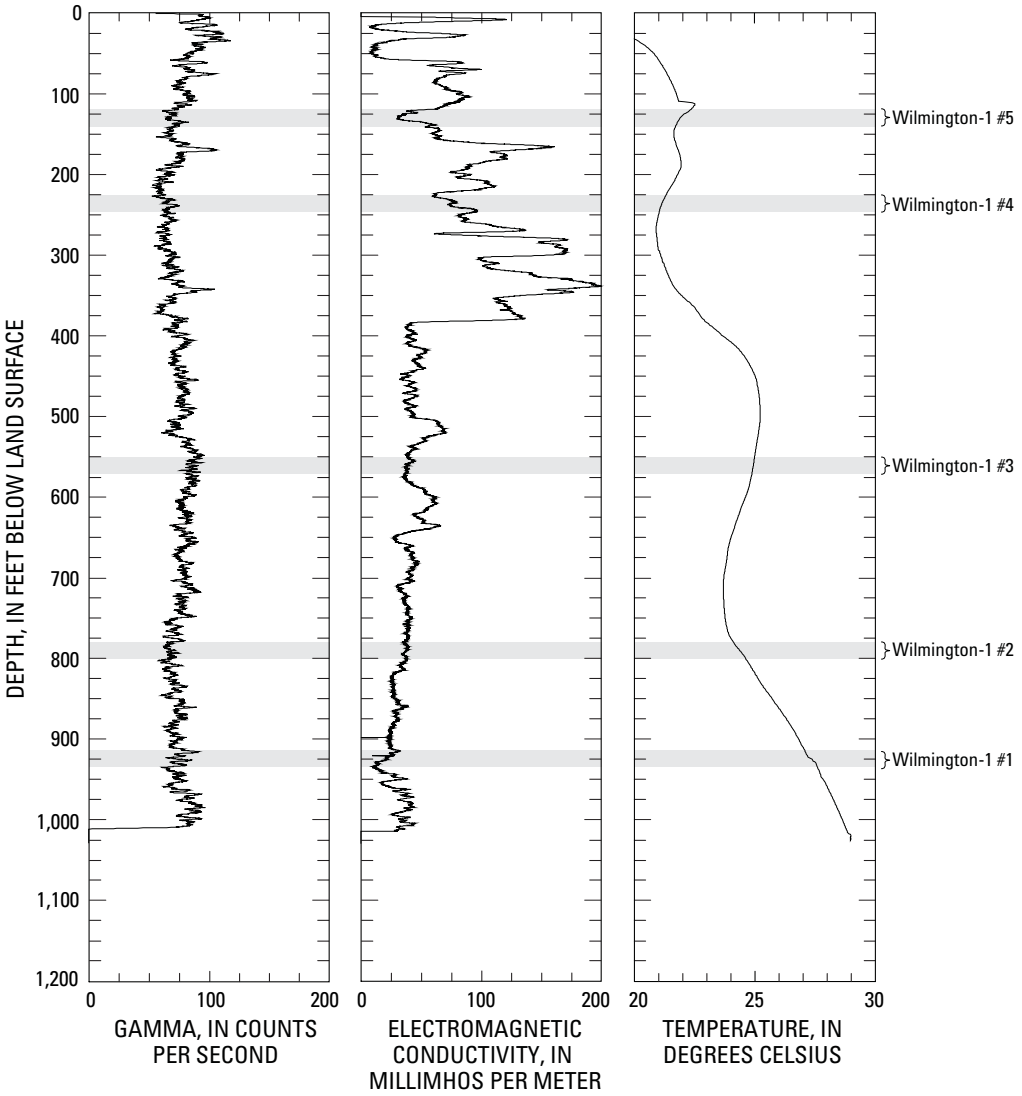

Figure C22. Wilmington-1.

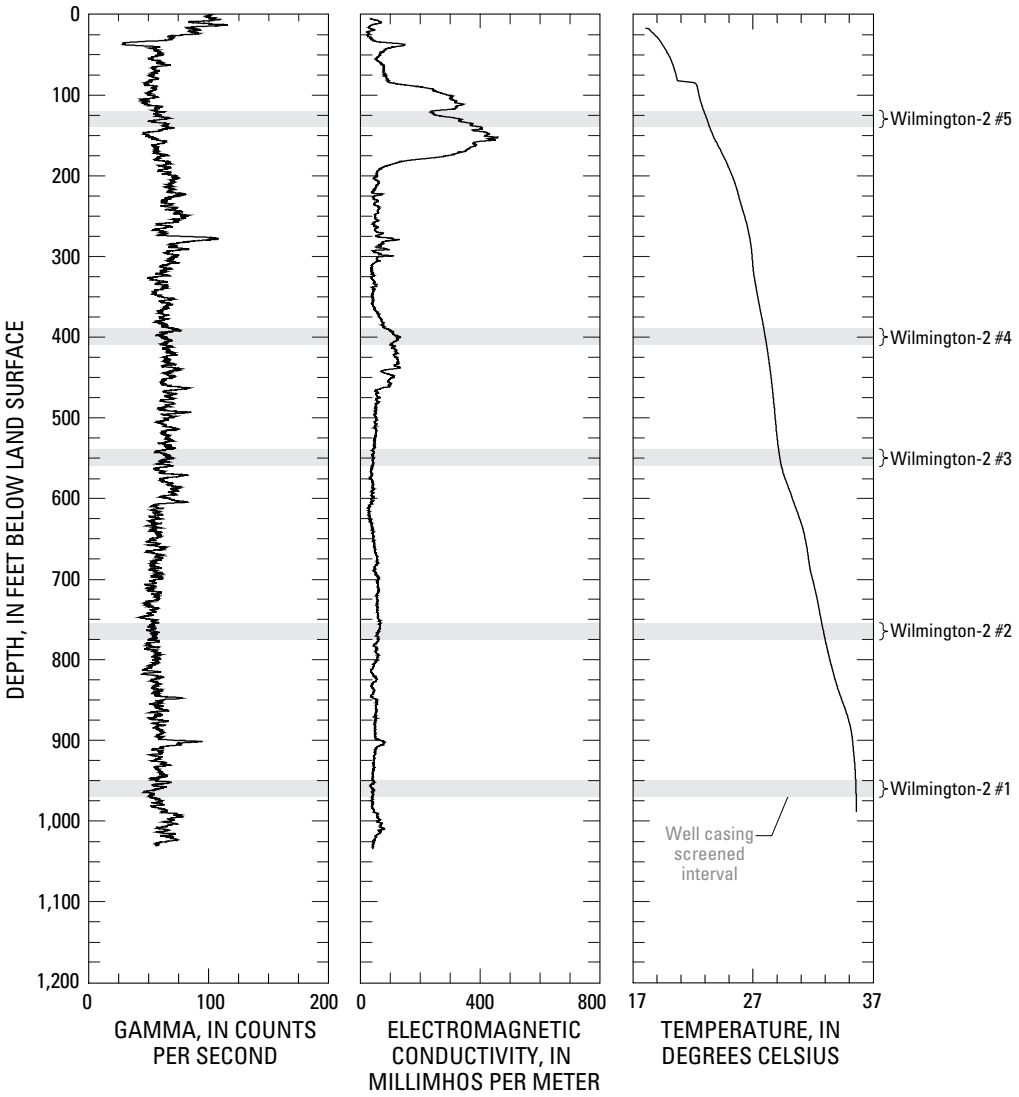

Figure C23. Wilmington-2.

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