

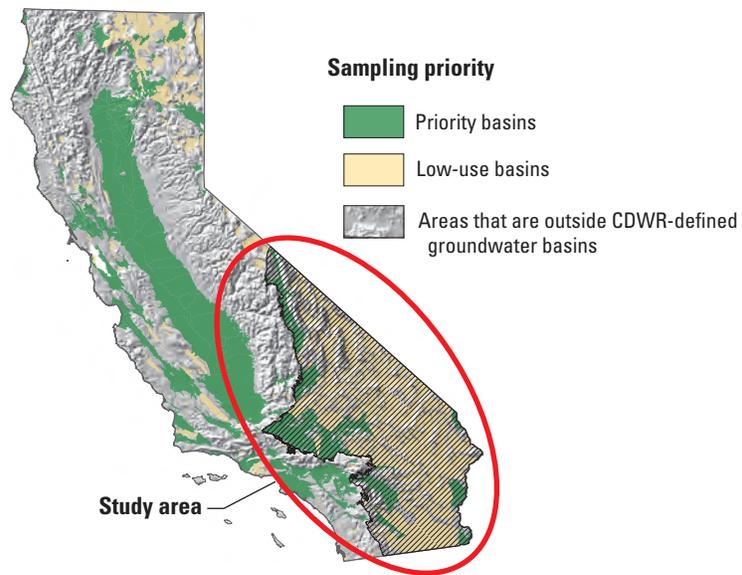
Prepared in cooperation with the California State Water Resources Control Board
A product of the California Groundwater Ambient Monitoring and Assessment (GAMA) Program

**Geochemical Conditions and the Occurrence of Selected Trace Elements
in Groundwater Basins Used for Public Drinking-Water Supply, Desert and
Basin and Range Hydrogeologic Provinces, 2006–11: California GAMA
Priority Basin Project**



Scientific Investigations Report 2014–5173

Front Cover Map: Groundwater basins categorized by sampling priority. Location of groundwater basin boundaries from California Department of Water Resources (CDWR, 2003).



Cover photographs:

Front cover: Sampling an observation well, Alabama Hills near Lone Pine, California, 2006. (Photograph by Michael Wright, U.S. Geological Survey.)

Back cover: Joshua Tree and public supply well, Yucca Valley, California. (Photograph by Dara Goldrath, U.S. Geological Survey.)

Geochemical Conditions and the Occurrence of Selected Trace Elements in Groundwater Basins Used for Public Drinking-Water Supply, Desert and Basin and Range Hydrogeologic Provinces, 2006–11: California GAMA Priority Basin Project

By Michael T. Wright, Miranda S. Fram, and Kenneth Belitz

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U.S. Geological Survey
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Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	2.590	square kilometer (km ²)
	Flow rate	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Conversion Factors and Datum—Continued

SI to Inch/Pound

Multiply	By	To obtain
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in ³)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)

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

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

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

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

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

Abbreviations and Acronyms

bls	below land surface
BP	before present
DBR	Desert and Basin and Range (hydrogeologic provinces and study unit)
GAMA	Groundwater Ambient Monitoring and Assessment Program (USGS)
HAL-US	U.S. Environmental Protection Agency lifetime health advisory level
I	ionic strength
MCL-CA	California Department of Public Health maximum contaminant level
MCL-US	U.S. Environmental Protection Agency maximum contaminant level
min	minute
NL-CA	California Department of Public Health notification level
PBP	Priority Basin Project (USGS GAMA)
pmc	percent modern carbon
SI	saturation indices
SM	speciation modeling
μm	micrometer
>	greater than
<	less than
≤	less than or equal to
≥	greater than or equal to

Organizations

CDPH	California Department of Public Health (Department of Health Services prior to July 1, 2007)
CDPR	California Department of Pesticide Regulation
CDWR	California Department of Water Resources
LLNL	Lawrence Livermore National Laboratory
NWQL	National Water Quality Laboratory (USGS)
SWRCB	State Water Resources Control Board (California)
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Selected chemical symbols or abbreviations

³ H	tritium
¹⁴ C	carbon-14
As	arsenic
B	boron
F	fluoride
Fe	iron
Mo	molybdenum
S	sulfur
Sr	strontium
U	uranium
V	vanadium
TDS	total dissolved solids

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By Michael T. Wright, Miranda S. Fram, and Kenneth Belitz

Abstract

The geochemical conditions, occurrence of selected trace elements, and processes controlling the occurrence of selected trace elements in groundwater were investigated in groundwater basins of the Desert and Basin and Range (DBR) hydrogeologic provinces in southeastern California as part of the Priority Basin Project (PBP) of the Groundwater Ambient Monitoring and Assessment (GAMA) Program. The GAMA PBP is designed to provide an assessment of the quality of untreated (raw) groundwater in the aquifer systems that are used for public drinking-water supply. The GAMA PBP is being conducted by the California State Water Resources Control Board in collaboration with the U.S. Geological Survey and the Lawrence Livermore National Laboratory.

The DBR hydrogeologic provinces consist of 141 defined groundwater basins separated by mountain ranges, faults, and other features. This report presents analyses of data collected from nine study areas within the DBR hydrogeologic provinces: Antelope Valley, Borrego Valley, the Central Desert area, Coachella Valley, Colorado River, Indian Wells Valley, Low-Use Basins of the Mojave and Sonoran Deserts, the Mojave, and Owens Valley. Collectively, these nine study areas are referred to as the DBR study unit. The study unit covers approximately 7,000 square miles and includes the 63 groundwater basins in the DBR hydrogeologic provinces in which groundwater is used for public drinking-water supply. The vast majority of the 223 wells sampled for this study were long-screened production wells used primarily for public supply.

Uncorrected carbon-14 (^{14}C) groundwater ages for samples collected in the DBR study unit ranged from less than ($<$) 100 to 33,700 years before present (BP). Sixty-six percent of sample ages were greater than ($>$) 100 years BP, and 40 percent were $>3,800$ years BP. Samples collected from wells located adjacent to mountain-front recharge areas or major surface-water features generally had younger groundwater

ages than did samples collected from wells located away from mountain fronts or towards the distal ends of basin groundwater flow paths. Most groundwater sampled in the DBR study unit had alkaline pH: 89 percent of sample pH values ranged from 7.1 to 9.8, with 37 percent greater than or equal to (\geq) 7.9. Groundwater age was significantly correlated (positively) with pH, likely because silicate weathering is a primary control on groundwater pH and is a slow process. The oxidation-reduction (redox) condition of the groundwater sampled in the DBR study unit was predominantly oxic (71 percent), except in the Colorado River study area where organic-rich fluvial aquifers provide the electron donors necessary to support iron-reducing (anoxic-Fe) redox processes. The cation type of 78 percent of the samples was either sodium- or mixed-type, and the anion type of 83 percent of the samples was either bicarbonate- or mixed-type. Sodium-type groundwaters generally were older and more alkaline than calcium-type groundwaters, consistent with the change in water chemistry expected from cation exchange between groundwater and aquifer sediments over long periods of time. Because of the correlation with young groundwater, calcium-type groundwater was predominantly from wells located adjacent to mountain-front recharge areas.

Arsenic (As), boron (B), fluoride (F), molybdenum (Mo), strontium (Sr), uranium (U), and vanadium (V) were selected for assessment in this study because they occurred at concentrations greater than California Department of Public Health or U.S. Environmental Protection Agency regulatory or non-regulatory drinking-water-quality benchmarks in more than 2 percent of the 223 samples collected in the DBR study unit. As and F were detected most commonly (18 and 13 percent, respectively) at concentrations above associated water-quality benchmarks and Sr and V least frequently (both at 3 percent). Given that ^{14}C groundwater ages are predominantly >100 years BP, land use in the study unit is primarily undeveloped, and chemicals derived from anthropogenic sources, such as volatile organic compounds,

were infrequently detected, high concentrations of these trace elements in groundwater were most likely the result of natural factors and not anthropogenic factors.

As, F, Mo, and V concentrations showed significant positive correlations to groundwater age and to pH. This relation is partly due to the sources of trace elements likely being the weathering of primary minerals, such as silicate minerals, which is a slow process that takes place over hundreds to thousands of years. This relation also reflects the positive correlation between groundwater age and pH. Geochemical modeling predicted that the dominant species of As, Mo, and V in solution were oxyanions (HAsO_4^{2-} , MoO_4^{2-} , and H_2VO_4^+), which are likely to be mobile in alkaline groundwater because mineral surfaces composing aquifer matrices have a predominantly negative surface charge under alkaline conditions. F also exists predominantly as a negatively charged ion (F^-). At pH values >7.5 , saturation indices generated by the geochemical modeling program PHREEQC indicated that F solubility may be somewhat limited by the precipitation of the mineral fluorapatite [$\text{Ca}_5(\text{PO}_4)_3\text{F}$]. Speciation modeling of As in anoxic-Fe groundwater (iron-reducing conditions) showed that samples were supersaturated with orpiment (As_2S_3), indicating that mineral precipitation may be responsible for low As concentrations observed in reducing groundwater.

In contrast, U concentrations showed significant negative correlations to groundwater age and to pH. Higher U concentrations generally occurred in samples for which geochemical modeling indicated that the uncharged ternary complex $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ was the dominant aqueous U species. This uncharged complex is not attracted to the charged surfaces of minerals and thus increases U solubility. Formation of $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ was greater in younger groundwaters because calcium and uranium concentrations generally were lower in older groundwaters, likely due to cation-exchange processes and precipitation of the mineral calcite as groundwater pH increased. Co-precipitation of U with the calcite (CaCO_3) may remove U from the aqueous phase. Saturation indices indicated that the anoxic-Fe groundwaters from the Colorado River study area were supersaturated with the mineral uraninite (UO_2), suggesting that UO_2 precipitation may be responsible for the low concentrations of U observed in these samples.

Concentrations of strontium, which exists primarily in a cationic form (Sr^{2+}), were not significantly correlated with either groundwater age or pH. Strontium concentrations showed a strong positive correlation with total dissolved solids (TDS). Dissolved constituents, such as Sr, that interact with mineral surfaces through outer-sphere complexation become increasingly soluble with increasing TDS concentrations of groundwater. Boron concentrations also showed a significant positive correlation with TDS, indicating the B may interact to a large degree with mineral surfaces through outer-sphere complexation.

Introduction

To assess the quality of ambient groundwater in aquifers used for drinking-water supply, and to establish a baseline groundwater-quality monitoring program, the California State Water Resources Control Board (SWRCB), in collaboration with the U.S. Geological Survey (USGS) and Lawrence Livermore National Laboratory (LLNL), implemented the Groundwater Ambient Monitoring and Assessment (GAMA) Program (California State Water Resources Control Board, 2003, website at <http://www.waterboards.ca.gov/gama/>). The statewide GAMA Program currently consists of four projects: the (1) GAMA Priority Basin Project (PBP), conducted by the USGS (U.S. Geological Survey, 2013, website at <http://ca.water.usgs.gov/gama/>); (2) the GAMA Domestic Well Project, conducted by the SWRCB; (3) the GAMA Special Studies, conducted by LLNL; and (4) the GeoTracker GAMA publicly available database, maintained by the SWRCB.

The SWRCB initiated the GAMA Program in 2000 in response to Legislative mandates (State of California, 1999, 2001a, Supplemental Report of the 1999 Budget Act 1999–00 Fiscal Year). The GAMA PBP was initiated in response to the Groundwater Quality Monitoring Act of 2001 (State of California, 2001b, Sections 10780–10782.3 of the California Water Code, Assembly Bill 599) to assess and monitor the quality of groundwater in California. The GAMA PBP is a comprehensive assessment of statewide groundwater quality, designed to help better understand and identify risks to groundwater resources and to increase the availability of information about groundwater quality to the public. For the PBP, the USGS, in collaboration with the SWRCB, developed a monitoring plan to assess groundwater basins through direct sampling of groundwater and other statistically reliable sampling approaches (Belitz and others, 2003; California State Water Resources Control Board, 2003). Additional partners in the GAMA PBP include the California Department of Public Health (CDPH), the California Department of Pesticide Regulation (CDPR), the California Department of Water Resources (CDWR), and local water agencies and well owners (Kulongoski and Belitz, 2004). Note that as of July 1, 2014, the Drinking Water Program administrated by the CDPH was transferred to the SWRCB.

The range of hydrologic, geologic, and climatic conditions that exist in California were considered in this statewide assessment of groundwater quality. Belitz and others (2003) partitioned the State into 10 hydrogeologic provinces, each with distinctive hydrologic, geologic, and climatic characteristics. These hydrogeologic provinces include groundwater basins and subbasins designated by the CDWR (California Department of Water Resources, 2003). Groundwater basins and subbasins throughout California generally consist of relatively permeable, unconsolidated

deposits of alluvial origin. Groundwater basins were prioritized for sampling on the basis of the number of public-supply wells, with secondary consideration given to municipal groundwater use, agricultural pumping, the number of historically leaking underground fuel tanks, and registered pesticide applications (Belitz and others, 2003). Of the 472 CDWR-designated basins, 116 contain approximately 95 percent of the public-supply wells in basins and were defined as priority basins. These 116 priority basins, a subset of the remaining low-use basins, and additional areas outside defined groundwater basins were grouped into 35 study units. The 6 study units located within the boundaries of the Desert and the Basin and Range (DBR) hydrogeologic provinces include 15 priority basins and 37 low-use basins and collectively form the Desert and Basin and Range (DBR) study unit.

Previous GAMA Work in the Desert and Basin and Range Hydrogeologic Provinces

USGS Data Series reports have been published for each of the six study units located within the DBR hydrogeologic provinces: Owens and Indian Wells Valleys (Densmore and others, 2009), Coachella Valley (Goldrath and others, 2009), Mojave (Mathany and Belitz, 2009), Antelope Valley (Schmitt and others, 2009), Colorado River (Goldrath and others, 2010), and Borrego Valley, Central Desert, and Low-Use Basins of the Mojave and Sonoran Deserts (Mathany and others, 2012). In addition to reporting all of the data collected for the study, Data Series reports also describe the hydrogeologic setting, study design, sample collection procedures, and results of quality-assurance and quality-control analyses. A total of 497 wells were sampled for the 6 study units; of these, samples from 223 wells were analyzed for the inorganic constituents presented in this report.

Two USGS Scientific Investigations Reports were published (Dawson and Belitz, 2012; Parsons and others, 2014) to describe the current status of groundwater quality in the six study units. GAMA status assessments are designed to provide a statistically robust characterization of groundwater quality in the primary aquifer system at the basin-scale (Belitz and others, 2003). The primary aquifer systems in the six study units are defined as that part of the aquifer corresponding to the depth of the open intervals of public-supply wells listed in the California Department of Public Health's water-quality database. The *status assessment* was also designed to identify the constituents and classes of constituents that may be of concern for drinking-water quality because of their high concentrations and (or) their prevalence. Concentrations of constituents were compared to concentrations of CDPH and U.S. Environmental Protection Agency (USEPA) regulatory and non-regulatory benchmarks used for drinking-water quality. Concentrations above the

comparison benchmark were defined as "high." GAMA status assessments included calculating the areal proportion of the primary aquifer system having high concentrations of an individual constituent or of one or more constituents in a constituent class. Constituent classes assessed for the GAMA PBP included volatile organic compounds, pesticides, trace elements, nutrients, and radioactive constituents. In all six DBR study units, trace elements were present at high concentrations in a greater proportion of the primary aquifer system than any other constituent class. Trace elements with health-based drinking-water-quality benchmarks that were most frequently detected at high concentrations were arsenic (As), boron (B), fluoride (F), molybdenum (Mo), strontium (Sr), uranium (U), and vanadium (V) (Dawson and Belitz, 2012; Parsons and others, 2014).

Purpose and Scope

The purpose of this report is to (1) identify the geochemical conditions present in groundwater sampled in the six study areas within the DBR study unit, (2) examine the distribution of arsenic, boron, fluoride (hereinafter classified as a trace element), molybdenum, strontium, uranium, and vanadium with respect to varying geochemical conditions of redox, pH, and major ion content and groundwater age, and (3) identify the processes that control the concentrations or solubility of these trace elements as they relate to the geochemical conditions of groundwater.

A rigorous identification of trace element sources in groundwater is beyond the scope of this report, and only a brief discussion of sources is provided. The DBR hydrogeologic provinces are geologically complex, and the mineralogical and geochemical compositions of the sediments composing the fill of the groundwater basins investigated in this study likely vary considerably across the provinces. This heterogeneity in the potential sources of trace elements to groundwaters may obscure identification of processes controlling the distribution of trace elements in groundwater. However, the large number ($n = 223$) of samples analyzed in this report, coupled with the spatial distribution of wells sampled, should help to mitigate uncertainty attributable to heterogeneity in source material. The groundwater wells sampled in this study were primarily production wells with long open intervals ([table 1](#)). Samples collected from wells with long open intervals can be a mixture of groundwater from different aquifer zones that have different geochemical conditions. Therefore, the geochemical conditions, trace element distribution, and processes controlling trace element distribution reported here should be considered a composite of what is occurring in the primary aquifer systems sampled in the DBR hydrogeologic provinces.

Description of the Study Unit and Hydrogeology

The DBR hydrogeologic provinces cover approximately 45,000 square miles (mi²) in southeastern California (fig. 1). The DBR provinces are bounded on the east by the Colorado River, on the northeast by the State of Nevada, on the south by Mexico, and on the west by crystalline rocks of five mountain ranges. From north to south, these mountain ranges are the Sierra Nevada, the San Gabriel Mountains, the San Bernardino Mountains, the San Jacinto Mountains, and Peninsular Ranges of Southern California. The boundary between the Desert and the Basin and Range hydrogeologic provinces is defined by groundwater basin boundaries that approximate the Garlock Fault.

The DBR study unit was defined as the 63 groundwater basins within the DBR hydrogeologic provinces that contained wells listed in the CDPH's database of public-supply wells as of 2003 (Belitz and others, 2003). The DBR study unit covers approximately 7,000 mi² and was divided into nine study areas for this report: Owens Valley, Indian Wells Valley, Antelope Valley, Mojave, Central Desert, Low-Use Basins, Colorado River, Coachella Valley, and Borrego Valley (fig. 1). The following paragraphs consist of brief descriptions of each of the nine study areas in the DBR study unit. More complete descriptions can be found in Densmore and others (2009) (Owens and Indian Wells Valleys), Goldrath and others (2009) (Coachella Valley), Mathany and Belitz (2009) (Mojave River Valley), Schmitt and others (2009) (Antelope Valley), Goldrath and others (2010) (Colorado River basins), and Mathany and others (2012) (Borrego, Central Desert, and Low-Use Basins).

The northern Owens Valley is located in the Great Basin Desert, while the southern Owens Valley, Indian Wells Valley, Antelope Valley, Mojave, Central Desert, and the northern parts of the Low-Use Basins and Colorado River study areas are located in the Mojave Desert (Duell, 1987; Berenbrock and Martin, 1991; Putnam and Smith, 1995, p. 4; Izbicki and others, 2000). The Coachella Valley, Borrego Valley, and southern parts of the Low-Use Basins and Colorado River study areas are located in the Sonoran Desert, in the part locally known as the Colorado Desert (Phillips and Comus, 2000, p. 14). The climate in the DBR study unit varies from semi-arid to hyper-arid, with average precipitation ranging from approximately 8 inches per year in the Great Basin Desert to less than 1 inch per year in the Sonoran Desert (PRISM Group, Oregon State University, 2007). Because it is located at higher elevations than the other deserts, the Great Basin Desert has relatively cold winters. Precipitation in the Great Basin Desert falls infrequently throughout the year, with snow in winter and rain in summer. The Mojave Desert has hot summers and cold winters. Precipitation here falls mostly in the winter, though summer thunderstorms provide moisture east of the 117° W longitude (Hereford and others, 2004). The Colorado Desert is located at lower elevations in southern California and has hot, dry summers and mild

winters. Most of the precipitation occurs in the winter in the form of rain. Except for the Colorado River study area, all the study areas are closed groundwater basins. Stream and river flow originates in the surrounding mountains or along valley edges and discharges into dry lake beds or the Salton Sea. The major rivers that drain internally are the Owens and Mojave Rivers, which drain into Owens Lake and Soda Dry Lake, respectively, and the Whitewater, New, and Alamo Rivers, which drain into the Salton Sea.

The DBR study unit is predominantly composed of undeveloped, natural landscape (Dawson and Belitz, 2012; Parsons and others, 2014). Areas of intensive agricultural operations are made possible in part by the conveyance of surface water from the Colorado River and northern California through a network of canals. The largest urban centers in the DBR study unit are located along the mountain fronts of the San Gabriel, San Jacinto, and San Bernardino Mountains and the Peninsular Ranges of Southern California.

Groundwater basins in the DBR hydrogeologic provinces are underlain by granitic, metamorphic, sedimentary, and volcanic rocks (Hollet and others, 1991; Berenbrock and Schroeder, 1994; Danskin, 1998; Stonestrom and Harrill, 2007). The basins primarily are filled with sediments derived from erosion of the surrounding mountains, in particular the Sierra Nevada, San Gabriel, San Bernardino, San Jacinto, and Southern California Peninsular mountain ranges that form the western boundary of the provinces. These high-relief mountains are composed mainly of Mesozoic granite and associated metamorphic rocks (Jennings and others, 1977). In the eastern parts of the provinces, the geology is much more varied, with groundwater basins that are bounded by relatively low-relief mountains composed of Quaternary, Tertiary, and Mesozoic volcanic rock, Mesozoic granitic rock, and Paleozoic marine sedimentary and metasedimentary rocks, among others.

Groundwater recharge in the DBR hydrologic provinces primarily comes from mountain-front recharge and infiltration of surface water from rivers and ephemeral streams as they flow from the mountains towards the centers of the basins (Tyley, 1974; Berenbrock and Schroeder, 1994; Danskin, 1998; Leighton and Phillips, 2003; California Department of Water Resources, 2004; U.S. Geological Survey, 2009). The exception is in the northern and central area of the Colorado River study area where groundwater recharge comes primarily from the Colorado River (Metzger and Loeltz, 1973). In some basins, irrigation return flows, engineered recharge of surface water imported from northern California and the Colorado River, and leakage from surface-water canals, wastewater treatment plants, and septic systems are sources of groundwater recharge. Historically, groundwater discharge occurred through evapotranspiration and underflow to dry lake beds. Groundwater pumping is now the primary mechanism of groundwater discharge in many of the basins (Metzger and Loeltz, 1973; Tyley, 1974; Mitten and others, 1988; Berenbrock and Schroeder, 1994; Danskin, 1998; Nishikawa and others, 2001, 2003, 2005; Stamos and others, 2001; California Department of Water Resources, 2003).

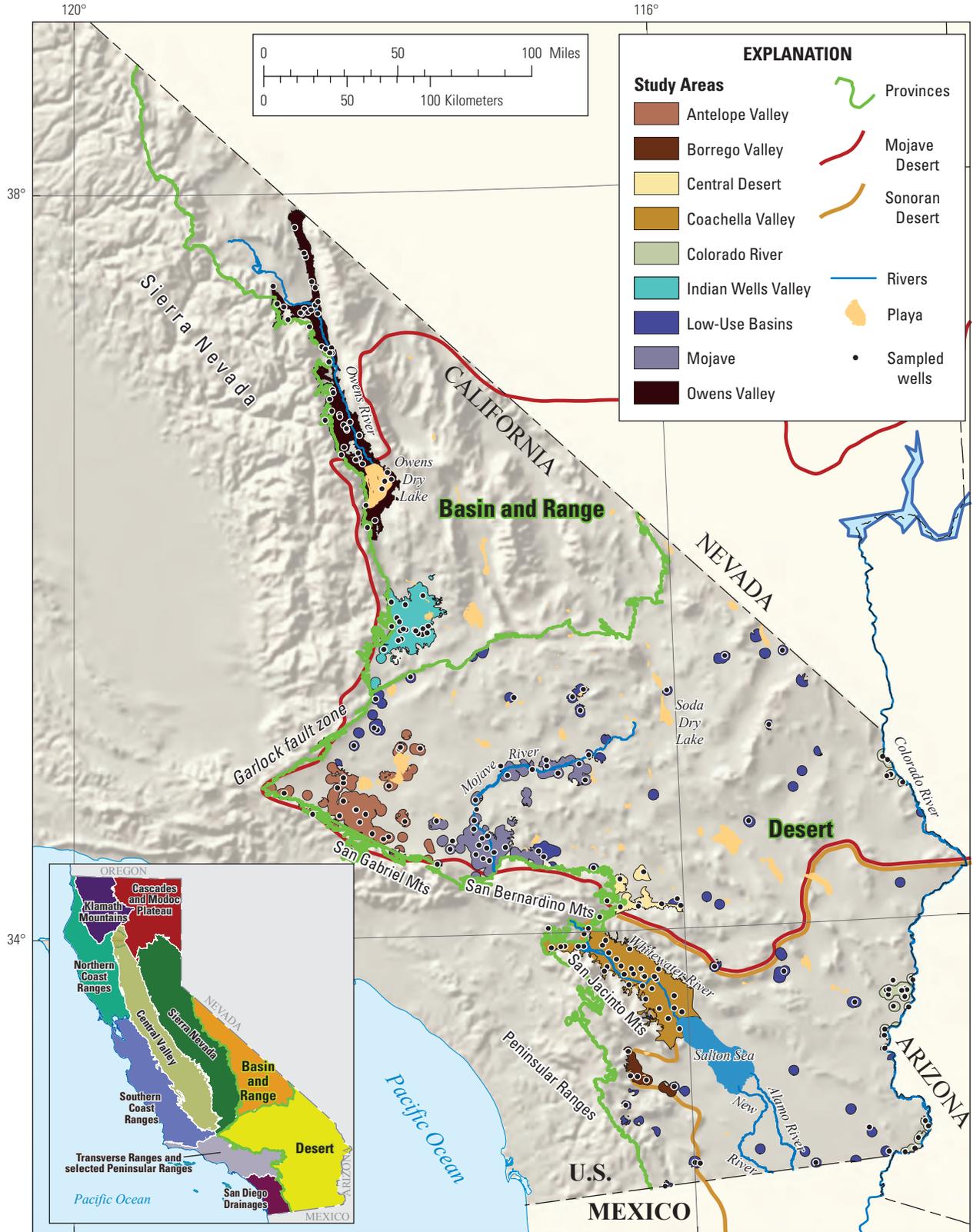


Figure 1. Geographic features, boundaries, and well locations of the Desert and Basin and Range hydrogeologic provinces and the nine individual study areas, California GAMA Priority Basin Project.

Description of Wells Sampled

Groundwater samples were collected from 223 production and monitoring wells in the DBR study unit (table 1). Eighty-seven percent of the wells sampled were classified as production wells and 13 percent as monitoring wells. The majority of production wells were being used for public drinking-water supply (70 percent), while smaller percentages of the production wells sampled were being used for irrigation (13 percent), domestic supply (11 percent), or commercial, industrial, or recreational purposes (6 percent). The production wells that were not public-supply wells generally had openings in the same depth interval as nearby public-supply wells. The monitoring wells generally had openings in shallower parts of the aquifer system. An additional 82 wells were sampled by the GAMA-PBP in these study areas, but were not included in this study because data for trace elements were not collected for those wells.

Differences in well depths between study areas were characterized by comparing the median depths to the tops and bottoms of the perforated intervals for each study area (fig. 2). The median depth to the top of the uppermost opening for wells sampled in the DBR study unit ranged from 118 feet (ft) below land surface (bls) in the Owens Valley study area to 430 ft bls in the Mojave study area. The median depth to the lowermost well opening ranged from 226 ft bls in the Owens Valley study area to 652 ft bls in the Coachella study area. The median length of open intervals ranged from 54 ft in the Owens Valley study area to 306 ft in the Coachella Valley study area.

Methods

Sample Collection and Analysis

Prior to sampling, each well was pumped continuously to purge at least three casing-volumes of water from the well (U.S. Geological Survey, 2006). Sampling points were located as close to the well head as possible and were upstream from water-storage tanks and well-head treatment systems. Most samples were collected inside an enclosed chamber in a mobile laboratory and connected to the well head by a 10–50-ft length of Teflon® tubing, and some were collected at the well head using a 1-ft length of Teflon® tubing (Lane and others, 2003).

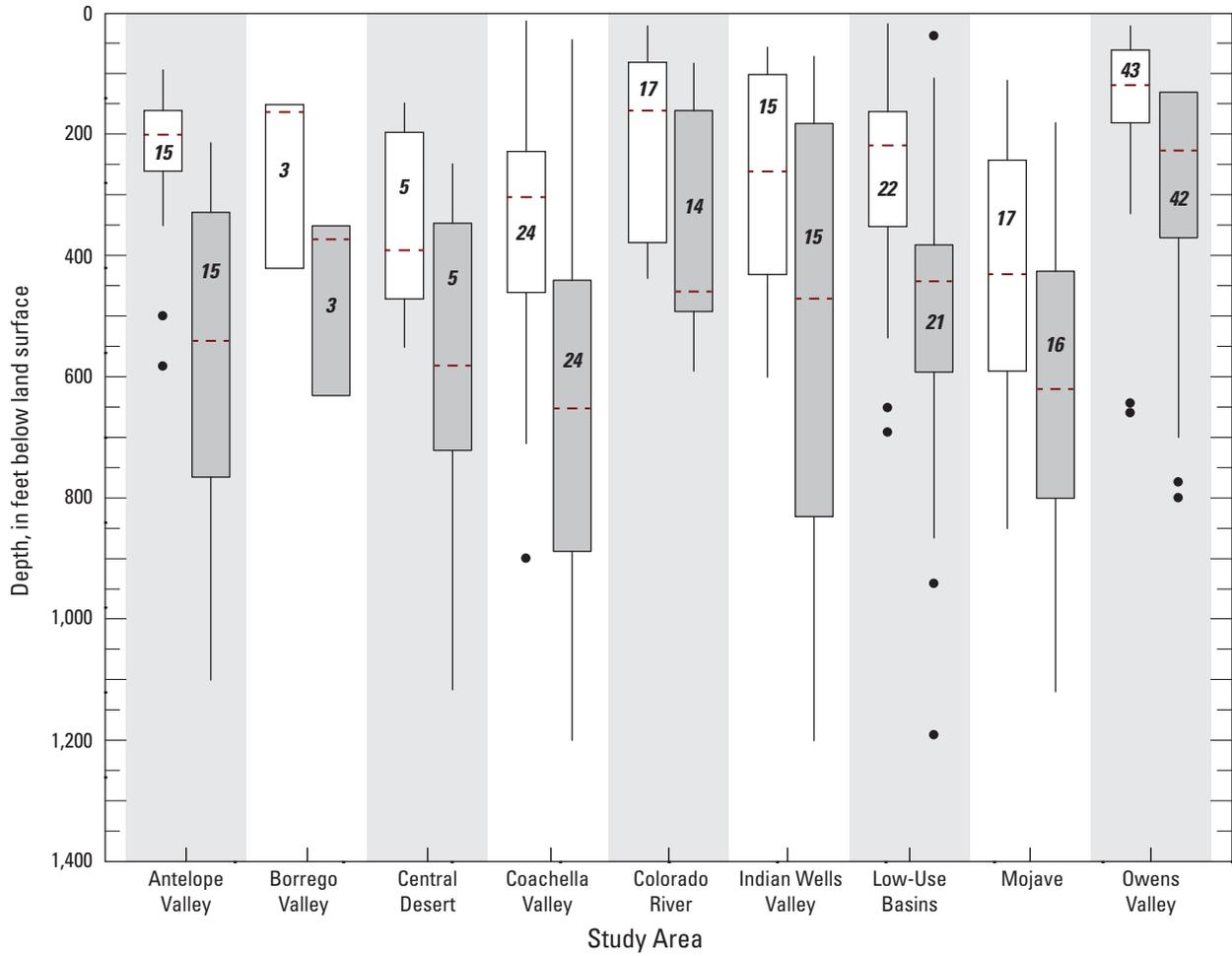
Field measurements of dissolved oxygen, temperature, pH, and specific conductance were collected using a flow-through chamber fitted with a multi-probe meter that simultaneously measures all parameters. Field

measurements were made in accordance with protocols in the U.S. Geological Survey National Field Manual (U.S. Geological Survey, variously dated). Field measurements were recorded at 5-minute (min) intervals for at least 30 min, and when these values remained stable for 20 min, samples were collected. For a subset of samples collected in the DBR study unit, if a sulfide odor was detected, then a sulfide measurement was done onsite using a portable colorimeter (Eaton and Franson, 2005).

Detailed sampling protocols are described in Koterba and others (1995) and the U.S. Geological Survey's National Field Manual (U.S. Geological Survey, variously dated); therefore, only brief descriptions are given here. Before sample collection, all polyethylene sample bottles were rinsed twice with deionized water and then rinsed once with groundwater. Samples were filtered using a 0.45-micrometer (μm) pore-size capsule filter that was rinsed with 2 liters (L) of deionized water and then rinsed with 1 L of groundwater prior to sample collection. Trace element and major cation samples were filtered and preserved to pH <2 with certified, traceable 7.5-Normal (N) nitric acid. Major anions, total dissolved solids (TDS; residue on evaporation), and nutrient samples were filtered, but not preserved with acid; nutrient samples were stored in brown polyethylene bottles. Stable isotopes of carbon in dissolved inorganic carbon and carbon-14 abundance samples were filtered and bottom-filled into 500-milliliter (mL) glass bottles that first were overfilled with three bottle volumes of groundwater. These samples had no headspace and were sealed with conical caps to avoid atmospheric contamination. All samples were stored and shipped cold after collection.

Trace element, major ion, and nutrient samples were analyzed at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, and stable isotopes of carbon in dissolved inorganic carbon and carbon-14 abundance samples were analyzed at the Woods Hole Oceanographic Institution, National Ocean Sciences Accelerator Mass Spectrometry Facility in Woods Hole, Massachusetts (MA-WHAMS) under a contract with the NWQL. Iron speciation samples were analyzed at the USGS National Research Program Trace Metal Laboratory in Boulder, Colorado.

Data used in this study are available from the six USGS Data Series reports referenced in the section "Previous GAMA Work in the Desert and Basin and Range Hydrogeologic Provinces," from the USGS National Water Information System online database (U.S. Geological Survey, <http://waterdata.usgs.gov/ca/nwis/>), and from the SWRCB's GeoTracker GAMA online database (California State Water Resources Control Board, 2009, website at <https://geotracker.waterboards.ca.gov/gama>).



EXPLANATION

Top of the uppermost opening

Bottom of the lowermost opening

26 Number of wells with data

• Data point that is outside of $1.5 \times \text{IQR}$ of the 75th percentile
 • Nearest data point that is within $1.5 \times \text{IQR}$ of the 75th percentile
 Interquartile range (IQR)
 75th percentile
 Median
 25th percentile
 • Nearest data point that is within $1.5 \times \text{IQR}$ of the 25th percentile
 • Data point that is outside of $1.5 \times \text{IQR}$ of the 25th percentile

Figure 2. Depths to the uppermost and lowermost well openings for wells sampled in each study area, 2006–11, Desert and Basin and Range study unit, California GAMA Priority Basin Project.

Groundwater Age Determination

Carbon-14 (^{14}C) chronology was used to determine the approximate groundwater ages of the samples collected in this study. Correlating age with concentrations of trace elements in groundwater can be useful in helping to determine geochemical processes that affect trace element solubility. The age dating method relies on evaluating the radiocarbon (^{14}C) content of dissolved inorganic carbon species in groundwater. ^{14}C is formed in the atmosphere by the interaction of cosmic-ray neutrons with atmospheric gases, is incorporated into carbon dioxide (CO_2), and then is assimilated into living organisms by uptake of CO_2 in photosynthesis. Decay of organic material and root respiration releases CO_2 in soils and in the unsaturated zone, and this CO_2 dissolves in groundwater during recharge. The ^{14}C age (residence time) is calculated based on the decrease in ^{14}C activity as a result of radioactive decay with time since groundwater recharge, relative to an assumed initial ^{14}C concentration using the following equation (Clark and Fritz, 1997):

$$t = -\frac{t_{1/2}}{\ln 2} \times \ln\left(\frac{A_{meas}}{A_0}\right) \quad (1)$$

where A_{meas} is the measured ^{14}C activity in groundwater in percent modern carbon (pmc),
 $t_{1/2}$ is the half-life of ^{14}C , 5,730 years,
 A_0 is the initial ^{14}C activity (84 pmc for this study), and
 t is the ^{14}C age.

A_0 refers to the ^{14}C activity of groundwater entering the saturated zone and is generally less than 100 pmc under natural conditions because of reactions between infiltrating groundwater and carbonate minerals in the unsaturated zone that contain older carbon (and hence, have lower ^{14}C activities). A_0 under natural conditions cannot generally be directly measured because atmospheric testing of nuclear weapons increased ^{14}C production, raising the ^{14}C activity of groundwater recharged since 1952 above natural levels. The initial ^{14}C activity used in this study is based on a previous study that examined the ages of groundwaters in the western Mojave Desert (Izbicki and Michel, 2004). In that study, A_0 was empirically defined as the highest A_{meas} in tritium “dead” groundwater samples. However, calculated ^{14}C ages presented here are still considered “uncorrected” because they have not been adjusted to account for dilution by older CO_2 produced by oxidation of sedimentary organic carbon. Therefore, groundwater ages presented in this report should not be thought of as absolute ages, but rather as approximate ages, which were instructive for making comparisons of groundwater geochemistry in samples collected at local and regional scales. Solely for the purpose of discussing

distribution in the DBR study unit, groundwater ages were categorized into four groups based on Jenks Natural Breaks (Jenks and Caspall, 1971). A fifth category, <100 years before present (BP), was added to show where modern groundwater recharge is occurring in the DBR study unit. The age categories are as follows: <100 years BP; 100–3,800 years BP; 3,801–11,000 years BP; 11,001–20,800 years BP; and 20,801–33,700 years BP.

Redox Classification

Geochemical conditions investigated as potential explanatory variables in this report include oxidation-reduction (redox) characteristics. Microorganisms can affect the redox conditions of groundwater by utilizing terminal electron acceptors during the degradation of organic carbon. A terminal electron acceptor is a compound that receives or accepts an electron during oxidation of a carbon source. The order of terminal electron acceptor utilization is $\text{O}_2 > \text{NO}_3^- > \text{Mn}^{4+} > \text{Fe}^{3+} > \text{SO}_4^{2-} > \text{CO}_2$ (Drever, 1997). With the successive utilization and subsequent depletion of terminal electron acceptors, the redox condition of groundwater progresses from oxidizing (positive Eh values) to reducing (negative Eh values). Oxidation-reduction (redox) conditions affect the mobility of many inorganic constituents, and thus redox class was considered an important potential explanatory factor.

Classification of redox conditions was done using a modification of the framework of McMahon and Chapelle (2008) and an automated Excel® workbook developed by Jurgens and others (2009). Groundwater samples were classified as oxic, anoxic, anoxic-Fe, or mixed based on dissolved redox indicator species. Samples were classified as oxic if dissolved $\text{O}_2 > 0.5$ milligram per liter (mg/L) and total dissolved Fe ≤ 100 micrograms per liter ($\mu\text{g/L}$); anoxic if $\text{O}_2 \leq 0.5$ mg/L and total dissolved Fe ≤ 100 $\mu\text{g/L}$; anoxic-Fe if $\text{O}_2 \leq 0.5$ mg/L and total dissolved Fe > 100 $\mu\text{g/L}$; and mixed if $\text{O}_2 > 0.5$ mg/L and total dissolved Fe > 100 $\mu\text{g/L}$. These classifications were used because all redox-sensitive elements presented in this report, except for V, are thermodynamically predicted to be reduced from their more oxidized states to their more reduced states at redox potentials low enough for iron reduction to occur (Turner and others, 1981; Wang, 2007). Samples with a mixed redox classification ($\text{O}_2 > 0.5$ mg/L and total dissolved Fe > 100 $\mu\text{g/L}$) are identified, but are not used in analysis of the occurrence of trace elements in groundwater because of the ambiguity in the dominant redox processes occurring.

Aqueous Speciation and Saturation State

The distribution of aqueous species in groundwater and the saturation state of groundwater relative to a set of minerals and amorphous solid phases were calculated for each sample in order to assess whether mineral precipitation and electrostatic

interactions between aqueous species and mineral surfaces may affect the distribution of trace elements. PHREEQC version 2 (Parkhurst and Appelo, 1999), a computer program for simulating chemical reactions in natural or polluted water, was used to calculate aqueous species and saturation indices for the chemical constituents presented in this report. Thermodynamic data contained in the *minteq.v4* database that is distributed with PHREEQC version 2 were used for these calculations (U.S. Environmental Protection Agency, 1998). In addition to the trace elements discussed in this report, the constituents and water-quality parameters used for modeling were: Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , CO_3^{2-} , Cl^- , H_2S , SO_4^{2-} , NH_4^+ , NO_3^{2-} , PO_4^{3-} , Fe^{2+} , Fe^{3+} , dissolved O_2 , pH, and temperature. Additional thermodynamic data were added to the *minteq.v4* database for F, Mo, and U aqueous species and solid phases. These supplemental data are presented in [table 2](#).

Statistical Analysis

Nonparametric statistical methods were used to test the significance of correlations between water-quality variables and potential explanatory factors. Nonparametric statistics are robust techniques that generally are not affected by outliers and do not require that the data follow any particular distribution (Helsel and Hirsch, 2002). The significance level (p) used to test hypotheses for this report was compared to a threshold value (α) of 5 percent ($\alpha = 0.05$) to evaluate whether the relation was significant ($p \leq \alpha$). Correlations were investigated by using Spearman's method to calculate the rank-order correlation coefficient (ρ) between continuous variables. The values of ρ can range from +1.0 (perfect positive correlation) to 0.0 (no correlation) to -1.0 (perfect negative correlation). The Kruskal-Wallis Analysis of Variance on Ranks was the statistical test used to compare three of the more independent populations (data groups or categories) to determine whether one population contains larger values than the others (Helsel and Hirsch, 2002). If a significant difference was found among the groups, a multiple comparison test (Dunn's Test) was used to determine exactly which groups are different.

Geochemical Conditions of the Study Unit

Groundwater Age

Uncorrected ^{14}C groundwater ages for samples collected in the DBR study unit ranged from <100 to 33,600 years BP ([table 3](#)). Thirty-four percent of the samples were classified as having ages <100 years BP and are considered in this study as being recharged during modern times. The majority of groundwater sampled in the DBR study unit appears to have

been recharged before modern times. Thirty-five percent of the samples were classified as having ages of 100 to 11,000 years BP and 21 percent as having ages >11,000 years BP ([fig. 3](#)).

The areal distribution of groundwater ages in the DBR study unit generally followed the expected groundwater flow patterns of groundwater recharge that occurs along mountain fronts and major surface-water drainages flowing towards discharge areas of basins that are often demarcated by the presence of playas and terminal lakes. The Colorado River study area had the highest percentage of young groundwater ages with 54 percent of the samples classified as <100 years BP ([fig. 3B](#)). Most of the wells sampled were relatively shallow wells ([fig. 2](#)) tapping fluvial aquifers that were recharged either directly or indirectly (through irrigation practices) by the Colorado River (Metzger and Loeltz, 1973; Olmsted and others, 1973; California Department of Water Resources, 2003). In the Owens Valley study area, 49 percent of the wells were classified as having ages <100 years BP ([fig. 3B](#)). Samples of relatively young groundwater in the Owens Valley study area were primarily collected from shallow wells ([fig. 2](#)) located in the western part of the groundwater basin that abuts the Sierra Nevada ([fig. 3A](#)). In contrast, the oldest groundwater in the study area came from wells located at the terminal end of the basin flow path at Owens Dry Lake. The Sierra Nevada is the major source of groundwater recharge because 60 to 80 percent of the annual precipitation in the drainage basin falls in these mountains and flows towards the discharge area at Owens Dry Lake (Danskin, 1998). Groundwater age distribution also followed the general groundwater flow patterns in the Coachella Valley study area where groundwater ages were the youngest (<100 years BP) in samples collected from wells near the San Bernardino and San Jacinto mountain-front recharge areas and oldest (>3,800 years BP) in samples collected from wells located towards the basin discharge area near the Salton Sea ([fig. 3A](#)). In the Mojave study area, several samples classified as having ages <100 years BP were collected from wells located away from mountain-front recharge areas and adjacent to the Mojave River ([fig. 3A](#)). These wells are tapping the flood plain aquifer of the Mojave River, which is a major and relatively constant source of groundwater recharge in the western Mojave Desert (Lines, 1996).

The Low-Use Basins and the Indian Wells Valley study areas had the oldest groundwater ages in the DBR study unit, with 47 percent of groundwater samples having ages >11,000 years BP ([fig. 3B](#)). The Low-Use Basins study area is primarily composed of groundwater basins located away from mountain-front recharge areas that are also not bisected by major surface-water drainages. In the Indian Wells study area, groundwater ages generally increased from west to east across the basin ([fig. 3A](#)). The oldest groundwater samples (>28,800 years BP) were collected from deep wells located close to historical discharge areas of the groundwater basin.

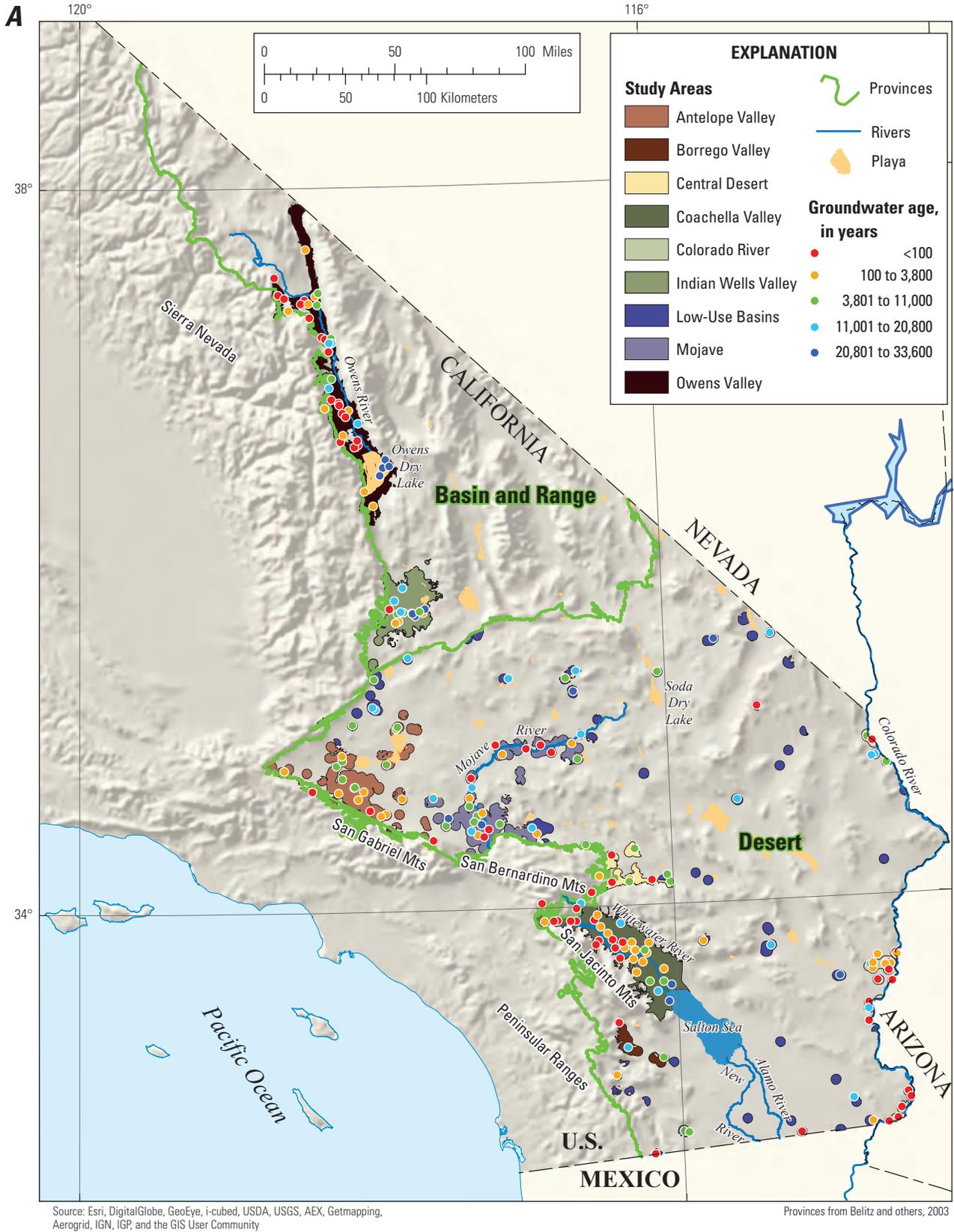


Figure 3. (A) Distribution of groundwater ages in the Desert and Basin and Range study unit, California GAMA Priority Basin Project, and (B) groundwater age categories for the overall study unit, for each study area, and for the categories of ≤ 212 and >212 feet median depth to the top of the uppermost interval. Groundwater ages categorized for purposes of discussion. Categories based on Jenks Natural Breaks.

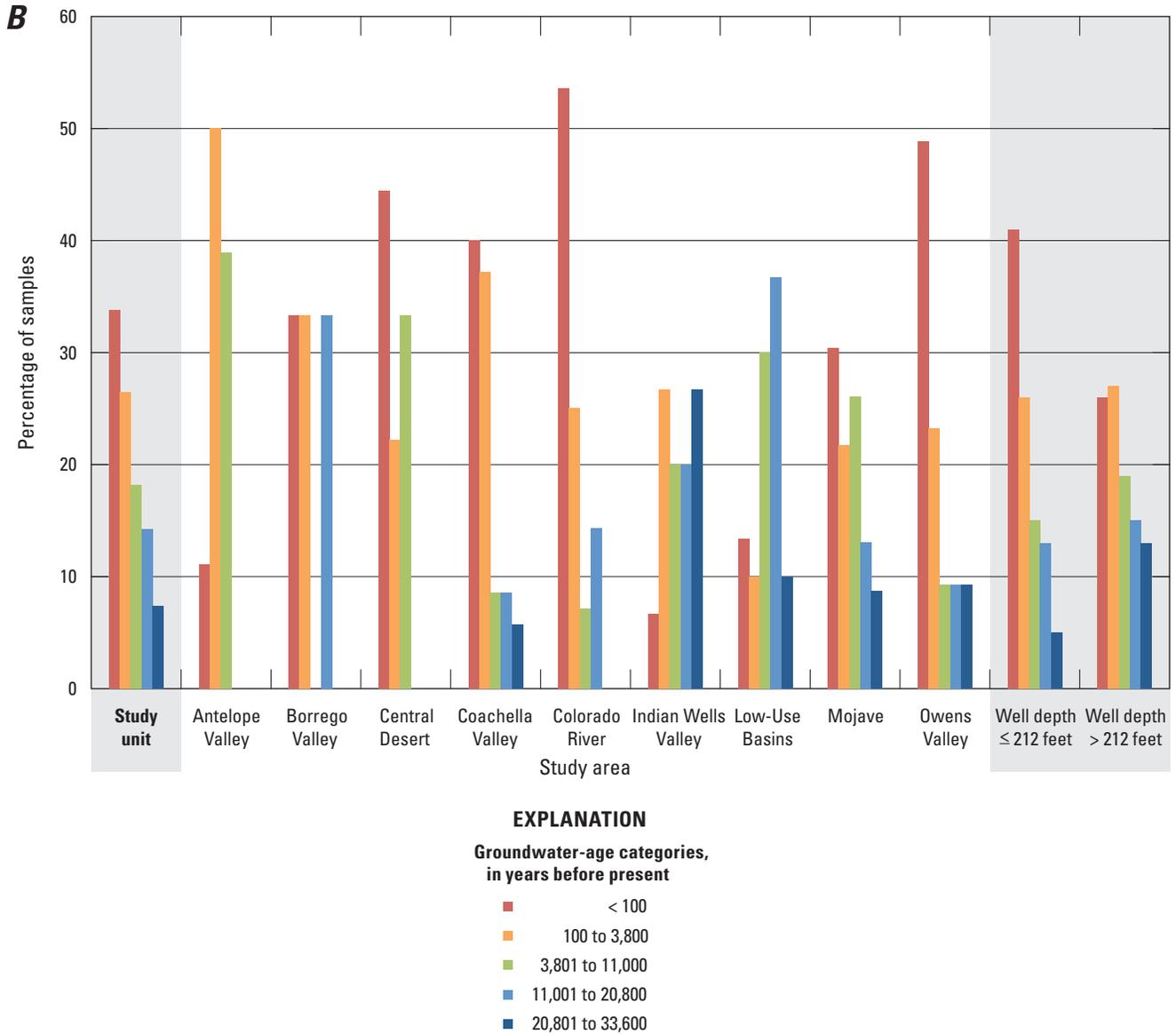


Figure 3. —Continued

Redox and pH

Seventy-one percent of the samples collected in the DBR study unit were classified as oxic, 16 percent as anoxic, 7 percent as mixed, and 6 percent as anoxic-Fe (iron-reducing) (table 3; fig. 4). Samples were predominantly classified as oxic in each of the study areas, with the exception of the Colorado River study area where anoxic-Fe samples were detected just as frequently as oxic samples. A recent study conducted by McMahon and Chapelle (2008) shows that oxic redox conditions are predominating in arid areas across the southwestern United States. In arid areas, the predominance of oxic conditions has been attributed to groundwater bearing deposits that are generally lacking the electron donors necessary (for example, organic carbon) to support anoxic redox processes (Winograd and Robertson, 1982; McMahon

and others, 2004). In the Colorado River study area, anoxic-Fe and anoxic conditions are likely predominant because samples were often collected from wells tapping flood plain aquifers that are composed of organically rich fluvial deposits. These organic-matter-rich deposits provide the electron donors necessary to deplete dissolved O₂ in groundwater, which promotes anoxic-Fe and anoxic redox conditions.

Redox conditions and pH showed significant relations to groundwater age. Anoxic samples had the oldest groundwater ages, and anoxic-Fe samples had the youngest (table 4). Seventy-four percent of the anoxic samples that have age data had ages >3,800 years BP, and 51 percent had ages >11,000 years BP. Groundwater near the Owens Dry Lake and the Salton Sea, the distal ends of the general groundwater flow systems in the Owens and Coachella Valleys, respectively, generally were anoxic (fig. 4A) and old (fig. 3A).

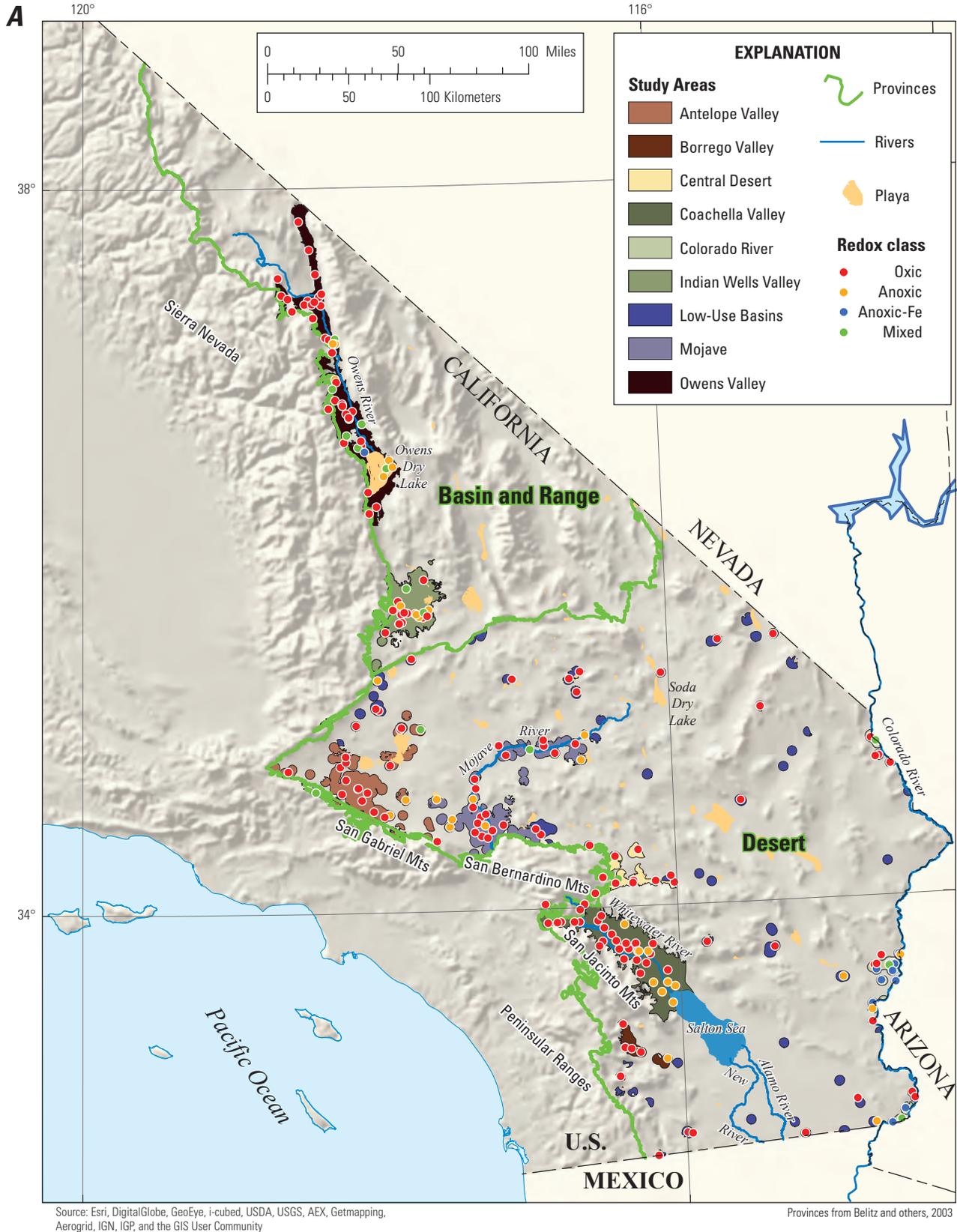


Figure 4. (A) Distribution of redox classes in the Desert and Basin and Range study unit, California GAMA Priority Basin Project, and (B) Redox classes organized by study unit, study area, and depth to the top of the uppermost interval. Classes based on McMahon and Chapelle (2008).

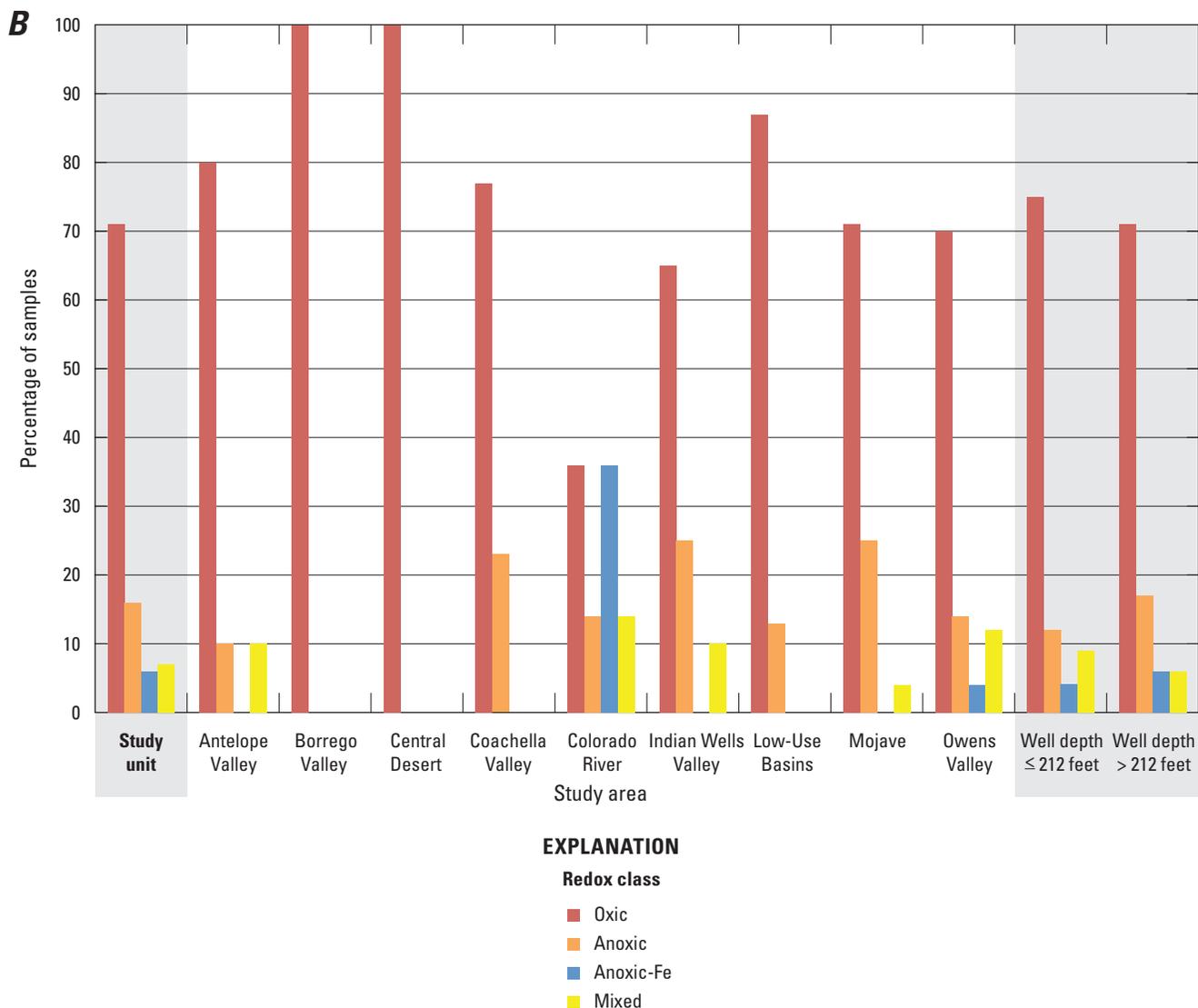
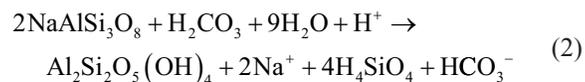


Figure 4. —Continued

The occurrence of old, anoxic groundwater at the distal ends of groundwater flow systems likely reflects that groundwater has been in the subsurface for thousands of years where redox processes have had time to remove dissolved O_2 from groundwater. Eighty percent of anoxic-Fe samples had groundwater ages of <100 years BP. The reason anoxic-Fe samples have the youngest ages is because anoxic-Fe samples were almost exclusively collected from wells in the Colorado River study area where organic-rich fluvial groundwater basins are rapidly recharged by the Colorado River.

Groundwater samples collected in the DBR study unit have pH values ranging from 6.4 to 9.8 (table 3; fig. 5). The pH of groundwater was categorized by using Jenks Natural Breaks (Jenks and Caspall, 1971) for the purpose of discussing the distribution of pH values in the study unit. Eighty-nine percent of the samples have pH values ≥ 7.1 , and 37 percent have pH values ≥ 7.9 (fig. 5B). Sample pH is positively correlated to groundwater age and well depth (table 4). The

correlation of pH with well depth is likely due to the fact that deeper wells are generally tapping older groundwater. The correlation between pH and groundwater age is likely due to pH being primarily controlled by the dissolution of silicate minerals. For example, the incongruent dissolution of the silicate mineral albite to form kaolinite is represented by the following reaction:



This reaction consumes carbonic acid (dissolved CO_2) and H^+ , thus increasing the pH of groundwater. Because the weathering of silicate minerals takes place over long time periods (Appelo and Postma, 2005), pH values generally increase with increasing groundwater age.



Figure 5. (A) Distribution of pH values in the Desert and Basin and Range study unit, California GAMA Priority Basin Project, and (B) pH values organized by study unit, study area, and median depth to the top of the uppermost interval. pH values categorized for purposes of discussion. Categories based on Jenks Natural Breaks.

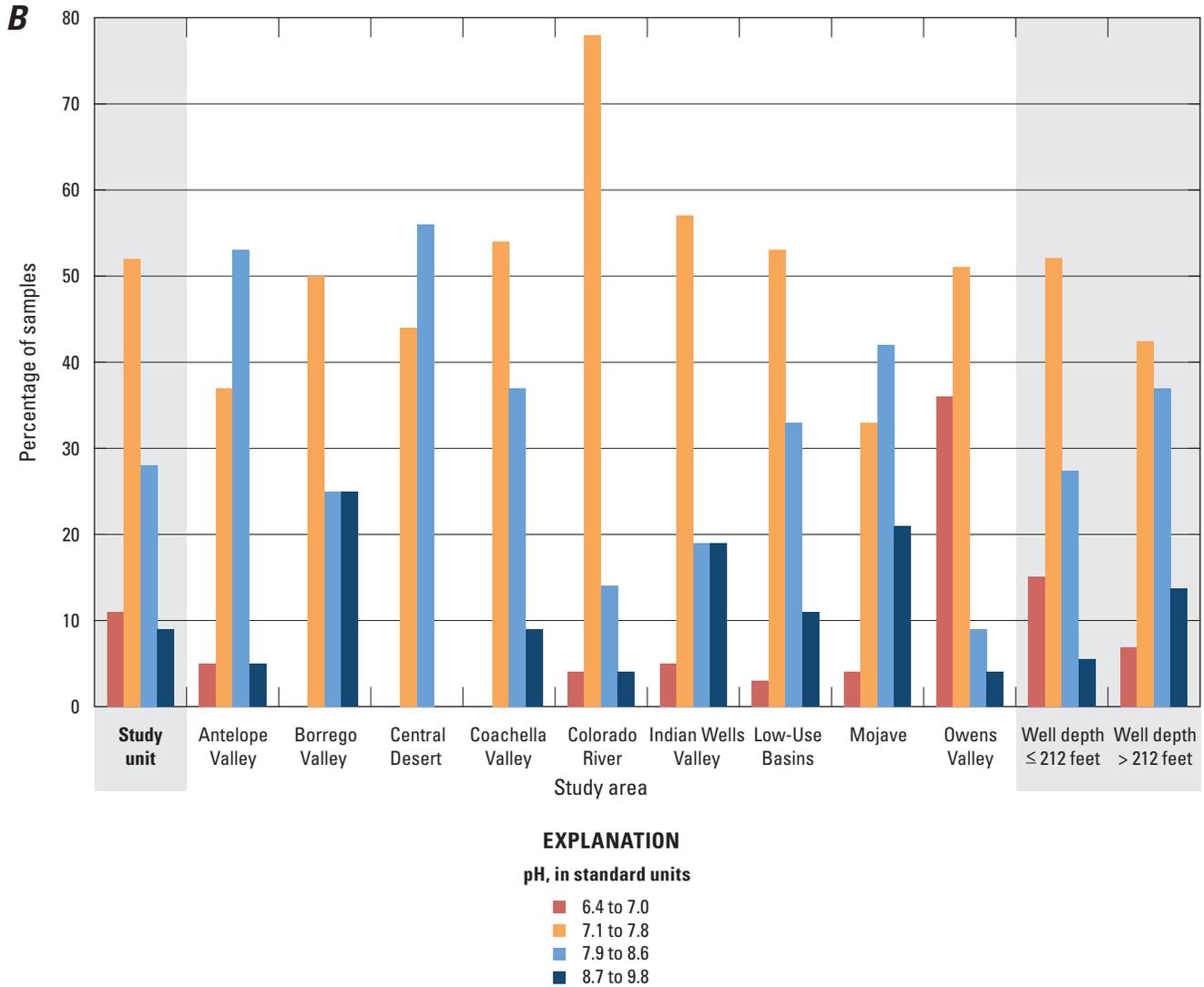


Figure 5. —Continued

The significant positive correlation with groundwater age means the distribution of pH values in the study unit was similar to the distribution of groundwater ages. Samples collected near mountain-front recharge areas tended to be acidic or near neutral, and samples collected away from mountain-front recharge areas or near the distal end of groundwater flow paths tended to be more alkaline. Several samples collected from wells in the Mojave study area that are adjacent to the San Bernardino Mountains had pH values >8.7, where near-neutral pH values could reasonably be expected. The tops of the uppermost openings for these wells were deeper (365–850 ft bls) than the tops of the uppermost openings for other wells nearby that had lower pH values, and the groundwater in the wells that had pH values >8.7 also was older than the groundwater from the other nearby wells, which may explain the high pH values.

Seventy-five percent (18/23) of the samples with pH values ≤7.0 were collected from wells located in the western

part of the Owens Valley study area (fig. 5A). Nearly all of these samples were also oxidic (fig. 4A) and had ages <100 years BP (fig. 3A). These wells are located close to the Sierra Nevada mountain front and likely tap groundwater at the proximal end of flow paths, where the minimal dissolution of aquifer minerals has likely occurred and pH values of groundwater are likely closest to the initial pH values of precipitation. Annual data collected from several sites in the central Sierra Nevada showed that pH values of precipitation ranged from 5.1 to 5.9 (National Atmospheric Deposition Program, 2014).

The evolution of groundwater pH from near-neutral values to alkaline values is particularly evident in the distribution of sample pH values collected in the Coachella Valley study area. Groundwater pH values increased from ≤7.8 near the major mountain-front recharge areas of the groundwater basin to ≥8.7 near the discharge area of the groundwater basin close to the Salton Sea where groundwater ages are tens of thousands of years old (figs. 3A, 5A).

Major Ion Content

Groundwater samples are classified by major ion content based on whether or not an ion composes greater than 50 percent of the total cations or anions, on a milliequivalent basis, in a sample; if no one ion is greater than 50 percent of the total, then the groundwater was classified as mixed. With respect to cations, 46 percent of the samples were classified as sodium-type, 32 percent as mixed-cation, and 22 percent as calcium-type (table 3; fig. 6). Samples classified as sodium-type were significantly older, had higher pH values and TDS concentrations, and were from wells with greater depths to the top of the open interval compared to samples classified as calcium-type (table 4). The dominance of sodium over calcium in older groundwater may be due to the replacement of calcium ions in groundwater by sodium ions associated with mineral surfaces through cation-exchange processes over time (Drever, 1997). Samples with a mixed-cation-type had significantly younger groundwater ages than sodium-type samples and significantly older groundwater than calcium-type samples. These relations may be due to the evolution of groundwater as it moves through the aquifer system, evolving from a younger, calcium-type to an older, sodium-type. With respect to anions, 49 percent of the samples were classified as bicarbonate-type, 34 percent were classified as mixed-anion, 10 percent were classified as sulfate-type, and 7 percent were classified as chloride-type (table 3; fig. 6). Samples classified as chloride-type had significantly older groundwater ages than all other types, and samples classified as bicarbonate-type had significantly lower TDS than all other types (table 4). Eleven different combined cation-anion classes were present, and 80 percent of the samples were classified in the following five classes: sodium or mixed-cation with mixed-anion, and calcium or sodium or mixed-cation with bicarbonate.

Calcium-type samples predominantly came from wells located next to mountain-front recharge areas. Seventy-six percent of calcium-type samples were from wells located in either the Owens Valley (46 percent) or Coachella Valley (30 percent) study areas. The majority of these wells

were located in the western part of the groundwater basins that abut major mountain-front recharge areas where groundwater ages were the youngest. Sodium-type samples were more spatially distributed across the DBR study unit than were the calcium-type samples, but areal patterns were still discernable. The Low-Use Basins and Indian Wells Valley study areas had the highest percentage of samples classified as sodium-type, with 70 and 62 percent of their samples classified as such, respectively. Sodium-type samples in the Low-Use Basins and Indian Wells Valley study areas primarily came from wells located away from mountain-front recharge areas where wells are tapping some of the oldest groundwater in the DBR study unit (fig. 3A). In the Owens and Coachella Valley study areas, sodium-type samples only came from wells located near the discharge areas of Owens Dry Lake and the Salton Sea. A similar pattern was observed in the Mojave study area where the majority of samples collected at the terminal end of the Mojave River (fig. 1) were sodium-type.

Bicarbonate-type samples came from wells located in every study area except for the Colorado River and the Borrego Valley study areas (table 3). The Owens Valley and Coachella Valley study areas had the largest percentage of bicarbonate-type samples. Forty-four percent of bicarbonate-type samples came from wells in the Owens Valley, and 16 percent came from wells in the Coachella Valley. Bicarbonate-type samples came from wells located throughout the Owens Valley, while in the Coachella Valley, the majority of bicarbonate-type samples came from wells located in the northern and western parts of the basin. The majority of sulfate-type samples came from wells located in study areas that are south of the Mojave study area. The largest percentage (36 percent) of sulfate-type samples came from wells located in the Coachella Valley; most of these wells were located in the eastern and northeastern parts of the basin. Chloride-type samples came from areas in the DBR study that had the oldest groundwater ages. Forty-four percent of chloride-type samples came from wells located in the Low-Use Basins that were tapping groundwater that ranged in age from 7,400 to 27,400 years BP.

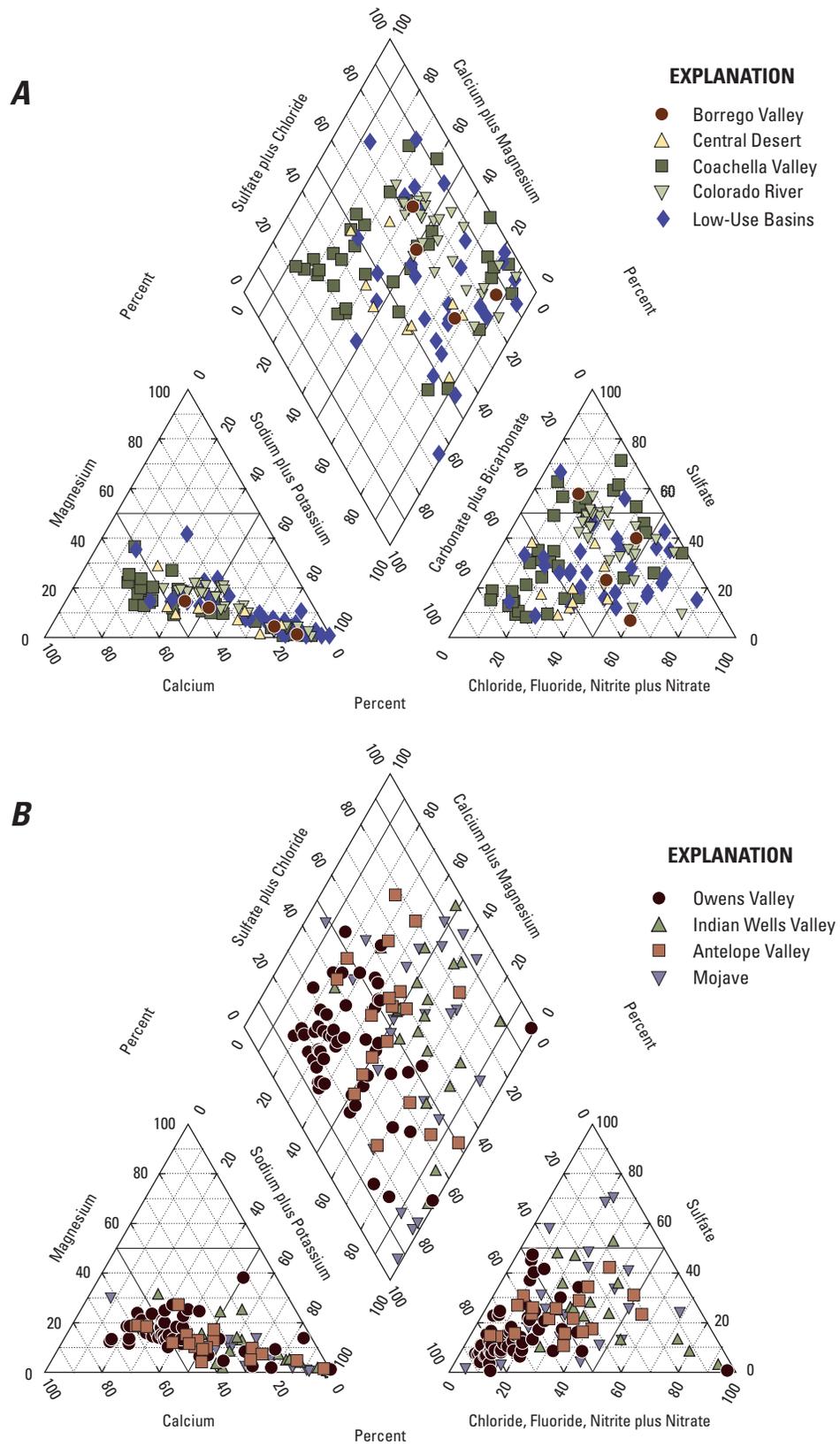


Figure 6. Major ion content of samples categorized by study area in the Desert and Basin and Range study unit: (A) Borrego Valley, Central Desert, Coachella Valley, Colorado River, and Low-Use Basins, and (B) Owens Valley, Indian Wells Valley, Antelope Valley, and Mojave.

Occurrence of Selected Trace Elements

Summary statistics for the concentrations of selected trace elements are shown in [table 5](#). Concentrations ranged over several orders of magnitude, from less than laboratory reporting levels to more than 50 times the associated water-quality benchmarks. B and As had the widest range in sample concentration, and F and U had the narrowest. As and F were most frequently detected at concentrations above associated water-quality benchmarks (18 and 13 percent, respectively), and Sr and V were the least frequently detected at concentrations above associated water-quality benchmarks (both at 3 percent). B, Mo, and U were detected at concentrations above their respective benchmarks in 11, 7, and 4 percent of samples, respectively. A robust statistical analysis of the occurrence of these constituents in groundwater of the DBR study unit can be found in Dawson and Belitz (2013) and Parsons and others (2014).

Sources of Trace Elements to Groundwater

A rigorous analysis of the sources of trace elements in groundwater sampled in the DBR study unit is beyond the scope of this report. Insight to possible sources of trace elements, however, may be obtained by determining if groundwater is mainly influenced by geologic factors, anthropogenic inputs, or both. Given that urban and agricultural land use is relatively sparse in the DBR study unit, volatile organic compounds (which can indicate anthropogenic influence) were rarely detected, nitrate concentrations were rarely greater than associated water-quality benchmarks (Dawson and Belitz, 2013; Parsons and others, 2014), and the majority of groundwater ages are >100 years BP, it can reasonably be assumed that geologic, not anthropogenic, sources are the main contributors of trace elements to groundwater. Geologic sources of the constituents presented in this report may include the dissolution of trace element minerals such as arsenopyrite, fluorite, or powellite, or minerals that host trace elements such as the silicate minerals feldspar, mica, and amphibole (Reimann and de Caritat, 1998). Trace elements adsorbed to mineral surfaces that compose aquifer matrices may also be a source to groundwater. Adsorbed trace elements can be mobilized due to exchange reactions and dissolution of mineral coatings that can occur under reducing redox conditions or because of variations in groundwater pH. In addition, the distribution of trace elements in groundwater can be affected by heterogeneity in the source material.

Relation to Groundwater Age

Groundwater geochemistry evolves over time in large part because of the interaction with the minerals composing aquifer matrices. Generally, in groundwater unaffected by anthropogenic inputs, the longer the water has been in an aquifer, the greater the concentrations of dissolved solids. This is because the dissolution of trace-element-containing minerals, such as silicate minerals, in the natural environment is a slow process that takes place over hundreds to thousands of years (Appelo and Postma, 2005). Therefore, it can reasonably be expected that many trace element concentrations in groundwater will generally increase with increasing groundwater age.

All constituent concentrations, with the exception of Sr, were significantly correlated to groundwater age ([table 6](#); [fig. 7](#)). As, B, F, Mo, and V concentrations had significant positive correlations with groundwater age, with the correlations for As, F, and B being the most significant. The majority of As, B, and F detections with concentrations above their respective water-quality benchmarks were in samples having groundwater ages >10,000 years BP. In contrast, U concentrations have a significant negative correlation to groundwater age. Of the six samples with groundwater age data and U concentrations above the USEPA maximum contaminant level (MCL-US) of 30 µg/L, five had groundwater ages <100 years BP. The fact that U concentrations tend to be higher in younger groundwater indicates that other factors, such as the presence of complexing ions, are more important in contributing U to groundwater than long dissolution times of minerals composing aquifer matrices.

The solubility of trace elements in groundwater is largely controlled by adsorption/desorption reactions at the particle-water interface and (or) the precipitation/dissolution of secondary mineral phases. These reactions are in turn controlled by the geochemical conditions of the aquifer system. Geochemical conditions that affect trace element solubility in groundwater include (1) oxidation-reduction (redox) conditions, (2) pH, and (3) major ion content. Evaporative effects can also increase the concentration of trace elements in groundwater. An analysis of the stable isotopes deuterium and oxygen-18 (data not shown) indicates that evaporative effects may be important in a limited number of cases, but is not a dominant process in the relatively deeper aquifer systems sampled in the DBR study unit. The effects that redox conditions, pH, and major ion content have on the distribution of trace elements in the DBR study unit are discussed in the following sections.

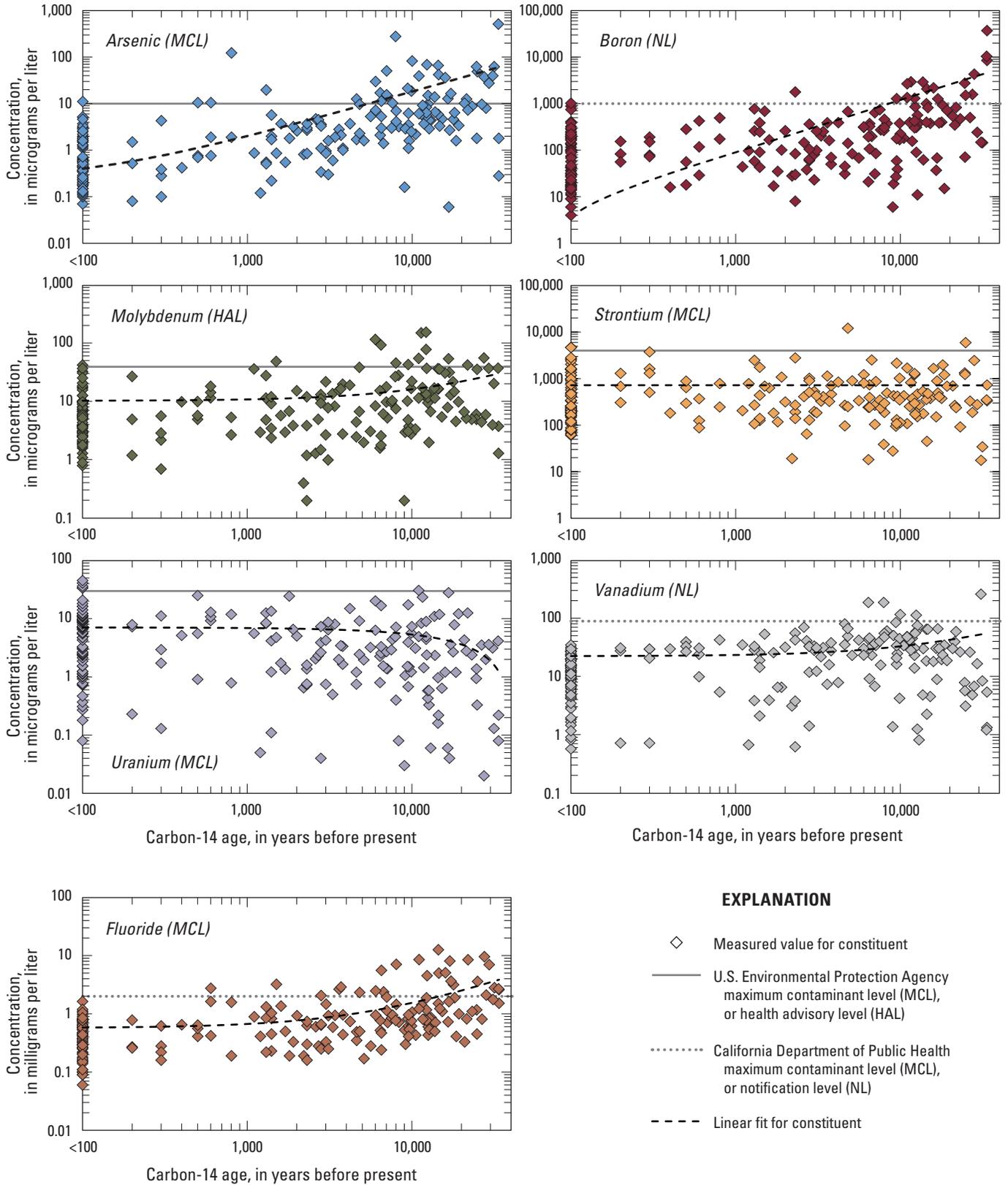


Figure 7. Relations of trace element concentrations to (uncorrected) groundwater age, Desert and Basin and Range study unit, California GAMA Priority Basin Project.

Relation to Redox and pH

The effects of redox can account for substantial variability in the concentrations of trace elements in groundwater. The solubility of trace elements may be sensitive to redox conditions in groundwater because (1) some trace elements can exist in multiple oxidation states in natural waters, and the aqueous species formed by the element in these different oxidation states may have different adsorption and ion complexation properties; (2) redox conditions of the groundwater can affect the adsorbing surface of aquifer matrices; and (3) redox conditions can control the formation of secondary mineral phases. Variation in pH may have an effect on the adsorption of many trace elements by altering the variable surface charge of minerals such as iron oxyhydroxides. Some redox-sensitive trace elements, such as U, are more mobile under relatively acidic pH and oxic conditions (Fox and others, 2006), while oxyanion-forming trace elements, such as As, are generally more mobile under alkaline pH conditions (Smedley and Kinniburgh, 2002; Stollenwerk, 2003).

Anoxic-Fe samples only accounted for a small percentage (fig. 4B) of the total samples for which redox classification was possible (table 3). Of the 12 samples classified as anoxic-Fe, 10 samples were from the Colorado River study area. Samples classified as anoxic-Fe account for 36 percent of the total samples collected in the Colorado River study area. Therefore, while anoxic-Fe groundwater conditions are not important at the study-unit scale, they are important in describing trace element distribution in the Colorado River study area.

Figure 8 shows the distribution of the selected trace element concentrations with respect to redox classification and pH. The seven trace elements were put into four groups on the basis of correlations between trace element concentrations, redox class, and pH (table 6): (1) positively correlated with pH and greater in anoxic conditions than in oxic conditions—As; (2) positively correlated with pH and no significant difference between oxic and anoxic—Mo, F, V; (3) negatively correlated with pH and greater in oxic conditions—U; (4) no correlation with pH—B, Sr.

Arsenic

Arsenic concentrations were significantly higher in samples collected from wells tapping anoxic groundwater than in wells tapping oxic groundwater (table 6). In part, concentrations of As may be higher in anoxic rather than oxic samples because anoxic redox conditions tend to occur in relatively old groundwater where the dissolution of primary aquifer minerals has likely occurred to a greater extent due to the longer period of interaction between groundwater and minerals that compose aquifer matrices. Furthermore, anoxic samples tend to be more alkaline (higher pH), which could increase the mobility of As in the aqueous phase. In oxic and anoxic redox conditions, speciation modeling (SM) predicts

that As exists in a fully oxidized state (As^{5+}) primarily as the oxyanion HASO_4^{2-} (table 7). In alkaline conditions, HASO_4^{2-} is expected to be more mobile in groundwater as the variable surface charge on aquifer minerals becomes increasingly negative as pH increases, thus inhibiting the adsorption and (or) promoting the desorption of anionic species (Stumm, 1992). Reductive dissolution of secondary minerals, such as Fe-oxides, that can release adsorbed trace elements like As to the aqueous phase is not likely an important process under anoxic conditions as defined in this study. This is because reduction potentials are likely not low enough for oxide reduction to occur as is indicated by the low concentrations of Fe in anoxic samples.

Arsenic concentrations were lowest in anoxic-Fe groundwater (table 6; fig. 8). This was unexpected because dissolution of iron oxyhydroxides under iron-reducing conditions would normally release As into solution (Smedley and Kinniburgh, 2002; Welch and others, 2006; Izbicki and others, 2008). Geochemical modeling indicates that precipitation of As-bearing sulfide minerals may explain the low As concentrations in anoxic-Fe groundwater from the Colorado River study area.

In the sequence of reduction reactions that occur as reduction potential decreases, As is thermodynamically predicted to be reduced from As^{5+} to As^{3+} at lower reduction potentials than the potentials at which reduction of iron from Fe^{3+} to Fe^{2+} begins (Turner and others, 1981). Because reduction of sulfur from SO_4^{2-} to HS^- also begins at lower reduction potentials than the potentials at which reduction of iron from Fe^{3+} to Fe^{2+} begins (McMahon and Chapelle, 2008), SM for As in anoxic-Fe samples requires data for SO_4^{2-} and HS^- concentrations (Parkhurst and Appelo, 1999). A sulfide odor was detected in 7 of 12 anoxic-Fe samples collected; sulfide concentrations were determined for 3 of these samples (table 3). Dissolved arsenic species in samples with a sulfide odor were modeled using a sulfide concentration of 50 $\mu\text{g/L}$, which is half the lowest concentration of the three sulfide samples analyzed. Speciation modeling predicted that the uncharged H_3AsO_3 molecule would be the dominant species in sulfidic groundwater. Because an uncharged As species would not be attracted to charged mineral surfaces, thereby decreasing adsorption and increasing As concentrations in groundwater, As concentrations in the anoxic-Fe samples are likely affected by processes other than adsorption-desorption reactions. Calculated saturation indices (SI) for As-bearing minerals indicated that low As concentrations in anoxic-Fe samples may be partly due to precipitation of As-bearing minerals. SI calculations showed that anoxic-Fe samples are supersaturated with orpiment (As_2S_3 ; SI = -1.0 to 4.3, median = 1.2) and pyrite (FeS_2 , SI = 4.9 to 6.3, median = 5.2). Arsenic can co-precipitate with FeS_2 forming arsenopyrite (FeAsS) and other pyrite analogs (Lowers and others, 2007). Therefore, the low As concentrations observed in anoxic-Fe groundwater may be due in part to the precipitation of As-containing minerals.

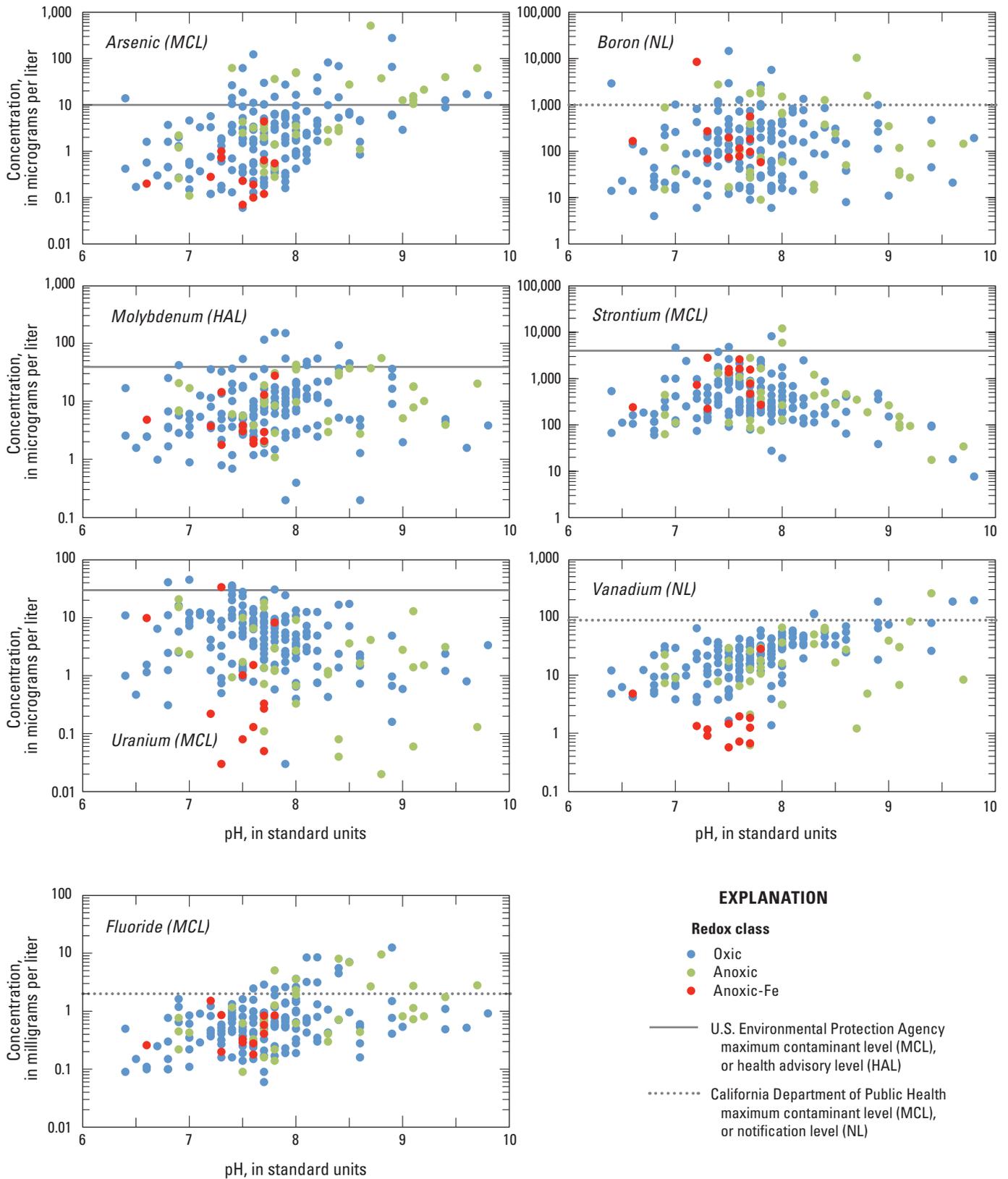


Figure 8. Distribution of selected trace element concentrations with respect to redox classification and pH, Desert and Basin and Range study unit, California GAMA Priority Basin Project.

Low concentrations of As in anoxic-Fe groundwater could also be due to lack of source material and (or) the flushing of groundwater with surface water that has relatively low concentrations of As.

Previous investigations have indicated two primary mechanisms for elevated arsenic concentrations in groundwater (Welch and others, 2000; Stollenwerk, 2003; Welch and others, 2006). One is the release of arsenic resulting from reductive dissolution of iron or manganese oxyhydroxides, and the other is desorption of arsenic from mineral surfaces under oxic, alkaline conditions. The results from this study indicate that the latter mechanism is more important in the DBR study unit.

Vanadium, Molybdenum, and Fluoride

V concentrations in oxic and anoxic groundwater were not significantly different; however, V concentrations in anoxic-Fe groundwater were significantly lower than in either oxic or anoxic groundwater (table 6). In oxic and anoxic redox conditions, SM predicts that V is in a fully oxidized state (V^{5+}) primarily as the oxyanion $H_2VO_4^-$ (table 7). In this form, V is expected to be more mobile in alkaline conditions than in neutral or acidic conditions because repulsive forces from negatively charged mineral surfaces decrease adsorption of negatively charged species. Within the DBR study unit, V concentrations showed a significant positive correlation to pH (table 6), indicating that V is more mobile in oxic and alkaline groundwater. The positive correlation between V concentrations and oxic and alkaline groundwater conditions observed in this study was also observed in a study that examined the distribution of V concentrations in groundwater throughout the State of California (Wright and Belitz, 2010).

The distribution of V concentrations in anoxic-Fe samples indicates that V is sparingly soluble when reduction potentials are low enough for Fe reduction to occur. Vanadium concentrations in anoxic-Fe samples did not exceed 1.8 $\mu\text{g/L}$, and 92 percent of the samples had concentrations $<0.8 \mu\text{g/L}$. Speciation modeling predicts that soluble V exists as the uncharged $V(\text{OH})_3$ molecule in anoxic-Fe redox conditions (table 7). If V did exist as an uncharged, aqueous species, concentrations would be higher in anoxic-Fe groundwater because adsorption to charged mineral surfaces would be mitigated. A laboratory study conducted by Wanty and Goldhaber (1992) showed that H_2S is capable of reducing V^{4+} to V^{3+} and that V^{3+} subsequently precipitates as a solid oxyhydroxide. Hydrogen sulfide detected in anoxic-Fe samples occurred at lower concentrations than those used in the laboratory experiments. Nevertheless, the detection of H_2S indicates that the precipitation of V^{3+} oxyhydroxide may be a viable mechanism for the removal of aqueous V in anoxic-Fe groundwater. Additionally, a study by Wright and others (2014) indicated that in anoxic-Fe groundwater, V^{3+} may be removed from the aqueous phase by co-precipitating with Fe^{3+} to form mixed (Fe,V)-oxide minerals.

Like As and V, Mo was predicted to exist primarily in an oxyanionic form. Unlike As and V, Mo concentrations were not significantly correlated to redox conditions (table 6). Speciation modeling predicts that molybdenum exists primarily in an uncomplexed form as the oxyanion MoO_4^{2-} (table 7). The prediction that Mo exists primarily as an oxyanion is in agreement with the variations of Mo concentrations observed with respect to the pH of groundwater. Molybdenum concentrations generally increased with increasing high pH values, although the correlation was weaker than for that of As and V.

F concentrations were not significantly associated with any redox conditions. This is likely due to the fact the F is not a redox sensitive element, and therefore its speciation, and consequently adsorption and precipitation behavior in groundwater, is not directly affected by the redox conditions of groundwater. F was predicted by SM to exist primarily as a negatively charged species (table 7). As a negatively charged species, F^- would be repelled from negatively charged mineral surface, thus increasing its solubility in groundwater. This hypothesis is supported by the significant positive correlation of F concentrations with pH.

Uranium

Uranium concentrations are significantly higher in oxic groundwater than in either anoxic or anoxic-Fe groundwater (fig. 8; table 6). Uranium may be less soluble in anoxic-Fe redox conditions because the predominant form of U in reducing conditions is U^{4+} , which has low solubility and tends to precipitate as uraninite (Langmuir, 1997). If sulfide concentrations of 50 $\mu\text{g/L}$ are assumed for anoxic-Fe samples, SM predicts that uraninite (UO_2) would be supersaturated (SI = 0.7 to 3.5, median = 1.6) in anoxic-Fe samples. Therefore, under anoxic-Fe groundwater conditions, U concentrations may be controlled by mineral precipitation.

In oxic and alkaline conditions, the predominant oxidation state of U in groundwater is U^{6+} , and concentrations are primarily controlled by adsorption/desorption reactions (Hsi and Langmuir, 1985; Davis and Curtis, 2003). U^{6+} will form the uranyl (UO_2^{+2}) cation in the absence of complexing ions, such as HCO_3^- . However, complexing ions are generally abundant in groundwater, and samples collected in the DBR study unit are predicted to exist as an uncharged ternary complex $Ca_2UO_2(\text{CO}_3)_3$ (table 7). The results of previous studies have indicated that this uncharged ternary complex is responsible for increased U mobility in groundwater (Bernhard and others, 2001; Fox and others, 2006; Jurgens and others, 2010). Uranium concentrations in samples from the DBR study unit generally decreased with increasing pH values (fig. 8) indicating that reactions other than adsorption/desorption are controlling the solubility of U in solution at alkaline pH values. Further discussions on the controls on U solubility are presented later in this report.

Boron and Strontium

B was predicted by SM to only exist in a single oxidation state in groundwater sampled in the DBR study unit (table 7). Boron concentrations were significantly higher in samples collected from wells tapping anoxic rather than oxic groundwater (table 6). The positive correlation with anoxic redox conditions for B may be due in part to the fact the anoxic samples generally had older groundwater ages than oxic samples (table 4). SM predicts that B exists predominantly as an uncharged molecule, H_3BO_3 , at pH values <9.2 and predominantly as an anion, H_2BO_3^- , at pH values >9.2 . A study by Goldberg and Glaubig (1986) showed that B adsorption was greatest between pH values of 8.5 and 10. However, B concentrations in samples collected in the DBR study unit were not significantly correlated with pH values (table 6).

Sr was also predicted to only exist in a single oxidation state in groundwater sampled in the DBR study unit. Concentrations of Sr were higher in anoxic-Fe groundwater than in oxic or anoxic groundwater (table 6). Because Sr was predicted to exist in only one oxidation state, the association between anoxic-Fe groundwater and higher Sr concentrations likely reflects processes other than oxidation-reduction-related processes. Sr concentrations showed a strong positive correlation with TDS concentrations (table 6), and TDS concentrations were significantly greater in anoxic-Fe groundwater (table 4). The relation of TDS and Sr concentrations is discussed more in the following section. Although Sr concentrations were not correlated with pH over the full range of pH values (fig. 8; table 6), Sr concentrations showed a negative correlation with pH for pH values ≥ 8.0 (Spearman's test, p -value <0.001 , $\rho = -0.48$). SM predicted that Sr predominantly exists as the cation Sr^{2+} (table 7). The negatively charged mineral surfaces that predominate at alkaline pH values would favor adsorption of cationic species as pH increased, thereby decreasing the aqueous concentration of Sr. Additionally, Sr may also be removed from the aqueous phase by co-precipitating with calcite and (or) aragonite (Banner, 1995; Reimann and de Caritat, 1998).

Relation to Major Ion and Phosphate Content

Complexation reactions with major ions and phosphate can play an important role in influencing the solubility of trace elements in groundwater (Violante and others, 2007). Trace elements that exist primarily as oxyanionic or anionic species (table 7) can form complexes with alkali earth metals, and trace elements that exist as oxycationic or cationic species can form complexes with inorganic ligands. Complexes of cationic species with organic ligands, such as oxalate, are also important, but are not addressed in this report because organic ligand content in samples were not determined as part of this study. Trace element complexes with major ions and phosphate can increase or decrease solubility by altering

adsorption/desorption characteristics or by inducing the precipitation of mineral phases. For example, the anionic species of Mo (MoO_4^{2-}) can form uncharged complexes with the alkali earth metals Ca^{2+} and Mg^{2+} (CaMoO_4 and MgMoO_4) that may increase the solubility of Mo in groundwater (Essington, 1992). However, if the geochemical conditions are right and minerals are supersaturated in groundwater, then Mo and Ca complexes can lead to the precipitation of the mineral powellite (CaMoO_4), thereby removing Mo from the aqueous phase (Conlan and others, 2012). Boron also has been shown to form complexes with Ca and Mg [$\text{CaB}(\text{OH})_4^+$ and $\text{MgB}(\text{OH})_4^+$], which may be important at alkaline pH values (Mattigod and others, 1985; Goldberg and Suarez, 2011). In groundwater, the cationic species of U (UO_2^{2+}) forms complexes with the inorganic ligand HCO_3^- , which can increase the solubility of U in groundwater (Fox and others, 2006; Jurgens and others, 2010). Conversely, complexes of UO_2^{2+} with phosphate (PO_4^{3-}) can decrease the solubility of U at acidic to near-neutral pH values (Payne and others, 1998).

Effects of Complexation and Mineral Precipitation on the Distribution of Molybdenum and Fluoride

Speciation modeling predicted that MoO_4^{2-} and F^- are the only oxyanionic/anionic species to form complexes with alkali earth metals in groundwater sampled in the DBR study unit (table 7). Mo forms aqueous complexes with Na (NaMoO_4^-), Ca (CaMoO_4), and Mg (MgMoO_4), although the uncomplexed form of Mo is the predominant species in the majority of samples. The negatively charged NaMoO_4^- complexes rarely consist of more than 20 percent of the total Mo in solution (table 7) and are therefore not to be expected to significantly affect the distribution of Mo concentrations in groundwater. The uncharged species, CaMoO_4 and MgMoO_4 , are more frequently predicted to occur in samples collected in the DBR study unit. These uncharged species would be expected to be more mobile in groundwater because they would not be attracted to the surface charge of minerals. The distribution of Mo concentrations, however, shows no significant increase with increasing percentage of CaMoO_4 and MgMoO_4 species in samples (Spearman's $\rho = 0.004$, p -value = 0.95). Saturation indices obtained from speciation modeling indicate that the mineral powellite (CaMoO_4) is undersaturated in all samples and thus is not indicated as an important factor in controlling the solubility of Mo.

Aqueous complexes of F with Ca and Mg (CaF^+ and MgF^+) were predicted to only occur to a small extent and are thus not likely an important factor controlling F concentrations in groundwater (table 7). Calculation of SIs indicated the precipitation of the mineral fluorapatite [$\text{Ca}_5(\text{PO}_4)_3\text{F}$] may be a factor in controlling F solubility (fig. 9A). Saturation indices for fluorapatite ranged from -8.3 to 6.1 with a median of 0.4 . Conversely, fluorite (CaF_2), a mineral that has been attributed to controlling F solubility in groundwater in other

hydrogeologic settings (Jacks and others, 2005; Chae and others, 2007), was undersaturated in most samples (SI range = -4.0 to 0.4, median = -1.8).

The precipitation of fluorapatite occurs by the following reaction (Ball and Nordstrom, 1991):



According to the law of mass action, when the reaction is at or near equilibrium, fluorapatite precipitation is proportional to the concentrations of Ca^{2+} , PO_4^{3-} , and F^- in groundwater and inversely proportional to the H^+ concentration. From a pH of 6.4 to 7.3, fluorapatite is predominantly undersaturated in samples (fig. 9B). At low pH values, high concentrations of H^+ coupled with low concentrations of F and Ca (figs. 8, 9C) favor the dissolution of fluorapatite. However, F solubility at this pH range may be limited by adsorption reactions because mineral surfaces will have a relatively high density of positive charge. Above a pH of approximately 7.3, F solubility may be controlled by mineral precipitation. Saturation index calculations predicted that groundwater in the DBR study unit with pH greater than about 7.3 becomes increasingly more supersaturated with fluorapatite (fig. 9B), which approximately corresponds with peak concentrations of Ca^{2+} and PO_4^{3-} (figs. 9C, D); the precipitation of fluorapatite would decrease F concentrations in groundwater. However, at alkaline pH values, Ca^{2+} can be removed from solution through cation-exchange reactions and precipitation of carbonate minerals such as calcite (CaCO_3), and phosphate may be removed from solution through hydroxylapatite [$\text{Ca}_5(\text{PO}_4)_3\text{OH}$] precipitation, which is predicted to be favored over fluorapatite precipitation at increasingly higher pH values (fig. 9B). Precipitation of calcite and hydroxylapatite would decrease Ca and P concentrations and thereby increase the amount of F that could remain in solution without causing precipitation of fluorapatite. This process may partially be responsible for the positive correlation between pH and F.

Slow-reaction kinetics may provide a barrier to the precipitation of calcium phosphate minerals such as fluorapatite and hydroxylapatite. However, laboratory studies have shown that poorly crystalline hydroxylapatite will precipitate in relatively short time periods in a simplified system such as $\text{Ca}(\text{OH})_2\text{-H}_3\text{PO}_4\text{-H}_2\text{O}$ (Zawacki and others, 1990; Borkiewicz and others, 2010). Wright and others (2011) showed that poorly crystalline hydroxylapatite formed in a synthetic groundwater within a week at 25 degrees Celsius ($^{\circ}\text{C}$). Phosphate concentrations in that experiment were three

orders of magnitude greater than the phosphate concentrations of the groundwater sampled in this study. Nevertheless, these studies indicate that the precipitation of fluorapatite and hydroxylapatite may be a viable control of F solubility in groundwater in the DBR study unit.

Effects of Complexation and Mineral Precipitation on the Distribution of Uranium

In oxic conditions, and in the absence of complexing ions, U is thermodynamically predicted to exist as the UO_2^{2+} oxyanion. However, in groundwater, Ca and $\text{HCO}_3^-/\text{CO}_3^{2-}$ will complex with dissolved U (Bernhard and others, 2001; Dong and others, 2005). Speciation modeling predicted that U predominantly exists as the ternary complex $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ in samples collected in the DBR study unit (table 7). Because it is an uncharged molecule, the formation of this ternary complex increases the solubility of U in groundwater because it is not attracted to charged particle surfaces. The increased solubility of U due to the formation of the $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ ternary complex is supported by the significant positive correlation between the percentage of total U that is predicted to exist as $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ and the total U concentration in samples (Spearman's rho = 0.28, p-value = 0.00). Except for one sample, U does not occur at concentrations greater than one-half the MCL-US of 30 $\mu\text{g/L}$ if the predicted percentage of $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ is not greater than 70 percent (fig. 10A).

SM predicted that the U-PO_4^{3-} complex, $\text{UO}_2(\text{HPO}_4)_2^{2-}$, was present in groundwater sampled in the DBR study unit. On a study-unit scale, $\text{UO}_2(\text{HPO}_4)_2^{2-}$ complexes were predicted to be the dominant U species in only 8 percent of samples. On a study-area scale, the $\text{UO}_2(\text{HPO}_4)_2^{2-}$ complex was fairly prevalent in the Owens Valley study area and was the dominant U species in 32 percent of samples. Previous studies have shown that under acidic to neutral pH conditions, negatively charged U-PO_4^{3-} complexes strongly adsorb to iron oxide surfaces (Payne and others, 1998; Cheng and others, 2004). The pH values of samples from the Owens Valley study area, where $\text{UO}_2(\text{HPO}_4)_2^{2-}$ was dominant, ranged from 6.4 to 8.4 with 14 of 17 measurements being ≤ 7.0 . Samples that were predicted to have the $\text{UO}_2(\text{HPO}_4)_2^{2-}$ complex as the dominant U species in solution had significantly lower U concentrations than samples where $\text{UO}_2(\text{HPO}_4)_2^{2-}$ was not the dominant species in solution (Wilcoxon Rank Sum, p = 0.05). This result indicates that the $\text{UO}_2(\text{HPO}_4)_2^{2-}$ complex decreases the solubility of U in groundwater sampled in the Owens Valley study area.

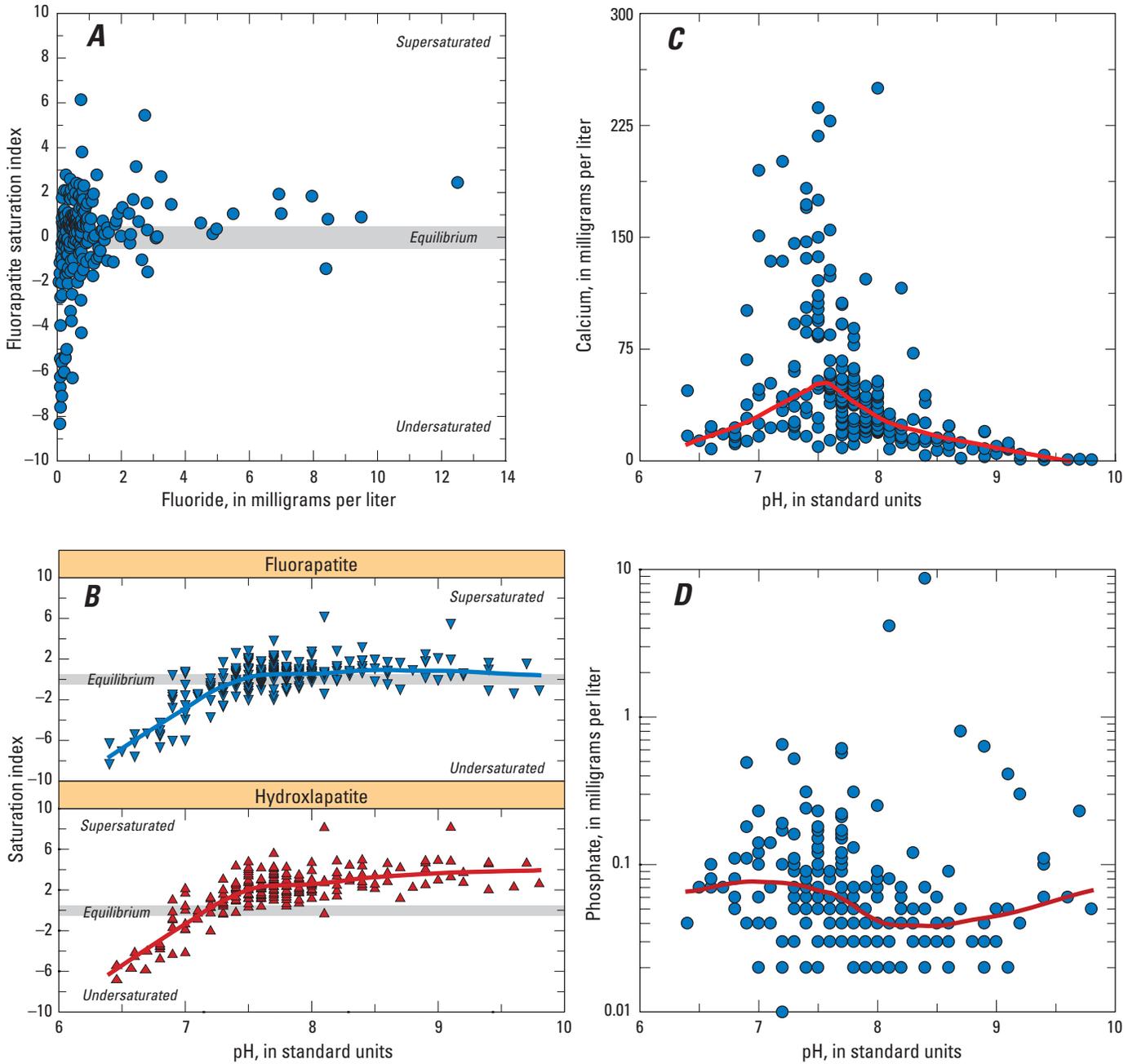


Figure 9. Factors affecting the solubility of fluoride in groundwater: (A) Relation of fluoride concentrations to saturation indices of fluorapatite, (B) relation of pH to the saturation indices of fluorapatite and hydroxylapatite, (C) distribution of calcium in samples with regard to pH, and (D) distribution of phosphate in samples with regard to pH, Desert and Basin and Range study unit, California GAMA Priority Basin Project. Trend lines for figs. 9B–D are Lowess smoothing curves.

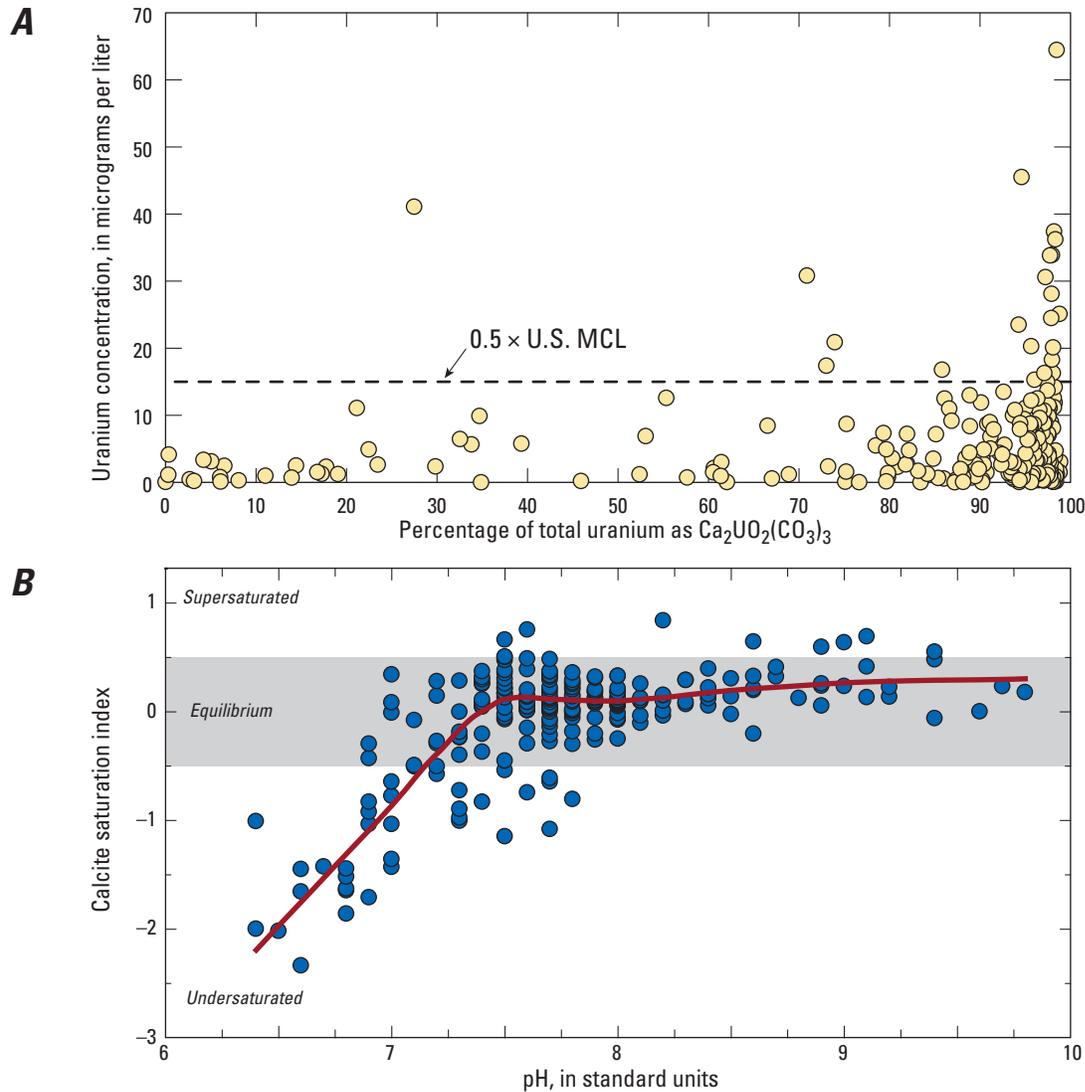


Figure 10. Factors affecting the solubility of uranium in groundwater: (A) Relation of the percentage of total uranium that exists as $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ and uranium concentrations in samples, and (B) relation of pH to the saturation index of calcite, Desert and Basin and Range study unit, California GAMA Priority Basin Project. Trend line is Lowess smoothing curve.

Uranium concentrations showed a negative correlation with pH (fig. 8; table 6). At increasingly alkaline pH values, adsorption processes are not likely an important solubility limit on U in groundwater because $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ and $\text{UO}_2(\text{CO}_3)_3^{4-}$ are predicted to be the predominant U species at pH values ≥ 8 . SI calculations indicate that U minerals are well undersaturated in all samples and thus are not likely a control on U solubility. However, the co-precipitation of U with CaCO_3 may be a viable mechanism to explain decreases in U concentrations with increasing pH. The co-precipitation of U^{6+} with CaCO_3 has been confirmed in laboratory studies (Meece and Benninger, 1993; Reeder and others, 2001), and U has

been identified as a component of naturally occurring calcite minerals (Kelly and others, 2003, 2006). CaCO_3 is generally undersaturated in solution at acidic to neutral pH values (fig. 10B). At pH values >7.0 , SIs show that samples are predominantly in equilibrium with CaCO_3 and trend towards increasingly more supersaturated conditions with increasing pH. This indicates that CaCO_3 may be precipitating to a greater extent as the pH of groundwater becomes increasingly more alkaline. The co-precipitation of U with CaCO_3 would be in agreement with the variation of U concentrations with respect to pH values observed for samples collected in the DBR study unit.

Relation of Total Dissolved Solids and Trace Elements

As, B, F, Mo, and Sr concentrations had significant positive correlations with TDS concentrations (table 6). Part of the reason for this correlation may be the dissolution of minerals and amorphous phases that compose aquifer matrices; dissolution of minerals releases trace elements to the aqueous phase while simultaneously increasing the TDS concentration of groundwater. However, as discussed in preceding sections, the trace elements presented in this report interact with the surfaces of aquifer matrices and thus do not behave conservatively. Therefore, correlation of trace element concentrations with TDS also may be caused by the effects that the ionic strength of groundwater has on adsorption/desorption reactions due to complexation reactions and competitive ion effects.

Ionic strength is related to the electrolyte concentration in solution and is a measure of the interaction of ions in solution (Sparks, 1995). Ionic strength (I) can be estimated from TDS concentrations by the following equation (Wang and others, 2005):

$$I = (2.5 \times 10^{-5})(TDS). \quad (4)$$

This relation shows that ionic strength increases with increasing TDS. Ionic strength is used as an indirect measurement to determine the type of adsorption reactions (inner-sphere versus outer-sphere) that occur with trace elements at the mineral–water interface (Violante and others, 2007). An increase in trace element concentration with increasing ionic strength or TDS indicates that a trace element interacts with mineral surfaces by way of relatively weak outer-sphere coordination (McBride, 1997). Conversely, trace elements whose concentrations are not, or are only slightly, affected by ionic strength are thought to interact with mineral surfaces through inner-sphere coordination.

Results from this study indicate that Sr, a constituent known to interact with particle surfaces through outer-sphere complexes (Chen and others, 1998), has a significant positive correlation to TDS (table 6). B concentrations also showed a significant positive correlation to TDS in samples collected from the DBR study unit. B adsorption can occur by way of both outer- and inner-sphere coordination (Peak and others, 2003; Goldberg, 2005), which may explain the lower strength of the statistical correlation between B and TDS as compared to that of Sr and TDS. Conversely As and V show weak or no significant correlation with TDS concentrations. Both of these trace elements, in their most oxidized form, have been shown to interact with mineral surfaces through inner-sphere coordination (Foster, 2003; Peacock and Sherman, 2004) and therefore would not be expected to be greatly affected by variations in TDS concentrations in groundwater.

Conclusions

The geochemical conditions of the groundwater sampled in the DBR study unit are predominantly oxidic and alkaline and are coupled with generally older groundwater ages. The major ion classification (water type) was primarily sodium-type with respect to cations and bicarbonate-type with respect to anions. Young groundwater generally came from wells near mountain-front recharge areas and was characterized by calcium-type waters with near-neutral pH values. Older groundwater generally came from wells located away from mountain-front recharge areas and was characterized by sodium-type water with alkaline pH values. The dominance of sodium over calcium in older groundwater may be due to cation-exchange processes where the replacement of sodium ions adsorbed to mineral surfaces by dissolved calcium ions occurs over time. The correlation of alkaline pH values with old groundwater ages may be due to pH being primarily controlled by the dissolution of silicate minerals, which is a process that takes place over long periods of time. Oxidic redox conditions were predominant throughout the DBR study unit, likely because the aquifer systems are low in electron-rich organic matter needed to support redox processes that promote reducing groundwater conditions.

Concentrations for the majority of trace elements (As, Mo, V, and F) examined in this study had significant positive correlations to groundwater age and pH. The correlation with groundwater age is likely due in part to the long time periods required for the dissolution of trace-element-containing silicate minerals to occur. The correlation with groundwater age is also likely due to the fact the older groundwater is generally alkaline in pH. Because As, Mo, V, and F are predicted to primarily exist as uncomplexed oxyanions and anions (HAsO_4^{2-} , MoO_4^{2-} , H_2VO_4^- , and F^-), these trace elements should be more soluble in alkaline groundwater where the variable surface charge of minerals is predominantly negative. In addition to adsorption/desorption reactions, F solubility may also be limited due to the precipitation of the mineral fluorapatite, which saturation indices indicate may be important at near neutral to slightly alkaline pH values. B concentrations also had a significant positive correlation to groundwater age. However, unlike As, F, Mo, and V, B exists primarily as the uncharged species H_3BO_3 and thus adsorption/desorption reactions are not likely as an important factor controlling B solubility; this hypothesis is supported by the lack of a significant correlation between B concentrations and pH.

U concentrations had a significant negative correlation with groundwater age and pH, which is likely due to a combination of processes. One process could be that contributing sources of U are relatively labile minerals, such as U-substituted carbonate minerals, which dissolve relatively quickly. Another, perhaps more important process, is the mobilization of adsorbed U from mineral surfaces by

HCO_3^- and the subsequent formation of the uncharged ternary complex $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$. At increasingly more alkaline pH values, calcite becomes supersaturated in solution, indicating that U may be co-precipitating with calcite. The formation of an uncharged U complex at acidic to slightly alkaline pH values and the co-precipitation of U with calcite at more alkaline pH values is consistent with the correlations of groundwater age, pH, and U concentrations observed in this study.

Sr concentrations showed a strong correlation with TDS, but no significant correlation with either groundwater age or pH. The relation of Sr concentrations with TDS may be due to the effect that competitive ions have on dissolved constituents, such as Sr, that interact with the mineral surface through outer-sphere complexation reactions. Although Sr concentrations were not correlated with pH over the full range of pH values, Sr concentrations showed a negative correlation with pH for values ≥ 8.0 . This correlation indicates that the adsorption of the Sr^{2+} on negatively charged mineral surfaces and (or) removal from the aqueous phase by co-precipitation with carbonate minerals are limiting Sr concentrations in alkaline groundwater. B concentrations were also strongly correlated with TDS, indicating that competitive ion effects may be an important factor in controlling B solubility in the DBR study unit.

Oxic redox conditions in groundwater were predominant throughout the DBR study unit, and thus anoxic-Fe redox conditions were only an important factor in the Colorado River study area. Under anoxic-Fe conditions, saturation indices indicate that mineral precipitation of orpiment and pyrite may be limiting As solubility and that uraninite precipitation may be limiting U solubility. Saturation indices did not indicate the precipitation of V-containing minerals. However, the relatively low concentrations of V in anoxic-Fe conditions suggest that V may be precipitating as an insoluble phase which is consistent with the findings of previous studies.

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References

- Appelo, C.A.J., and Postma, D., 2005, *Geochemistry, groundwater and pollution* (2d ed.): Leiden, The Netherlands, A.A. Balkema Publishers, 649 p.
- Ball, J.W., and Nordstrom, D.K., 1991, WATEQ4F—User's manual with revised thermodynamic data base and test cases for calculating speciation of major, trace and redox elements in natural waters: U.S. Geological Survey Open-File Report 90-129, 185 p.
- Banner, J.L., 1995, Application of the trace element and isotope geochemistry of strontium to studies of carbonate diagenesis: *Sedimentology*, v. 42, no. 5, p. 805-824.
- Belitz, Kenneth, Dubrovsky, N.M., Burow, Karen, Jurgens, Bryant, and John, Tyler, 2003, Framework for a groundwater quality monitoring and assessment program for California: U.S. Geological Survey Water-Resources Investigations Report 2003-4166, 78 p. (Also available at <http://pubs.usgs.gov/wri/wri034166/>.)
- Berenbrock, Charles, and Martin, P.M., 1991, The groundwater flow system in Indian Wells Valley, Kern, Inyo, and San Bernardino Counties, California: U.S. Geological Survey Water-Resources Investigations Report 89-4191, 81 p. (Also available at <http://pubs.usgs.gov/wri/1989/4191/report.pdf>.)
- Berenbrock, Charles, and Schroeder, R.A., 1994, Groundwater flow and quality, and geochemical processes, in Indian Wells Valley, Kern, Inyo, and San Bernardino Counties, California, 1987-88: U.S. Geological Survey Water-Resources Investigations Report 93-4003, 59 p. (Also available at <http://pubs.usgs.gov/wri/1993/4003/report.pdf>.)
- Bernhard, G., Geipel, G., Reich, T., Brendler, V., Amayri, S., and Nitsche, H., 2001, Uranyl (VI) carbonate complex formation—Validation of the $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ (aq.) species: *Radiochimica Acta*, v. 89, no. 8, p. 511-518.
- Borkiewicz, Olaf, Rakovan, John, and Cahill, C.L., 2010, Time-resolved in situ studies of apatite formation in aqueous solutions: *American Mineralogist*, v. 95, p. 1224-1236.
- California Department of Public Health, 2008, California drinking water-related laws—Drinking water-related regulations, Title 22: California Department of Public Health, accessed July 25, 2014, at <http://www.cdph.ca.gov/certlic/drinkingwater/Pages/Lawbook.aspx>.

- California Department of Public Health, 2010, Drinking water notification levels and response levels, an overview: California Department of Public Health, Drinking Water Program, accessed March 2013 at <http://www.cdph.ca.gov/certlic/drinkingwater/Documents/Notificationlevels/notificationlevels.pdf>.
- California Department of Water Resources, 2003, California's groundwater: California Department of Water Resources Bulletin 118, update 2003, 246 p., accessed July 22, 2014, at http://www.water.ca.gov/pubs/groundwater/bulletin_118/california's_groundwater_bulletin_118_-_update_2003/bulletin118_entire.pdf, http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/7-36.pdf, http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/7-38.pdf, http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/7-44.pdf.
- California Department of Water Resources, 2004, California's groundwater—Individual basin descriptions, Borrego Valley: California Department of Water Resources Bulletin 118, accessed October 12, 2010, at http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/7-24.pdf.
- California State Water Resources Control Board, 2003, A comprehensive groundwater quality monitoring program for California: Assembly Bill 599—Report to the Governor and Legislature, March 2003, 100 p., accessed May 2013 at http://www.waterboards.ca.gov/gama/docs/final_ab_599_rpt_to_legis_7_31_03.pdf.
- California State Water Resources Control Board, 2009, Geotracker GAMA: State Water Resources Control Board database accessed December 20, 2013, at <https://geotracker.waterboards.ca.gov/gama/>.
- Chae, G.-T., Yun, S.-T., Mayer, Bernhard, Kim, K.-H., Kim, S.-Y., Kwon, J.-S., Kim, Kangjoo, and Koh, Y.-K., 2007, Fluorine geochemistry in bedrock groundwater of South Korea: *Science of the Total Environment*, v. 385, no. 1–3, p. 272–283.
- Chen, C.-C., Hapelis, C., and Hayes, K.F., 1998, Extended x-ray absorption fine structure (EXAFS) analysis of aqueous Sr(II) ion sorption at clay-water interfaces, *in* Jenne, E.A., ed., Adsorption of metals by geomedia—Variables, mechanisms, and model applications: San Diego, California, Academic Press, p. 333–348.
- Cheng, Tao, Barnett, M.O., Roden, E.E., and Zhuang, Jinling, 2004, Effects of phosphate on uranium (VI) adsorption to goethite-coated sand: *Environmental Science & Technology*, v. 38, no. 22, p. 6059–6065.
- Clark, I.D., and Fritz, Peter, 1997, Environmental isotopes in hydrogeology: New York, Lewis Publishers, 328 p.
- Conlan, M.J., Mayer, K.U., Blaskovich, Randy, and Beckie, R.D., 2012, Solubility controls for molybdenum in neutral rock drainage: *Geochemistry—Exploration, Environment, Analysis*, v. 12, no. 1, p. 21–32, accessed July 22, 2014, at <http://dx.doi.org/10.1144/1467-7873/10-RA-043>.
- Danskin, W.R., 1998, Evaluation of the hydrologic system and selected water-management alternatives in the Owens Valley, California: U.S. Geological Survey Water-Supply Paper 2370–H, 175 p. (Also available at <http://pubs.usgs.gov/wsp/2370h/report.pdf>.)
- Davis, J.A., and Curtis, G.P., 2003, Application of surface complexation modeling to describe uranium (VI) adsorption and retardation at the uranium mill tailings site at Naturita, Colorado: Rockville, Maryland, U.S. Nuclear Regulatory Commission Report NUREG/CR-6820, 223 p., accessed February 17, 2014, at <http://www.nrc.gov/reading-rm/docollections/nuregs/contract/cr6820/>.
- Dawson, B.J.M., and Belitz, Kenneth, 2013, Status of groundwater quality in the California Desert Region, 2006–2008—California GAMA Priority Basin Project: U.S. Geological Survey Scientific Investigations Report 2012–5040, 110 p. (Also available at <http://pubs.usgs.gov/sir/2012/5040/>.)
- Densmore, J.N., Fram, M.S., and Belitz, Kenneth, 2009, Ground-water quality data in the Owens and Indian Wells Valleys study unit, 2006—Results from the California GAMA Program: U.S. Geological Survey Data Series 427, 88 p. (Also available at <http://pubs.usgs.gov/ds/427/>.)
- Dong, Wenming, Ball, W.P., Liu, Chongxuzn, Wang, Zheming, Stone, A.T., Bai, Jing, and Zachara, J.M., 2005, Influence of calcite and dissolved calcium on uranium (VI) sorption to a Hanford subsurface sediment: *Environmental Science & Technology*, v. 39, no. 20, p. 7949–7955.
- Dong, Wenming, and Brooks, S.C., 2006, Determination of the formation constants of ternary complexes of uranyl and carbonate with alkaline earth metals (Mg^{2+} , Ca^{2+} , Sr^{2+} , and Ba^{2+}) using anion exchange method: *Environmental Science & Technology*, v. 40, no. 15, p. 4689–4695, accessed July 22, 2014, at <http://dx.doi.org/10.1021/es0606327>.
- Drever, J.I., 1997, The geochemistry of natural waters—Surface and groundwater environments: Upper Saddle River, New Jersey, Prentice Hall, Inc., 436 p.
- Duell, L.F.W., Jr., 1987, Geohydrology of the Antelope Valley area, California, and design for a ground-water-quality monitoring network: U.S. Geological Survey Water-Resources Investigations Report 84–4081, 72 p. (Also available at <http://pubs.usgs.gov/wri/1984/4081/report.pdf>.)

- Eaton, A.D., and Franson, M.A.H., eds., 2005, American Public Health, American Water Works, Water Environment—Standard methods for the examination of water & wastewater (21st ed.): Washington D.C., American Public Health Association.
- Essington, M.E., 1990, Calcium molybdate solubility in spent oil shale and a preliminary evaluation of the association constants for the formation of CaMoO_4^0 , KMoO_4^- , and NaMoO_4^- : *Environmental Science & Technology*, v. 24, no. 2, p. 214–220, accessed July 22, 2014, at <http://dx.doi.org/10.1021/es00072a010>.
- Essington, M.E., 1992, Formation of calcium and magnesium molybdate complexes in dilute aqueous solutions: *Soil Science Society of America Journal*, v. 56, no. 4, p. 1124–1127.
- Foster, A.L., 2003, Spectroscopic investigations of arsenic species in solid phases, in Welch, A.H., and Stollenwerk, K.G., eds., *Arsenic in ground water*: Boston, Massachusetts, Kluwer Academic Publishers, p. 27–65.
- Fox, P.M., Davis, J.A., and Zachara, J.M., 2006, The effect of calcium on aqueous uranium(VI) speciation and adsorption to ferrihydrite and quartz: *Geochimica et Cosmochimica Acta*, v. 70, no. 6, p. 1379–1387, accessed July 22, 2014, at <http://dx.doi.org/10.1016/j.gca.2005.11.027>.
- Goldberg, Sabine, 2005, Inconsistency in the triple layer model description of ionic strength dependent boron adsorption: *Journal of Colloid and Interface Science*, v. 285, no. 2, p. 509–517, accessed July 22, 2014, at <http://dx.doi.org/10.1016/j.jcis.2004.12.002>.
- Goldberg, Sabine, and Glaubig, R.A., 1986, Boron adsorption on California soils: *Soil Science Society of America Journal*, v. 50, no. 5, p. 1173–1176, accessed July 22, 2014, at <http://dx.doi.org/10.2136/sssaj1986.03615995005000050016x>.
- Goldberg, Sabine, and Suarez, D.L., 2011, Influence of soil solution cation composition on boron adsorption by soils: *Soil Science*, v. 176, no. 2, p. 80–83.
- Goldrath, D.A., Wright, M.T., and Belitz, Kenneth, 2009, Ground-water quality data in the Coachella Valley study unit, 2007—Results from the California GAMA Program: U.S. Geological Survey Data Series 373, 71 p. (Also available at <http://pubs.usgs.gov/ds/373/>.)
- Goldrath, D.A., Wright, M.T., and Belitz, Kenneth, 2010, Groundwater-quality data in the Colorado River study unit, 2007—Results from the California GAMA Program: U.S. Geological Survey Data Series 474, 66 p. (Also available at <http://pubs.usgs.gov/ds/474/>.)
- Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 510 p. (Also available at <http://water.usgs.gov/pubs/twri/twri4a3/>.)
- Hereford, Richard, Webb, R.H., and Longpre, C.I., 2004, Precipitation history of the Mojave Desert region, 1893–2001: U.S. Geological Survey Fact Sheet 117–03, 4 p. (Also available at <http://pubs.usgs.gov/fs/fs117-03/>.)
- Hollett, K.J., Danskin, W.R., McCaffrey, W.F., and Walti, C.L., 1991, Geology and water resources of Owens Valley, California: U.S. Geological Survey Water-Supply Paper 2370–B, 77 p. (Also available at <http://pubs.usgs.gov/wsp/2370b/report.pdf>.)
- Hsi, C.-K.D., and Langmuir, Donald, 1985, Adsorption of uranyl onto ferric oxyhydroxides—Application of the surface complexation site-binding model: *Geochimica et Cosmochimica Acta*, v. 49, no. 9, p. 1931–1941, accessed July 22, 2014, at [http://dx.doi.org/10.1016/0016-7037\(85\)90088-2](http://dx.doi.org/10.1016/0016-7037(85)90088-2).
- Izbicki, J.A., Clark, D.A., Pimentel, M.I., Land, M.T., Radyk, J.C., and Michel, R.L., 2000, Data from a thick unsaturated zone underlying the Oro Grande and Sheep Creek Washes in the western part of the Mojave Desert, near Victorville, San Bernardino County, California: U.S. Geological Survey Open-File Report 2000–262, 133 p. (Also available at <http://pubs.usgs.gov/of/2000/0262/report.pdf>.)
- Izbicki, J.A., and Michel, R.L., 2004, Movement and age of ground water in the western part of the Mojave Desert, southern California, USA: U.S. Geological Survey Water-Resources Investigations Report 2003–4314, 42 p. (Also available at <http://pubs.usgs.gov/wri/wrir034314/>.)
- Izbicki, J.A., Stamos, C.L., Metzger, L.F., Halford, K.J., Kulp, T.R., and Bennett, G.L., 2008, Source, distribution, and management of arsenic in water from wells, Eastern San Joaquin Ground-Water Subbasin, California: U.S. Geological Survey Open-File Report 2008–1272, 8 p. (Also available at <http://pubs.usgs.gov/of/2008/1272/>.)
- Jacks, Gunnar, Bhattacharya, Prosun, Chaudhary, Vikas, and Singh, K.P., 2005, Controls on the genesis of some high-fluoride groundwaters in India: *Applied Geochemistry*, v. 20, no. 2, p. 221–228, accessed July 22, 2014, at <http://dx.doi.org/10.1016/j.apgeochem.2004.07.002>.
- Jenks, G.F., and Caspall, F.C., 1971, Error on choroplethic maps—Definition, measurement, reduction: *Annals of the Association of American Geographers*, v. 61, no. 2, p. 217–244, accessed July 22, 2014, at <http://dx.doi.org/10.1111/j.1467-8306.1971.tb00779.x>.

- Jennings, C.W., Strand, R.G., and Rogers, T.H., 1977, Geologic map of California: California Division of Mines and Geology, scale 1:750,000.
- Jurgens, B.C., Fram, M.S., Belitz, Kenneth, Burow, K.R., and Landon, M.K., 2010, Effects of groundwater development on uranium—Central Valley, California, USA: *Ground Water*, v. 48, no. 6, p. 913–928, accessed July 22, 2014, at <http://dx.doi.org/10.1111/j.1745-6584.2009.00635.x>.
- Jurgens, B.C., McMahon, P.B., Chapelle, F.H., and Eberts, S.M., 2009, An Excel® workbook for identifying redox processes in ground water: U.S. Geological Survey Open-File Report 2009–1004, 8 p. (Also available at <http://pubs.usgs.gov/of/2009/1004/>.)
- Kaback, D.S., and Runnells, D.D., 1980, Geochemistry of molybdenum in some stream sediments and waters: *Geochimica et Cosmochimica Acta*, v. 44, no. 3, p. 447–456.
- Kelly, S.D., Newville, M.G., Cheng, L., Kemner, K.M., Sutton, S.R., Fenter, P., Sturchio, N.C., and Spötl, C., 2003, Uranyl incorporation in natural calcite: *Environmental Science & Technology*, v. 37, no. 7, p. 1284–1287, accessed July 22, 2014, at <http://dx.doi.org/10.1021/es025962f>.
- Kelly, S.D., Rasbury, E.T., Chattopadhyay, Soma, Kropf, A.J., and Kemner, K.M., 2006, Evidence of a stable uranyl site in ancient organic-rich calcite: *Environmental Science & Technology*, v. 40, no. 7, p. 2262–2268, accessed July 22, 2014, at <http://dx.doi.org/10.1021/es051970v>.
- Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95–399, 114 p. (Also available at <http://pubs.usgs.gov/of/1995/ofr-95-399/>.)
- Kulongoski, Justin, and Belitz, Kenneth, 2004, Ground-Water Ambient Monitoring and Assessment Program: U.S. Geological Survey Fact Sheet 2004–3088, 2 p. (Also available at <http://pubs.usgs.gov/fs/2004/3088/>.)
- Lane, S.L., Flanagan, Sarah, and Wilde, F.D., 2003, Selection of equipment for water sampling (ver. 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A2, accessed June 19, 2012, at <http://pubs.water.usgs.gov/twri9A2/>.
- Langmuir, Donald, 1997, *Aqueous environmental chemistry: Upper Saddle River, New Jersey*, Prentice Hall, 600 p.
- Leighton, D.A., and Phillips, S.P., 2003, Simulation of ground-water flow and land subsidence in the Antelope Valley ground-water basin, California: U.S. Geological Survey Water-Resources Investigations Report 2003–4016, 118 p. (Also available at <http://pubs.usgs.gov/wri/wrir034016/text.html>.)
- Lines, G.C., 1996, Ground-water and surface-water relations along the Mojave River, southern California: U.S. Geological Survey Water-Resources Investigations Report 95–4189, 43 p. (Also available at <http://pubs.usgs.gov/wri/1995/4189/report.pdf>.)
- Lowers, H.A., Breit, G.N., Foster, A.L., Whitney, John, Yount, James, Uddin, M.N., and Muneem, A.A., 2007, Arsenic incorporation into authigenic pyrite, Bengal Basin sediment, Bangladesh: *Geochimica et Cosmochimica Acta*, v. 71, no. 11, p. 2699–2717, accessed July 22, 2014, at <http://dx.doi.org/10.1016/j.gca.2007.03.022>.
- Maloney, T.J., ed., 2005, Quality management system, U.S. Geological Survey National Water Quality Laboratory: U.S. Geological Survey Open-File Report 2005–1263, variously paged, accessed June 19, 2012, at <http://pubs.usgs.gov/of/2005/1263/>.
- Mathany, T.M., and Belitz, Kenneth, 2009, Groundwater quality data in the Mojave study unit, 2008—Results from the California GAMA Program: U.S. Geological Survey Data Series 440, 81 p. (Also available at <http://pubs.usgs.gov/ds/440/>.)
- Mathany, T.M., Wright, M.T., Beuttel, B.S., and Belitz, Kenneth, 2012, Groundwater-quality data in the Borrego Valley, Central Desert, and Low-Use Basins of the Mojave and Sonoran Deserts study unit, 2008–2010—Results from the California GAMA Program: U.S. Geological Survey Data Series 659, 100 p. (Also available at <http://pubs.usgs.gov/ds/659/>.)
- Mattigod, S.V., Frampton, J.A., and Lim, C.H., 1985, Effect of ion-pair formation on boron adsorption by kaolinite: *Clays and Clay Minerals*, v. 33, no. 5, p. 433–437, accessed July 22, 2014, at <http://dx.doi.org/10.1346/CCMN.1985.0330509>.
- McBride, M.B., 1997, A critique of diffuse double layer models applied to colloid and surface chemistry: *Clays and Clay Minerals*, v. 45, no. 4, p. 598–608.
- McMahon, P.B., Böhlke, J.K., and Christenson, S.C., 2004, Geochemistry, radiocarbon ages, and paleorecharge conditions along a transect in the central High Plains aquifer, southwestern Kansas, USA: *Applied Geochemistry*, v. 19, no. 11, p. 1655–1686, accessed July 22, 2014, at <http://dx.doi.org/10.1016/j.apgeochem.2004.05.003>.
- McMahon, P.B., and Chapelle, F.H., 2008, Redox processes and water quality of selected principal aquifer systems: *Ground Water*, v. 46, no. 2, p. 259–271, accessed July 22, 2014, at <http://dx.doi.org/10.1111/j.1745-6584.2007.00385.x>.

- Meece, D.E., and Benninger, L.K., 1993, The coprecipitation of Pu and other radionuclides with CaCO₃: *Geochimica et Cosmochimica Acta*, v. 57, no. 7, p. 1447–1458, accessed July 22, 2014, at [http://dx.doi.org/10.1016/0016-7037\(93\)90005-H](http://dx.doi.org/10.1016/0016-7037(93)90005-H).
- Metzger, D.G., and Loeltz, O.J., 1973, *Geohydrology of the Needles area, Arizona, California, and Nevada*: U.S. Geological Survey Professional Paper 486-J, 53 p. (Also available at <http://pubs.usgs.gov/pp/0486j/report.pdf>.)
- Metzger, D.G., Loeltz, O.J., and Burdge, Ireland, 1973, *Geohydrology of the Parker-Blythe-Cibola area, Arizona and California*: U.S. Geological Survey Professional Paper 486-G, 130 p. (Also available at <http://pubs.usgs.gov/pp/0486g/report.pdf>.)
- Mitten, H.T., Lines, G.C., Berenbrock, Charles, and Durbin, T.J., 1988, *Water resources of Borrego Valley and vicinity, San Diego County, California—Phase 2, Development of a ground-water flow model*: U.S. Geological Survey Water-Resources Investigations Report 87–4199, 27 p. (Also available at <http://pubs.usgs.gov/wri/1987/4199/report.pdf>.)
- National Atmospheric Deposition Program, 2014, *Annual trends in NADP/NTN wet deposition pH data, 1980–2012*, accessed May 14, 2014, at <http://nadp.sws.uiuc.edu/NADP/>.
- Nishikawa, Tracy, Rewis, D.L., and Martin, Peter, 2001, *Numerical simulation of ground-water flow and land subsidence at Edwards Air Force Base, Antelope Valley, California*: U.S. Geological Survey Water-Resources Investigations Report 2001–4038, 111 p. (Also available at <http://pubs.usgs.gov/wri/2001/4038/>.)
- Nishikawa, Tracy, Densmore, J.N., Martin, Peter, and Matti, Jonathan, 2003, *Evaluation of the source and transport of high nitrate concentrations in ground water, Warren subbasin, California*: U.S. Geological Survey Water-Resources Investigations Report 2003–4009, 133 p. (Also available at <http://pubs.er.usgs.gov/publication/wri034009>.)
- Nishikawa, Tracy, Izbicki, J.A., Hevesi, J.A., Stamos, C.L., and Martin, Peter, 2005, *Evaluation of geohydrologic framework, recharge estimates and ground-water flow of the Joshua Tree area, San Bernardino County, California*: U.S. Geological Survey Scientific Investigations Report 2004–5267, 115 p. (Also available at <http://pubs.er.usgs.gov/publication/sir20045267>.)
- Olmsted, F.H., Loeltz, O.J., and Ireland, Burdge, 1973, *Geohydrology of the Yuma area, Arizona and California*: U.S. Geological Survey Professional Paper 486-H, 226 p. (Also available at <http://pubs.er.usgs.gov/publication/pp486H>.)
- Parkhurst, D.L., and Appelo, C.A.J., 1999, *User's guide to PHREEQC (version 2)—A computer program for speciation, batch-reaction, one-dimensional transport and inverse geochemical calculations*: U.S. Geological Survey Water-Resources Investigations Report 99–4259, 312 p. (Also available at <http://pubs.er.usgs.gov/publication/wri994259>.)
- Parsons, M.C., Hancock, T.C., Kulongoski, J.T., and Belitz, Kenneth, 2014, *Status of groundwater quality in the Borrego Valley, Central Desert, and Low-Use Basins of the Mojave and Sonoran Deserts study unit, 2008–2010—California GAMA Priority Basin Project*: U.S. Geological Survey Scientific Investigations Report 2014–5001, 88 p., (Also available at <http://dx.doi.org/10.3133/sir20145001>.)
- Payne, T.E., Lumpkin, G.R., and Waite, T.D., 1998, Uranium (VI) adsorption on model minerals—Controlling factors and surface complexation models, *in* Jenne, E.A., ed., *Adsorption of metals by geomedia—Variables, mechanisms, and model applications*: San Diego, California, Academic Press, p. 75–97.
- Peacock, C.L., and Sherman, D.M., 2004, Vanadium (V) adsorption onto goethite (α -FeOOH) at pH 1.5 to 12—A surface complexation model based on ab initio molecular geometries and EXAFS spectroscopy: *Geochimica et Cosmochimica Acta*, v. 68, no. 8, p. 1723–1733, July 25, 2014, <http://www.sciencedirect.com/science/article/pii/S0016703703007889>.
- Peak, Derek, Luther, G.W., III, and Sparks, D.L., 2003, ATR-FTIR spectroscopic studies of boric acid adsorption on hydrous ferric oxide: *Geochimica et Cosmochimica Acta*, v. 67, no. 14, p. 2551–2560, accessed July 22, 2014, at [http://dx.doi.org/10.1016/S0016-7037\(03\)00096-6](http://dx.doi.org/10.1016/S0016-7037(03)00096-6).
- Phillips, S.J., and Comus, P.W., eds., 2000, *A natural history of the Sonoran Desert*: Tucson, Arizona, Arizona-Sonoran Desert Museum Press, 628 p.
- Pirkey, K.D., and Glodt, S.R., 1998, *Quality control at the U.S. Geological Survey, National Water Quality Laboratory*: U.S. Geological Survey Fact Sheet 026–98, 4 p., accessed June 19, 2012, at <http://pubs.er.usgs.gov/usgspubs/fs/fs02698>.
- PRISM Climate Group, Oregon State University, 2007, *United States average annual precipitation, maximum and minimum temperature, 1971–2000*, accessed August 9, 2007, at <http://prism.oregonstate.edu/>.
- Putnam, J., and Smith, G., eds., 1995, *Deepest valley—Guide to Owens Valley—Its roadsides and mountain trails* (2d ed.): Mammoth Lakes, California, Genny Smith Books, 280 p.

- Reeder, R.J., Nugent, M., Tait, C.D., Morris, D.E., Heald, S.M., Beck, K.M., Hess, W.P., and Lanzirrotti, A., 2001, Coprecipitation of uranium (VI) with calcite—XAFS, micro-XAS, and luminescence characterization: *Geochimica et Cosmochimica Acta*, v. 65, no. 20, p. 3491–3503.
- Reimann, Clemens, and de Caritat, P., 1998, *Chemical elements in the environment—Factsheets for the geochemist and environmental scientist*: Berlin, Germany, Springer-Verlag, 398 p.
- Schmitt, S.J., Milby Dawson, B.J., and Belitz, Kenneth, 2009, Groundwater-quality data in the Antelope Valley study unit, 2008—Results from the California GAMA Program: U.S. Geological Survey Data Series 479, 80 p. (Also available at <http://pubs.er.usgs.gov/publication/ds479>.)
- Smedley, P.L., and Kinniburgh, D.G., 2002, A review of the source, behaviour and distribution of arsenic in natural waters: *Applied Geochemistry*, v. 17, no. 5, p. 517–568, accessed July 24, 2014, at [http://dx.doi.org/10.1016/S0883-2927\(02\)00018-5](http://dx.doi.org/10.1016/S0883-2927(02)00018-5).
- Smith, R.M., and Martell, A.E., 1976, *Critical stability constants—Inorganic complexes*: New York, Plenum Press, v. 4, 257 p.
- Sparks, D.L., 1995, *Environmental soil chemistry*: San Diego, California, Academic Press, 352 p.
- Stamos, C.L., Martin, Peter, Nishikawa, Tracy, and Cox, B.F., 2001, Simulation of ground-water flow in the Mojave River basin, California: U.S. Geological Survey Water-Resources Investigations Report 01–4002, 129 p. (Also available at <http://pubs.usgs.gov/wri/wri014002/>.)
- State of California, 1999, Supplemental report of the 1999 Budget Act, 1999–00 Fiscal Year, Item 3940-001-0001: State Water Resources Control Board, accessed May 2013 at http://www.lao.ca.gov/1999/99-00_supp_rpt_lang.html#3940.
- State of California, 2001a, Assembly Bill No. 599, Chapter 522, accessed May 2013 at http://www.swrcb.ca.gov/gama/docs/ab_599_bill_20011005_chaptered.pdf.
- State of California, 2001b, Groundwater Monitoring Act of 2001, California State Water Code, division 6, part 2.76, sections 10780–10782.3, accessed August 11, 2010, at <http://www.leginfo.ca.gov/>.
- Stollenwerk, K.G., 2003, Geochemical processes controlling transport of arsenic, in *Groundwater—A review of adsorption*, in Welch, A.H., and Stollenwerk, K.G., eds., *Arsenic in ground water, geochemistry and occurrence*: Boston, Kluwer Academic Publishers, 475 p.
- Stonestrom, D.A., and Harrill, J.R., 2007, Ground-water recharge in the arid and semiarid southwestern United States—Climatic and geologic framework: U.S. Geological Survey Professional Paper 1703–A, 27 p. (Also available at <http://pubs.usgs.gov/pp/pp1703/a/>.)
- Stumm, Werner, 1992, *Chemistry of the solid-water interface—Processes at the mineral-water and particle-water interface in natural systems*: John Wiley & Sons, Inc., 488 p.
- Turner D.R., Whitfield, M., and Dickson, A.G., 1981, The equilibrium speciation of dissolved components in freshwater and sea water at 25°C and 1 atm pressure: *Geochimica et Cosmochimica Acta*, v. 45, no. 6, p. 855–881, accessed July 24, 2014, at [http://dx.doi.org/10.1016/0016-7037\(81\)90115-0](http://dx.doi.org/10.1016/0016-7037(81)90115-0).
- Tyley, S.J., 1974, Analog model study of the ground-water basin of the Upper Coachella Valley, California: U.S. Geological Survey Water Supply Paper 2027, 77 p. (Also available at <http://pubs.er.usgs.gov/publication/wsp2027>.)
- U.S. Environmental Protection Agency, 1998, MINTEQA2/PRODEFA2, A geochemical assessment model for environmental systems—User manual supplement for version 4.0: Athens, Georgia, National Exposure Research Laboratory, Ecosystems Research Division, 77 p., revised September 1999, accessed July 24, 2014, at <http://www.epa.gov/osw/hazard/wastetypes/wasteid/hwirwste/pdf/risk/reports/s0536.pdf>.
- U.S. Environmental Protection Agency, 2009, National primary drinking water regulations, accessed January 2011 at <http://water.epa.gov/drink/contaminants/upload/mcl-2.pdf>.
- U.S. Environmental Protection Agency, 2012, 2012 Edition of the drinking water standards and health advisories, accessed March 2013 at <http://water.epa.gov/action/advisories/drinking/upload/dwstandards2012.pdf>.
- U.S. Geological Survey, 2006, Collection of water samples (ver. 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4, accessed February 4, 2014, at <http://pubs.water.usgs.gov/twri9A4/>.
- U.S. Geological Survey, 2009, Mojave water resources, accessed July 27, 2012, at <http://ca.water.usgs.gov/mojave/index.html>.
- U.S. Geological Survey, 2013, California Water Science Center (CAWSC)—Groundwater Ambient Monitoring and Assessment (GAMA) Program, accessed May 2013 at <http://ca.water.usgs.gov/gama/>.
- U.S. Geological Survey, 2014, National Water Information System—Web interface, accessed May 10, 2014, at <http://waterdata.usgs.gov/nwis/>.

- U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A1–A9, accessed June 19, 2012, at <http://water.usgs.gov/owq/FieldManual/>.
- Violante, Antonio, Krishnamurti, G.S.R., and Pigna, Massimo, 2007, Factors affecting the sorption–desorption of trace elements in soil environments, *in* Violante, Antonio, Huang, P.M., and Gadd, G.M., eds., *Biophysico-chemical processes of heavy metals and metalloids in Soil Environments*: Hoboken, New Jersey, John Wiley & Sons, Inc., p. 169–214.
- Wang, Deli, 2007, *Biogeochemistry of redox-sensitive elements in natural waters—Chemical speciation of molybdenum and vanadium*: Stony Brook University, New York, Ph.D. Dissertation, 179 p.
- Wang, L.K., Hung, Y.T., and Shammas, N.K., eds., 2005, *Physicochemical treatment processes*: New York City, Humana Press, *Handbook of Environmental Engineering Series*, v. 3, 723 p.
- Wanty, R.B., and Goldhaber, M.B., 1992, Thermodynamics and kinetics of reactions involving vanadium in natural systems—Accumulation of vanadium in sedimentary rocks: *Geochimica et Cosmochimica Acta*, v. 56, no. 4, p. 1471–1483, accessed July 24, 2014, at [http://dx.doi.org/10.1016/0016-7037\(92\)90217-7](http://dx.doi.org/10.1016/0016-7037(92)90217-7).
- Welch, A.H., Oremland, R.S., Davis, J.A., and Watkins, S.A., 2006, Arsenic in ground water—A review of current knowledge and relation to the CALFED solution area with recommendations for needed research: *San Francisco Estuary and Watershed Science*, v. 4, no. 2, article 4, 32 p., accessed May 19, 2008, at <http://repositories.cdlib.org/jmie/sfew/s/vol4/iss2/art4/>.
- Welch, A.H., Westjohn, D.B., Helsel, D.R., and Wanty, R.B., 2000, Arsenic in ground water of the United States—Occurrence and geochemistry: *Ground Water*, v. 38, no. 4, p. 589–604, accessed July 24, 2014, at http://water.usgs.gov/nawqa/trace/pubs/gw_v38n4/.
- Winograd, I.J., and Robertson, F.N., 1982, Deep oxygenated ground water—Anomaly or common occurrence?: *Science*, v. 216, no. 4551, p. 1227–1230.
- Wright, M.T., and Belitz, Kenneth, 2010, Factors controlling the regional distribution of vanadium in groundwater: *Groundwater*, v. 48, no. 4, p. 515–525, accessed July 24, 2014, at <http://dx.doi.org/10.1111/j.1745-6584.2009.00666.x>.
- Wright, K.E., Hartmann, Thomas, and Fujita, Yoshiko, 2011, Inducing mineral precipitation in groundwater by addition of phosphate: *Geochemical Transactions*, v. 12, no. 8, 13 p., accessed July 24, 2014, at <http://dx.doi.org/10.1186/1467-4866-12-8>.
- Wright, M.T., Stollenwerk, K. G., and Belitz, K., 2014, Assessing the solubility controls on vanadium in groundwater, northeastern San Joaquin Valley, CA: *Applied Geochemistry*, v. 48, p. 41–52.
- Zawacki, S.J., Heughebaert, J.C., Nancollas, G.H., 1990, The growth of nonstoichiometric apatite from aqueous solution at 37°C—II. Effects of pH upon the precipitated phase: *Journal of Colloid and Interface Science*, v. 135, no. 1, p. 33–44, accessed July 24, 2014, at [http://dx.doi.org/10.1016/0021-9797\(90\)90286-W](http://dx.doi.org/10.1016/0021-9797(90)90286-W).

Table 1. Identification and construction information for wells sampled in the Desert and Basin and Range hydrogeologic provinces, California GAMA Priority Basin Project, 2006–11.

[ft, foot; bls, below land surface; na, not available]

GAMA identification	Well type	Depth of well (ft bls)	Bottom of lower-most opening (ft bls)	Top of upper-most opening (ft bls)	Screen length (ft bls)	GAMA identification	Well type	Depth of well (ft bls)	Bottom of lower-most opening (ft bls)	Top of upper-most opening (ft bls)	Screen length (ft bls)
Antelope Valley						Coachella Valley—Continued					
ANT-02	Production	400	400	190	210	COA-05	Production	1,090	1,090	710	380
ANT-04	Production	765	765	350	415	COA-06	Production	654	654	203	451
ANT-07	Production	527	527	260	267	COA-07	Production	240	na	na	na
ANT-09	Production	213	213	93	120	COA-08	Production	342	342	258	84
ANT-12	Production	1,200	na	na	na	COA-09	Production	na	na	na	na
ANT-15	Production	680	na	na	na	COA-10	Production	na	na	na	na
ANT-17	Production	552	552	192	360	COA-11	Production	na	na	na	na
ANT-26	Production	320	300	160	140	COA-12	Production	525	525	445	80
ANT-34	Production	606	606	96	510	COA-13	Production	890	870	510	360
ANT-40	Production	843	833	583	250	COA-14	Production	820	820	420	400
ANT-43	Production	550	540	210	330	COA-15	Production	400	380	180	200
ANT-45	Production	na	na	na	na	COA-16	Production	650	650	300	350
ANT-46	Production	475	475	250	225	COA-17	Production	na	na	na	na
ANT-47	Production	1,100	1,100	115	985	COA-18	Production	790	790	280	510
ANT-48	Production	na	na	na	na	COA-19	Production	na	na	na	na
ANT-49	Production	801	801	500	301	COAU-01	Production	96	43	12	31
ANT-51	Production	328	328	188	140	COAU-02	Production	600	600	288	312
ANT-52	Production	300	300	200	100	COAU-03	Production	na	na	na	na
ANT-U	Production	700	693	235	458	COAU-04	Production	400	400	280	120
Borrego Valley						COAU-05	Production	909	906	306	600
BV-03	Production	350	350	150	200	COAU-06	Production	1,130	1,110	580	530
BV-04	Production	630	630	420	210	COAU-07	Production	553	553	225	328
BV-07	Production	95	na	na	na	COAU-08	Production	730	726	476	250
BVU-01	Production	392	372	162	210	COAU-09	Production	na	na	na	na
Central Desert						COAU-10	Production	1,070	1,050	410	640
CD-01	Production	na	na	na	na	COAU-11	Production	400	400	220	180
CD-03	Production	na	na	na	na	COAU-12	Production	160	155	55	100
CD-04	Production	350	345	195	150	COAU-13	Production	na	na	na	na
CD-07	Production	740	720	470	250	COAU-14	Production	550	530	330	200
CD-09	Production	1,115	1,115	550	565	COAU-15	Production	700	700	400	300
CD-11	Production	na	na	na	na	COAU-16	Production	na	na	na	na
CD-12	Production	550	na	na	na	Colorado River					
CD-13	Production	260	247	147	100	COLOR-01	Production	na	na	na	na
CD-14	Production	600	580	390	190	COLOR-02	Production	na	na	na	na
Coachella Valley						COLOR-03	Production	512	497	437	60
COA-01	Production	1,200	1,200	900	300	COLOR-04	Production	90	90	30	60
COA-02	Production	na	480	230	250	COLOR-05	Production	610	590	380	210
COA-03	Production	na	na	na	na	COLOR-06	Production	505	na	421	na
COA-04	Production	1,070	1,060	500	560	COLOR-07	Production	438	438	20	418

Table 1. Identification and construction information for wells sampled in the Desert and Basin and Range hydrogeologic provinces, California GAMA Priority Basin Project, 2006–11.—Continued

[ft, foot; bls, below land surface; na, not available]

GAMA identification	Well type	Depth of well (ft bls)	Bottom of lower-most opening (ft bls)	Top of upper-most opening (ft bls)	Screen length (ft bls)	GAMA identification	Well type	Depth of well (ft bls)	Bottom of lower-most opening (ft bls)	Top of upper-most opening (ft bls)	Screen length (ft bls)
Colorado River—Continued						Indian Wells Valley—Continued					
COLOR-08	Production	500	480	140	340	OIWU-05	Monitoring	na	na	na	na
COLOR-09	Production	na	na	na	na	OIWU-06	Monitoring	na	na	na	na
COLOR-10	Production	1,000	na	na	na	OIWU-07	Monitoring	215	215	na	215
COLOR-11	Production	na	na	na	na	OIWU-08	Monitoring	150	130	55	75
COLOR-12	Production	420	420	300	120	Low-Use Basins					
COLOR-13	Production	205	na	na	na	LUB-01	Production	381	381	205	176
COLOR-14	Production	na	na	na	na	LUB-02	Production	543	na	na	na
COLOR-15	Production	na	na	na	na	LUB-03	Production	456	na	na	na
COLOR-16	Production	600	486	378	108	LUB-04	Production	na	na	na	na
COLOR-17	Production	210	200	80	120	LUB-05	Production	490	480	322	158
COLOR-18	Production	600	580	150	430	LUB-06	Production	490	475	220	255
COLOR-19	Production	143	140	118	22	LUB-07	Production	660	440	160	280
COLOR-20	Production	700	na	na	na	LUB-08	Production	800	780	300	480
COLORU-01	Production	492	492	292	200	LUB-09	Production	224	224	184	40
COLORU-02	Production	454	na	436	na	LUB-10	Production	300	300	190	110
COLORU-03	Production	335	na	310	na	LUB-11	Production	600	590	452	138
COLORU-04	Production	241	160	54	106	LUB-12	Production	840	800	650	150
COLORU-05	Production	105	82	38	44	LUB-13	Production	500	500	100	400
COLORU-06	Production	500	480	160	320	LUB-14	Production	240	na	na	na
COLORU-07	Production	130	na	na	na	LUB-15	Production	312	312	212	100
COLORU-08	Production	na	na	na	na	LUB-16	Production	105	105	na	105
Indian Wells Valley						LUB-17	Production	584	584	484	100
OIW-01	Production	850	830	320	510	LUB-18	Production	36	36	15	21
OIW-02	Production	480	470	310	160	LUB-19	Production	na	na	na	na
OIW-03	Production	na	na	na	na	LUB-20	Production	100	na	70	na
OIW-04	Production	400	400	320	80	LUB-21	Production	400	400	300	100
OIW-05	Production	1,020	1,000	560	440	LUB-22	Production	1,200	1,190	690	500
OIW-06	Production	232	181	135	46	LUB-23	Production	403	400	200	200
OIW-07	Production	620	600	260	340	LUB-24	Production	788	na	235	na
OIW-08	Production	190	na	na	na	LUB-25	Production	866	864	534	330
OIW-09	Production	na	na	na	na	LUB-26	Production	711	na	na	na
OIW-10	Production	260	260	200	60	LUB-27	Production	400	400	140	260
OIW-11	Monitoring	77	77	75	2	LUBU-01	Production	1,010	940	350	590
OIW-12	Monitoring	200	na	100	na	LUBU-02	Monitoring	400	380	140	240
OIW-13	Monitoring	70	70	60	10	LUBU-03	Production	na	na	na	na
OIWU-01	Production	1,220	1,200	600	600	Mojave					
OIWU-02	Production	730	730	430	300	MOJO-12	Production	360	360	110	250
OIWU-03	Production	920	900	600	300	MOJO-13	Production	na	na	na	na
OIWU-04	Monitoring	690	690	232	458	MOJO-14	Production	530	505	365	140

Table 1. Identification and construction information for wells sampled in the Desert and Basin and Range hydrogeologic provinces, California GAMA Priority Basin Project, 2006–11.—Continued

[ft, foot; bls, below land surface; na, not available]

GAMA identification	Well type	Depth of well (ft bls)	Bottom of lower-most opening (ft bls)	Top of upper-most opening (ft bls)	Screen length (ft bls)	GAMA identification	Well type	Depth of well (ft bls)	Bottom of lower-most opening (ft bls)	Top of upper-most opening (ft bls)	Screen length (ft bls)
Mojave—Continued						Owens Valley—Continued					
MOJO-15	Production	720	700	495	205	OV-17	Monitoring	616	322	47	275
MOJO-16	Production	1,000	1,000	515	485	OV-18	Production	642	640	210	430
MOJO-17	Production	810	810	410	400	OV-19	Production	na	na	na	na
MOJO-18	Production	na	na	na	na	OV-20	Production	na	na	na	na
MOJO-19	Production	420	180	160	20	OV-21	Production	255	240	140	100
MOJO-25	Production	na	na	na	na	OV-22	Production	650	640	300	340
MOJO-27	Production	1,110	1,110	850	260	OV-23	Production	188	na	na	na
MOJO-29	Production	480	na	na	na	OV-24	Production	305	300	120	180
MOJO-30	Production	650	630	430	200	OV-25	Production	390	390	70	320
MOJO-31	Production	1,130	1,120	660	460	OV-26	Production	128	120	70	50
MOJO-35	Production	400	400	160	240	OV-27	Production	200	200	100	100
MOJO-36	Production	140	na	na	na	OV-28	Production	150	150	130	20
MOJO-39	Production	na	na	na	na	OV-29	Production	200	200	180	20
MOJO-41	Production	na	na	na	na	OV-30	Production	388	360	143	217
MOJO-42	Production	388	na	242	na	OV-31	Production	240	180	150	30
MOJO-49	Production	400	390	200	190	OV-32	Production	125	108	51	57
MOJOU-01	Production	451	451	251	200	OV-33	Monitoring	319	298	258	40
MOJOU-02	Monitoring	790	790	770	20	OV-34	Monitoring	na	700	660	40
MOJOU-03	Monitoring	610	610	590	20	OV-35	Monitoring	290	290	250	40
MOJOU-04	Monitoring	583	574	534	40	OV-36	Production	na	na	na	na
MOJOU-05	Monitoring	750	750	730	20	OV-37	Production	400	390	100	290
Owens Valley						OV-38	Production	232	232	80	152
OV-01	Production	217	na	70	na	OV-39	Production	272	272	55	217
OV-02	Production	126	120	60	60	OV-40	Monitoring	775	774	644	130
OV-03	Production	250	250	50	200	OVU-01	Production	590	570	180	390
OV-04	Production	340	na	na	na	OVU-02	Production	280	na	na	na
OV-05	Production	na	na	na	na	OVU-03	Monitoring	78	78	58	20
OV-06	Production	196	196	155	41	OVU-04	Monitoring	138	138	118	20
OV-07	Production	650	650	290	360	OVU-05	Monitoring	47	47	27	20
OV-08	Production	800	800	240	560	OVU-06	Monitoring	48	48	28	20
OV-09	Production	na	na	na	na	OVU-07	Monitoring	390	370	330	40
OV-10	Production	na	na	na	na	OVU-08	Production	600	600	150	450
OV-11	Production	161	161	121	40	OVU-09	Monitoring	41	41	21	20
OV-12	Production	126	116	96	20	OVU-10	Monitoring	315	315	275	40
OV-13	Production	114	109	69	40	OVU-11	Production	91	86	66	20
OV-14	Production	237	220	40	180	OVU-12	Monitoring	700	na	na	na
OV-15	Monitoring	202	180	150	30	OVU-13	Monitoring	130	130	110	20
OV-16	Production	185	130	20	110						

Table 2. Fluoride, molybdenum, and uranium reactions added to the minteqV4.dat database that is distributed with PHREEQC version 2 computer program (Parkhurst and Appelo, 1999).

[(s)= solid phase. All other constituents are in the aqueous phase]

Reactions	Equilibrium constants (log K)	Reference
$\text{Ca}_5(\text{PO}_4)_3\text{F}_{(s)} + 3\text{H}^+ = 5\text{Ca}^{2+} + \text{F}^- + 3\text{HPO}_4^{2-}$	-17.6	Ball and Nordstrom [1991]
$\text{MoO}_4^{2-} + \text{H}^+ = \text{HMoO}_4^-$	4.24	Smith and Martell [1976]
$\text{MoO}_4^{2-} + 2\text{H}^+ = \text{H}_2\text{MoO}_4^0$	6.85	Kaback and Runnells [1980]
$\text{MoO}_4^{2-} + 3\text{H}^+ = \text{MoO}_2\text{OH}^+ + \text{H}_2\text{O}$	7.89	Kaback and Runnells [1980]
$\text{MoO}_4^{2-} + 4\text{H}^+ = \text{MoO}_2^{2+} + 2\text{H}_2\text{O}$	8.34	Kaback and Runnells [1980]
$\text{MoO}_4^{2-} + \text{e}^- + 4\text{H}^+ = \text{MoO}_2^+ + 2\text{H}_2\text{O}$	20.95	Kaback and Runnells [1980]
$\text{MoO}_4^{2-} + 3\text{e}^- + 8\text{H}^+ = \text{Mo}^{3+} + 4\text{H}_2\text{O}$	29.52	Kaback and Runnells [1980]
$\text{Na}^+ + \text{MoO}_4^{2-} = \text{NaMoO}_4^-$	1.66	Essington [1990]
$\text{K}^+ + \text{MoO}_4^{2-} = \text{KMoO}_4^-$	1.29	Essington [1992]
$\text{Mg}^{2+} + \text{MoO}_4^{2-} = \text{MgMoO}_4^0$	3.03	Essington [1992]
$\text{Ca}^{2+} + \text{MoO}_4^{2-} = \text{CaMoO}_4^0$	2.57	Essington [1992]
$\text{Ca}^{2+} + \text{MoO}_4^{2-} = \text{CaMoO}_4(s)$	8.45	Kaback and Runnells [1980]
$\text{UO}_2^{2+} + 2\text{Ca}^{2+} + 3\text{HCO}_3^- = \text{Ca}_2\text{UO}_2(\text{CO}_3)_3^0 + 3\text{H}^+$	-0.29	Dong and Brooks [2006]

Table 3. Geochemical conditions determined from the analyses of samples collected at well sites in the each of the nine study areas, Desert and Basin and Range study unit, California GAMA Priority Basin Project, 2006–11.

[<, less than; >, greater than; µg/L, micrograms per liter; na, not available; PMC, percent modern carbon; BP, before present; U, analyzed for but not detected; M, presence verified but not quantified; nc, not collected; Ca, calcium; Na, sodium; HCO₃, bicarbonate; SO₄, sulfate; Cl, chloride; mixed, no single cation or anion constitutes more than half of the cations or anions]

GAMA identification number	Uncorrected carbon-14 age, years BP (A ₀ =84 PMC) ¹	pH	Sulfide		Redox category ²	Major ion type ³		
			Presence / absence	Concentration (µg/L)		Cations	Anions	
Antelope Valley								
ANT-02	< 100	7.7	U	nc	Oxic	Ca	HCO ₃	
ANT-04	5,600	8.0	U	nc	Oxic	Mixed	HCO ₃	
ANT-07	4,800	8.0	U	nc	Oxic	Na	HCO ₃	
ANT-09	< 100	7.0	U	nc	Mixed	Mixed	Mixed	
ANT-12	2,200	8.0	U	nc	Oxic	Na	Mixed	
ANT-15	1,400	7.2	U	nc	Oxic	Mixed	HCO ₃	
ANT-17	3,000	8.0	U	nc	Oxic	Mixed	HCO ₃	
ANT-26	300	7.8	U	nc	Anoxic	Ca	HCO ₃	
ANT-34	na	7.4	U	nc	Mixed	Na	Mixed	
ANT-40	9,000	7.9	U	nc	Oxic	Na	HCO ₃	
ANT-43	1,400	7.9	U	nc	Oxic	Mixed	Mixed	
ANT-45	10,000	8.3	U	nc	Oxic	Na	HCO ₃	
ANT-46	2,800	7.8	U	nc	Oxic	Ca	Mixed	
ANT-47	6,500	7.9	M	nc	Oxic	Mixed	HCO ₃	
ANT-48	500	7.4	U	nc	Oxic	Ca	Mixed	
ANT-49	2,300	8.2	U	nc	Oxic	Na	HCO ₃	
ANT-51	7,900	8.9	U	nc	Oxic	Na	HCO ₃	
ANT-52	3,800	8.6	U	nc	Anoxic	Mixed	HCO ₃	
ANT-U	4,600	8.2	U	nc	Oxic	Mixed	HCO ₃	

Table 3. Geochemical conditions determined from the analyses of samples collected at well sites in the each of the nine study areas, Desert and Basin and Range study unit, California GAMA Priority Basin Project, 2006–11.—Continued

[<, less than; >, greater than; µg/L, micrograms per liter; na, not available; PMC, percent modern carbon; BP, before present; U, analyzed for but not detected; M, presence verified but not quantified; nc, not collected; Ca, calcium; Na, sodium; HCO₃, bicarbonate; SO₄, sulfate; Cl, chloride; mixed, no single cation or anion constituent more than half of the cations or anions]

GAMA identification number	Uncorrected carbon-14 age, years BP (A ₀ =84 PMC) ¹	pH	Sulfide		Redox category ²	Major ion type ³	
			Presence / absence	Concentration (µg/L)		Cations	Anions
Borrego Valley							
BV-03	< 100	7.4	U	nc	Oxic	Mixed	SO ₄
BV-04	500	7.3	U	nc	Oxic	Na	Cl
BV-07	na	8.9	U	nc	Oxic	Na	Mixed
BVU-01	12,500	8.3	U	nc	Oxic	Na	Mixed
Central Desert							
CD-01	< 100	7.8	U	nc	Oxic	Mixed	HCO ₃
CD-03	800	7.6	U	nc	Oxic	Na	HCO ₃
CD-04	< 100	7.9	U	nc	Oxic	Ca	HCO ₃
CD-07	2,800	8.1	U	nc	Oxic	Na	HCO ₃
CD-09	< 100	7.6	U	nc	Oxic	Ca	Mixed
CD-11	< 100	7.4	U	nc	Oxic	Mixed	HCO ₃
CD-12	9,500	8.5	U	nc	Oxic	Na	HCO ₃
CD-13	8,000	8.5	U	nc	Oxic	Na	Mixed
CD-14	9,600	8.6	U	nc	Oxic	Na	Mixed
Coachella Valley							
COA-01	< 100	7.6	U	nc	Oxic	Ca	HCO ₃
COA-02	24,900	8.0	U	nc	Anoxic	Na	Cl
COA-03	2,900	8.0	U	nc	Oxic	Na	SO ₄
COA-04	< 100	8.1	U	nc	Oxic	Mixed	HCO ₃
COA-05	400	8.0	U	nc	Oxic	Mixed	HCO ₃
COA-06	100	7.7	U	nc	Anoxic	Ca	Mixed
COA-07	300	7.4	U	nc	Oxic	Ca	SO ₄
COA-08	3,800	8.0	U	nc	Oxic	Na	SO ₄
COA-09	< 100	7.6	U	nc	Oxic	Ca	HCO ₃
COA-10	9,400	9.2	U	nc	Anoxic	Na	HCO ₃
COA-11	16,500	9.1	U	nc	Anoxic	Na	Mixed
COA-12	29,300	8.5	U	nc	Anoxic	Na	Mixed
COA-13	< 100	7.7	U	nc	Oxic	Ca	HCO ₃
COA-14	< 100	7.9	U	nc	Oxic	Ca	HCO ₃
COA-15	< 100	7.8	U	nc	Oxic	Mixed	Mixed
COA-16	1,500	8.1	U	nc	Oxic	Na	SO ₄
COA-17	16,700	7.5	U	nc	Oxic	Mixed	SO ₄
COA-18	1,400	8.0	U	nc	Oxic	Na	Mixed
COA-19	16,900	8.4	U	nc	Anoxic	Na	SO ₄
COAU-01	< 100	7.5	U	nc	Oxic	Ca	HCO ₃
COAU-02	1,300	7.8	nc	nc	Oxic	Mixed	Mixed
COAU-03	< 100	7.7	U	nc	Oxic	Ca	HCO ₃
COAU-04	4,800	8.0	U	nc	Anoxic	Na	SO ₄

Table 3. Geochemical conditions determined from the analyses of samples collected at well sites in the each of the nine study areas, Desert and Basin and Range study unit, California GAMA Priority Basin Project, 2006–11.—Continued

[<, less than; >, greater than; µg/L, micrograms per liter; na, not available; PMC, percent modern carbon; BP, before present; U, analyzed for but not detected; M, presence verified but not quantified; nc, not collected; Ca, calcium; Na, sodium; HCO₃, bicarbonate; SO₄, sulfate; Cl, chloride; mixed, no single cation or anion constituent more than half of the cations or anions]

GAMA identification number	Uncorrected carbon-14 age, years BP (A ₀ =84 PMC) ¹	pH	Sulfide		Redox category ²	Major ion type ³	
			Presence / absence	Concentration (µg/L)		Cations	Anions
Coachella Valley—Continued							
COAU-05	< 100	7.6	U	nc	Oxic	Ca	HCO ₃
COAU-06	1,700	7.7	U	nc	Oxic	Mixed	HCO ₃
COAU-07	< 100	7.3	U	nc	Oxic	Ca	HCO ₃
COAU-08	< 100	7.1	U	nc	Oxic	Ca	HCO ₃
COAU-09	7,000	9.1	U	nc	Anoxic	Na	HCO ₃
COAU-10	200	7.6	U	nc	Oxic	Mixed	SO ₄
COAU-11	1,100	7.7	U	nc	Oxic	Na	HCO ₃
COAU-12	< 100	7.2	U	nc	Oxic	Ca	HCO ₃
COAU-13	< 100	7.9	U	nc	Oxic	Ca	HCO ₃
COAU-14	100	7.8	U	nc	Oxic	Ca	Mixed
COAU-15	< 100	7.5	U	nc	Oxic	Mixed	Mixed
COAU-16	500	7.9	U	nc	Oxic	Ca	HCO ₃
Colorado River							
COLOR-01	< 100	7.5	U	nc	Oxic	Mixed	SO ₄
COLOR-02	< 100	7.6	U	nc	Oxic	Na	Mixed
COLOR-03	< 100	7.5	M	250	Anoxic-Fe	Na	Mixed
COLOR-04	< 100	7.7	M	150	Anoxic-Fe	Mixed	Mixed
COLOR-05	< 100	7.5	M	nc	Anoxic	Mixed	Mixed
COLOR-06	< 100	7.5	M	100	Anoxic-Fe	Mixed	Mixed
COLOR-07	< 100	7.3	M	nc	Anoxic-Fe	Mixed	Mixed
COLOR-08	12,200	8.0	M	nc	Oxic	Na	Cl
COLOR-09	2,800	7.8	U	nc	Anoxic-Fe	Na	Mixed
COLOR-10	< 100	7.4	U	nc	Anoxic-Fe	Na	Mixed
COLOR-11	< 100	7.0	U	nc	Oxic	Na	Mixed
COLOR-12	12,200	7.9	U	nc	Oxic	Na	Mixed
COLOR-13	6,000	7.6	U	nc	Oxic	Na	Mixed
COLOR-14	1,900	7.6	U	nc	Anoxic	Na	Mixed
COLOR-15	< 100	7.2	U	nc	Anoxic-Fe	Mixed	SO ₄
COLOR-16	< 100	7.6	M	nc	Anoxic-Fe	Mixed	Mixed
COLOR-17	6,700	7.8	U	nc	Oxic	Na	Cl
COLOR-18	3,600	8.0	U	nc	Oxic	Na	Mixed
COLOR-19	< 100	7.5	U	nc	Mixed	Mixed	Mixed
COLOR-20	14,400	8.9	U	nc	Oxic	Na	Mixed
COLORU-01	200	7.7	M	nc	Anoxic	Mixed	Mixed
COLORU-02	300	7.6	M	nc	Anoxic-Fe	Mixed	Mixed
COLORU-03	1,200	7.7	M	nc	Mixed	Na	Mixed
COLORU-04	< 100	7.1	U	nc	Mixed	Na	SO ₄
COLORU-05	< 100	7.5	U	nc	Mixed	Mixed	SO ₄

Table 3. Geochemical conditions determined from the analyses of samples collected at well sites in the each of the nine study areas, Desert and Basin and Range study unit, California GAMA Priority Basin Project, 2006–11.—Continued

[<, less than; >, greater than; µg/L, micrograms per liter; na, not available; PMC, percent modern carbon; BP, before present; U, analyzed for but not detected; M, presence verified but not quantified; nc, not collected; Ca, calcium; Na, sodium; HCO₃, bicarbonate; SO₄, sulfate; Cl, chloride; mixed, no single cation or anion constituent more than half of the cations or anions]

GAMA identification number	Uncorrected carbon-14 age, years BP (A ₀ =84 PMC) ¹	pH	Sulfide		Redox category ²	Major ion type ³	
			Presence / absence	Concentration (µg/L)		Cations	Anions
Colorado River—Continued							
COLORU-06	1,600	7.9	U	nc	Oxic	Na	Mixed
COLORU-07	15,900	7.8	U	nc	Anoxic	Na	Cl
COLORU-08	< 100	7.5	U	nc	Anoxic-Fe	Mixed	SO ₄
Indian Wells Valley							
OIW-01	23,100	9.4	U	nc	Oxic	Na	HCO ₃
OIW-02	6,400	7.9	U	nc	Oxic	Na	Mixed
OIW-03	na	9.8	U	nc	Oxic	Na	HCO ₃
OIW-04	na	na	U	nc	na	Mixed	HCO ₃
OIW-05	2,100	7.4	U	nc	Oxic	Mixed	Mixed
OIW-06	na	7.8	U	nc	Oxic	Na	Cl
OIW-07	26,500	8.7	M	nc	Anoxic	Na	Mixed
OIW-08	14,700	7.2	U	nc	Oxic	Na	Mixed
OIW-09	< 100	6.9	U	nc	Oxic	Ca	Mixed
OIW-10	na	7.8	U	nc	Anoxic	Na	Mixed
OIW-11	2,300	7.7	U	nc	Anoxic	Na	SO ₄
OIW-12	11,600	7.5	U	nc	Mixed	Na	Mixed
OIW-13	na	7.5	U	nc	Oxic	Mixed	Cl
OIWU-01	10,500	8.1	U	nc	Oxic	Na	HCO ₃
OIWU-02	21,400	9.0	U	nc	Anoxic	Na	HCO ₃
OIWU-03	11,800	8.2	U	nc	Oxic	Na	Mixed
OIWU-04	3,400	7.7	U	nc	Oxic	Mixed	Mixed
OIWU-05	3,100	7.7	U	nc	Oxic	Mixed	Mixed
OIWU-06	28,100	8.0	M	nc	Anoxic	Na	Cl
OIWU-07	6,000	7.7	U	nc	Mixed	Mixed	Mixed
OIWU-08	na	7.4	U	nc	Oxic	Mixed	Mixed
Low-Use Basins							
LUB-01	5,100	7.7	U	nc	Oxic	Ca	Mixed
LUB-02	11,300	7.9	U	nc	Oxic	Na	Mixed
LUB-03	4,200	7.7	U	nc	Anoxic	Mixed	HCO ₃
LUB-04	12,200	7.8	U	nc	Oxic	Na	Mixed
LUB-05	2,700	7.8	U	nc	Oxic	Mixed	HCO ₃
LUB-06	11,000	8.2	U	nc	Oxic	Na	Mixed
LUB-07	21,800	8.1	U	nc	Oxic	Na	Mixed
LUB-08	19,200	7.6	U	nc	Oxic	Na	Cl
LUB-09	11,000	7.8	U	nc	Oxic	Na	Mixed
LUB-10	14,500	9.2	M	120	Anoxic	Na	HCO ₃
LUB-11	20,800	7.7	U	nc	Oxic	Na	Mixed
LUB-12	9,900	8.1	U	nc	Oxic	Na	Mixed

Table 3. Geochemical conditions determined from the analyses of samples collected at well sites in the each of the nine study areas, Desert and Basin and Range study unit, California GAMA Priority Basin Project, 2006–11.—Continued

[<, less than; >, greater than; µg/L, micrograms per liter; na, not available; PMC, percent modern carbon; BP, before present; U, analyzed for but not detected; M, presence verified but not quantified; nc, not collected; Ca, calcium; Na, sodium; HCO₃, bicarbonate; SO₄, sulfate; Cl, chloride; mixed, no single cation or anion constituent more than half of the cations or anions]

GAMA identification number	Uncorrected carbon-14 age, years BP (A ₀ =84 PMC) ¹	pH	Sulfide		Redox category ²	Major ion type ³	
			Presence / absence	Concentration (µg/L)		Cations	Anions
Low-Use Basins—Continued							
LUB-13	13,800	7.9	U	nc	Oxic	Mixed	HCO ₃
LUB-14	3,300	7.3	U	nc	Oxic	Mixed	SO ₄
LUB-15	8,000	8.0	U	nc	Oxic	Na	Mixed
LUB-16	< 100	7.6	U	nc	Oxic	Mixed	SO ₄
LUB-17	18,100	7.8	U	nc	Oxic	Na	Cl
LUB-18	< 100	6.9	U	nc	Oxic	Na	Mixed
LUB-19	8,300	8.4	U	nc	Anoxic	Na	Cl
LUB-20	7,400	7.7	U	nc	Oxic	Na	Cl
LUB-21	14,400	8.9	U	nc	Oxic	Na	Cl
LUB-22	27,400	8.8	U	nc	Anoxic	Na	Cl
LUB-23	3,700	7.7	U	nc	Oxic	Mixed	HCO ₃
LUB-24	24,700	7.5	U	nc	Oxic	Ca	SO ₄
LUB-25	17,800	8.2	U	nc	Oxic	Na	Cl
LUB-26	< 100	7.6	U	nc	Oxic	Mixed	Mixed
LUB-27	17,200	8.0	U	nc	Oxic	Na	Mixed
LUBU-01	6,500	8.4	U	nc	Oxic	Na	HCO ₃
LUBU-02	12,500	7.8	U	nc	Oxic	Na	HCO ₃
LUBU-03	< 100	7.5	U	nc	Oxic	Mixed	Mixed
Mojave							
MOJO-12	< 100	7.3	U	nc	Oxic	Mixed	HCO ₃
MOJO-13	18,500	8.3	U	nc	Anoxic	Mixed	SO ₄
MOJO-14	4,600	9.3	U	nc	Oxic	Na	HCO ₃
MOJO-15	6,400	9.6	U	nc	Oxic	Na	HCO ₃
MOJO-16	2,300	8.6	U	nc	Oxic	Na	HCO ₃
MOJO-17	< 100	7.0	U	nc	Oxic	Ca	HCO ₃
MOJO-18	< 100	7.3	U	nc	Oxic	Ca	HCO ₃
MOJO-19	2,600	8.6	U	nc	Oxic	Na	Mixed
MOJO-25	300	7.5	U	nc	Anoxic	Mixed	Mixed
MOJO-27	12,700	9.0	U	nc	Oxic	Na	HCO ₃
MOJO-29	9,500	7.6	U	nc	Oxic	Na	Cl
MOJO-30	7,100	8.4	U	nc	Oxic	Na	SO ₄
MOJO-31	9,100	8.3	U	nc	Anoxic	Na	SO ₄
MOJO-35	< 100	7.7	U	nc	Oxic	Mixed	Mixed
MOJO-36	7,000	8.0	U	nc	Anoxic	Na	HCO ₃
MOJO-39	1,300	8.2	U	nc	Oxic	Na	Mixed
MOJO-41	200	7.6	U	nc	Oxic	Na	HCO ₃
MOJO-42	< 100	7.9	U	nc	Oxic	Na	HCO ₃
MOJO-49	na	7.9	U	nc	Oxic	Na	SO ₄

Table 3. Geochemical conditions determined from the analyses of samples collected at well sites in the each of the nine study areas, Desert and Basin and Range study unit, California GAMA Priority Basin Project, 2006–11.—Continued

[<, less than; >, greater than; µg/L, micrograms per liter; na, not available; PMC, percent modern carbon; BP, before present; U, analyzed for but not detected; M, presence verified but not quantified; nc, not collected; Ca, calcium; Na, sodium; HCO₃, bicarbonate; SO₄, sulfate; Cl, chloride; mixed, no single cation or anion constituent more than half of the cations or anions]

GAMA identification number	Uncorrected carbon-14 age, years BP (A ₀ =84 PMC) ¹	pH	Sulfide		Redox category ²	Major ion type ³	
			Presence / absence	Concentration (µg/L)		Cations	Anions
Mojave—Continued							
MOJOU-01	< 100	7.2	U	nc	Oxic	Ca	HCO ₃
MOJOU-02	30,900	9.4	U	nc	Anoxic	Na	HCO ₃
MOJOU-03	< 100	7.4	U	nc	Mixed	Mixed	Mixed
MOJOU-04	12,300	8.4	U	nc	Oxic	Na	Mixed
MOJOU-05	31,500	9.7	U	nc	Anoxic	Na	HCO ₃
Owens Valley							
OV-01	< 100	7.7	U	nc	Oxic	Ca	HCO ₃
OV-02	< 100	6.5	U	nc	Oxic	Ca	HCO ₃
OV-03	na	na	nc	nc	na	Mixed	Mixed
OV-04	< 100	6.8	U	nc	Oxic	Mixed	HCO ₃
OV-05	< 100	6.6	nc	nc	Oxic	Ca	HCO ₃
OV-06	9,500	8.0	U	nc	Anoxic	Ca	HCO ₃
OV-07	< 100	6.8	U	nc	Oxic	Ca	HCO ₃
OV-08	< 100	6.8	U	nc	Oxic	Ca	HCO ₃
OV-09	< 100	6.9	U	nc	Oxic	Ca	HCO ₃
OV-10	< 100	6.8	U	nc	Oxic	Ca	HCO ₃
OV-11	600	8.0	U	nc	Oxic	Mixed	HCO ₃
OV-12	< 100	6.6	U	nc	Oxic	Ca	HCO ₃
OV-13	1,300	7.0	U	nc	Oxic	Mixed	HCO ₃
OV-14	< 100	7.3	U	nc	Oxic	Mixed	HCO ₃
OV-15	2,700	8.6	U	nc	Oxic	Na	HCO ₃
OV-16	< 100	7.5	U	nc	Oxic	Mixed	HCO ₃
OV-17	7,600	7.7	U	nc	Oxic	Na	HCO ₃
OV-18	1,800	7.9	U	nc	Oxic	Ca	HCO ₃
OV-19	< 100	6.8	U	nc	Mixed	Mixed	HCO ₃
OV-20	na	7.8	U	nc	na	Ca	HCO ₃
OV-21	na	7.5	U	nc	Oxic	Mixed	HCO ₃
OV-22	< 100	7.7	U	nc	Oxic	Mixed	HCO ₃
OV-23	na	7.3	U	nc	Oxic	Ca	HCO ₃
OV-24	< 100	7.3	U	nc	Oxic	Ca	HCO ₃
OV-25	< 100	6.6	U	nc	Oxic	Ca	HCO ₃
OV-26	< 100	6.4	U	nc	Oxic	Ca	HCO ₃
OV-27	800	7.5	U	nc	Oxic	Ca	Mixed
OV-28	na	7.7	U	nc	Oxic	Ca	Mixed
OV-29	na	7.4	U	nc	Oxic	Ca	HCO ₃
OV-30	6,500	7.6	U	nc	Oxic	Mixed	HCO ₃
OV-31	2,300	7.4	U	nc	Oxic	Mixed	HCO ₃
OV-32	24,600	7.4	U	nc	Anoxic	Mixed	HCO ₃

Table 3. Geochemical conditions determined from the analyses of samples collected at well sites in the each of the nine study areas, Desert and Basin and Range study unit, California GAMA Priority Basin Project, 2006–11.—Continued

[<, less than; >, greater than; µg/L, micrograms per liter; na, not available; PMC, percent modern carbon; BP, before present; U, analyzed for but not detected; M, presence verified but not quantified; nc, not collected; Ca, calcium; Na, sodium; HCO₃, bicarbonate; SO₄, sulfate; Cl, chloride; mixed, no single cation or anion constituent more than half of the cations or anions]

GAMA identification number	Uncorrected carbon-14 age, years BP (A ₀ =84 PMC) ¹	pH	Sulfide		Redox category ²	Major ion type ³	
			Presence / absence	Concentration (µg/L)		Cations	Anions
Owens Valley—Continued							
OV-33	na	7.3	M	nc	Anoxic-Fe	Mixed	HCO ₃
OV-34	3,100	6.7	U	nc	Mixed	Mixed	HCO ₃
OV-35	13,700	6.4	U	nc	Mixed	Na	Mixed
OV-36	600	7.2	U	nc	Oxic	Mixed	HCO ₃
OV-37	< 100	6.9	U	nc	Oxic	Ca	HCO ₃
OV-38	na	6.9	U	nc	Oxic	Ca	HCO ₃
OV-39	na	7.1	U	nc	Anoxic-Fe	Na	HCO ₃
OV-40	33,600	7.2	M	nc	Mixed	Na	HCO ₃
OVU-01	< 100	7.8	U	nc	Oxic	Ca	HCO ₃
OVU-02	9,900	7.5	U	nc	Mixed	Mixed	Mixed
OVU-03	12,700	7.7	M	nc	Mixed	Mixed	HCO ₃
OVU-04	< 100	7.7	U	nc	Oxic	Mixed	HCO ₃
OVU-05	< 100	7.0	U	nc	Oxic	Ca	HCO ₃
OVU-06	1,400	7.7	U	nc	Anoxic	Na	HCO ₃
OVU-07	15,200	7.7	M	10	Anoxic	Na	HCO ₃
OVU-08	600	9.1	U	nc	Oxic	Na	HCO ₃
OVU-09	< 100	6.9	U	nc	Oxic	Mixed	HCO ₃
OVU-10	13,000	7.8	M	100	Anoxic	Mixed	HCO ₃
OVU-11	na	7.5	U	nc	Oxic	Ca	HCO ₃
OVU-12	33,600	8.4	M	nc	Anoxic	Na	HCO ₃
OVU-13	33,400	8.7	U	nc	Anoxic	Na	HCO ₃

¹ Carbon-14 age calculated using equation: $t = -8267 \cdot \ln(A_{meas}/A_0)$. Ages rounded to nearest hundred [A_0 , Initial percent modern carbon-14; A_{meas} , measured percent modern carbon]

² Mixed redox conditions are not discussed in this report with respect to distribution in groundwater or in relation to trace element occurrence.

³ Major ion types are classifications based on the major ion composition expressed in units of milliequivalents per liter. Cations: Ca, calcium >50 percent; Na, the sum of sodium and potassium >50 percent; mixed, Ca, Na, and magnesium each are less than 50 percent of cations. Anions: Cl, chloride >50 percent; HCO₃, the sum of bicarbonate plus carbonate >50 percent; SO₄, sulfate >50 percent; mixed, Cl, HCO₃, and SO₄ each are less than 50 percent of anions.

Table 4. Results of non-parametric analysis of correlations between selected potential explanatory variables, Desert and Basin and Range study unit, California GAMA Priority Basin Project.

[Results are shown only for those correlations with a p-value <0.05; Rho (ρ), Spearman’s correlation statistic; a positive rho value indicates positive correlations; a negative rho value indicates negative correlations. Kruskal-Wallis multiple comparison test shows which categorical variable tends to have higher values of the tested explanatory variable. For example, anoxic versus oxic tested against groundwater age, anoxic > oxic means that samples categorized as anoxic tended to have older groundwater ages than samples categorized as oxic; Na, sodium; Ca, calcium; Cl, chloride; SO₄, sulfate; HCO₃, bicarbonate; —, p-value greater than or equal to 0.05]

Explanatory factor	pH	Depth to the top of uppermost opening	Total dissolved solids	Oxidation-reduction (redox) class (oxic, anoxic, anoxic-Fe)	Cation class (Na, Mixed, Ca)	Anion class (HCO ₃ , Cl, SO ₄ , Mixed)
Groundwater age	0.61	0.25	0.21	anoxic > oxic > anoxic-Fe	Na > Mixed > Ca	Cl > HCO ₃ , SO ₄ , and Mixed
pH		0.39	—	anoxic > oxic and anoxic-Fe	Na > Ca and Mixed	—
Depth to the top of uppermost opening			—	—	Na > Ca	—
Total dissolved solids				anoxic-Fe > anoxic > oxic	Na and Mixed > Ca	Cl and SO ₄ > Mixed > HCO ₃

Table 5. Summary concentration statistics for trace elements and minor ions presented in this report, California GAMA Priority Basin Project.

[**Benchmarks:** MCL-US, USEPA maximum contaminant level; MCL-CA, CDPH maximum contaminant level; NL-CA, CDPH notification level; HAL-US, USEPA lifetime health advisory level. **Other abbreviations:** USEPA, U.S. Environmental Protection Agency; CDPH, California Department of Public Health; µg/L, micrograms per liter; mg/L, milligrams per liter]

Constituent	Units	Concentrations in 223 groundwater samples					Benchmark ¹		Percentage of samples above benchmark
		Min	10th percentile	Median	90th percentile	Max	Type	Concentration	
Arsenic	µg/L	0.07	0.22	2.15	18.6	513	MCL-US	10	18
Boron	µg/L	8.0	17	145.5	1,050	37,100	NL-CA	1,000	11
Fluoride	mg/L	0.1	0.19	0.64	2.6	12.6	MCL-CA ²	2	13
Molybdenum	µg/L	0.4	2.0	6.8	36.4	157	HAL-US	40	7
Strontium	µg/L	7.7	104	348	1,660	12,100	HAL-US	4,000	3
Uranium	µg/L	0.02	0.37	3.42	15	64.4	MCL-US	30	4
Vanadium	µg/L	0.09	0.72	7.45	24.60	190	NL-CA	50	3

¹ Benchmark values as of March 2014 (U.S. Environmental Protection Agency, 2009, 2012; California Department of Public Health, 2008, 2010).

² The MCL-US for fluoride is 4 mg/L.

Table 6. Results of non-parametric analysis of correlations between water-quality constituents and potential explanatory factors, Desert and Basin and Range hydrogeologic provinces, California GAMA Priority Basin Project.

[Results are shown only for those correlations with a p-value < 0.05; rho (ρ), Spearman's correlation statistic; a positive rho value indicates positive correlations; a negative rho value indicates negative correlations. Kruskal-Wallis multiple comparison test shows which categorical variable tended to have higher concentrations of the tested constituent. For example, anoxic versus oxic tested against arsenic, anoxic > oxic means that samples categorized as anoxic tended to have higher concentrations of arsenic than samples categorized as oxic; Na, sodium; Ca, calcium; Cl, chloride; SO₄, sulfate; HCO₃, bicarbonate; —, p-value greater than or equal to 0.05]

Constituent	Spearman's Rho (ρ)				Kruskal-Wallis multiple comparison test		
	Uncorrected carbon-14 age	pH	Total dissolved solids	Depth to the top of the uppermost opening	Oxidation-reduction class (oxic, anoxic, anoxic-Fe)	Cation class (Na, mixed, Ca)	Anion class (HCO ₃ , Cl, SO ₄ , mixed)
Arsenic	0.66	0.48	0.17	—	anoxic > oxic > anoxic-Fe	Na > mixed > Ca	Cl > HCO ₃ and SO ₄
Boron	0.52	—	0.62	—	anoxic > oxic	Na > mixed > Ca	Cl > HCO ₃ , mixed, and SO ₄ mixed > HCO ₃
Fluoride	0.56	0.41	0.36	—	—	Na > mixed > Ca	Cl > HCO ₃
Molybdenum	0.32	0.22	0.29	—	—	Na > Ca and mixed	Cl and SO ₄ > HCO ₃
Strontium	—	—	0.84	—	anoxic-Fe > oxic and anoxic	Na and mixed > Ca	Cl, mixed, and SO ₄ > HCO ₃
Uranium	-0.26	-0.26	—	-0.16	oxic > anoxic and anoxic-Fe	Ca > Na	—
Vanadium	0.33	0.50	—	0.25	oxic and anoxic > anoxic-Fe	Na > Ca and mixed	—

Table 7. Aqueous speciation predicted by speciation modeling (PHREEQC) in groundwater and summary statistics for trace element concentrations, Desert and Basin and Range hydrogeologic provinces, California GAMA Priority Basin Project.

Aqueous species	Portion of the total concentration in a sample present as the species					Number of samples containing species ¹
	Minimum	10th percentile	Median	90th percentile	Maximum	
Arsenic						
HAsO ₄ ²⁻	24	61	89	98	99	223
H ₂ AsO ₄ ⁻	0	2	11	40	76	216
Boron						
H ₃ BO ₃	20	80	97	99	100	223
H ₂ BO ₃ ⁻	0	0	3	19	79	205
Fluoride						
F ⁻	79	91	97	99	100	223
CaF ⁺	0	0	1	1	2	122
MgF ⁺	0	0	2	7	18	189
Molybdenum						
MoO ₄ ²⁻	35	52	72	86	93	223
MgMoO ₄	0	1	10	23	41	212
CaMoO ₄	0	4	10	16	22	217
NaMoO ₄ ⁻	1	2	6	19	63	223
Strontium						
Sr ²⁺	68	82	92	97	99	223
SrSO ₄	0	1	5	15	30	216
SrHCO ₃ ⁺	1	1	2	4	21	223
SrCO ₃	0	0	0	1	16	47
Uranium						
Ca ₂ UO ₂ (CO ₃) ₃	0	31	94	98	99	221
CaUO ₂ (CO ₃) ₃ ²⁻	0	1	1	4	7	213
UO ₂ (CO ₃) ₂ ²⁻	0	0	2	6	13	180
UO ₂ (CO ₃) ₃ ⁴⁻	0	1	1	13	99	206
UO ₂ CO ₃	0	0	0	0	5	130
UO ₂ (HPO ₄) ₂ ²⁻	0	0	0	24	100	56
Vanadium						
H ₂ VO ₄ ⁻	0	28	82	96	99	222
HVO ₄ ²⁻	0	3	14	56	95	221
V(OH) ₃	0	0	0	0	100	13

¹ Total number of samples is 223.

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