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Geochemical Relations and Distribution of Selected Trace Elements in Ground Water of the Northern Part of the Western San Joaquin Valley, California

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Geochemical Relations and Distribution of Selected Trace Elements in Ground Water of the Northern Part of the Western San Joaquin Valley, California

By NEIL M. DUBROVSKY, JOHN M. NEIL, MARY C. WELKER, and KRISTIN D. EVENSON

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FOREWORD

This report was prepared by the U.S. Geological Survey as part of the Regional Aquifer-System Analysis (RASA) Program.

The RASA Program of the U.S. Geological Survey was started in 1978 to evaluate the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system, and accordingly transcend the political subdivisions to which investigations were often arbitrarily limited in the past. The broad objectives for each study are to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The Central Valley RASA study, which focused on the hydrology and geochemistry of ground water in the Central Valley of California, began in 1979. Phase II of the Central Valley RASA began in 1984 and was completed in 1990. The focus during this second phase was on more detailed study of the hydrology and geochemistry of ground water in the San Joaquin Valley, which is the southern half of the Central Valley.

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the metric system of units to the inch-pound system of units, the conversion factors are listed below:

Multiply metric unit	By	To obtain inch-pound unit
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meter per second (m/s)	3.281	foot per second
millimeter (mm)	0.03937	inch
square kilometer (km^2)	0.3861	square mile

For temperature, degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) by using the formula: Temp. °F=1.8(temp. °C)+32.

SEA LEVEL

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

WATER-QUALITY INFORMATION

Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is about the same as for concentrations in parts per million.

Trace-element concentrations in water samples are given in micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to 1 milligram per liter. Micrograms per liter is equivalent to "parts per billion." Trace-element concentrations in soils are given in micrograms per gram (µg/g). Micrograms per gram is equivalent to "parts per million."

Geochemical Relations and Distribution of Selected Trace Elements in Ground Water of the Northern Part of the Western San Joaquin Valley, California

By Neil M. Dubrovsky, John M. Neil, Mary C. Welker, *and* Kristin D. Evenson

Abstract

Water samples were collected from 44 wells in the northern part of the western San Joaquin Valley, California, between March and July 1985 to assess the geochemical relations and distribution of major ions and selected trace-element concentrations in ground water of the area. The ground-water-flow system consists of a semiconfined zone and a confined zone separated by a regionally extensive clay bed.

The data show that the areal and vertical distribution of ground-water chemistry in the ground-water-flow system has been affected by different agricultural and natural sources of recharge and the source and redox status of the sediments. Tritium and stable-isotope data indicate extensive infiltration of the semiconfined zone by post-1952 irrigation water originating as runoff from the Sierra Nevada. Tritium concentrations greater than 2 tritium units in most samples from the confined zone indicate that the post-1952 water also has infiltrated to wells completed in this zone. Stable-isotope data indicate that ground water from the semiconfined zone, characterized by the enriched oxygen-18 that is indicative of a Coast Ranges source, occurs in many wells in the confined zone. Movement of water from the semiconfined zone to the confined zone likely is taking place by downward flow through the many wells that perforate the confining clay bed.

Trace-element concentrations in the semiconfined and confined zones generally are similar. In contrast, concentrations were significantly different between ground water from Coast Ranges sediments and ground water from Sierra Nevada sediments in both zones. Ground water from Coast Ranges sediments contains significantly higher concentrations of nitrate, boron, and selenium than water from Sierra Nevada sediments. Ground water from Sierra Nevada sediments was significantly higher in arsenic, molybdenum, and manganese than ground water from Coast Ranges sediments. These differences result from a combination of variable availability of the constituents and redox controls on mobility.

Selenium, the only priority pollutant to exceed the U.S. Environmental Protection Agency's drinking-water standard, equaled or exceeded the standard of 10 micrograms per liter in water from two wells completed in the semiconfined zone and one well in the confined zone. The conservative nature of selenium behavior in the oxidized Coast Ranges deposits is shown by the high correlation (r=0.88) between selenium concentrations and specific conductance in water from these deposits in the semiconfined zone. High selenium concentrations in both zones are spatially related to the location of Coast Ranges streams that have high selenium concentrations and that were historical sources of recharge to the zones.

Principal-component analysis confirmed the association of boron, chromium, lithium, and selenium, and the association of arsenic, iron, manganese, and molybdenum to sediments in the study area. The analysis indicated that the first group is associated with Coast Ranges sediments and the second with Sierra Nevada sediments.

INTRODUCTION

Background

The chemistry of irrigation water that recharges the ground-water system in the western San Joaquin Valley, California, is affected by the leaching of naturally occurring elements in soil, evaporation, and a large variety of agricultural chemicals. Some soils in the area are saline and contain high concentrations of trace elements, such as boron and selenium. Salinity problems commonly are controlled by the addition of sufficient irrigation water to prevent accumulation of salts near the surface and by the installation of subsurface tile drains to remove the resulting excess water. High concentrations of selenium in agricultural drain water from some parts of the western San Joaquin Valley have caused particular concern (Deverel and others, 1984; Presser and Barnes, 1984). Some of this drain water was stored in Kesterson Reservoir, where selenium was concentrated in the food chain and high mortality and birth defects in waterfowl nestlings were observed (U.S. Bureau of Reclamation, 1984).

In addition to contamination of surface water, a key concern in the western San Joaquin Valley is the potential for contamination by infiltration of irrigation water into the regional ground-water-flow system used for water supply. The effects of agricultural activities on ground-water quality are important because in the northern part of the western valley, where this study was done, ground water is used for irrigation and domestic water supply.

The purpose of this study is to assess the geochemical relations and the distribution of major ions and selected trace-element concentrations in ground water of the northern part of the western San Joaquin Valley, California. Because agriculture began affecting ground water in this area in the mid-1800's, a necessary part of this analysis is an understanding of the ages and origins of ground water in various parts of the ground-water-flow system. This study was done as part of the Regional Aquifer-System Analysis Program of the U.S. Geological Survey.

Purpose and Scope

Specific objectives of the report are (1) to provide an overview of the nature and variability of the major-ion chemistry of ground water in the study area, (2) to examine the age and origin of ground water in different parts of the ground-water-flow system by using environmental isotopes and supporting major-ion chemistry, (3) to describe the distribution of selected trace elements in the ground-water-flow system in relation to the dominant factors and processes that affect them, and (4) to assess the relations among major ions and trace elements in ground water by using multivariate analyses and the consistency of these relations with the distributions of major ions and trace elements. This report focuses on the distribution of arsenic, boron, molybdenum, and selenium, the elements most likely to affect ground-water quality in the area.

Acknowledgments

This report would not have been possible without the cooperation of the residents of the study area who permitted access to their wells.

DESCRIPTION OF STUDY AREA

The San Joaquin Valley occupies the southern two-thirds of the Central Valley of California and is bounded by the Sierra Nevada on the east, the Tehachapi Mountains on the south, and the Coast Ranges on the west. The area described in this report is in the northwest corner of the San Joaquin Valley, between the cities of Tracy to the north and Dos Palos to the south (fig. 1). The western boundary of the study area is the contact between the valley fill of unconsolidated alluvium and the Coast Ranges. The eastern boundary of the study area generally follows the San Joaquin River, though some data are included for areas east of the river.

The boundary of valley deposits shown on the western side of all maps of the study area follows the contact between younger Pleistocene and Pliocene-Pleistocene nonmarine deposits of the valley and older deposits of the Coast Ranges. This boundary is similarly defined on the eastern side of the valley, with the exception that the unit mapped as Pliocene-Pleistocene nonmarine deposits (California Division of Mines and Geology, 1959, 1966) is included in the valley. This unit was included in the east because it is of larger areal extent than in the west, and because it commonly is farmed.

The climate of the study area is semiarid, with mild winters and hot summers. The mean annual temperature is 16.7 °C (Hotchkiss and Balding, 1971). The area lies in the rain shadow of the Coast Ranges and usually receives only 250 to 380 mm of rain annually, most of which occurs during the winter. Because of the mild climate, long growing season, and readily available water from ground water and runoff from the Sierra Nevada, the area has a long history of agriculture dating back to the mid-1800's. In 1971, more than 1,300 km^2 of land, about 40 percent, in the study area was irrigated.

HYDROGEOLOGY

The aquifers of the study area consist of unconsolidated sediments derived from the Coast Ranges and the Sierra Nevada. Unconsolidated deposits are more than 610

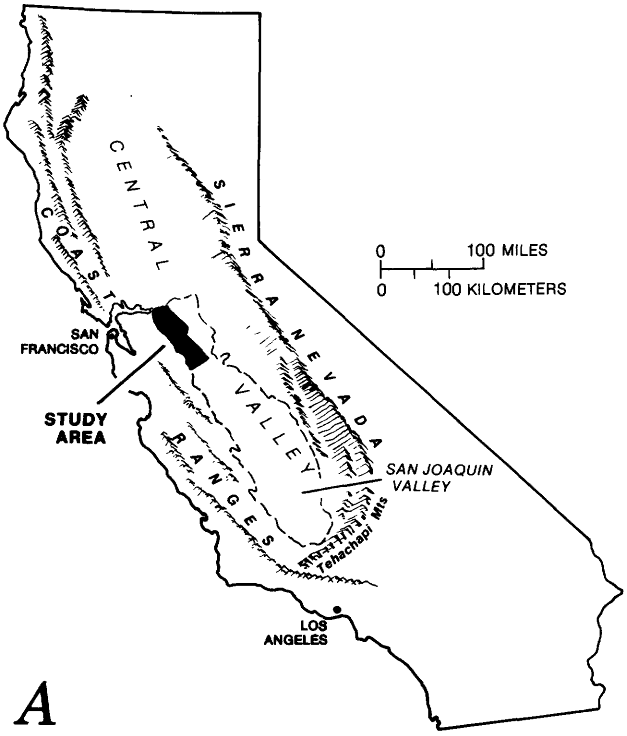

Figure 1. Location of study area and wells sampled. *A*, Index map of California. *B*, Location of wells sampled.

m thick in places and thin toward the Coast Ranges (fig. 2). These deposits are part of the Tulare Formation of Tertiary and Quaternary age.

The upper part of the Tulare Formation above the Corcoran Clay Member of the Tulare Formation consists of sediments derived from the Coast Ranges on the west

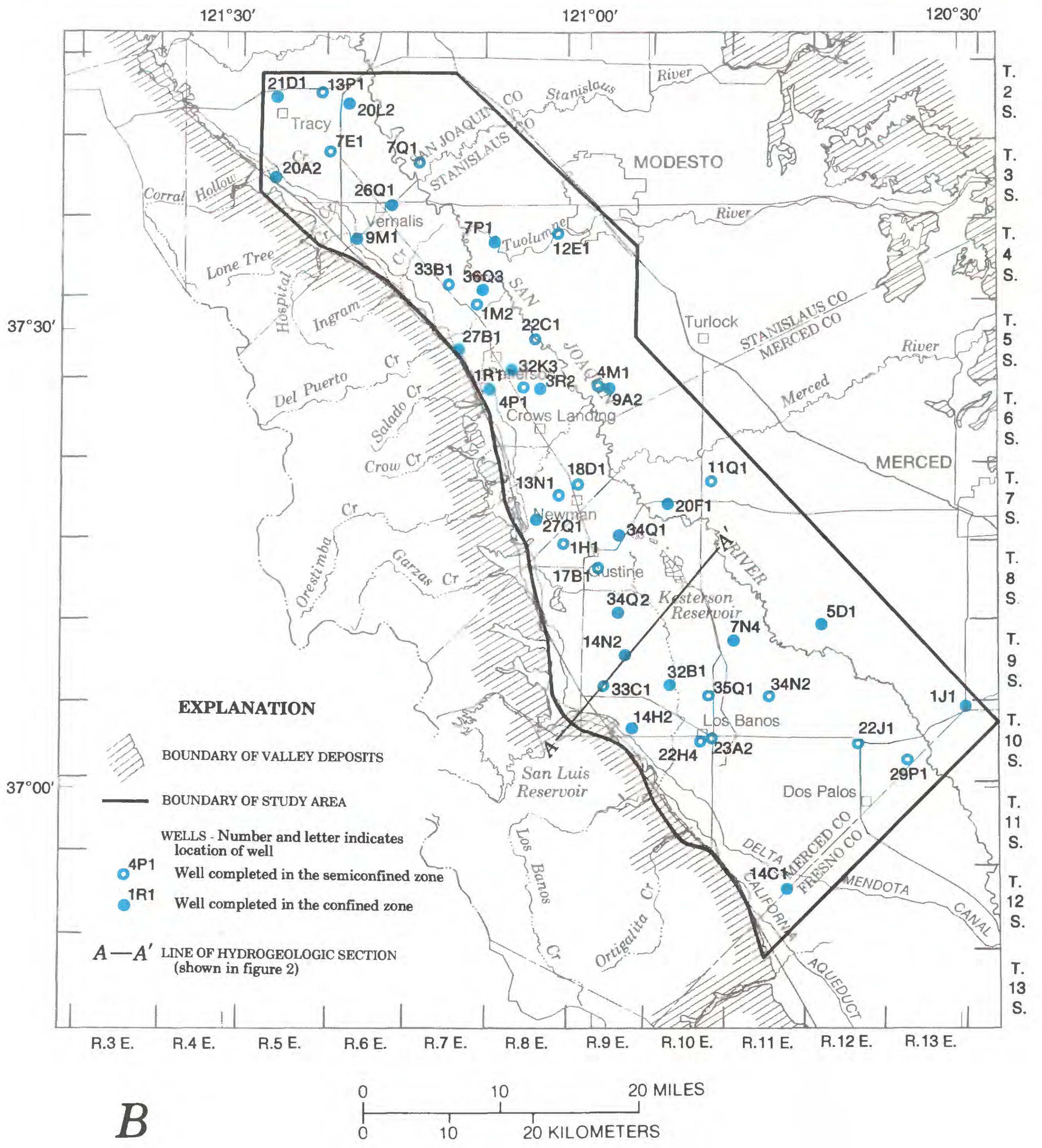

Figure 1.—Continued

that interfinger eastward with sediments derived from the Sierra Nevada (fig. 2). Detailed analysis of the Coast Ranges sediments in western Fresno County near the southern edge of the study area shows that the sediments are coarsest at the heads of the alluvial fans where streams enter the valley and mainly fine-grained silt and clay in the rest of the area (Julie Laudon, U.S. Geological Survey, written commun., 1987). The Sierra Nevada sediments in the study area are primarily well-sorted micaceous sands (Miller and others, 1971).

The Coast Ranges and Sierra Nevada sediments differ in aspects of their petrology as well as texture. The Sierra Nevada sediments are light colored, micaceous, arkosic sand, with greater than 25 percent feldspar (Meade, 1967). They contain 2 to 5 percent mica, most of which is unweathered biotite and 1 to 2 percent prismatic grains of hornblende (Meade, 1967). Calcium carbonate content is low, generally less than 0.5 weight percent (Davis and Poland, 1957). Small amounts of magnetite and other heavy minerals also are present as thin, dark layers, and smaller amounts of pyroxene and muscovite are present (Flexser, 1988).

Coast Ranges sediments are darker than the Sierra Nevada sediments, which is attributed to the high amount of lithic fragments in the Coast Ranges sediments including andesite, serpentinite, and brick-red cherts (Meade, 1967). In western Fresno County, the Coast Ranges sediments commonly contain 2 to 7 weight percent gypsum near land surface possibly to a depth of 61 m (Davis and Poland, 1957; Tanji and others, 1978). The sediments are calcareous, containing 1 to 6 weight percent calcium carbonate (Davis and Poland, 1957). The Coast Ranges sediments also contain less than 2 percent mica, present as weathered flakes (Meade, 1967).

The part of the ground-water-flow system above the Corcoran Clay Member is referred to as the semiconfined

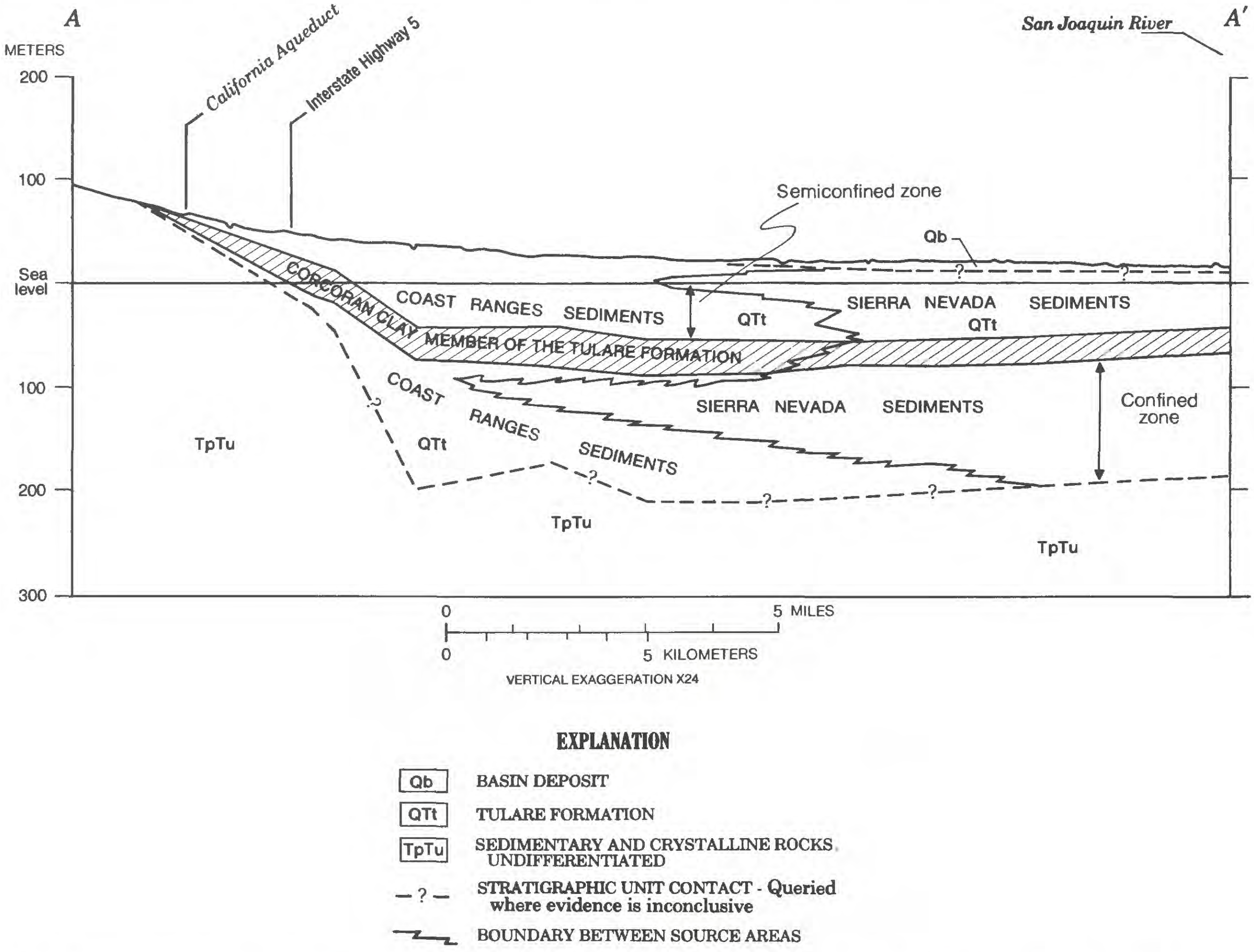

Figure 2. Generalized hydrogeologic section of the study area. (Modified from Hotchkiss and Balding, 1971.) (See figure 1 for line of section.)

zone. Generally, this zone is semiconfined with local occurrences of confined and unconfined conditions. The semiconfined zone thickens from the Coast Ranges eastward to a maximum of 91 m (Page, 1986).

The semiconfined zone is underlain by the most extensive bed of clay in the San Joaquin Valley, the Corcoran Clay Member of the Tulare Formation. This distinctive "blue" diatomaceous clay ranges from about 12 to 40 m thick and underlies almost the entire study area. The Corcoran Clay Member can effectively separate the semiconfined zone from underlying ground water under natural conditions; however, simulation of ground-water flow in the Central Valley by Williamson and others (1989) indicates that the flux of water has increased sixfold between the semiconfined and confined zones as a result of flow through multilayer perforated wells.

The part of the ground-water-flow system below the Corcoran Clay Member is referred to as the confined zone. The variety of deposits of the confined zone is similar to the semiconfined zone, except that Sierra Nevada sediments may extend farther to the west.

The lower boundary of the ground-water-flow system in the study area is the base of fresh water, which is arbitrarily selected as ground water with a specific conductance of less than 3,000 µS/cm (microsiemen per centimeter at 25 °C) (Olmsted and Davis, 1961). The boundary between fresh and saline water is at a depth ranging from 120 to 610 m below sea level in the study area (Page, 1973).

The surficial geology of the study area is shown in figure 3. Most of the northern one-half of the area is underlain by alluvial and stream-channel deposits. In the southern part of the study area, the surficial materials largely are flood-basin deposits, which exclude the alluvial and stream-channel deposits. Stream-channel deposits are mostly along channels of the San Joaquin River and the major rivers draining the Sierra Nevada.

Because of low rainfall and high evaporation, little recharge is by infiltration of precipitation. The dominant form of recharge in western Fresno County under natural conditions was infiltration of streams flowing out of the Coast Ranges (Mendenhall and others, 1916). Recharge by this mechanism is shown by small zones of distinctive ground-water chemistry that resemble the chemistry of the stream waters that recharge the ground-water-flow system locally in the study area (Hotchkiss and Balding, 1971, p. 85). Additional evidence for this mechanism of recharge in western Fresno County is summarized by Belitz and Heimes (1990).

An inventory of water supply in the study area during 1962–66 was done by Hotchkiss and Balding (1971, p. 48–64). Their results show that on the average 72 percent of the total water supplied to the study area was by canal delivery and seepage from canals. In contrast, an average of only 8 percent of the total supply originated as effective precipitation or stream infiltration. The remaining 20 percent was derived from ground-water pumpage. Although the proportions of each component that eventually recharge the flow system are not known, the primary source of recharge since at least 1962 has been imported water.

Prior to modification of the natural flow system, water-level contours drawn using data for the semiconfined and confined zones showed ground-water flow northeast from the Coast Ranges toward the San Joaquin River (Mendenhall and others, 1916, pl. 1). Ground water that was recharged by infiltration of Coast Ranges streams discharged in a wide zone along the valley axis through evapotranspiration or seepage. Early descriptions of the valley noted extensive marshlands in this area. Mendenhall and others (1916) identified artesian conditions in an area about 11 km wide near Tracy, narrowing to less than 2 km wide near Newman, and widening to 19 km south of Los Banos (Hotchkiss and Balding, 1971). By 1960, extensive use of ground-water resources led to large decreases in hydraulic head, with water-level depressions around local pumping centers (Hotchkiss and Balding, 1971). The increase in use of surface water in lieu of ground water after the completion of the Delta Mendota Canal in 1951 resulted in a reversal of this hydraulic head trend. In the western San Joaquin Valley, as much as 30 to 60 m of water-table rise has resulted from the combined effects of decreased pumpage and increased irrigation since about 1960 (Belitz and Heimes, 1990).

A map of the water levels in the semiconfined zone in 1967 indicates that ground water flowed toward the San Joaquin River (Hotchkiss and Balding, 1971, fig. 11). A more detailed study of a section of the study area surrounding the Kesterson Reservoir showed that local flows developed in the upper 6 m of the semiconfined zone, with seasonal discharge to or recharge from the creeks and sloughs (Mandle and Kontis, 1986). A map of the water levels in the confined zone in 1967 indicates a pattern of northeastward flow in the northern one-third of the study area similar to that in the semiconfined zone (Hotchkiss and Balding, 1971, fig. 10). However, water levels in the south show southward flow toward a pumping depression in western Fresno County.

Water levels measured in wells completed in the semiconfined and confined zones show downward gradients between the two zones over most of the study area. In 1967, a comparison of 12 pairs of wells, one screened in the semiconfined zone and one in the confined zone, showed downward gradients with total head differences ranging between 1.2 and 45 m, with an average of 16 m (Hotchkiss and Balding, 1971, table 7). Water levels measured in wells along the San Joaquin River between Crows

Landing and the Stanislaus River and in two small areas north and east of Tracy, however, showed upward gradients (Hotchkiss and Balding, 1971).

Water levels measured in wells in 1984 (California Department of Water Resources, 1985a, 1985b) were virtually the same as those measured in 1967. This implies that ground-water flow in the study area may be in approximate equilibrium with the recharge established since the import of surface water for irrigation by the Delta Mendota Canal in 1951 (Belitz and Heimes, 1990).

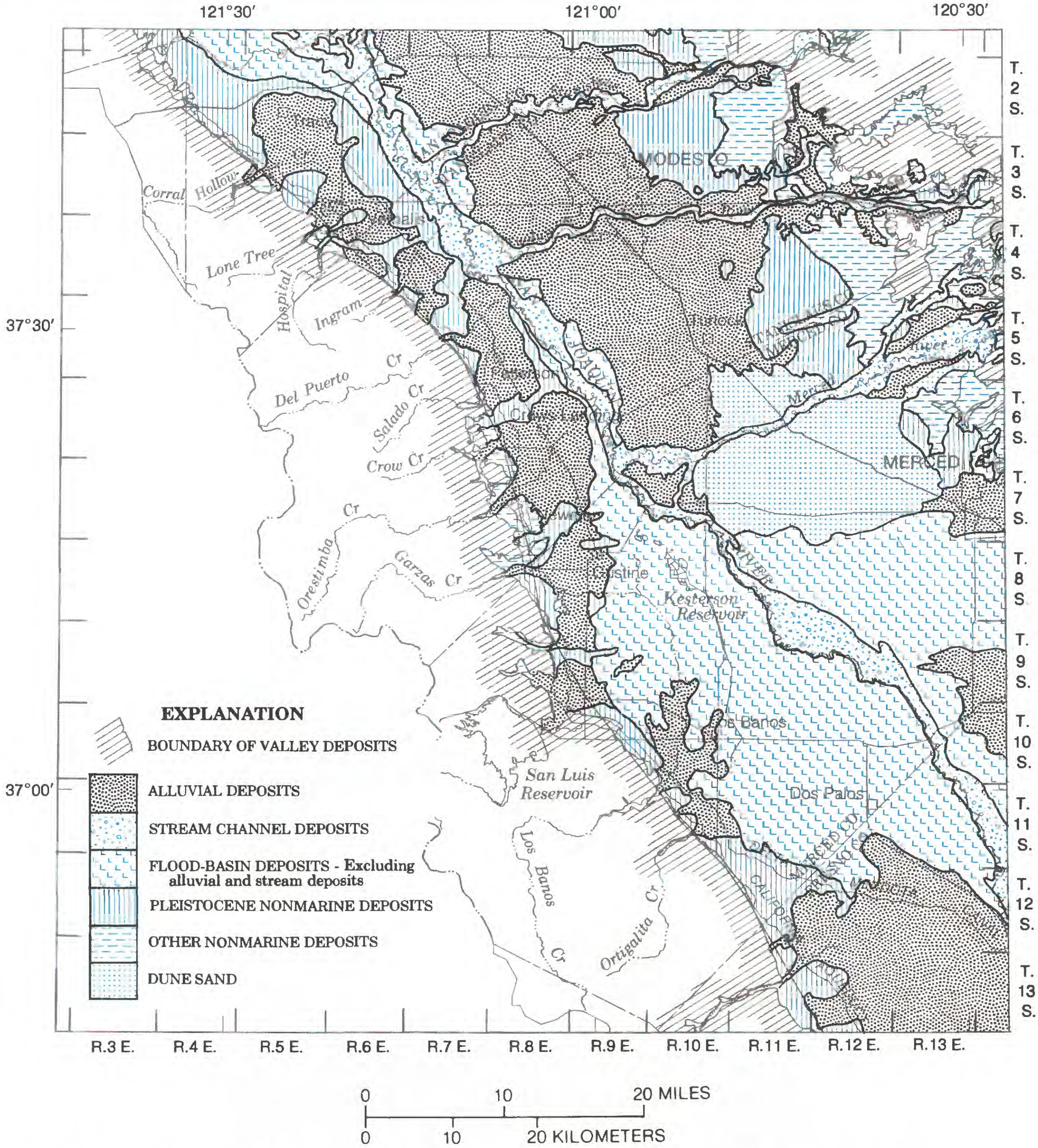

Figure 3. Surficial geology of study area. (Adapted from California Division of Mines and Geology, 1959 and 1966.)

A more comprehensive summary of the hydrogeology of the ground-water-flow system in the San Joaquin Valley was done by Page (1986). The historical and present hydrology of the western San Joaquin Valley is discussed in detail by Williamson and others (1989) and Belitz and Heimes (1990). A detailed evaluation of the stratigraphy of the study area was done by Lettis (1982).

METHODS OF INVESTIGATION

Selection of Wells for Sampling

In order to examine the distribution of major and trace elements in ground water, a sampling scheme was devised to obtain (1) a uniform areal distribution of samples and (2) an indication of the variation of chemistry with depth. The township/range system for the division of public lands was used as a grid for attempting to obtain uniform areal coverage. Wells completed in the semiconfined and confined zones were sampled because studies of ground-water chemistry in the San Joaquin Valley have noted that the Corcoran Clay Member of the Tulare Formation geochemically and hydrologically affects ground water in the study area (Davis and Poland, 1957; Davis and Coplen, 1989). The goal of well selection for chemical sampling was to locate one existing production well completed only in the semiconfined zone and one completed only in the confined zone in each township in the study area.

Owing to the large size of the study area and the high cost of installing new monitoring wells, data from existing wells were used in this study. These data show element distributions in ground-water resources presently in use, allow an approximation of the natural distributions of elements, and provide information on infiltration of the ground-water-flow system by imported irrigation water. Limitations to using only existing wells are (1) the areal distribution is irregular, (2) a bias may be introduced to the sampling because zones with water quality suitable for most uses are preferentially penetrated and zones with deteriorated quality not suitable for use are avoided or wells were abandoned, (3) the quality of the driller's logs is variable and details such as well construction and location of the screened interval are uncertain, (4) land subsidence in the study area has damaged the casings of many wells that were present prior to 1952, when most of the subsidence occurred, so that leakage due to casing failures may result in a sample that is a mixture of ground water from the zones above and below the Corcoran Clay Member, (5) representative measurements of oxidation-reduction potential cannot be made because of various water-delivery systems in the field, and (6) water samples may not be representative of the quality of water coming from the zone that is supposed to be represented because of the downward gradient generated locally by heavily pumped wells and the possibility of induced flows through leaky casing.

Drillers' logs compiled by the California Department of Water Resources were used to select sampling wells. The criterion for well selection was that the well have a driller's log with the depth of the screened interval clearly noted. In spite of the large number of wells in the study area, only a limited number satisfied the criterion. Field inspection of candidate wells prior to sampling eliminated wells that are no longer in use. For the 35 townships in the study area, 21 wells were sampled for the semiconfined zone and 23 wells were sampled for the confined zone between March and July 1985 (fig. 1; table 1).

Well-Numbering System

Wells are identified according to their location in the rectangular system for the subdivision of public lands. Their identification consists of the township number, north or south; the range number, east or west; and the section numbers. Each section is further divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with A in the northeast corner of the section and progressing in a sinusoidal manner to R in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter in a well identification number refers to the base line and meridian. All wells in the study area are referenced to the Mount Diablo base line and meridian. Figure 4 shows how the well number 10S/13E–29P1 is derived.

Sample Collection and Analysis

Samples were collected using existing pumps and piping systems. Prior to sample collection, about three well-casing volumes of water were pumped in order to ensure the collection of a representative sample. All sampling apparatus and containers were rinsed three times with the well water to be sampled. Samples to be analyzed for major and trace dissolved constituents were filtered using 0.45-μm (micrometer) membrane filters and stored in polyethylene bottles. The exception was the mercury sample, which was collected in a glass bottle with a Teflon-lined cap.

The samples collected for cation analysis were preserved by using nitric acid, and the mercury sample was preserved by using dichromate blend. Samples for anion analysis were untreated, although the sample for nitrate and phosphate analysis was chilled. An unfiltered sample

Table 1. Location and description of wells sampled in the semiconfined and confined zones

[State well No.: See "Well-Numbering System" in text. Station No.: Unique number for each site based on the latitude and longitude of the site. First six digits are latitude, next seven digits are longitude, and final two digits are a sequence number to identify wells at each site. Altitude of land surface in meters above sea level. Casing: Top and bottom of open interval was measured from the top of the casing. Primary use of water: C, commercial; D, dewatering; H, domestic; I, irrigation; N, industrial; P, public supply; S, stock; U, unused. Location of well screen: Source of sediments in which well is screened—CR, Coast Ranges; SN, Sierra Nevada. m, meter. <, actual value is less than value shown]

State well No.	Station No.	Altitude of land surface (m)	Casing: Top of open interval (m)	Casing: Bottom of open interval (m)	Primary use of water	Location of well screen
Semiconfined zone						
2S/5E-13P1	374528121221801	4.6	20.7	24.4	H	CR
3S/6E-7E1	374136121213601	23.2	5.5	14.3	I	CR
3S/7E-7Q1	374058121141501	7.6	30.8	32.3	H	SN
4S/7E-33B1	373258121115901	27.4	16.8	22.9	H	CR
4S/8E-12E1	373616121025001	18.3	27.7	32.3	H	SN
5S/7E-1M2	373137121092701	27.7	27.4	36.6	H	CR
5S/8E-22C1	372927121044401	15.2	18.9	22.0	H	CR
6S/8E-4P1	372608121054401	32.0	26.8	32.9	H	CR
6S/9E-4M1	372619120593001	18.3	21.6	24.7	D	SN
7S/8E-13N1	371912121025001	32.9	11.0	14.0	H	CR
7S/9E-18D1	371953121013701	29.0	33.5	36.6	H	CR
7S/10E-11Q1	372004120501301	26.8	14.3	19.8	H	SN
8S/8E-1H1	371613121015201	33.5	19.2	23.8	H	CR
8S/9E-17B1	371433120595601	32.0	17.1	23.2	H	CR
9S/9E-33C1	370644120591601	38.1	12.2	18.3	H	CR
9S/10E-35Q1	370600120503501	29.0	36.6	42.7	H	SN
9S/11E-34N2	370557120453901	29.0	27.4	33.5	H	SN
10S/10E-22H4	370259120511201	37.5	(1)	(1)	H	CR
10S/10E-23A2	370322120501901	35.1	28.4	76.2	N	SN
10S/12E-22J1	370248120380701	32.0	36.6	48.8	H	SN
10S/13E-29P1	370145120341701	35.1	35.1	39.6	H	SN
Confined zone						
2S/5E-21D1	374509121260001	8.5	[2]102.7	[2]344.5	P	CR
2S/6E-20L2	374445121200001	4.6	180.5	198.8	U	CR
3S/5E-20A2	373957121260101	70.1	103.6	122.0	H	CR
3S/6E-26Q1	373820121163501	23.8	61.0	63.1	C	CR
4S/6E-9M1	373557121191901	64.0	80.8	93.0	H	CR
4S/7E-36Q3	373224121085201	19.5	70.1	76.2	H	CR
4S/8E-7P1	373548121075701	12.2	85.4	91.5	H	SN
5S/7E-27B1	372843121110401	54.9	57.6	69.8	H	CR
5S/8E-32K3	372722121063301	29.6	77.7	83.8	H	CR
6S/7E-1R1	372610121083101	59.4	[2]62.5	[2]208.8	H	CR

See footnotes at end of table.

Table 1.—Continued

[State well No.: See "Well-Numbering System" in text. Station No.: Unique number for each site based on the latitude and longitude of the site. First six digits are latitude, next seven digits are longitude, and final two digits are a sequence number to identify wells at each site. Altitude of land surface in meters above sea level. Casing: Top and bottom of open interval was measured from the top of the casing. Primary use of water: C, commercial; D, dewatering; H, domestic; I, irrigation; N, industrial; P, public supply; S, stock; U, unused. Location of well screen: Source of sediments in which well is screened—CR, Coast Ranges; SN, Sierra Nevada. m, meter. <, actual value is less than value shown]

State well No.	Station No.	Altitude of land surface (m)	Casing		Primary use of water	Location of well screen
			Top of open interval (m)	Bottom of open interval (m)		
		Confined zone--*Continued*				
6S/8E-3R2	372608121041201	23.5	74.1	83.2	H	CR
6S/9E-9A2	372603120584701	17.7	103.6	122.0	C	SN
7S/8E-27Q1	371723121042901	47.2	44.8	75.3	H	CR
7S/9E-34Q1	371631120574401	22.0	137.2	200.6	H	CR
7S/10E-20F1	371833120534701	21.3	82.3	109.8	S	SN
8S/9E-34Q2	371125120575701	26.5	125.0	143.3	H	SN
9S/9E-14N2	370843120572301	30.2	122.0	189.0	N	SN
9S/10E-32B1	370650120534101	28.6	134.1	152.4	S	CR
9S/11E-7N4	370936120484701	25.9	97.6	128.0	H	SN
9S/12E-5D1	371109120411401	30.5	[2]73.2	[2]225.0	I	SN
10S/9E-14H2	370355120564901	42.7	79.3	91.5	H	CR
10S/13E-1J1	370515120293001	41.2	88.4	137.2	S	SN
12S/11E-14C1	365327120441301	55.5	123.8	215.2	H	CR

[1] Open bottom at 22.9 m.

[2] Uppermost and lowermost depth of multiperforated well casing.

for total organic carbon was collected in a glass bottle and chilled. Unfiltered samples also were collected for analysis of tritium and stable isotopes of oxygen and hydrogen.

Several characteristics were measured in the field. The pH was measured by using a portable meter that was calibrated at each site. Incremental alkalinity titrations were done as soon as the sample was collected. Specific conductance was measured by using a field meter, and temperature was measured by using a standardized mercury thermometer.

Major and trace elements were analyzed by the U.S. Geological Survey Laboratory in Arvada, Colorado, by standard procedures described by Skougstad and others (1985). Selenium and arsenic concentrations were determined by hydride generation and atomic adsorption spectrometry. The stable isotopes were analyzed at the U.S. Geological Survey in Reston, Virginia. The tritium samples were analyzed by electrolytic enrichment and liquid scintillation counting at the Environmental Isotope Laboratory of the University of Waterloo, Ontario, Canada.

DISTRIBUTION OF MAJOR IONS

The distribution of major ions in ground water in the study area is largely the result of the initial major-ion chemistry of the surface water that recharges the flow system. The study area has received surface-water recharge from Coast Ranges streams along the western boundary and the San Joaquin River along the eastern boundary. Surface water was not sampled for this study; however, the chemistry of water from these two areas has some basic differences that have been described by previous researchers.

Davis (1961) evaluated the relation between the lithology of Coast Ranges drainage basins and the composition of the associated stream water, including five streams in the study area. He found that the relative abundances of bicarbonate and sulfate are controlled by the lithology of the drainage area. The ratio of bicarbonate to sulfate, expressed as equivalents per million, ranges from 0.8 to 6 in stream water collected at low-flow stage from areas where clastic marine sedimentary rocks of Jurassic and Cretaceous age are the dominant lithology. Sulfate is the dominant anion in stream water collected at low-flow stage from drainage basins underlain predominantly by marine and continental rocks of Tertiary-age and continental rocks of Quaternary age.

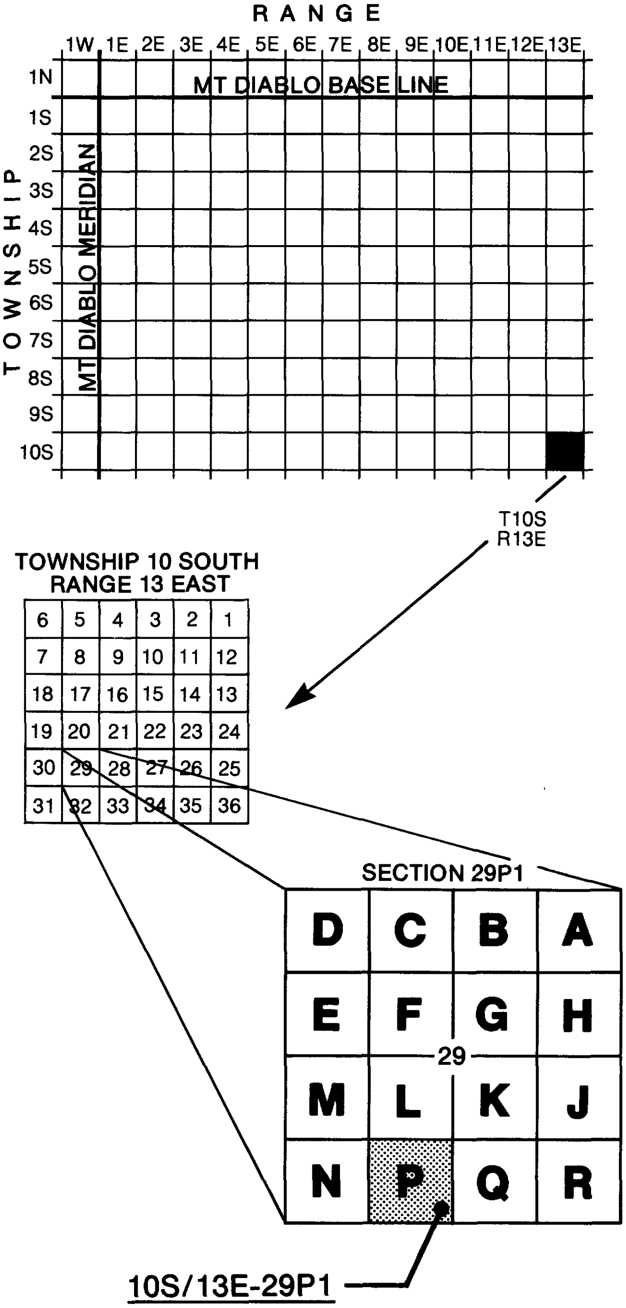

Figure 4. Well-numbering system.

The Coast Ranges west of the study area are underlain predominantly by Cretaceous marine rocks and rocks of the Cretaceous and Jurassic Franciscan Formation. Data for eight of the Coast Ranges streams sampled on several occasions indicate that in most of the streams that enter the study area, bicarbonate is the dominant anion (Hotchkiss and Balding, 1971). Water from Corral Hollow Creek, however, is dominated by sulfate. The anion content of a particular stream is variable in time. Chloride is the dominant anion in two streams on occasion, and sulfate is the dominant anion in two additional streams in at least one water sample. Dissolved-solids concentrations of these streams ranged from 120 to 1,800 mg/L.

Sodium is usually the most abundant cation, expressed as equivalents per million; calcium, however, is often present in a similar proportion and is the most abundant cation at times in four of the eight Coast Ranges streams sampled (Hotchkiss and Balding, 1971). Magnesium occasionally exceeds 35 percent of the total cation equivalents in four of the streams and is the dominant cation in water sampled from Del Puerto Creek on most sampling dates (Hotchkiss and Balding, 1971). The high proportion of magnesium in water from Del Puerto Creek is due to a large outcropping of ultrabasic rocks in its drainage basin.

Davis (1961) found that, where adequate data are available, the dissolved-solids concentrations and major-ion ratios of the stream water are related to the stream discharge. As discharge decreased, dissolved-solids concentrations increased and the proportions of sulfate and chloride increased. These trends reflect increased contribution of ground-water discharge to total streamflow at low discharges.

In contrast to the Coast Ranges streams, analyses of water from streams that drain the Sierra Nevada—the Merced, Stanislaus, and Tuolumne Rivers—indicate dissolved-solids concentrations are low, ranging from 29 to 167 mg/L (Shelton and Miller, 1988), and are calcium bicarbonate waters where they enter the valley (Hotchkiss and Balding, 1971). Low dissolved-solids concentrations and a higher proportion of bicarbonate in the Sierra Nevada runoff are due to the low solubility of metamorphic and igneous rocks in the Sierra Nevada drainage basins. Under natural conditions, the water chemistry of the San Joaquin River probably was similar to the other Sierra Nevada rivers that enter the study area; however, owing to the addition of irrigation drainage, the San Joaquin River has high dissolved-solids concentrations and generally higher proportions of sodium, chloride, and sulfate than the other Sierra Nevada rivers. North of the confluence with the Stanislaus River, the dissolved-solids concentrations of the San Joaquin River ranged from 103 to 714 mg/L for

June 1985 to March 1987, and the water was a sodium chloride bicarbonate type (Shelton and Miller, 1988).

Results of the analyses of field measurements and major ions in ground water sampled in this study in March through July 1985 are summarized in table 2, and all the data are given in table 11 (at the end of report). Among 44 samples, a nonparametric test (Mann-Whitney test, Conover, 1980) shows no significant differences (α=0.05) in the magnitudes of major-ion concentrations in water between the semiconfined and confined zones, with the exception of alkalinity, which was higher in water in the semiconfined zone.

The dissolved-solids concentration of a water sample commonly is used as a general indicator of water quality. The dissolved-solids concentrations in ground water sampled from the semiconfined zone ranged from 210 to 2,400 mg/L, with a median of 940 mg/L (table 2). Areal distribution of the data shows that dissolved-solids concentrations in ground water were highest near Patterson, west of Newman, and northwest of Los Banos (fig. 5*A*). Dissolved-solids concentrations in wells near the San Joaquin River generally were low (less than 500 mg/L), with the exception of two wells east of Crows Landing.

Areal distribution of dissolved-solids concentrations shown in figure 5*A* does not show the increase in dissolved-solids concentrations along the flow path that is sometimes characteristic of ground-water-flow systems. This is due to the sparseness of data and low dissolved-solids concentrations in water in some of the wells near the San Joaquin River. These wells withdraw water from Sierra Nevada sediments that extend west of the San Joaquin River. Ground water from these sediments previously was noted to have low dissolved-solids concentrations, and the low concentrations were considered evidence that this ground water originated in the Sierra Nevada (Davis and others, 1959).

Dissolved-solids concentrations in water in the confined zone range from 190 to 4,400 mg/L, with a median of 920 mg/L (table 2). Distinct trends are not apparent in the areal distribution of dissolved solids in this zone (fig. 5*B*). In general, the values are low in the northwest and high through the central part of the area from south of Patterson to north of Los Banos. Dissolved-solids concentrations are lowest in the southeast corner of the area. The distribution of dissolved-solids concentrations in ground water in the two zones has little similarity. Dissolved-solids concentrations in ground water in both zones were less than 500 mg/L in the southeast and greater than 1,500 mg/L in the Crows Landing area.

The ionic composition of ground water sampled is illustrated by using Piper diagrams (Piper, 1944). Cation

Table 2. Summary of field measurements and concentrations of major ions in ground water sampled in March through July 1985 in 44 wells in the semiconfined and confined zones

[µS/cm, microsiemen per centimeter at 25 °C; °C, degrees Celsius; mg/L, milligram per liter. <, actual value is less than value shown]

Property or constituent	Semiconfined zone (21 samples)			Confined zone (23 samples)		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Field measurements						
Specific conductance (µS/cm)	295	1,380	3,320	282	1,390	7,960
pH (units)	7.2	7.5	8.0	7.4	7.8	8.4
Temperature (°C)	16.5	19.0	20.5	17.5	21.0	25.0
Major ions (mg/L)						
Calcium, dissolved	22	110	260	9.1	70	260
Magnesium, dissolved	6.8	57	150	1.5	37	93
Sodium, dissolved	28	140	500	49	170	1,500
Potassium, dissolved	1.0	2.2	4.3	1.3	2.1	9.7
Alkalinity, total (as $CaCO_3$)	82	76	505	109	170	710
Sulfate, dissolved	14	140	1,200	6.1	210	630
Chloride, dissolved	5.7	180	750	17	160	2,000
Fluoride, dissolved	<.1	.1	.8	<.1	.2	.6
Silica, dissolved	21	30	63	20	26	43
Solids, sum of constituents, dissolved	210	940	2,400	190	920	4,400
Nitrogen, nitrate, dissolved (as N)	<.10	5.6	18	<.10	2.3	20
Phosphorus, orthophosphate, dissolved (as P)	<.01	.03	.41	<.01	.02	.14
Carbon, organic, total (as C)	.1	.6	3.6	<.10	.2	3.3

data for samples from the semiconfined zone are plotted in the central part of the triangle and indicate that 85 percent of the samples have no dominant cation (fig. 6*A*). The remaining 15 percent consists of two samples in which sodium plus potassium constitutes more than 50 percent of the total cationic charge and one sample in which magnesium constitutes more than 50 percent of the cationic charge.

A simple criterion based on the ratios shown in the Piper diagram is used to define water type. Samples

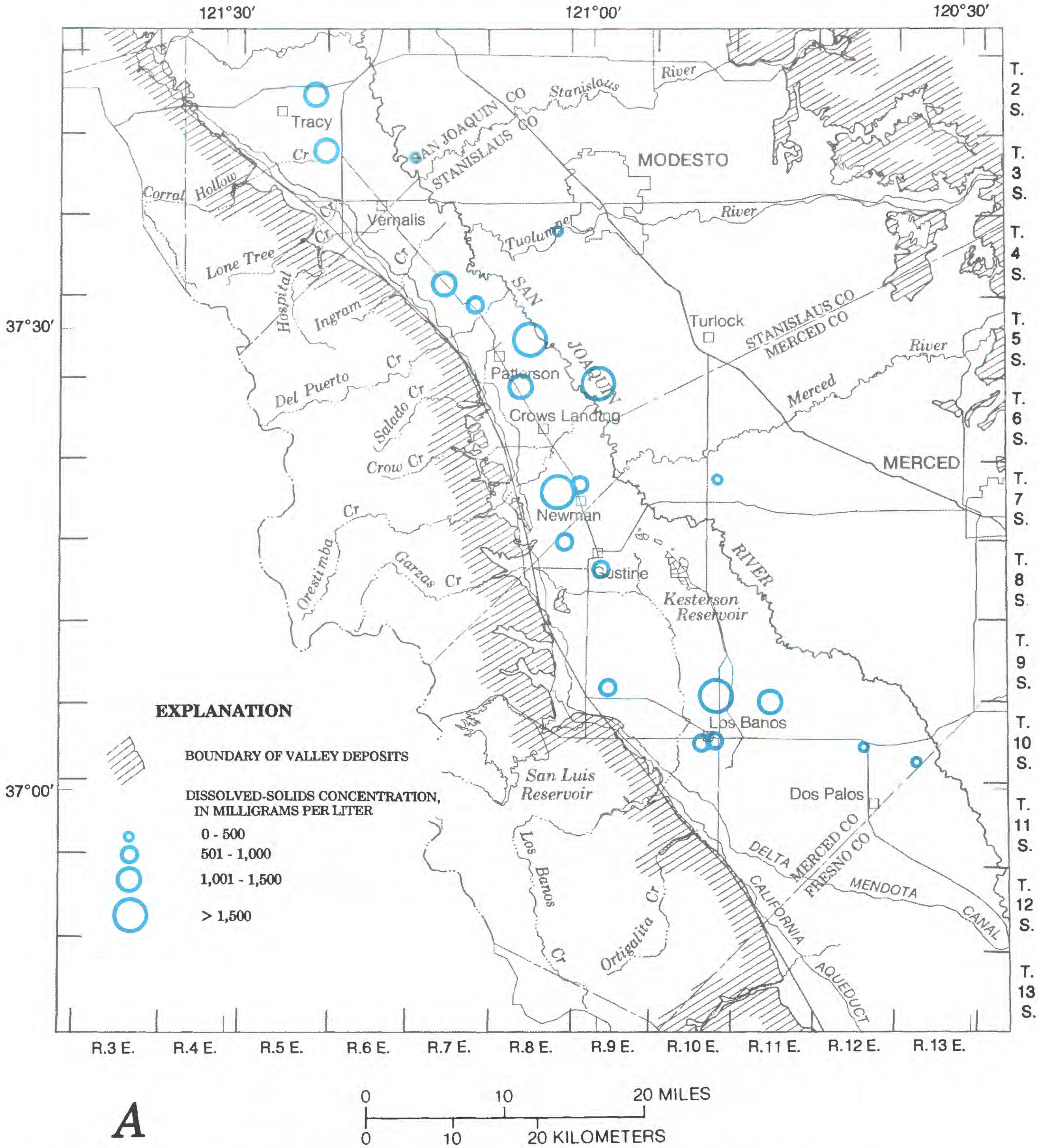

Figure 5. Dissolved-solids concentrations in ground water, 1985. *A*, Semiconfined zone. *B*, Confined zone.

in which one cation or anion constitutes more than 50 percent of the total cationic or anionic charge are referred to by the dominant cation and anion, such as sodium sulfate. Water in which no cation or anion dominates to that degree will be referred to herein as transitional.

All but 3 of the 21 samples from the semiconfined zone had no dominant cation and were classified as transitional. The anionic composition of ground water in the semiconfined zone is more variable than the cationic composition. Sixty percent of the samples can be assigned to

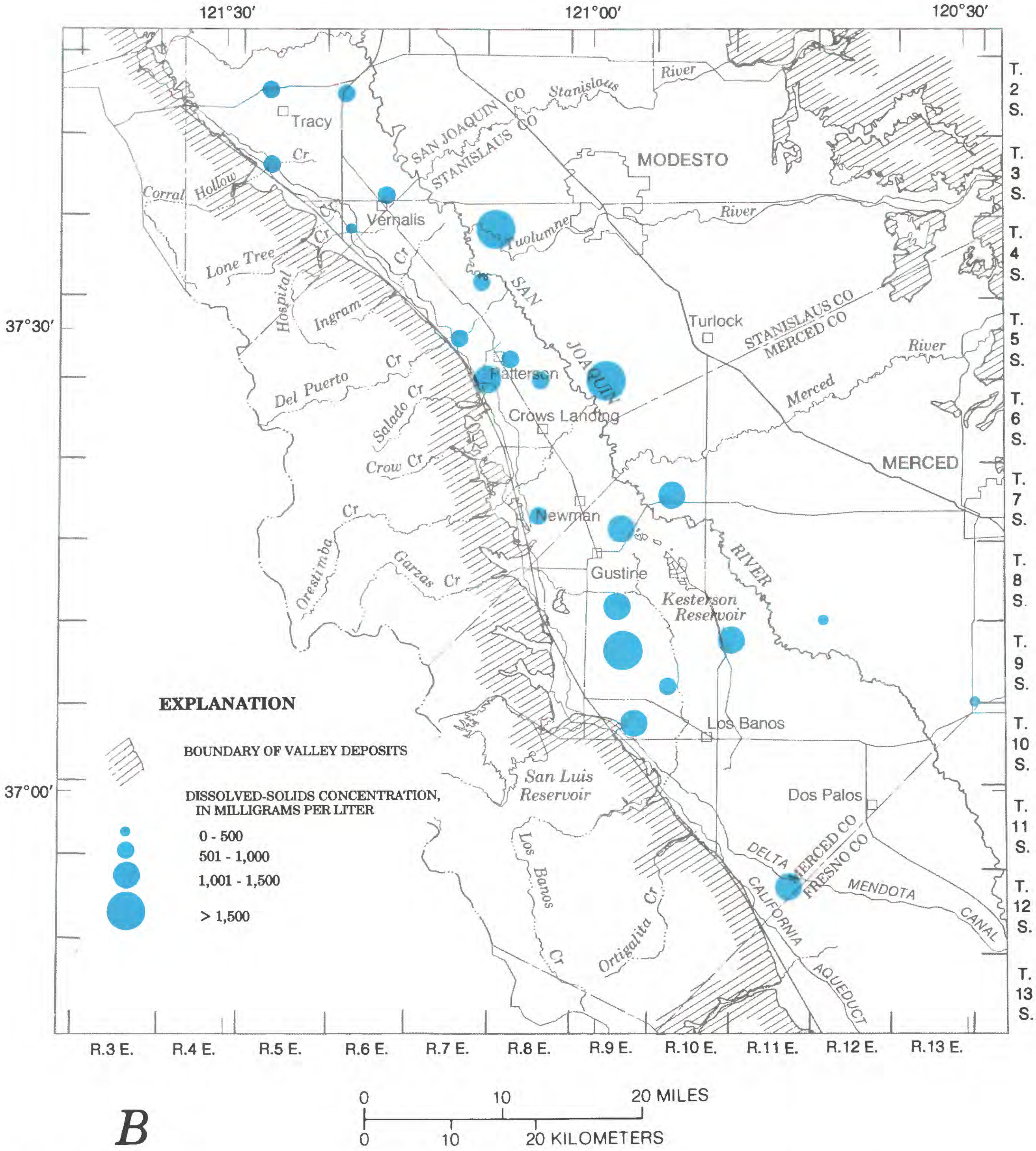

Figure 5.—Continued

an anion water type: bicarbonate, 35 percent; chloride, 15 percent; and sulfate, 10 percent.

Water samples from the confined zone contain a higher proportion of sodium than those from the semiconfined zone (fig. 6*B*). Sixty-seven percent of the samples contain a sodium type water, and one sample contains magnesium type water. As in ground water from the semiconfined zone, the anionic composition of water in the confined zone is more variable than the cationic composition; 46 percent of ground-water samples have a dominant anion—sulfate, 21 percent; chloride, 17 percent; and bicarbonate, 8 percent.

Major-ion ratios for ground water in both zones were compared using the Chi-square procedure (Snedecor and Cochran, 1967). The only significant differences (α=0.05) were that more samples from the confined zone had sodium plus potassium water and more samples from the semiconfined zone had a transitional chemistry with no dominant cation. Although there seems to be more bicarbonate type ground water in samples from the semiconfined zone and more sulfate type ground water in samples from the confined zone, these differences were not statistically significant (α=0.05).

The areal distribution of sulfate concentrations was more closely examined because high sulfate concentrations are characteristic of ground water that originated in the Coast Ranges. Evidence of this is the high sulfate

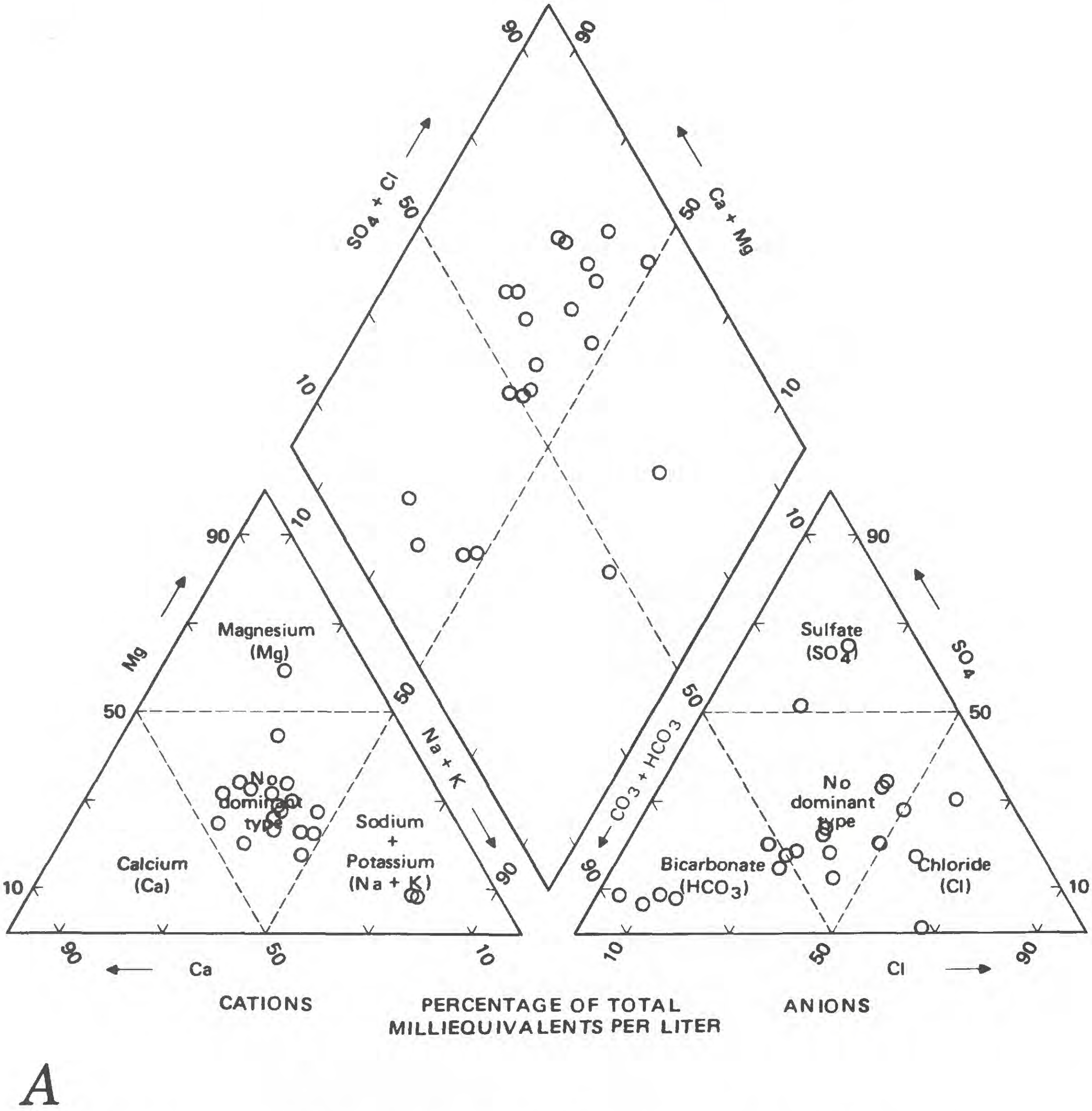

Figure 6. Chemical composition of ground water, 1985. *A*, Semiconfined zone. *B*, Confined zone.

concentrations, present as gypsum, in Coast Ranges sediments compared to Sierra Nevada sediments; high sulfate concentrations in streams draining the Coast Ranges; and contrasts in ground-water chemistry on either side of the valley axis (Davis and others, 1959). The contrast in sulfate concentrations east and west of the valley axis was noted as early as 1916 (Mendenhall and others, 1916).

Sulfate concentrations vary greatly in both zones (table 2). The maximum concentration was measured in the semiconfined zone, but concentrations in the two zones are not significantly different ($\alpha=0.05$). Areal distribution of sulfate is similar in both zones (figs. 7*A* and 7*B*). The highest concentrations are in an area centered near the towns of Crows Landing and Patterson, and the lowest concentrations are near the San Joaquin River. A similar area of high sulfate concentrations was noted by Hotchkiss and Balding (1971) and is likely related to the chemistry of the Coast Ranges streams that recharge this area (Hotchkiss and Balding, 1971, p. 85). Sulfate also is likely derived by leaching of sulfate salts, such as gypsum, which are present in some Coast Ranges sediments in the western San Joaquin Valley (Davis and Poland, 1957; Tanji and others, 1978). The low concentrations along the east are an indication of a Sierran source for this ground water. Sulfate concentrations also were high in the confined zone near Gustine and Kesterson Reservoir.

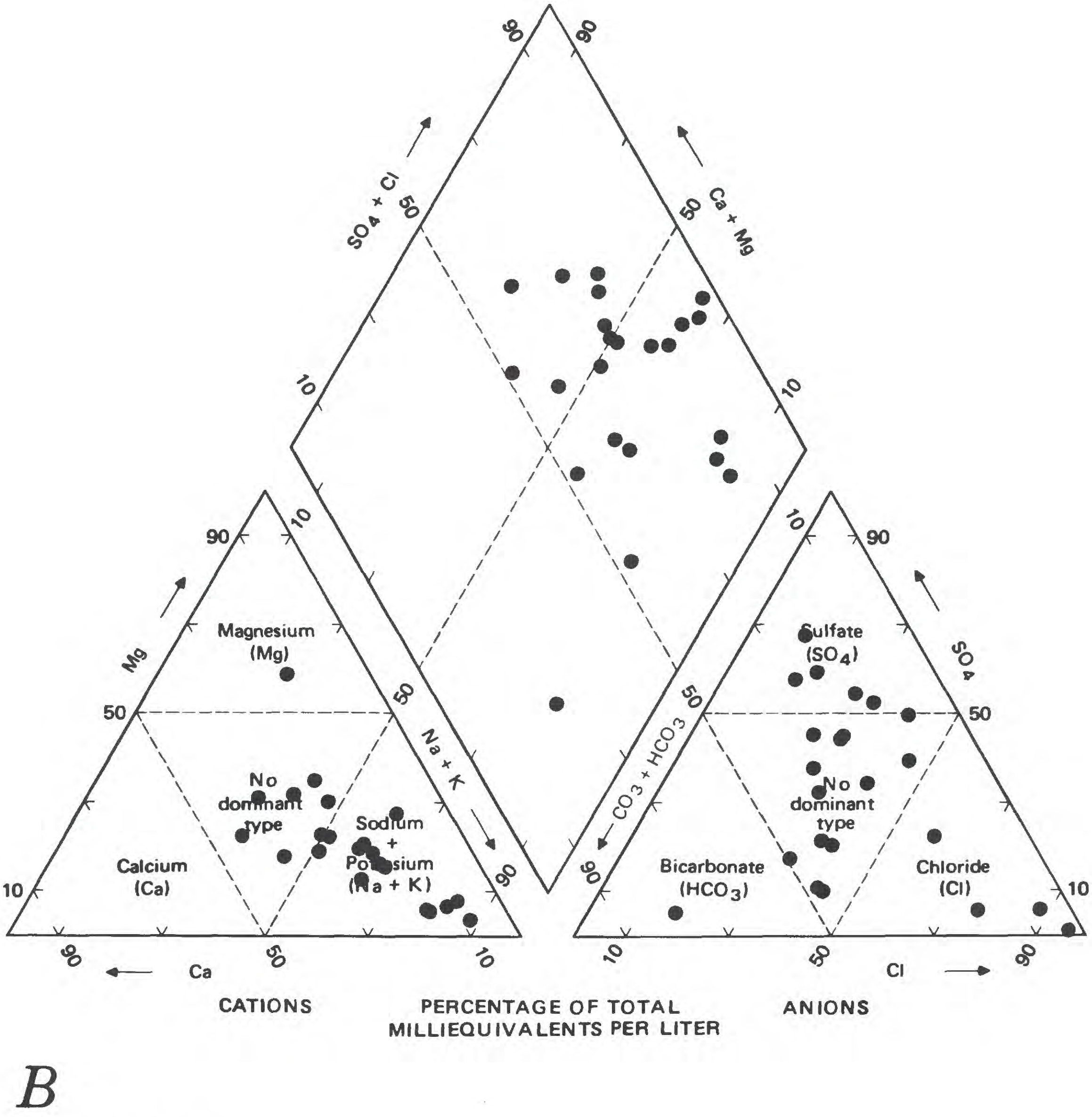

Figure 6.—Continued

In contrast to the similarity of sulfate concentrations in water in the two zones in the study area, studies of western Fresno County immediately south of the study area, between the towns of Mendota and Huron, indicate marked contrasts between the ground-water chemistry in both zones (Davis and others, 1959; Bertoldi, 1971). Ground water in the semiconfined zone generally had higher concentrations of calcium, magnesium, and sulfate than that in the confined zone. The similarity of sulfate concentrations in both zones in the study area could result from the persistence of

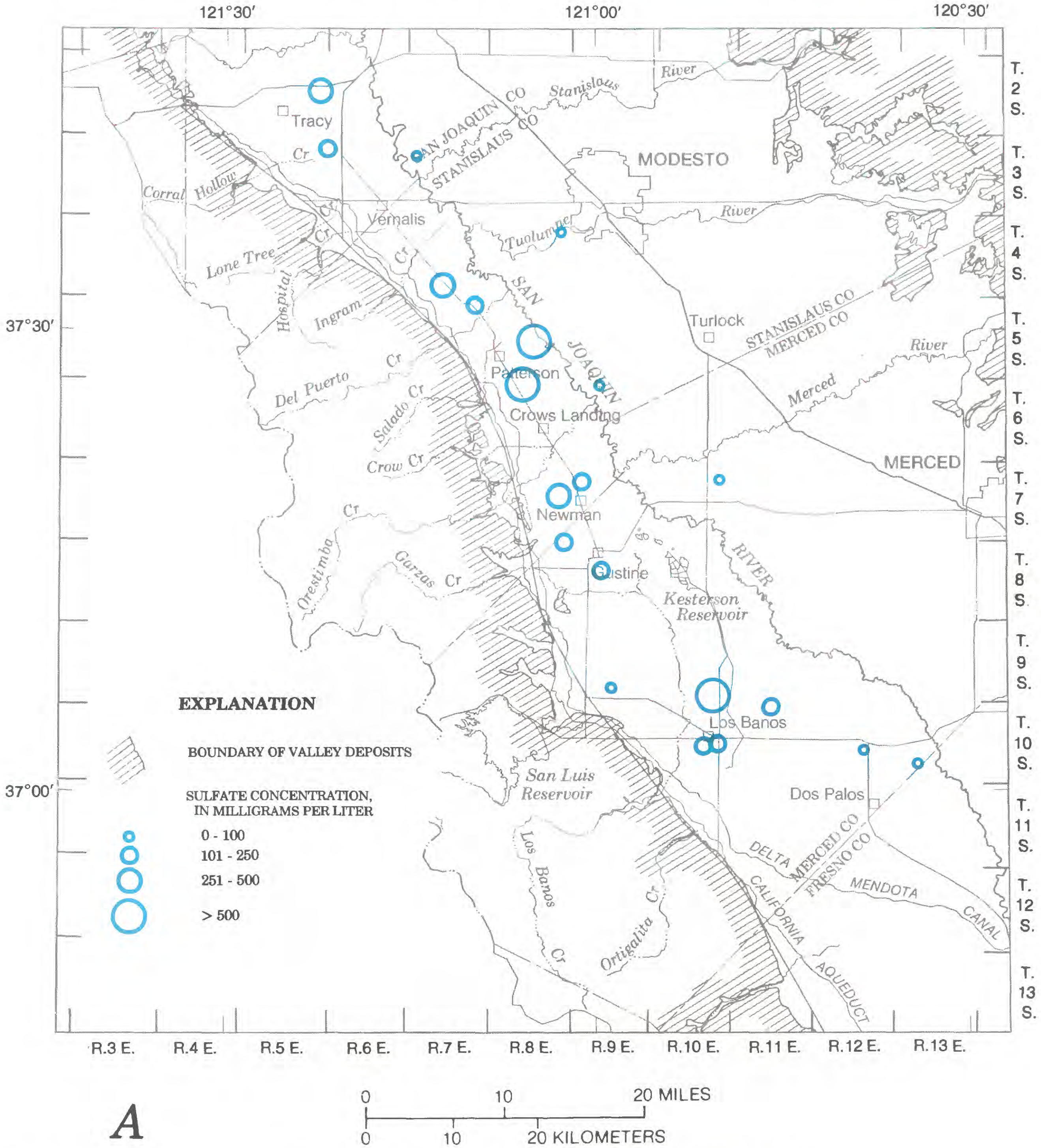

Figure 7. Sulfate concentrations in ground water, 1985. *A*, Semiconfined zone. *B*, Confined zone.

similar sulfate concentrations in the streams that were the major source of recharge under natural conditions over a long period of time. Mixing of ground water between the two zones due to interconnection by well boreholes is more likely the cause of the similar sulfate concentrations.

AGE AND ORIGIN OF GROUND WATER

The identification of water masses with different origins is necessary for understanding the effects of recharge of agricultural water on ground-water chemistry. Imported

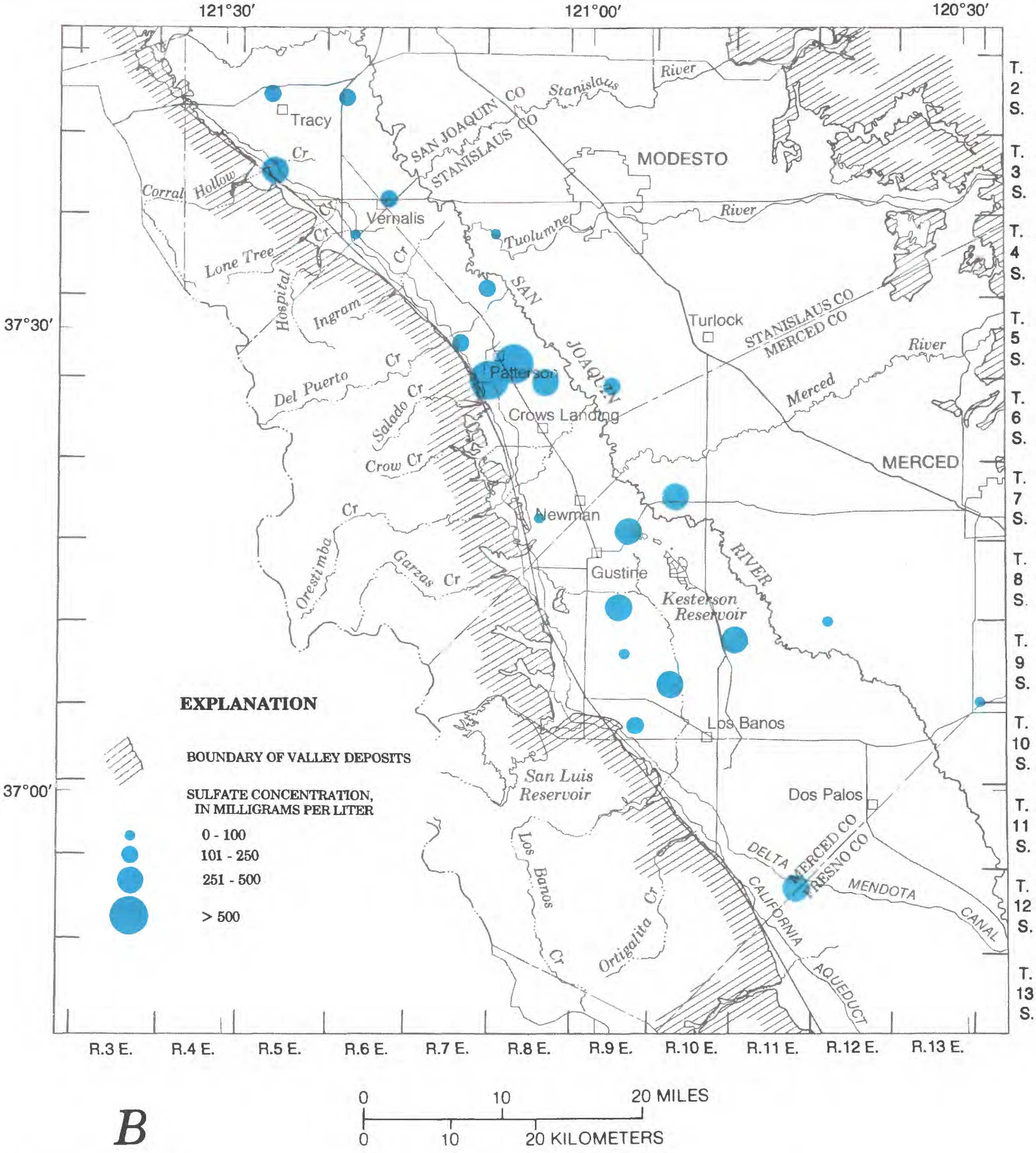

Figure 7.—Continued

water presently used for irrigation in the study area originates for the most part as runoff from the Sierra Nevada and differs from the native ground water in several geochemical respects. However, once the applied water comes in contact with soil and sediments, reaction between the solids and solution alters the water chemistry. Dissolution and ion-exchange reactions with soil minerals make the applied water tend to resemble the chemistry of the native ground water. Because of these reactions and because some irrigation water now and in the past was local ground water, the ground water derived from irrigation may no longer be readily identified by its solute load and ionic composition, so other methods are required.

A characteristic of ground water that is not readily affected by reaction during transport is its tritium concentration. Tritium, a radioactive isotope of hydrogen, was introduced to the atmosphere and hence to precipitation, sulfate water, and ground water by atmospheric nuclear testing in the 1950's and 1960's. Prior to 1952, precipitation contained less than 10 Tu (tritium units). In contrast, values in precipitation frequently exceeded several hundred tritium units in the 1960's. Excessive input of tritium to the atmosphere ceased in the late 1960's with the end of atmospheric testing. Tritium has a half-life of about 12 years, and the tritium introduced by the testing provides a tracer for distinguishing ground water recharged prior to 1952 from ground water subsequently recharged. Ground water that originated as precipitation before 1952 would now have less than 2 Tu.

Oxygen- and hydrogen-isotopic ratios are other ground-water characteristics that are largely conservative. These ratios are indicative of the source of the water although they can be altered by evaporation prior to infiltration. For example, precipitation, and hence runoff, from the Sierra Nevada is depleted in heavy oxygen and hydrogen isotopes compared with ground water in the western San Joaquin Valley (Davis and Coplen, 1989). Therefore, data on these isotopes in ground water of the study area will be interpreted to identify the origins of the ground water.

Tritium

The large contrast in tritium concentration between pre- and post-1952 precipitation distinguishes between ground water that originated before and after 1952. However, the age of the ground water cannot be estimated precisely owing to areal variation in tritium in precipitation, small-scale temporal fluctuations in tritium in precipitation, mixing of ground water, and the complicated patterns generated by the concurrent irrigation with old, local ground water and young, imported Sierra Nevada surface water.

The analytical method has a detection limit of 0.8±0.8 Tu, and all samples with less than 2 Tu are believed to consist primarily of ground water recharged prior to 1952. Ground water that contains more than 10 Tu was considered to be primarily post-1952 recharge. The age of ground water is uncertain when tritium is from 2 to 10 Tu. This ground water likely represents a mixture of water.

Results of the analyses show tritium concentrations ranging from 1.8 to 28.1 Tu in the semiconfined zone. Of the 12 samples analyzed, 9 had more than 10 Tu, indicating ground water that has been recharged since 1952 (fig. 8; table 3). Two samples are of uncertain age and are likely mixtures, and one sample is predominantly pre-1952 water. The midpoints of the screened intervals for the 12 wells range from 10 to 43 m below land surface and average 26 m. The data indicate that ground water recharged since 1952, most of which was irrigation-derived recharge, has infiltrated at least to the depths of these screen intervals near the wells sampled. As discussed earlier, irrigation-return flow presently is the dominant source of recharge, and except in areas that may receive recharge directly from the San Joaquin River, all tritiated ground water is considered to be irrigation derived.

The depth of tritiated ground water possibly is exaggerated by high downward gradients induced by pumpage or by leakage down casings and gravel packs. Data from monitoring wells installed on alluvial fans in western Fresno County indicate that tritiated ground water is present at depths of 30 m or more. Although the rate of vertical ground-water flow may be higher in the alluvial fans to the south than in the study area, the depth of tritiated water in the semiconfined zone of more than 10 m is reasonable.

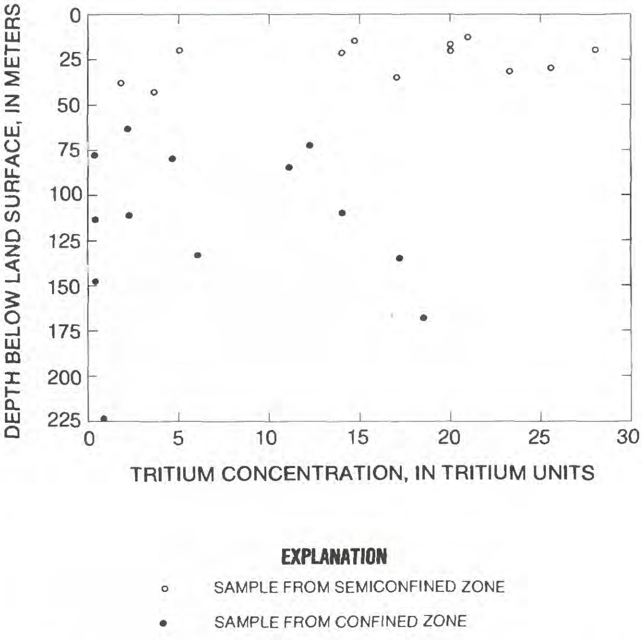

Figure 8. Relation between tritium concentrations and depth in the semiconfined and confined zones, 1985.

Table 3. Tritium concentrations and stable-isotope ratios in ground water from the semiconfined and confined zones

[Tu, tritium unit; --, no data. <, actual value is less than value shown]

State well No.	Semiconfined zone			State well No.	Confined zone		
	Tritium (Tu)	Delta oxygen-18 (per mil)	Delta deuterium (per mil)		Tritium (Tu)	Delta oxygen-18 (per mil)	Delta deuterium (per mil)
2S/5E-13P1	14.2	-8.55	-67.5	2S/5E-21D1	0.9	-7.90	-61.5
3S/6E-7E1	--	-9.60	-72.0	2S/6E-20L2	--	-9.50	-69.5
3S/7E-7Q1	--	-11.55	-82.5	3S/5E-20A2	<.8	-7.30	-58.0
4S/7E-33B1	--	-8.50	-68.5	3S/6E-26Q1	--	-9.80	-73.0
4S/8E-12E1	--	-12.05	-89.5	4S/6E-9M1	--	-8.65	-65.5
5S/7E-1M2	23.9	-9.00	-70.0	4S/7E-36Q3	12.2	-9.00	-68.0
5S/8E-22C1	5.7	-9.00	-69.0	4S/8E-7P1	--	-9.40	-71.0
6S/8E-4P1	25.6	-8.45	-64.0	5S/7E-27B1	2.3	-6.70	-53.0
6S/9E-4M1	--	-9.65	-73.5	5S/8E-32K3	4.6	-7.55	-57.0
7S/8E-13N1	21.8	-8.50	-66.5	6S/7E-1R1	17.8	-8.25	-63.0
7S/9E-18D1	17.0	-9.60	-74.5	6S/8E-3R2	<.8	-7.25	-52.5
7S/10E-11Q1	20.0	-9.25	-72.5	6S/9E-9A2	14.1	-8.50	-67.0
8S/8E-1H1	20.2	-9.30	-71.5	7S/8E-27Q1	--	-9.15	-69.5
8S/9E-17B1	28.1	-9.80	-75.5	7S/9E-34Q1	18.5	-8.95	-69.5
9S/9E-33C1	14.9	-9.40	-72.0	7S/10E-20F1	--	-9.20	-70.0
9S/10E-35Q1	1.8	-7.10	-52.5	8S/9E-34Q2	6.1	-7.75	-60.0
9S/11E-34N2	--	-9.85	-78.5	9S/9E-14N2	--	-7.40	-58.0
10S/10E-22H4	--	-9.70	-74.0	9S/10E-32B1	--	-8.00	-60.5
10S/10E-23A2	--	-9.50	-73.0	9S/11E-7N4	--	-9.45	-71.0
10S/12E-22J1	3.6	-11.95	-91.5	9S/12E-5D1	<.8	-10.90	-82.0
10S/13E-29P1	--	-12.25	-93.0	10S/9E-14H2	11.3	-9.75	-75.0
				10S/13E-1J1	2.4	-10.35	-77.5
				12S/11E-14C1	--	-8.55	-66.0

Tritium concentrations in the 13 samples from the confined zone range from less than the detection limit to 18.5 Tu. On the basis of tritium concentrations, five samples consisted of post-1952 recharge, four were pre-1952, and four were ground water of uncertain age. The wells average 118 m in depth to the midpoint of the screens—92 m deeper than the average for the wells completed in the semiconfined zone. Infiltration by irrigation water has occurred in at least one-third of the wells and possibly as many as two-thirds of the wells completed in the confined zone.

The median tritium concentration in water samples from wells completed in the semiconfined zone was 18.5 Tu, compared to a median of 4.6 Tu for wells completed in the confined zone. The Mann-Whitney test indicates that the tritium concentrations for the two zones are significantly different (α=0.05). The difference primarily is due to six samples from the semiconfined zone with 20 Tu or greater and a much larger proportion of sample wells with pre-1952 water in the confined zone.

The presence of post-1952 ground water in the confined zone below the Corcoran Clay Member of the Tulare Formation indicates that wells perforating the Corcoran have greatly altered the vertical leakage between the zones above and below the clay. Under natural conditions, the Corcoran Clay Member has a vertical hydraulic conductivity of about 3.2×10^{-11} m/s (Page, 1977). Assuming an average hydraulic gradient of 0.05 (Mandle and Kontis, 1986, p. 18) and a porosity of 0.25, a water mass would take about 1,500 years to traverse a 30-m thickness of intact clay. Therefore, the presence of tritium below the clay indicates that the flux of ground water between the zones separated by the clay greatly increased owing to leakage through perforations by wells. Williamson and others (1989) also concluded that the flux of water across the Corcoran Clay Member in the Central Valley increased owing to vertical flow through well casings and gravel packs. The occurrence of this short-circuiting through the clay layer makes it likely that zones of contamination are near wells, with larger zones of unaffected ground water in the surrounding aquifer.

An accurate estimate of the volume of the confined zone affected by vertical flow through well bores cannot be made on the basis of existing data. However, records exist for more than 450 wells with screened intervals of 76 m or greater in depth, which is the approximate depth to the top of the Corcoran Clay Member. The number of unrecorded and abandoned wells is at least equal. The large number of wells along with the dominantly downward gradients indicates that the problem may be widespread.

Stable Isotopes

The stable-isotope composition of water is an indicator of its history. When a vapor mass condenses to form rain, the heavier isotopes are removed in a higher proportion than the lighter isotopes, owing to the higher vapor pressure of the water containing the lighter isotopes. This process, known as isotopic fractionation, results in isotopically enriched precipitation and a depleted vapor mass. The repetition of this process in successive rainfall events as a vapor mass moves inland results in progressive depletion of the heavy isotopes, oxygen-18, and deuterium from precipitation. Isotope fractionation also is temperature dependent, and the combination of these two effects produces patterns in precipitation that are related to topography as well as proximity to the ocean.

Fractionation effects are similar as a result of freezing, melting, evaporation, and biological processes (Freeze and Cherry, 1979). However, inorganic reactions between these isotopes and the aquifer matrix are negligible at low temperatures. Therefore, once water infiltrates below the depth to which evaporation occurs, it becomes a stable indicator of the conditions during precipitation and recharge. Isotopic composition is expressed in the delta notation as parts per thousand (per mil) differences between oxygen isotope ratios in the sample and a standard (Vienna Standard Mean Ocean Water). The values are calculated as in the following example for oxygen-18:

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{\mathrm{sample}} - (^{18}O/^{16}O)_{\mathrm{standard}}}{(^{18}O/^{16}O)_{\mathrm{standard}}} \times 1,000.$$

A comprehensive study of oxygen-18 and deuterium in ground water in the San Joaquin Valley was reported by Coplen and others (1985) and Davis and Coplen (1989). They evaluated data for more than 300 analyses from Fresno County west of the San Joaquin River, an area just south of the study area. By using multiple criteria to remove from the analysis those samples that represented mixtures of ground water from different zones in the subsurface, they identified 10 separate populations or facies of water in the valley sediments that were then grouped into 6 categories. For this report, these were further combined into three groups on the basis of similarity in range of oxygen-18 values, which likely reflect a similar origin of the waters.

The first group, which has a delta oxygen-18 ranging from −9.7 to −12.75, consists of ground water underlying modern flood plains. This water is representative of present day runoff from the Sierra Nevada. The second group consists of most of the ground water in the semiconfined zone and ground water in the confined zone in an area in the extreme southwest, where the Corcoran Clay Member

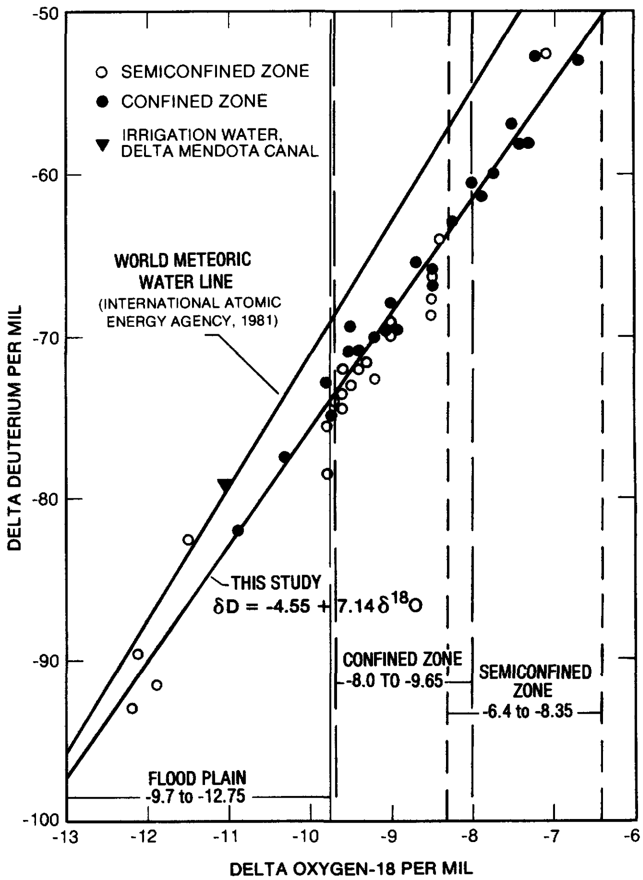

Figure 9. Relation between delta deuterium and delta oxygen-18 for ground water from the semiconfined and confined zones. The range of delta oxygen-18 values for the three categories of ground water present in the western San Joaquin Valley, based on the work of Davis and Coplen (1989), are shown.

of the Tulare Formation is absent. This group has the most enriched isotopic values, with delta oxygen-18 ranging from –6.4 to –8.35. This water probably was derived exclusively from recharge of streams draining the Coast Ranges. The third group of facies is ground water in the confined zone, in the semiconfined zone near the axis of the valley, and locally in the basal part of the semiconfined zone. Delta oxygen-18 of this group ranges from –8.0 to –9.65. The origin of water in this group is uncertain. The water probably is a mixture of water that drains the Sierra Nevada and Coast Ranges; however, the mechanism of mixing is unknown.

Data for the stable-isotopic composition of ground water collected during this study are plotted in figure 9. The data fall along a line fit by least squares that is similar to the world meteoric water line (International Atomic Energy Agency, 1981), indicating that the stable-isotope ratios have not been noticeably affected on a regional scale by any of the causes of fractionation listed above. The slightly flatter slope of the line for the data indicates that the amount of oxygen-18 enrichment was minimal owing to evaporation of rainfall during precipitation on the west side of the valley (Davis and Coplen, 1989). The fitted line also is similar to that calculated by Davis and Coplen (1989) for their data set. Under natural conditions, the stable-isotopic ratios of the water in the study area probably were similar to those described by Davis and Coplen (1989). However, as indicated by the tritium data, areas of the ground-water-flow system have been infiltrated by water applied since 1952. An evaluation of the stable-isotope ratios in the samples helps distinguish between native ground water and water introduced by irrigation.

Semiconfined Zone

Delta oxygen-18 for water samples from the semiconfined zone cluster between –8.45 and –9.85 (fig. 9; table 3). Four samples ranging from –11.55 to –12.25 are depleted substantially compared to most of the samples, and one sample has an enriched value of –7.10. The data indicate that the ground water in the study area is more depleted than most ground water in the semiconfined zone south of the study area. The oxygen-18 values are more similar to those of ground water in the basal and axial facies of the semiconfined zone but fail to meet the stratigraphic, depth, and chemical criteria for these ground waters (Davis and Coplen, 1989). However, comparisons between the study area and the area immediately to the south, which was studied by Davis and Coplen (1989), must be made with caution because of their different physiographic settings. The western valley to the south of the study area is dominated by wide alluvial-fan deposits; in contrast the southern part of the study area is dominated by flood-basin deposits, and the northern part is narrow.

An explanation for the differences in oxygen-18 between the study area and the area to the south could be derived from the tritium data, which indicate that in the study area much of the semiconfined zone has been infiltrated by irrigation water. Although no data on the stable-isotopic composition of the irrigation water applied in the past are available, the delta oxygen-18 values probably were close to the value of about –11 per mil for water from the Delta Mendota Canal in 1987 (S.J. Deverel, U.S. Geological Survey, oral commun., 1987). Much of the water sampled, therefore, probably originated as imported surface water from a Sierra Nevada source and, to a lesser extent, ground-water pumpage from the confined zone. The present-day composition of stable isotopes may reflect the mixing of depleted irrigation recharge with more enriched native ground water. This hypothesis also is consistent with the lack of a dominant cation in all but two of the samples from the semiconfined zone and the high proportion of bicarbonate to other anions.

Delta oxygen-18 was less than –11.55 in four water samples, which is markedly lower than other water samples from the semiconfined zone as well as the Delta Mendota Canal (fig. 9). Two of these samples are from wells east of the San Joaquin River (3S/7E–7Q1 and 4S/8E–12E1). Oxygen-18 values for these water samples are in the range for the flood-plain facies defined by Davis and Coplen (1989) and were derived by infiltration from the San Joaquin River. The other two samples are from wells west of the San Joaquin River, but stratigraphic information for this area indicates that these wells were completed in Sierra Nevada sediments. Thus, water derived from the San Joaquin River is in Sierra Nevada sediments west of the present location of the San Joaquin River. One explanation is that ground-water-flow rates in this area have been slow and the water was deposited at the same time as the sediments. Alternately, there may be a component of westward flow in this area, either naturally occurring or owing to high historical pumpage in the western valley. The depleted ground water also may have been recharged by irrigation of the area around these wells with San Joaquin River water.

The occurrence of ground water derived from the Sierra Nevada in some wells in the semiconfined zone west of the San Joaquin River prompted a more thorough examination of the relation between stratigraphic location of well screens and the oxygen-18 content of the ground water. On the basis of geologic sections of the area (Hotchkiss and Balding, 1971), nine wells, including the four discussed above, were determined to be screened in Sierra Nevada sediments. Four of the nine wells are east of the San Joaquin River. Seven of the nine wells have an oxygen-18 value less than the most depleted value measured in the semiconfined facies defined by Davis and Coplen (1989). In addition, the anion ratios of the most depleted samples show a dominance of bicarbonate and lack of sulfate, which are characteristic of water derived from the Sierra Nevada (fig. 10). These data further support the contention that Sierra Nevada sediments that underlie the western valley contain a large component of ground water derived from the Sierra Nevada. Most of this ground water probably originated as irrigation recharge, however, some of the ground water probably recharged directly from the San Joaquin River or its tributaries in areas close to the rivers.

Confined Zone

The delta oxygen-18 values measured in samples from the confined zone are evenly distributed in the range of –7.25 to –9.80, with two more depleted values of −10.35 and −10.90 and one enriched value of −6.70 (fig. 9; table 3). The Mann-Whitney test confirms that ground water in the confined zone is significantly more enriched in oxygen-18 than ground water in the semiconfined zone. In contrast, data from south of the study area showed the opposite. In western Fresno County, the delta oxygen-18 values of confined ground water ranged from –8.10 to –9.65 (Davis and Coplen, 1989), and facies identified in this zone were the most uniform (Davis and Coplen, 1989). Enriched oxygen-18 values in the confined zone indicate contamination of wells sampled in this zone by Coast Ranges-derived ground water that originated in the semiconfined zone.

As with the semiconfined zone, the presence of tritium in samples from the confined zone indicates infiltration by ground water that recharged after 1952, at least locally. A large component of irrigation water applied after 1952 originated as precipitation in the Sierra Nevada and would have had a depleted delta oxygen-18 similar to the present value of about −11 per mil. Of the four samples most depleted of oxygen-18, three were analyzed for tritium. Only one of the three samples had more than 10 Tu, indicating the dominance of water recharged after 1952 in this sample. The other two samples had values of 3.6 and 1.4 Tu. These data are too sparse to draw any conclusions, but there is no indication that the most depleted water is mainly post-1952 infiltrated irrigation water.

DISTRIBUTION OF TRACE ELEMENTS

Results of the analyses of 17 selected trace elements in the ground-water samples are summarized in table 4, and all data are listed in table 12 (at the end of report). Comparisons of concentrations of trace elements in ground water of the study area were made between samples from wells in the semiconfined and confined zones. On the basis of the Mann-Whitney procedure (Conover, 1980), which was used for all comparisons in this section, concentrations were similar for all water samples except molybdenum, regardless of the sampling depth. Concentrations of molybdenum were significantly higher (α=0.05) in samples from the confined zone. Of the trace elements analyzed, the following 10 are priority pollutants as defined by the U.S. Environmental Protection Agency (1986b): arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc. Of these 10, only selenium exceeded the maximum permissible concentration for drinking water of 10 µg/L (U.S. Environmental Protection Agency, 1986b).

This study focused on the distribution of arsenic, boron, molybdenum, and selenium, with particular emphasis on selenium. Previous studies have shown that trace elements are not uniformly distributed in the shallow ground water and soils in the study area. A literature review on the occurrence of boron, molybdenum, and selenium indicates that boron and molybdenum concentra-

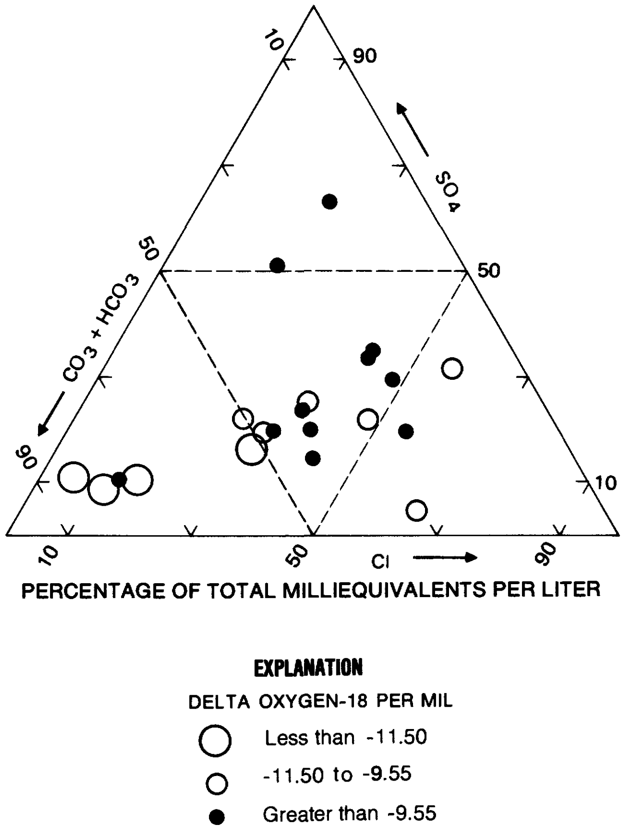

Figure 10. Anionic composition of ground water in the semiconfined zone for three categories of delta oxygen-18 values.

Table 4. Summary of concentrations of dissolved trace elements in ground water from the semiconfined and confined zones

[μg/L, microgram per liter. <, actual value is less than value shown]

Trace element (μg/L)	Semiconfined zone (21 samples)			Confined zone (23 samples)		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Aluminum	<10	10	20	<10	10	20
Arsenic	<1	2	38	<1	1	18
Boron	40	510	2,200	40	860	3,000
Cadmium	<1	<1	<4	<1	<1	<10
Chromium	<1	6	30	<1	<1	30
Copper	<1	2	9	<1	<1	<10
Iron	<3	30	5,200	<3	11	110
Lead	<1	1	5	<1	2	30
Lithium	<4	31	120	<4	40	130
Manganese	<1	5	2,300	<1	13	1,300
Mercury	<.1	<.1	<.2	<.1	<.1	.8
Molybdenum	<1	<1	7	<1	2	29
Nickel	<1	1	8	<1	2	26
Selenium	<1	1	13	<1	1	11
Silver	<1	<1	<4	<1	<1	<10
Vanadium	<1	10	25	<1	8	92
Zinc	10	20	200	<3	20	370

tions are similar in sedimentary rocks of the Coast Ranges and igneous rocks of the Sierra Nevada, but selenium seems to be substantially more abundant in the sulfide minerals common in Coast Ranges sedimentary rocks (Deverel and Millard, 1988). The greater abundance of selenium in Coast Ranges rocks also is shown by a map of total selenium in soils of the San Joaquin Valley. This map shows low concentrations of selenium (less than 0.11 μg/g) along the east side of the valley and high concentrations (greater than 0.18 μg/g) on the west side (Tidball and others, 1986). Similar data indicate that arsenic concentrations are higher in soils on the east side of the San Joaquin Valley than on the west side (R.R. Tidball, U.S. Geological Survey, written commun., 1986); this also might indicate a higher arsenic availability in these deposits. The effects of the origin of sediments on concentrations of arsenic, boron, molybdenum, and selenium in ground water in the study area also were evaluated by separating the data into two groups according to whether a well was completed in Sierra Nevada or Coast Ranges sediments.

In their investigation of trace elements in shallow ground water in the western San Joaquin Valley, Deverel and Millard (1988) found that molybdenum preferentially is associated with Sierra Nevada sediments and that selenium concentrations were higher in water samples from wells completed in Coast Ranges sediments than in water samples from wells completed in Sierra Nevada sediments. The absence of selenium in ground water in sediments derived predominantly from the Sierra Nevada but which are west of the San Joaquin River also was noted by Belitz and Heimes (1990). Data on the distribution of boron in shallow ground water showed that concentrations were higher in ground water in alluvial-fan and basin-rim deposits, which are derived from the Coast Ranges, than in ground water from deposits in the basin trough near the San Joaquin River (Deverel and others, 1984). Because the basin-trough deposits are composed of mostly Sierra Nevada sediments, higher boron concentrations in Coast Ranges-derived sediments are indicated. In addition, the concentration of boron in streamflow from the Coast Ranges is higher than in streamflow from the Sierra Nevada (table 5); Davis (1961) speculates that high boron concentrations are because of the discharge of connate marine water with high boron concentrations. Deverel and others (1984) also found that concentrations of arsenic were not significantly different ($\alpha=0.05$) among ground water from alluvial-fan, basin-rim, and basin-trough deposits. Arsenic concentrations in ground water, however, are high enough to cause concern in other areas underlain by Sierra Nevada sediments (California Department of Water Resources, 1970; Groundwater Pollutant Study Review Committee, 1982).

Table 5. Boron concentrations in streams draining the Sierra Nevada and Coast Ranges (modified from Hotchkiss and Balding, 1971)

[µg/L, microgram per liter; --, no data. <, actual value is less than value shown]

	Number of samples	Boron (µg/L)		
		Minimum	Mean	Maximum
Sierra Nevada rivers				
Merced at Exchequer	107	<100	<100	700
San Joaquin near Mendota	121	<100	200	1,800
Stanislaus at Tullock Dam	68	<100	<100	300
Tuolumne at La Grange Dam	84	<100	<100	200
Coast Ranges creeks				
Corral Hollow	8	1,400	4,100	7,500
Del Puerto	7	100	1,300	4,000
Garzas	3	200	400	700
Hospital	2	100	200	300
Ingram[1]	1	--	2,400	--
Lone Tree[1]	1	--	1,700	--
Los Banos	7	250	740	2,200
Orestimba	3	100	200	300

[1] Data from Davis (1961).

Trace-element concentrations in ground water are not necessarily proportional to their total concentrations in the associated sediments. The mobility of trace elements also is affected by solubility controls or, more often, sorption, which are in turn dependent on speciation, the concentrations of other solutes, and sediment surface properties. The mobility of trace elements that occur in multiple valences, such as arsenic, chromium, iron, manganese, and selenium, also may be strongly affected by the oxidation-reduction (redox) status of the ground water. On the basis of a distinct color change from red and brown in Coast Ranges sediments to gray in Sierra Nevada sediments, the boundary between these two sediments was mapped as a redox boundary (Davis and Poland, 1957; Hotchkiss and Balding, 1971; Lettis, 1982). This contrast in redox conditions, in particular, needs to be considered when evaluating the distribution of trace elements.

Direct measurements of redox potential were not made during the present study, but the relative redox status of the ground-water samples was assessed indirectly from the abundance of redox-sensitive solutes. Iron, manganese, and nitrate commonly are used for this purpose. Iron and manganese have oxidized forms that are highly insoluble under neutral to alkaline conditions. Elevated concentrations of these metals in water commonly are used as indicators of reduced conditions. Comparisons of iron and manganese concentrations indicate that the concentrations of both metals generally are higher in water in the Sierra Nevada sediments (fig. 11) than in water in Coast Ranges sediments, though only the difference in manganese concentrations is statistically significant (α=0.05). This indicates that the Sierra Nevada sediments are more reduced than the Coast Ranges sediments.

Nitrate concentrations are higher in ground water in Coast Ranges sediments in both zones, indicating more oxidized conditions (fig. 11). The presence of nitrate indicates oxidized conditions because reduced conditions may cause nitrate to be removed from solution by denitrification. However, other factors, such as insufficient nutrients for bacterial action, may prevent denitrification. Naturally high concentrations of nitrate in soils in the western San Joaquin Valley are partly due to the arid conditions and the lack of leaching of mudflow deposits (Sullivan, 1978). Conversely, the absence of nitrate in ground water in Sierra Nevada sediments likely is affected by flushing during annual flooding concurrent with the deposition of flood-basin deposits as well as by reducing conditions.

These data indicate that ground water in Sierra Nevada sediments is more reducing than ground water in Coast Ranges sediments. As a result of this difference, the pattern of areal distribution of redox status in the ground water is controlled by the areal distribution of these two lithologies. Because of this correspondence of redox status and lithology, the effects that these two factors have on the distribution of redox-sensitive trace elements cannot be separated on the basis of the available data.

Arsenic

Arsenic concentrations in ground water range from less than the detection limit of 1 to 38 µg/L (table 4). None of the samples exceed the standard of 50 µg/L for concentrations in drinking water established by the U.S. Environmental Protection Agency (1986b). Although arsenic concentrations are slightly higher in parts of the semiconfined zone than in the confined zone, the difference is not statistically significant (α=0.05) for the entire area. The areal distribution of arsenic also is similar in both zones, with concentrations greater than 5 µg/L primarily in the southeastern part of the study area (figs. 12*A* and 12*B*).

Arsenic concentrations in the semiconfined zone were significantly higher in ground water from Sierra Nevada sediments than in ground water from Coast Ranges sediments (fig. 13). Differences between arsenic concentrations of water in sediments of different origins are not apparent in the confined zone. The relatively high arsenic concentrations in ground water from Sierra Nevada sediments are in agreement with the previous observation of higher arsenic concentrations in Sierra Nevada sediments than in Coast Ranges sediments. Moreover, arsenic generally may be more mobile under the reducing conditions that predominate in the Sierra Nevada sediments than in the oxidized Coast

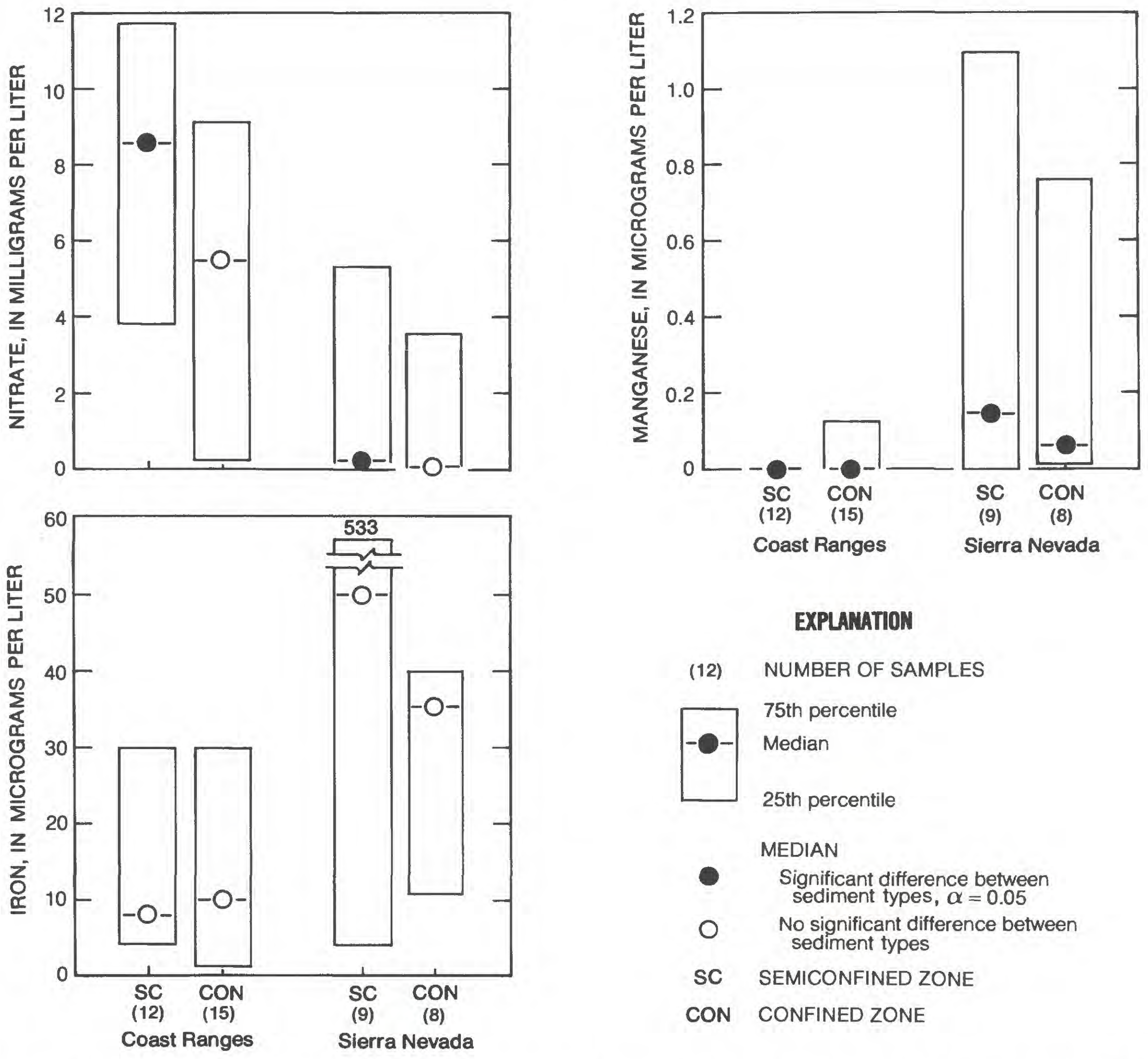

Figure 11. Concentrations of iron, manganese, and nitrate in Sierra Nevada and Coast Ranges sediments for the semiconfined and confined zones, 1985.

Ranges sediments for two reasons. First, the most oxidized arsenic species, arsenates (As-V), are the dominant species under the oxidizing conditions that may be expected in the Coast Ranges sediments. Arsenate is more strongly adsorbed and consequently less mobile than arsenite (As-III), as shown by field studies of arsenic mobility in oxidizing conditions (Gulens and others, 1979), under reduced conditions (Holm and others, 1979), and on pure iron and manganese hydroxides in the laboratory (Ferguson and Anderson, 1974). Secondly, the iron and manganese hydroxides that strongly ad-

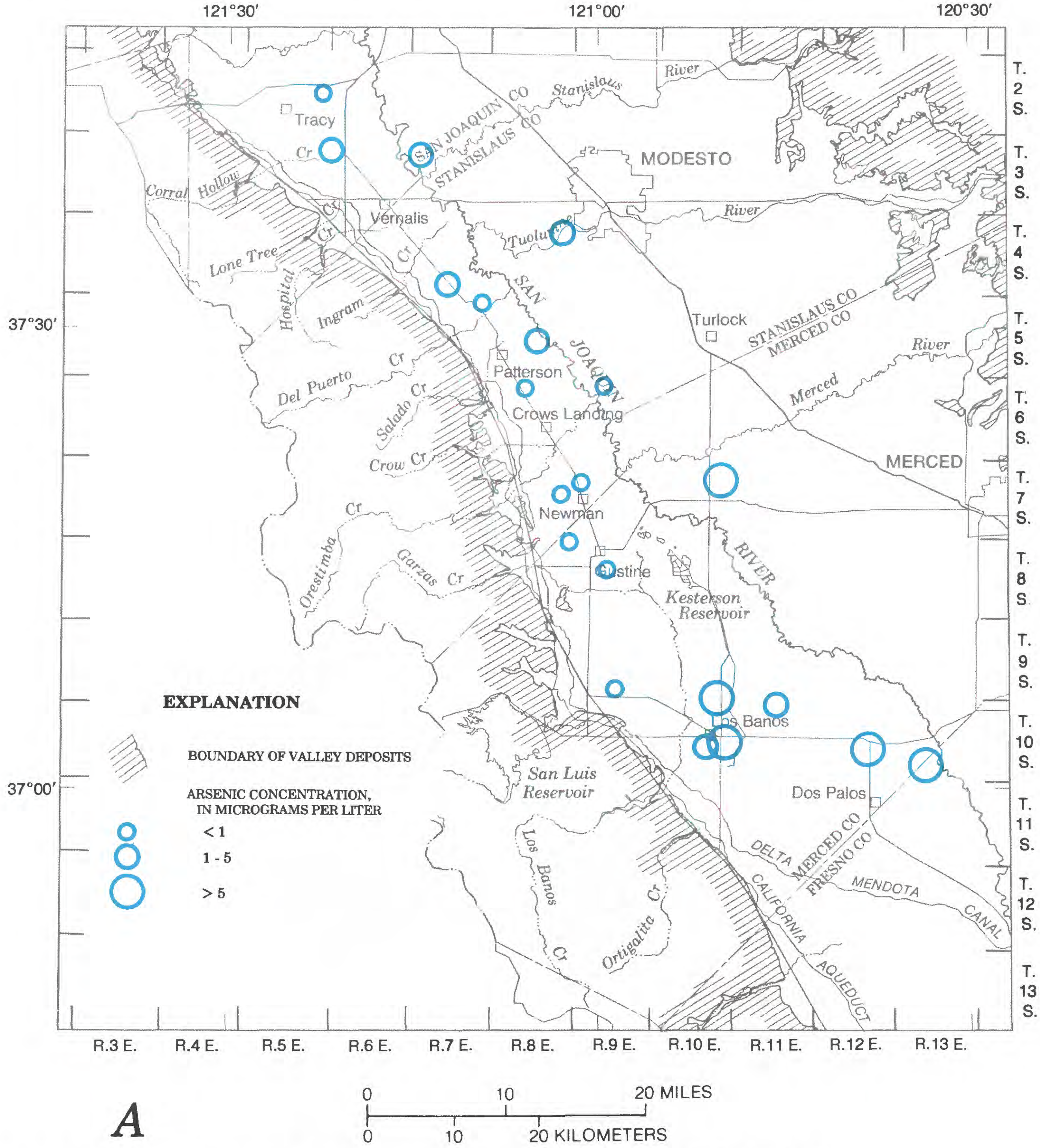

Figure 12. Arsenic concentrations in ground water, 1985. *A*, Semiconfined zone. *B*, Confined zone.

sorb arsenic are stable only under oxidizing conditions and probably are more abundant in Coast Ranges sediments than in Sierra Nevada sediments. The redox status, therefore, affects arsenic mobility by influencing arsenic speciation and the presence of potential arsenic-adsorbing sinks.

Consideration of availability and mobility favors higher concentrations of arsenic in ground water in Sierra Nevada sediments than in ground water in Coast Ranges sediments. Sierra Nevada sediments extend farther to the west of the San Joaquin River in the south-

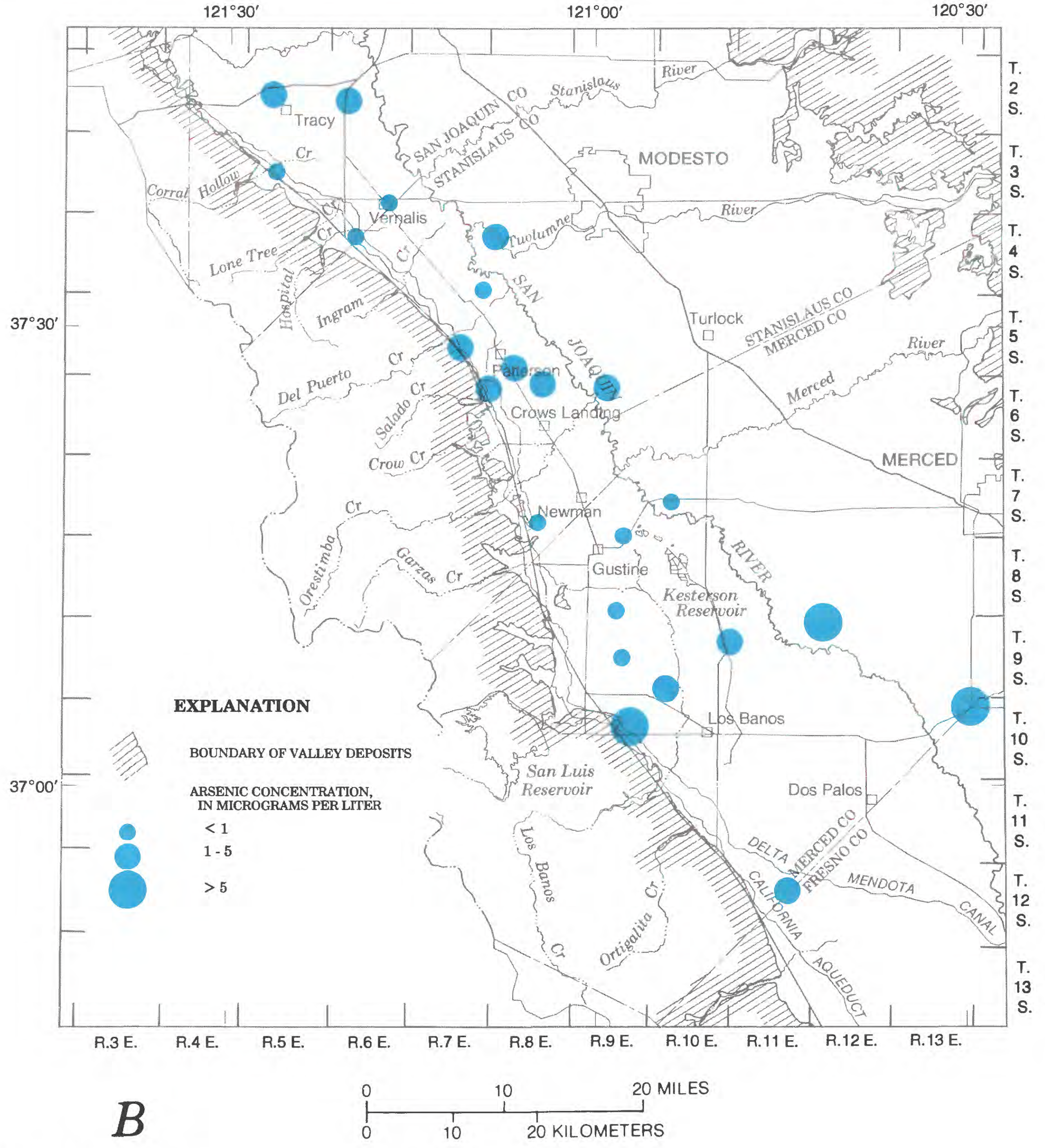

Figure 12.—Continued

ern part of the study area than in the northern part (Hotchkiss and Balding, 1971, pl. 1), and this distribution of sediment types probably is the dominant influence on the areal distribution of arsenic in the semiconfined and confined zones shown in figures 12*A* and 12*B*.

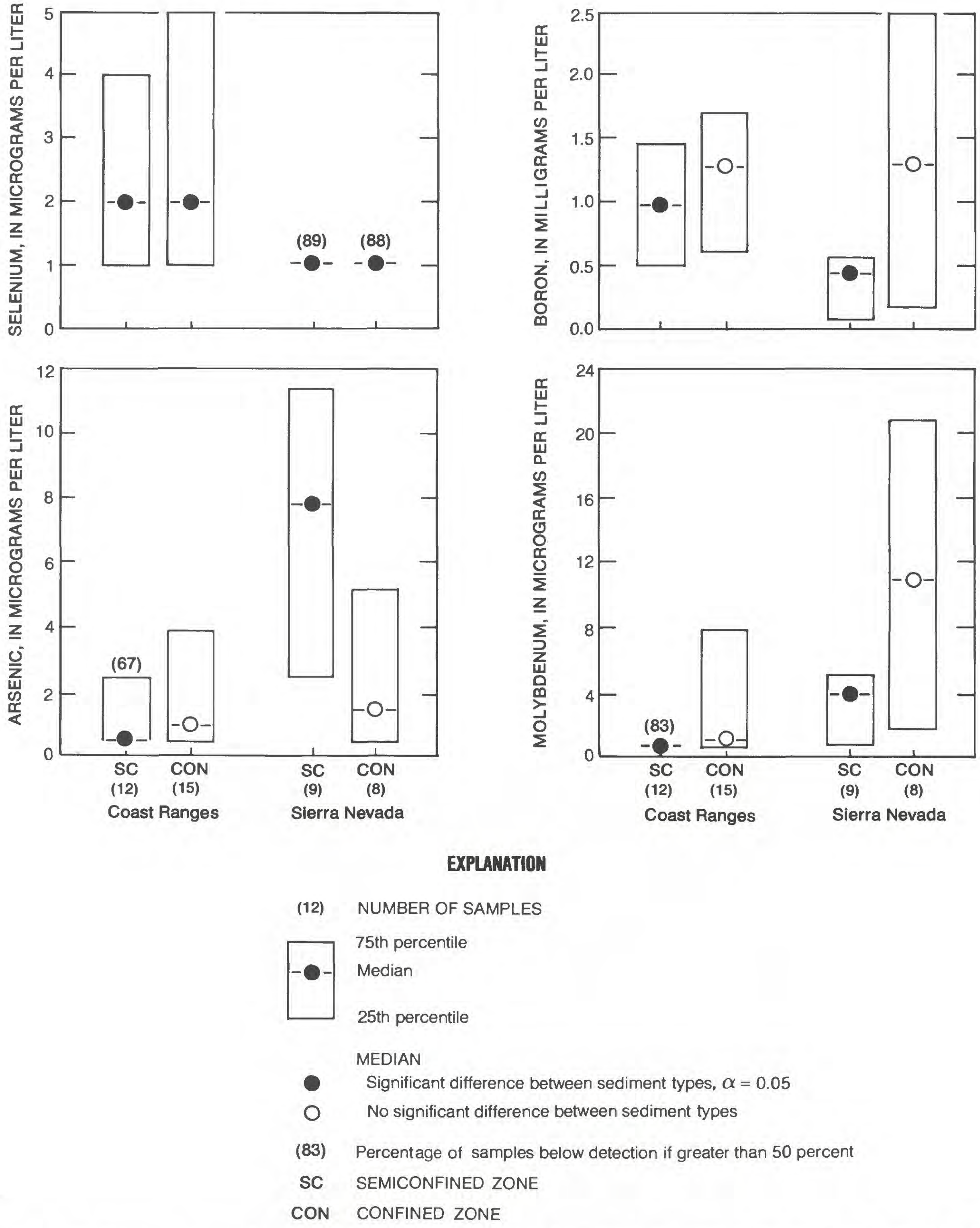

Figure 13. Concentrations of arsenic, boron, molybdenum, and selenium in water in Sierra Nevada and Coast Ranges sediments for the semiconfined and confined zones, 1985.

Boron

Concentrations of boron in ground water range from 40 to 3,000 µg/L (table 4). Although the concentrations in parts of the confined zone are somewhat higher than those in the semiconfined zone, the difference is not statistically significant (α=0.05) over the entire area. Areal distribution of boron in the semiconfined zone shows localized high concentrations near Tracy, northeast of Crows Landing, and in the Los Banos area (fig. 14*A*). The areal distribution is somewhat similar in the confined zone; however, boron concentrations in the confined zone are higher over a much larger area near Gustine and Los Banos (fig. 14*B*). Boron concentrations in both zones are lowest along the eastern boundary of the study area. The suggested criterion for boron concentrations in water used for long-term irrigation of sensitive crops is 750 µg/L (U.S. Environmental Protection Agency, 1986a). This limit is exceeded in 6 samples in the semiconfined zone and 13 samples in the confined zone.

Boron is the only trace element for which fairly extensive historical data are available. A map showing areal distribution of boron in the semiconfined zone in 1959 through 1968 shows a pattern similar to that in figure 14*A*, although the historical data showed higher concentrations southeast of Vernalis and in the south-central part of the study area between Gustine and Los Banos (Hotchkiss and Balding, 1971). These differences primarily are due to a lack of present-day data on boron concentrations in ground water in areas that had high boron concentrations in the earlier study.

In contrast to arsenic, boron concentrations in ground water from the semiconfined zone were significantly higher in samples from Coast Ranges sediments than concentrations in ground water from Sierra Nevada sediments (fig. 13). In fact, a moderate correlation between boron and sulfate (r^2=0.40, α=0.10) in ground water in Sierra Nevada sediments might indicate that boron is present because of infiltration by water from Coast Ranges sediments with high sulfate concentrations. As with arsenic, significant differences were not apparent between the two sediment types in the confined zone.

Boron has only one valence and is not directly affected by redox reactions. Boron probably is present as the uncharged species H_3BO_3 in ground water in the study area and, owing to the lack of charge, should not be strongly adsorbed (Hem, 1985). The close association of high boron concentrations with saline soil conditions and high specific conductance in shallow ground water in western Fresno County, immediately south of the study area, indicates that boron behaves conservatively in that ground water (Deverel and Millard, 1988). Boron and specific conductance were not significantly correlated in either the semiconfined or confined zones in the study area, and although high boron concentrations may be related to recharge derived from the Coast Ranges, the processes that produced the observed distribution of boron concentrations are not clear.

Molybdenum

Concentrations of molybdenum in ground water range from less than the detection limit of 1 to 29 µg/L (table 4). Molybdenum is the only trace element that had significantly different concentrations in the semiconfined and confined zones. Concentrations in the semiconfined zone, with a median of less than the detection limit, are smaller than molybdenum concentrations in the confined zone. Concentrations in the confined zone have a median of 2 µg/L. Seven of the wells in the confined zone have concentrations greater than or equal to the 10-µg/L criterion suggested for water used for continuous irrigation, but lower than the criterion of 50 µg/L suggested for short-term use (National Academy of Sciences, National Academy of Engineering, 1973).

The areal distribution of molybdenum is not uniform in either zone. In the semiconfined zone, the molybdenum concentrations are low in the north and west and high to the south and east (fig. 15*A*). The molybdenum distribution in ground water in the confined zone is similar although the range in concentrations is much greater (fig. 15*B*).

Molybdenum concentrations in the semiconfined zone are significantly higher in ground water samples from Sierra Nevada sediments than those from Coast Ranges sediments. The median molybdenum concentration was 4.0 µg/L in water from the Sierra Nevada sediments (fig. 13). In contrast, the median molybdenum concentration was less than 1.0 µg/L in ground water from the Coast Ranges sediments, and molybdenum concentrations were less than 1.0 µg/L in 10 of the 12 samples. A similar contrast was found in the data for the confined zone, and although the difference was not statistically significant (α=0.05), five of the seven samples with more than 10 µg/L of molybdenum were from Sierra Nevada sediments.

As with arsenic, molybdenum concentrations were highest in ground water in the southeast part of the study area and coincide with an area underlain by Sierra Nevada sediments. Because, as noted earlier, the availability of molybdenum is similar in the Sierra Nevada and Coast Ranges sediments, the difference in concentration in ground water from the two sediment types probably is due to differences in molybdenum mobility. Molybdate, the most common molybdenum species in oxidizing water with a pH greater than 4.24, may be controlled by adsorption onto ferric hydroxides in various hydrogeologic settings (Gonzalez and others, 1974; Jarrell and Dawson, 1978; Kaback and Runnells, 1980). Concentrations of molybdenum in Coast Ranges ground water are lower than in Sierra Nevada ground water and may be due to adsorption onto ferric hydroxides, which likely are more abundant in the oxidizing environment that dominates the Coast Ranges ground water.

Selenium

Selenium concentrations range from less than the detection limit of 1 to 13 µg/L (table 4). The U.S. Environmental Protection Agency (1986b) classifies selenium as a

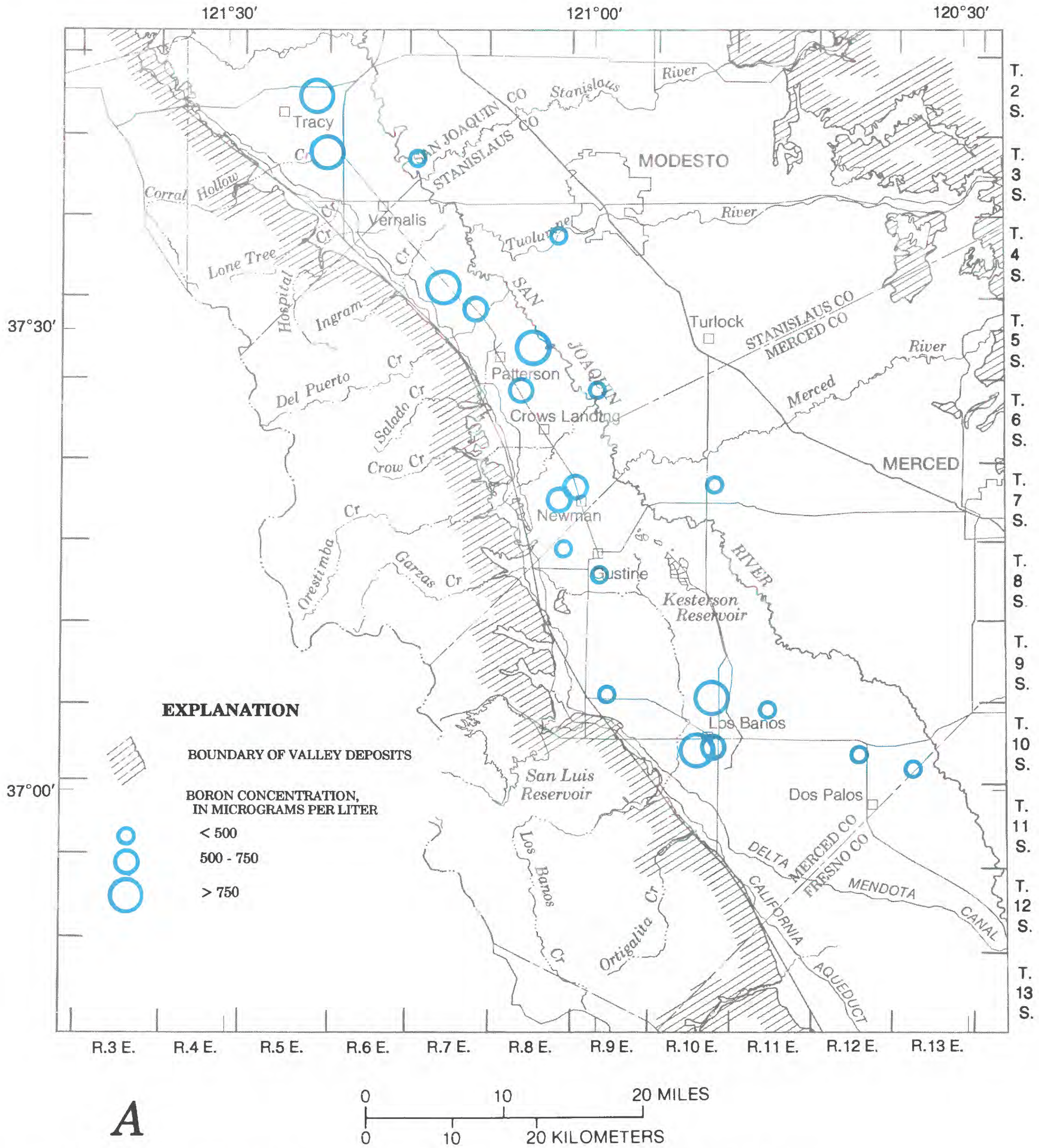

Figure 14. Boron concentrations in ground water, 1985. *A*, Semiconfined zone. *B*, Confined zone.

priority pollutant and recommends a maximum drinking water concentration of 10 µg/L. This concentration was equaled or exceeded in two samples from the semiconfined zone and in one sample from the confined zone. The concentrations and areal distribution of selenium are similar in both zones (figs. 16*A* and 16*B*). Selenium concentrations are relatively high in a narrow area of both zones between Pattersen and Crows Landing. Selenium concentrations generally are lower along the east side of the study area.

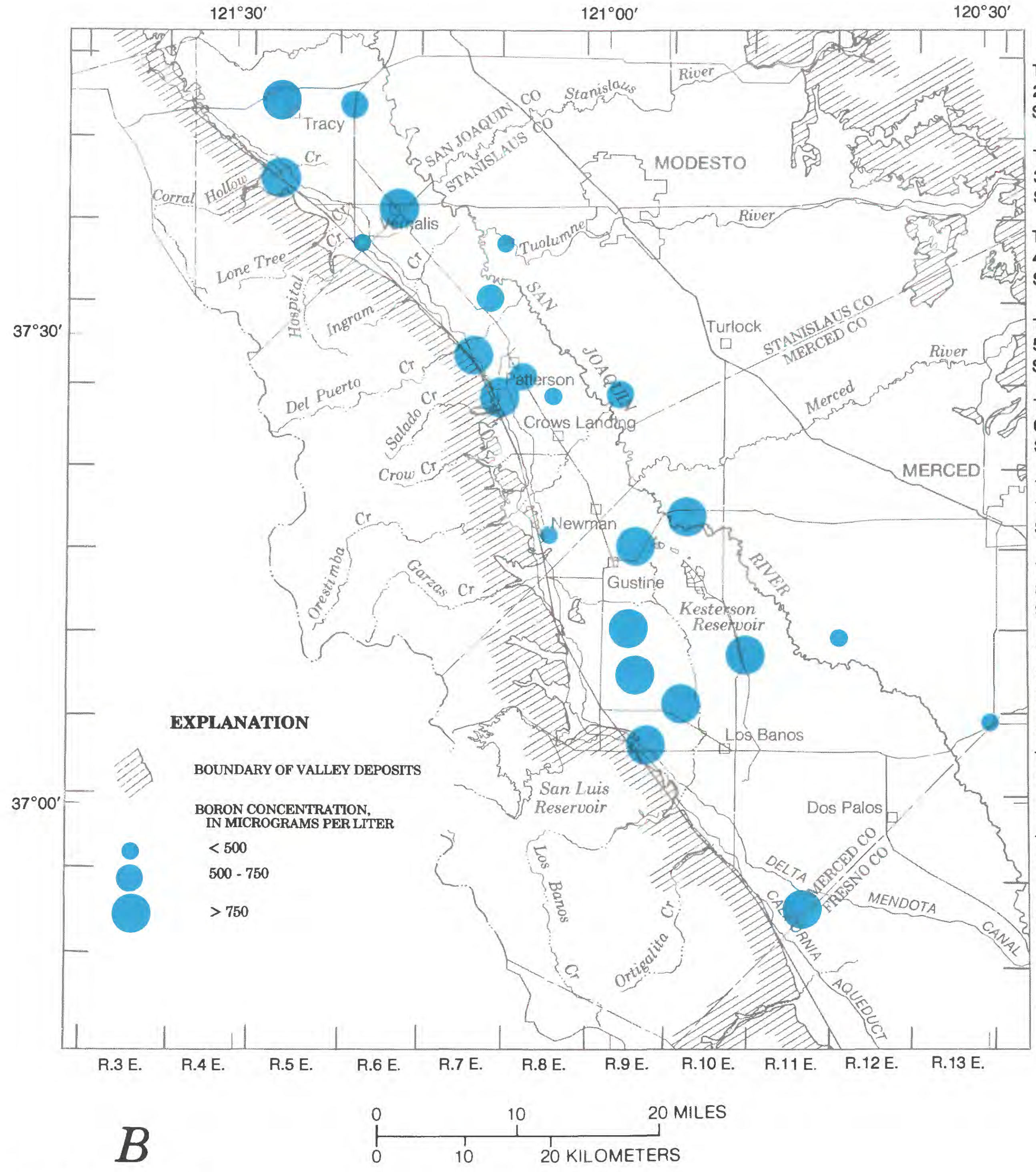

Figure 14.—Continued

A comparison of selenium values for ground water with those for several streams entering the study area from the west shows the relation of the chemistry of Coast Ranges runoff to selenium concentrations in the ground-water-flow system (table 6) (T.S. Presser, U.S. Geological Survey, written commun., 1987). In 11 samples, the 3 highest concentrations of selenium were measured in Crow, Salado, and Ingram Creeks. These creeks recharge parts of the study area where selenium concentrations were highest in ground water. These re-

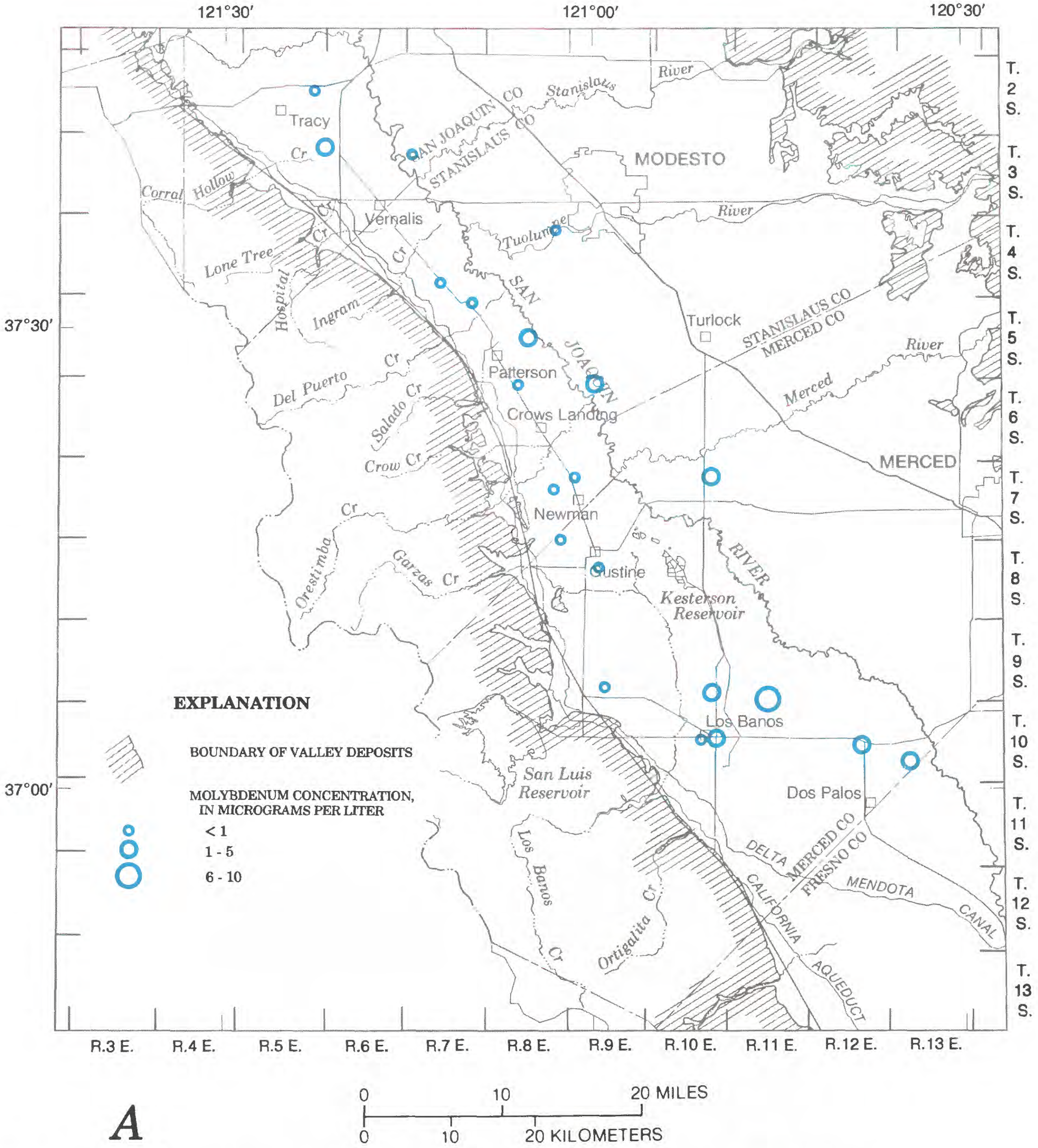

Figure 15. Molybdenum concentrations in ground water, 1985. *A*, Semiconfined zone. *B*, Confined zone.

sults indicate that selenium was transported to the study area under natural conditions by runoff from the Coast Ranges.

The relation between high selenium concentrations in ground water and water draining the Coast Ranges also is indicated by the strong correlation between selenium and sulfate concentrations in samples of ground water from Coast Ranges sediments in the semiconfined zone (fig. 17). A linear regression between the natural logarithms of selenium and sulfate, with the exclusion of

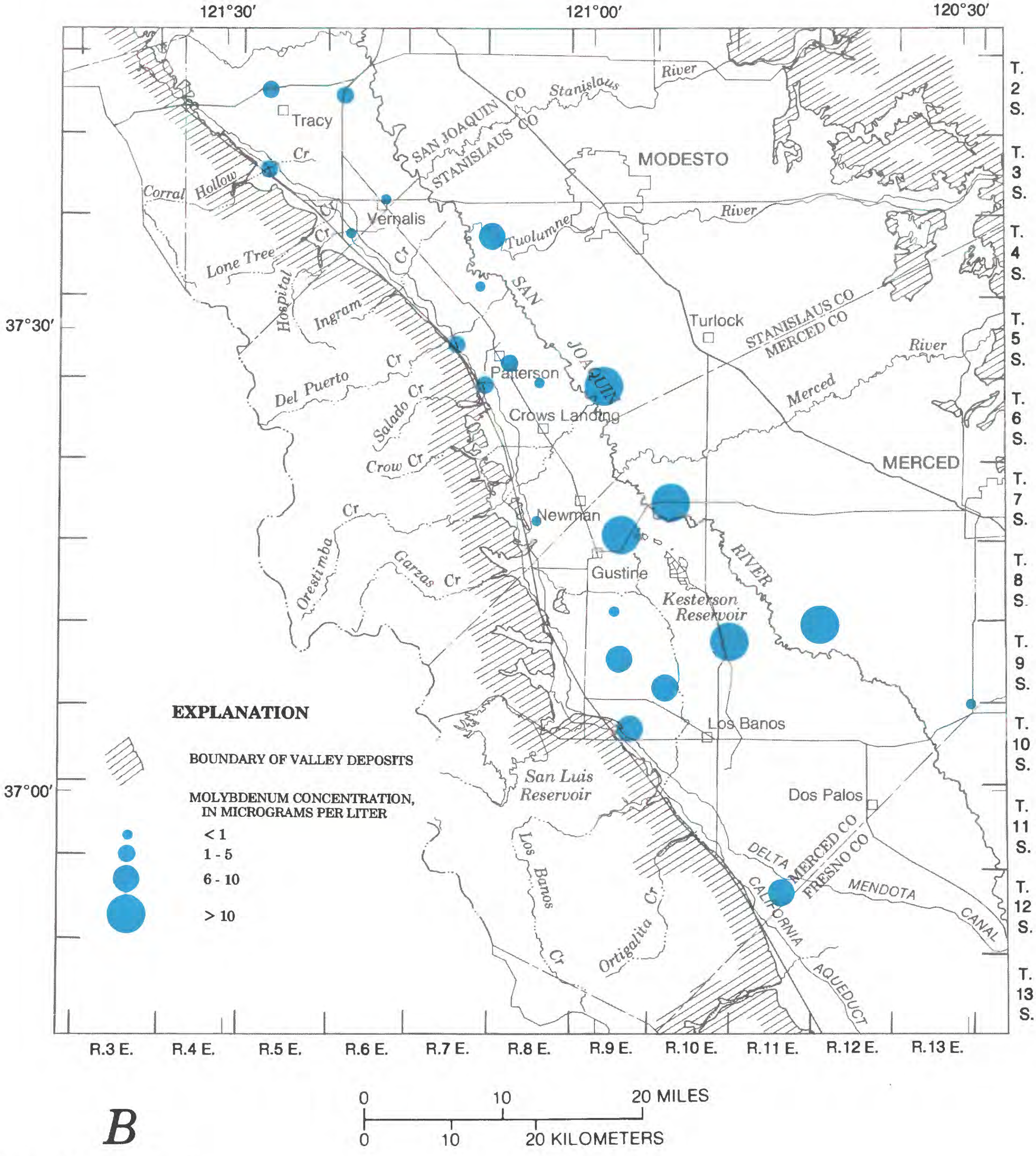

Figure 15.—Continued

one outlier, explains 78 percent of the variation ($\alpha=0.05$) in selenium concentrations. In addition, a plot of selenium concentrations on a Piper diagram showing the anionic composition of all the samples from the semiconfined zone indicates the lack of selenium in ground water with low percentage of sulfate (fig. 18). The relation between selenium and sulfate in ground water alternatively could result from leaching of these constituents from selenium- and sulfate-rich sediments of the Coast Ranges.

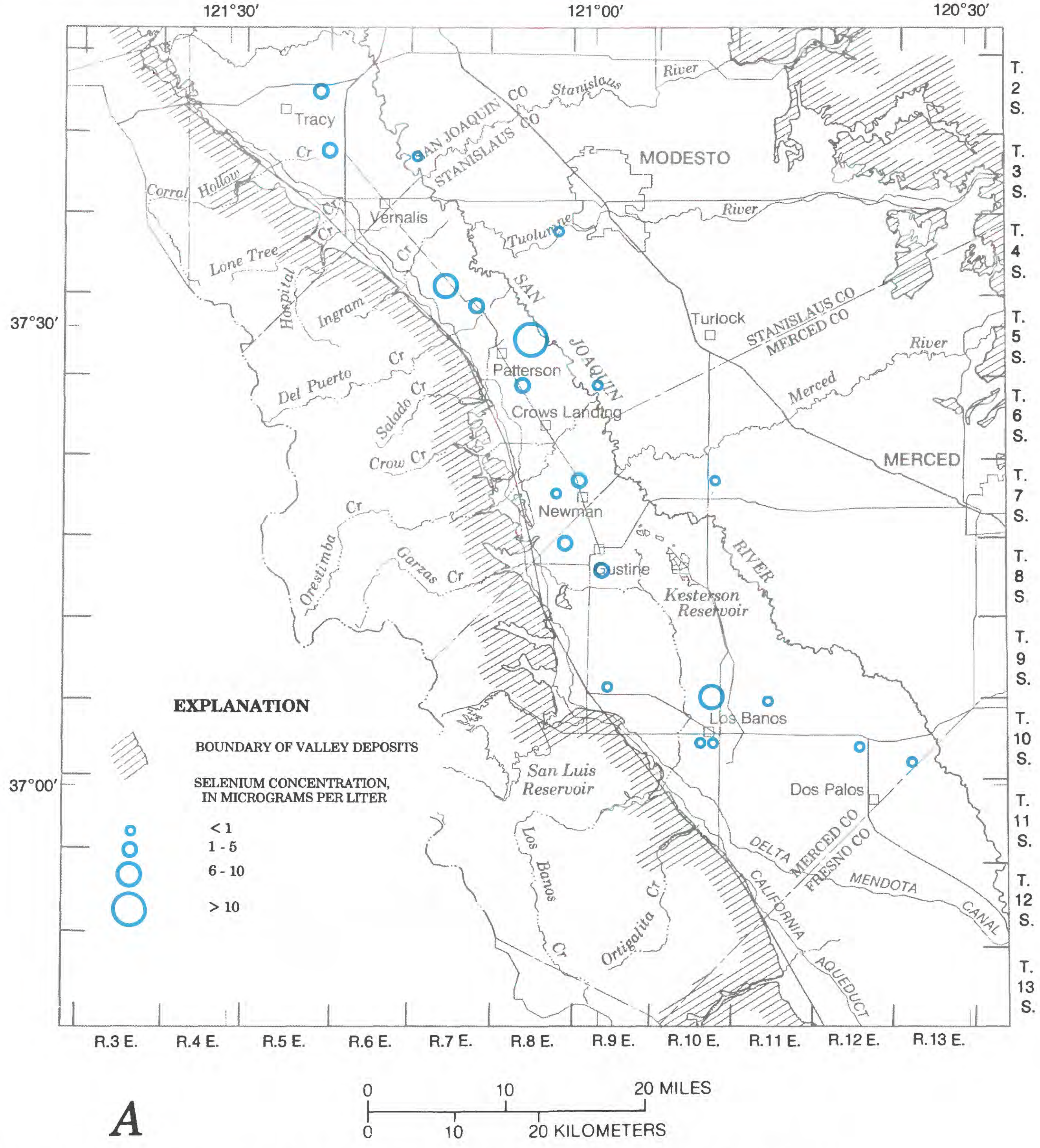

Figure 16. Selenium concentrations in ground water, 1985. *A*, Semiconfined zone. *B*, Confined zone.

Effects of Redox Conditions and Geologic Source of Sediment on the Distribution of Selenium

Selenium is the only trace element for which concentrations in samples of water from Coast Ranges sediments in both zones are significantly higher than in samples from Sierra Nevada sediments (fig. 13). This implies that the source of selenium is from the Coast Ranges and that ground water containing selenium has not appreciably infiltrated to the parts of the zone that

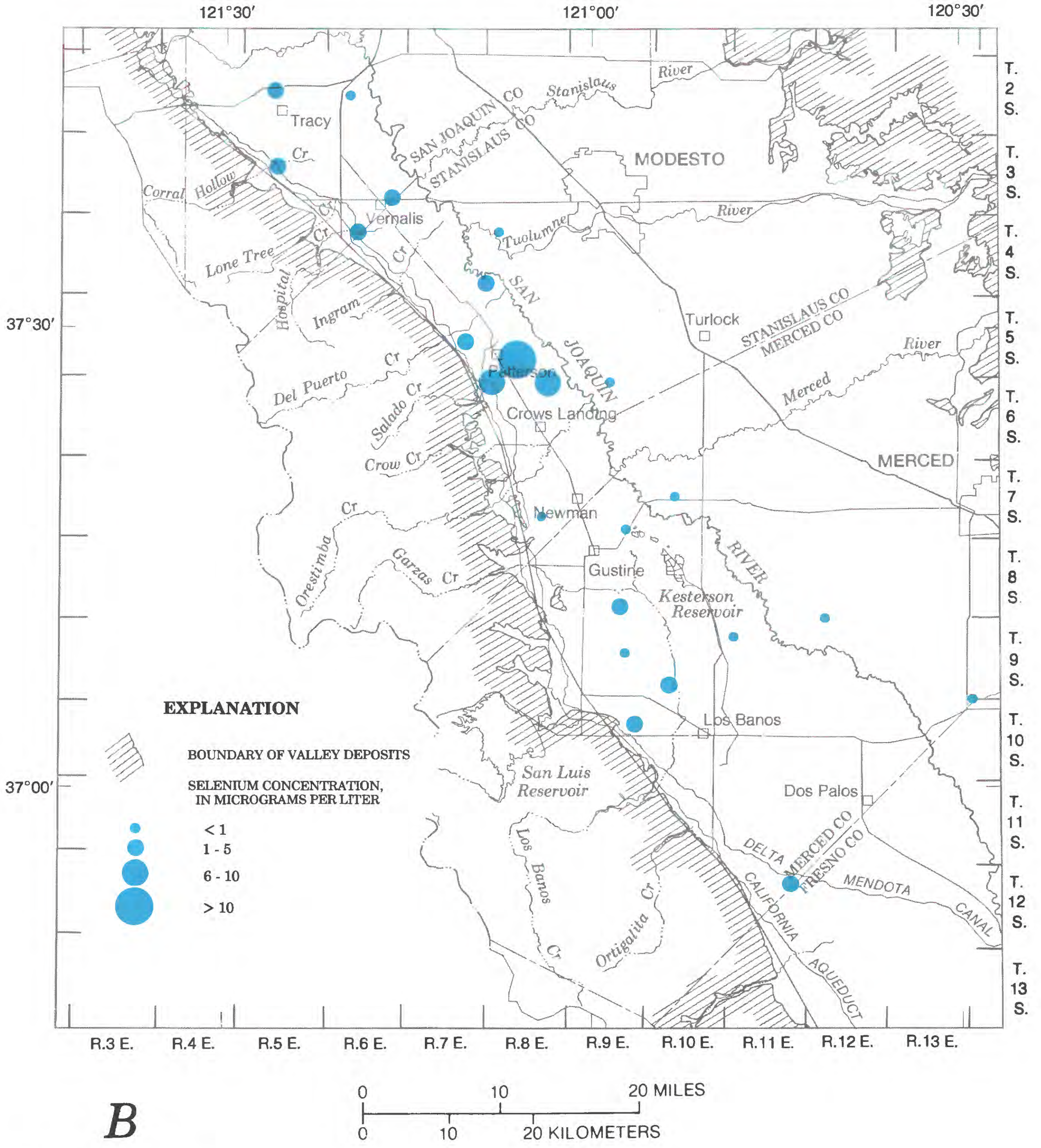

Figure 16.—Continued

Table 6. Concentrations of selenium in selected streams in the study area that drain the Coast Ranges

[Concentrations for samples collected in March 1984 and analyzed by T.S. Presser, U.S. Geological Survey, Menlo Park, California. µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 °C; °C, degrees Celsius. <, actual value is less than value shown]

Creek	Selenium (µg/L)	Specific conductance (µS/cm)
Corral Hollow	1	1,280
Crow	18	4,500
Del Puerto	<1	950
Garzas	2	1,600
Hospital	1	950
Ingram	4	1,600
Lone Tree	<1	1,550
Los Banos	<1	450
Orestimba	1	1,000
Ortigalita	1	2,600
Salado	5	1,900

are Sierra Nevada sediments. Whether this is due to the absence of water derived from Coast Ranges sediments in the Sierra Nevada sediments or due to low mobility of selenium in these sediments cannot be determined using data from this study.

For selenium, in particular, the relation between ground-water concentrations and the source of sediments may be partly due to the dominance of chemically reduced conditions in Sierra Nevada sediments and more oxidized conditions in most Coast Ranges sediments. The dominant form of selenium under oxidizing conditions is selenate (SeVI); however, under mildly reducing conditions, selenite (SeIV) species predominate. Laboratory experiments show that selenite is much more strongly adsorbed than selenate on goethite (Leckie and others, 1980; Balistrieri and Chao, 1987; Hayes and others, 1987) and on ferric oxide gel (Ryden and others, 1987). Similar experiments on San Joaquin Valley soils show that selenite is strongly adsorbed (Burau and others, 1987; Fio, 1987; Neal and others, 1987); however, selenate is not significantly adsorbed (Sposito and others, 1987).

Redox potential exerts a strong influence on selenium concentrations in ground water at Kesterson Reservoir, in the center of the study area. Data for shallow ground water underlying Kesterson Reservoir show that the infiltration of high selenium water is at a maximum in areas where organic-rich material is absent from the pond bottom and where nitrate concentrations are high (Lawrence Berkeley Laboratory, 1987). The high nitrate concentrations indicate oxidized conditions. In areas where an organic layer has accumulated on the pond bottom, selenium is removed from water infiltrating downward by bacterial reduction and subsequent sorption or

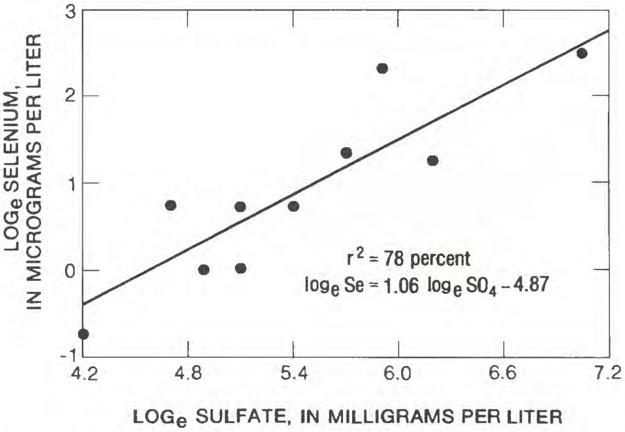

Figure 17. Relation between selenium and sulfate concentrations in water from wells screened in Coast Ranges sediments in the semiconfined zone.

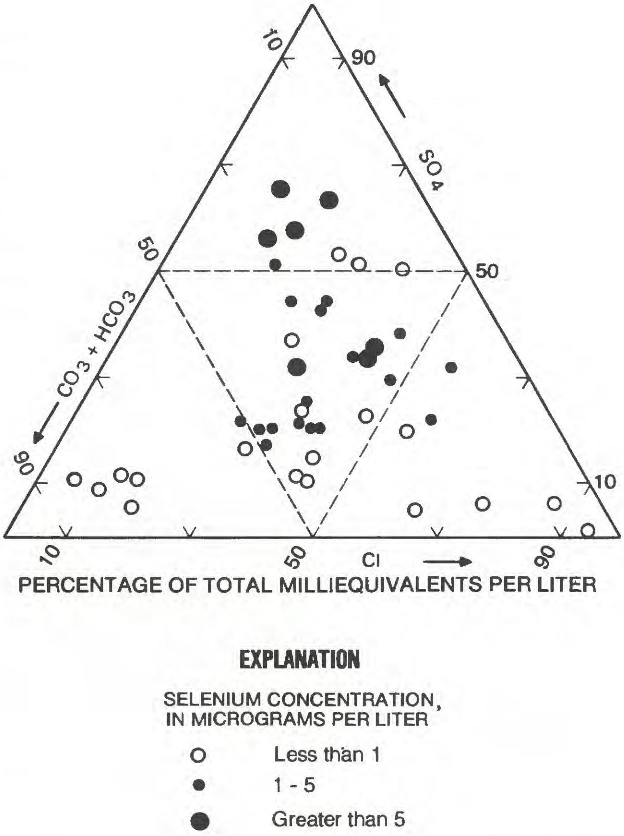

Figure 18. Anionic composition of ground water from the semiconfined and confined zones in relation to selenium concentrations.

precipitation (Lawrence Berkeley Laboratory, 1987). The exact mechanism of removal and the redox state of the selenium that is immobilized is not clear at this time. Conversely, the association of high selenium and nitrate indicates that when nitrate concentrations are sufficiently high, nitrate oxidizes the organic material and selenium is not reduced or removed from the solution (Lawrence Berkeley Laboratory, 1987). These interpretations are supported by platinum electrode measurements of redox potential.

On the basis of concentrations of redox indicators discussed earlier, evidence indicates that ground water in Sierra Nevada sediments is more reducing than ground water in Coast Ranges sediments, and the absence of selenium in ground water in Sierra Nevada sediments may be partly due to reduction and immobilization of selenium. However, because of the coincidence of the redox boundary with the division between sources of sediments, the relative contributions of these two factors cannot be quantitatively separated on the basis of the data available. Both oxidizing conditions and sediments derived from the Coast Ranges seem to be necessary for the occurrence of high selenium concentrations.

Effects of Evaporation on the Distribution of Selenium

Detailed studies on selenium in soils and shallow ground water of the western San Joaquin Valley south of the study area showed that a primary cause of the highest selenium concentrations was evaporation of shallow ground water (Deverel and others, 1984; Deverel and Fujii, 1988; Fujii and others, 1988). This conclusion is supported by a strong positive correlation of selenium with salinity and enrichment in oxygen-18 (Deverel and Fujii, 1988).

The relation between selenium and salinity in the ground-water-flow system in the study area was investigated by correlation analysis of the natural logarithms of specific conductance and selenium for samples from wells screened in Coast Ranges sediments. Correlation between selenium and specific conductance was significant only for the samples from the semiconfined zone. The data from this zone display a linear trend, with the exception of one sample that had a high specific conductance as a result of an anomalously high chloride concentration. Excluding this sample, the line fit to the data has a slope of 2.84 and an intercept of –20.2; specific conductance explains 78 percent of the variation (α=0.05) in selenium concentrations (fig. 19). The slope and intercept for this line are similar to lines fit to data from other areas in the western San Joaquin Valley (Deverel and Millard, 1988), which indicates a similar geochemical process. Concentrations of the other trace elements are not significantly correlated with specific conductance in ground water sampled in this study.

A linear relation between selenium and enriched oxygen-18 values was not identified for ground water from Coast Ranges sediments in the semiconfined zone. The lack of relation between selenium and oxygen-18 may be due to the extensive recharge with isotopically different irrigation water. Thus, isotope data do not support concentration by evaporation.

The natural logarithms of selenium and specific conductance data for surface water that drains the Coast Ranges in the study area also are significantly correlated (α=0.05, r^2=55.4 percent) (table 6). This implies that the tendency for high selenium concentrations in ground water with high dissolved-solids concentration may be due to recharge of surface water from the Coast Ranges. This relation cannot be evaluated further, however, because the data are insufficient especially with regard to possible variation in selenium concentration and specific conductance as a function of flow volume for individual streams.

The relation between selenium and specific conductance most likely results from the generally nonreactive geochemical behavior of selenium in the Coast Ranges sediments and perhaps from the leaching of salts from the unsaturated zone by irrigation water. In view of the complex history of ground water in the semiconfined zone, the degree to which selenium concentrations in this zone have been affected by evaporative concentration, leaching, mixing, or other processes is unknown.

The regression of the logarithms of selenium and delta oxygen-18 in ground water from Coast Ranges sediments in the confined zone is significant (α=0.05), explaining 42 percent of the variation in the selenium data (fig. 20). The oxygen-18 for these samples does not depart from the regional meteoric water line, as would occur if evaporation had taken place (fig. 9). The correlation implies that some of the selenium in the confined

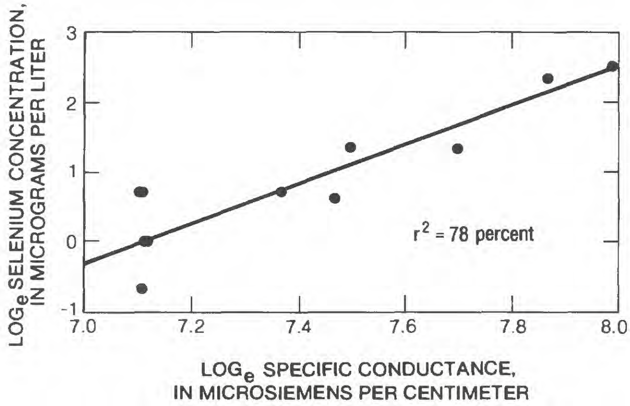

Figure 19. Relation between selenium concentrations and specific conductance in water from wells screened in Coast Ranges sediments in the semiconfined zone.

zone may be due to contamination by isotopically enriched, semiconfined ground water.

Comparison Between Semiconfined Zone and Shallow Ground Water

Shallow ground water near the top of the semiconfined zone and less than 9 m below the land surface generally has higher trace-element concentrations than the deeper parts. Data for the shallow ground water for the study area (Deverel and others, 1984) are summarized in table 7. Concentrations of boron, lithium, molybdenum, and vanadium sampled during this study are significantly higher ($\alpha=0.05$) in the shallow ground water compared with water from the deeper zones. Only zinc was significantly lower in the shallow ground water compared with the deeper parts of the semiconfined zone.

High trace-element concentrations in the shallow ground water might be correlated with the generally higher dissolved-solids concentrations of the shallow ground water, probably resulting from leaching of soil salts and evaporative concentration of shallow ground water near the land surface. This hypothesis is supported by a significant correlation ($\alpha=0.05$) between the natural logarithms of specific conductance and boron, molybdenum, selenium, and vanadium in a set of 118 samples of shallow ground water from the western San Joaquin Valley which include the data in table 7 (Deverel and Millard, 1988).

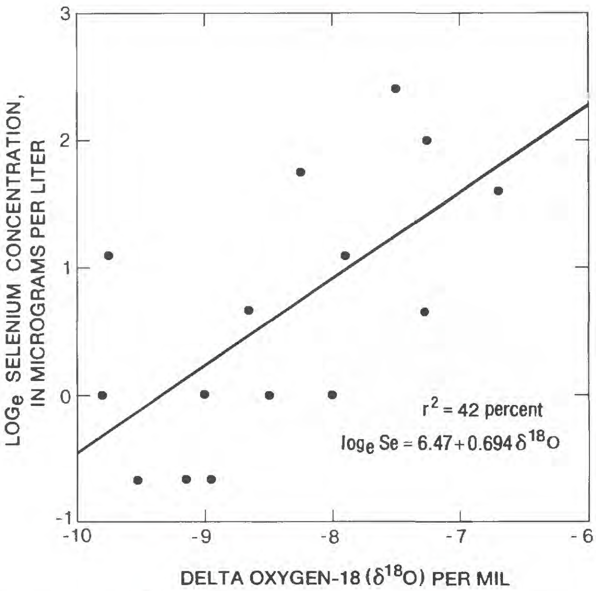

Figure 20. Relation between the natural logarithm of selenium concentrations and delta oxygen-18 for water from Coast Ranges sediments in the confined zone.

Table 7. Summary of concentrations of dissolved trace elements in shallow ground water less than 9 meters below land surface

[Summary of data collected in the study area by Deverel and others (1984) during May 5-12, 1984. μg/L, microgram per liter; --, no data. <, actual value is less than value shown]

Trace element (μg/L)	Number of samples	Minimum	Median	Maximum
Aluminum	--	--	--	--
Arsenic	50	<1	1.5	24
Boron	50	140	1,550	14,000
Cadmium	50	<1	<1	2
Chromium	50	<1	1.5	170
Copper	49	<1	2	20
Iron	49	2	40	4,000
Lead	50	<1	<1	12
Lithium	50	15	70	430
Manganese	49	<1	30	2,500
Mercury	50	<.1	<.1	.7
Molybdenum	50	<1	4	130
Nickel	--	--	--	--
Selenium	48	<1	2	490
Silver	--	--	--	--
Vanadium	50	.5	14	50
Zinc	49	10	10	60

The areal distributions of arsenic and molybdenum in the shallow ground water are similar to their distributions in deeper zones. However, the distributions of boron and in particular selenium differ between the shallow ground water and the semiconfined zone. The highest concentrations of selenium in the shallow ground water are in the southwest corner of the study area (fig. 21), where concentrations were low in samples collected from deeper ground water during this study (figs. 16*A* and 16*B*). Some of the difference in distribution might be caused by differences in the areal coverage of data. However, the water table is within 3 m of the land surface over most of the southwestern part of the study area (Hotchkiss and Balding, 1971), and the contrasts in the distribution more likely reflect the greater importance of evaporative concentration of selenium and boron in shallow ground water of the southwest part of the study area.

ELEMENT ASSOCIATIONS

Principal-component analysis (Davis, 1973; Daultrey, 1976) was used to investigate further associations among trace elements and between trace elements and major ions.

The procedure analyzes the covariance between pairs of variables, partitioning the total variance of a set of *n* variables into a corresponding set of *n* mutually independent components. Each component explains a part of the total variance, and components are numbered in order of descending amount of variance explained. Usually a large part of the variance is explained by the first several components. The degree of correlation of each variable with a component is expressed numerically as a loading of that variable on the component. Patterns in loadings can be interpreted in

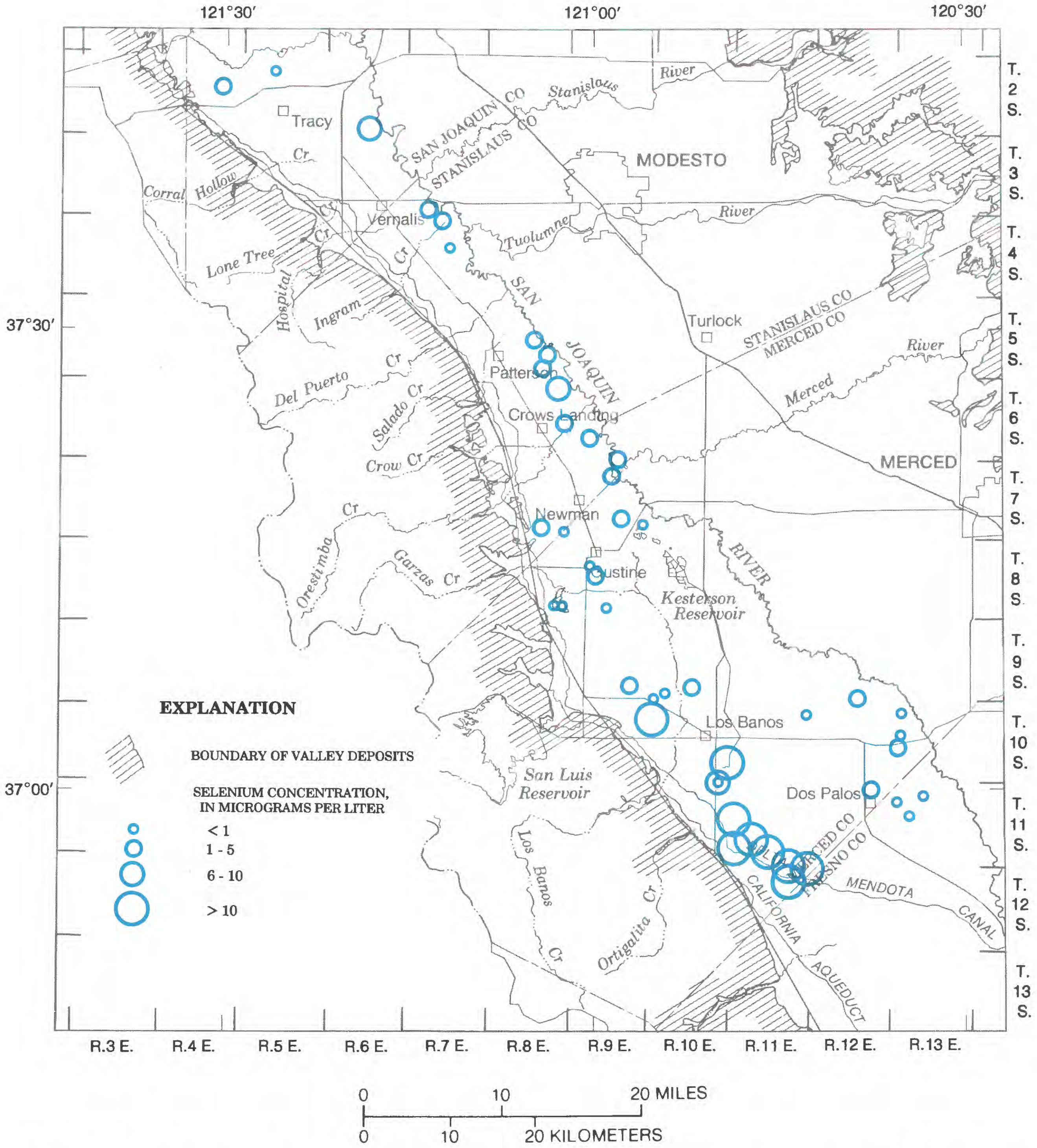

Figure 21. Distribution of selenium concentrations in shallow ground water, 1984. (Modified from Deverel and others, 1984.)

terms of a geochemical process that may affect element associations. Component scores that are a measure of the degree of association of an individual water sample with a particular component also are calculated. The analysis was done for major ions and trace elements separately and combined. An examination of normal probability plots of the data showed that most of the data are log-normally distributed, and therefore, the analysis was done on base-10 logarithms of the data.

Major Ions

The analysis of the major ions and specific conductance shows that 49 percent of the variation in the data is explained by the first principal component, and 75 percent is explained by the first three components (table 8). Specific conductance and the dominant major ions have the highest positive loadings for component I. This indicates that most of the variability is associated with the salinity of the ground water.

Component II is dominated mainly by nitrate, with moderate positive loadings for alkalinity and magnesium. Specific conductance and the major ions—sodium, chloride, and potassium—are inversely related to component II. Thus, nitrate concentrations seem to be most affected by processes different from those that affect salinity. A possible explanation is that this component reflects the residence time of ground water in the flow system. This is implied by the grouping of constituents that generally increase in concentration along a ground-water-flow path (sodium, chloride, and specific conductance) and constituents that usually decrease in concentration along a ground-water-flow path (nitrate and magnesium).

Component III shows an association with silica and potassium and an inverse relation with sulfate. This component probably reflects the weathering of feldspar. This process is most active in the Sierra Nevada sediments, which have abundant fresh feldspar. The negative correlation with sulfate results from the greater abundance of sulfate in water draining the Coast Ranges than in water from the Sierra Nevada. Owing to the slow kinetics of feldspar dissolution, a high score for component III also implies a long residence time for the water sample. However, other weathering factors and the type of feldspar present also are influential.

Variation in the components between samples from the semiconfined and confined zones and between samples from Sierra Nevada and Coast Ranges sediments was investigated by plotting histograms for the component scores of each sample by group. A component score represents the combined degree of association of each constituent in a water sample with respect to a single component; thus, a score is calculated for each sample. The distribution of scores for components I, II, and III was not significantly different between the semiconfined and confined zones. The lack of contrast indicates that the chemistry of ground water in these zones is similar.

Table 8. Results of principal-component analysis of major-ion data

Property or constituent	Principal-component number		
	I	II	III
pH	0.32	-0.25	-0.24
Silica	-.04	.07	.69
Nitrate	.14	.60	-.05
Potassium	.23	-.22	.43
Alkalinity	.24	.39	.01
Sulfate	.25	.07	-.52
Sodium	.33	-.42	-.06
Magnesium	.37	.24	-.00
Chloride	.37	-.28	.01
Calcium	.39	.08	.10
Specific conductance	.40	-.23	-.07
Total explained (percentage of total)	49	15	11

Differences between component scores for samples of water from wells screened in Sierra Nevada and Coast Ranges sediments are greater than differences between component scores for the semiconfined and confined zones. Component I scores for samples from Coast Ranges sediments group tightly, indicating a similar degree of association with this component (fig. 22). Component I scores for samples from the Sierra Nevada sediments vary greatly, indicating a high degree of variability in this group. Component III scores grouped by sediment type indicate that ground water from Coast Ranges sediments is dominated by the negative loading associated with sulfate, and component scores for samples from Sierra Nevada sediments are most strongly influenced by silica concentrations (fig. 22). This shows the effect of sediment source on sulfate and silica concentrations in the ground water.

Trace Elements

The results of the principal-component analysis of the trace elements are given in table 9. Only the first two components are shown because the assignment of values to samples with analytical values less than the detection limit greatly changed the results of the third and subsequent components.

Forty-six percent of the variance in the data set is explained by components I and II. Component I separates the trace elements into two groups: high positive loadings for chromium, lithium, selenium, zinc, and boron; and high negative loadings for manganese, molybdenum, arsenic, and iron. Some of the elements in the former group are most mobile under oxidizing conditions; however, in the latter group, iron, manganese and, to a lesser extent, arsenic are more mobile under reducing conditions.

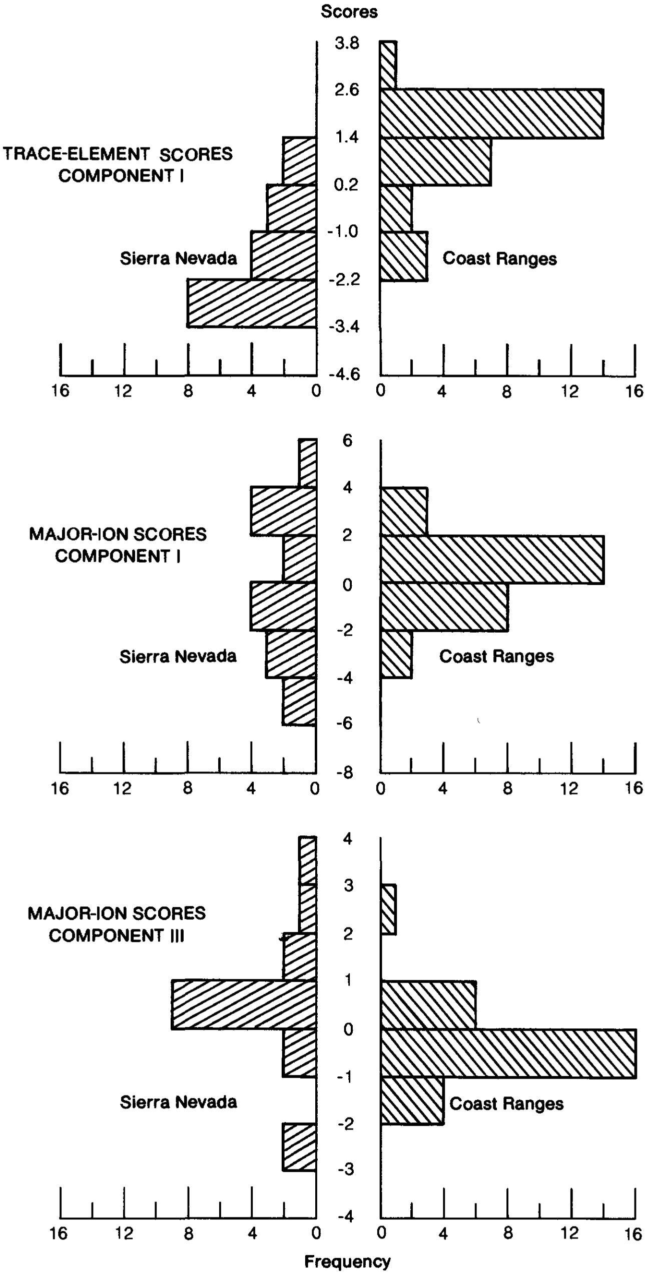

Figure 22. Component scores for principal-component analysis.

Table 9. Results of principal-component analysis of trace-element data

Property or constituent	Principal-component number I	Principal-component number II
Manganese	-0.43	0.15
Molybdenum	-.36	.32
Arsenic	-.30	.12
Iron	-.26	.20
Vanadium	-.11	.28
Lead	-.07	.33
Copper	.03	.42
Nickel	.06	.28
Boron	.20	.43
Zinc	.24	.01
Selenium	.35	.23
Lithium	.36	.37
Chromium	.39	-.03
Total explained (percentage of total)	29	17

Component II has loadings of greater than 0.20 on most of the trace elements. The high loads on the conservative constituents boron and lithium indicate that this component reflects a tendency for high trace-element concentrations in ground water with high dissolved-solids concentrations.

The distribution of sample scores was not different for components I or II in both zones, indicating that the occurrence of trace elements is similar. However, a histogram of component I scores shows that samples from wells screened in Sierra Nevada sediments tend to have negative scores, and samples from Coast Ranges sediments have positive scores (fig. 22). The separation of component I scores is in agreement with Mann-Whitney test results which indicate that concentrations of arsenic, molybdenum, and manganese were significantly higher in water from wells completed in Sierra Nevada sediment than in water from wells completed in Coast Ranges sediment; and concentrations of boron, chromium, lithium, and selenium were significantly higher in ground water from wells completed in Coast Ranges sediments in the semiconfined zone. This result indicates the contrast in redox status between these two groups; in addition, contrast in the component I scores for elements not affected by redox reactions, in particular boron and lithium, suggests that the source of sediment also is influential. The effects of mobility and source of sediments cannot be separated on the basis of these data.

Major Ions and Trace Elements Combined

An analysis also was done with major-ion and trace-element data combined. Components I and II explained 49 percent of the variation (table 10). Component I contains the same associations of major ions and trace elements as in the separate analyses. The trace elements that had positive loadings on the first component calculated for the trace-element data alone (boron, lithium, selenium, chromium, and copper) also have positive loadings on component I for the combined set. Component I scores are high for ground water from Coast Ranges sediments, indicating that high concentrations of this group of major and trace elements are associated with some combination of high salinity, a Coast Ranges source, and oxidizing conditions.

Component II is dominated by association of trace elements with similar redox behavior: high negative loadings were calculated for chromium, nitrate, selenium, zinc, and lithium; and high positive loadings were calculated for specific conductance, several major ions, molybdenum, manganese, iron, arsenic, and vanadium. The former group contains elements (nitrate, selenium, and chromium) mobile under oxidizing conditions, and the latter group contains elements (manganese, iron, and arsenic) mobile under reducing conditions. The association of several major ions and specific conductance with the group of trace elements favored by reduced conditions shows that these trace elements also have a tendency for higher concentrations in ground water with high dissolved-solids concentrations.

The principal-component analysis supports the earlier conclusions that major ions and trace elements are affected by the source and redox status of the sediment.

Table 10. Results of principal-component analysis of major-ion and trace-element data combined

Property or constituent	Principal-component number	
	I	II
pH	-.25	-.03
Silica	-.07	.03
Potassium	.16	.18
Nitrate	.18	-.30
Alkalinity	.20	-.05
Sodium	.24	.32
Sulfate	.26	.03
Chloride	.27	.22
Specific conductance	.32	.22
Calcium	.33	.04
Magnesium	.33	-.06
Arsenic	-0.17	0.17
Manganese	-.07	.41
Molybdenum	-.04	.39
Lead	.01	.12
Iron	.04	.28
Vanadium	.06	.18
Nickel	.11	.06
Zinc	.14	-.17
Chromium	.14	-.32
Copper	.14	.06
Selenium	.19	-.21
Boron	.26	.05
Lithium	.30	-.12
Total explained (percentage of total)	30	19

SUMMARY AND CONCLUSIONS

The areal and vertical distribution of ground-water chemistry in the ground-water-flow system in the western San Joaquin Valley has been affected by different agricultural and natural sources of recharge and by the source and redox status of the sediments. The main conclusions of this study are as follows:

Dissolved-solids concentrations in ground water in the study area range from 190 to 4,400 mg/L. In water in the semiconfined zone the highest dissolved-solids concentrations are present north of Los Banos and near Patterson. In the confined zone, dissolved-solids concentrations are generally highest through the central part of the valley. There was little similarity between dissolved-solids concentrations in water in the semiconfined and confined zones.

Major cation ratios in water from the semiconfined zone are dominantly transitional, and in only 15 percent of the samples did one particular cation exceed 50 percent of the total cationic charge. Cation ratios in the confined zone are less transitional, with sodium dominating in 67 percent of the samples. Both zones have a large range in anion ratios: bicarbonate dominates most commonly in the semiconfined zone, and sulfate dominates most commonly in the confined zone. The similarity of major-ion concentrations in water from both zones probably results from mixing of waters between the two zones.

All samples from the semiconfined zone had detectable tritium, and most had greater than 10 Tu, indicating the dominant effect of water that recharged since 1952. The depth to the midpoint of the well screen of these wells ranged from 10 to 43 m, and thus irrigation water applied since 1952 typically infiltrated the semiconfined zone at least to these depths near the wells sampled.

Four of the 13 ground-water samples from the confined zone have tritium concentrations of 2 Tu or less, indicating pre-1952 recharge. However, tritium concentrations ranging from 2 to 18.5 Tu indicated infiltration of the confined zone by water from the semiconfined zone in at least five and possibly as many as nine of these wells. The presence of tritium in the confined zone indicates that the vertical leakage between the zones above and below the Corcoran Clay Member of the Tulare Formation has been increased as a result of leakage down well casings and gravel packs, although the extent of the ground-water-flow system affected is not known.

Ground-water samples from the semiconfined zone have depleted oxygen-18 values, probably indicating their origin as irrigation water from the Sierra Nevada. The oxygen-18 concentration in ground water in the confined zone is more variable and significantly more enriched than that in ground water in the semiconfined zone. This is in contrast to the pattern of oxygen-18 distribution in ground water in western Fresno County, where oxygen-18 values are uniformly depleted in the confined zone. The enriched oxygen-18 concentration in ground water in the confined zone likely is due to infiltration of Coast Ranges-derived ground water from the semiconfined zone.

Concentrations of most trace elements were similar in wells completed in both zones, except for molybdenum concentrations, which were significantly higher in the confined zone.

Areal distributions of arsenic, molybdenum, and selenium are similar in both zones. Concentrations of arsenic and molybdenum are highest in the southeastern part of the study area. The areal distribution of boron shows locally high concentrations near Tracy, northeast of Crows Landing and Los Banos. Selenium concentrations were highest in a narrow band between Patterson and Crows Landing. The proximity of this band of high selenium concentrations in ground water to Coast Ranges streams with high selenium concentrations indicates that selenium was transported to the study area under natural conditions by runoff from the Coast Ranges. The association between selenium and sulfate also indicates that selenium was derived from the Coast Ranges.

Differences between trace-element concentrations in the Coast Ranges and Sierra Nevada sediments were most significant in the semiconfined zone. Molybdenum, arsenic, and manganese concentrations were significantly higher in ground water from Sierra Nevada sediments than in ground water from Coast Ranges sediments. Boron and selenium had significantly higher concentrations in ground water from Coast Ranges sediments than in ground water from Sierra Nevada sediments. Selenium is the only trace element that is present in significantly higher concentrations in ground water from Coast Ranges sediments than in ground water from Sierra Nevada sediments in the confined zone. This implies a Coast Ranges source for selenium and ground water containing selenium has not appreciably infiltrated to the parts of the zone that are Sierra Nevada sediments.

The high concentrations of iron and manganese in ground water from Sierra Nevada sediments indicate that these deposits are reduced. High concentrations of nitrate in ground water from Coast Ranges sediments indicate that these sediments are more highly oxidized than Sierra Nevada sediments. The redox status of the ground water likely affects the distribution of arsenic, molybdenum, and selenium; however, the relative degree to which the source of sediments and redox status affect the distribution of trace elements cannot be quantitatively determined because of the coincidence of the lithologic boundary between Coast Ranges and Sierra Nevada sediments with oxidized and reduced ground-water conditions.

Selenium was the only priority pollutant measured that exceeded the U.S. Environmental Protection Agency drinking-water standard of 10 µg/L. Selenium concentrations were greater than or equal to 10 µg/L in two wells completed in the semiconfined zone and one well completed in the confined zone.

The correlation between selenium and specific conductance in ground water from Coast Ranges sediments in the semiconfined zone explains 78 percent of the variation in selenium concentrations. The absence of a similar correlation between selenium and oxygen-18 concentrations in these samples indicates that the association between selenium and specific conductance in this zone might be due primarily to leaching or mixing rather than to evaporative concentration. A correlation between selenium and oxygen-18 concentrations in ground water from Coast Ranges sediments in the confined zone may indicate that some of the selenium is the result of contamination by isotopically enriched ground water from the semiconfined zone.

Principal-component analysis confirms the associations of (1) boron, chromium, lithium, and selenium and (2) arsenic, iron, manganese, and molybdenum. This statistical analysis indicated that the first group is associated with Coast Ranges sediments and the second group with Sierra Nevada sediments.

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TABLES 11 AND 12

Table 11. Chemical analyses of dissolved major ions

[Results in milligrams per liter except where otherwise noted. µS/cm, microsiemen per centimeter at 25 °C; °C, degrees Celsius; --, no data. <, actual value is less than value shown]

State well No.	Date	Specific conductance (µS/cm)	pH (units)	Temperature (°C)	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Potassium, dissolved
Semiconfined zone								
2S/5E-13P1	3-28-85	2,210	7.3	19.0	180	71	200	3.6
3S/6E-7E1	3-11-85	1,760	7.4	19.0	140	44	230	2.0
3S/7E-7Q1	3-12-85	295	8.0	18.5	31	8.5	28	1.8
4S/7E-33B1	3-12-85	2,620	7.5	18.0	130	140	180	1.7
4S/8E-12E1	5-01-85	504	7.7	20.0	50	16	34	2.3
5S/7E-1M2	5-01-85	1,260	7.9	19.0	50	110	83	2.2
5S/8E-22C1	4-30-85	2,900	7.5	20.5	210	150	310	3.4
6S/8E-4P1	5-16-85	1,890	7.2	18.0	150	67	190	1.0
6S/9E-4M1	5-15-85	3,080	7.8	20.0	100	30	500	2.0
7S/8E-13N1	3-26-85	2,920	7.3	17.0	260	140	220	4.3
7S/9E-18D1	3-26-85	1,590	7.6	16.5	110	65	140	2.2
7S/10E-11Q1	5-14-85	729	7.5	19.0	50	22	82	2.8
8S/8E-1H1	3-27-85	1,220	7.7	17.0	96	37	120	1.9
8S/9E-17B1	3-27-85	1,380	7.5	18.0	130	58	93	1.2
9S/9E-33C1	3-28-85	1,310	7.8	20.0	72	39	96	2.4
9S/10E-35Q1	4-09-85	3,320	7.3	20.0	180	110	280	3.0
9S/11E-34N2	4-10-85	2,870	7.2	19.5	120	77	250	3.2
10S/10E-22H4	4-30-85	1,320	7.4	19.0	110	57	150	2.7
10S/10E-23A2	4-11-85	1,000	8.0	20.5	82	44	80	2.2
10S/12E-22J1	4-29-85	485	7.7	20.0	30	14	56	1.7
10S/13E-29P1	4-30-85	608	7.9	19.5	22	6.8	120	1.0
Confined zone								
2S/5E-21D1	3-27-85	1,030	7.7	22.0	61	28	120	3.6
2S/6E-20L2	5-21-85	794	8.1	21.0	31	14	120	2.1
3S/5E-20A2	3-28-85	1,390	7.7	19.5	91	32	170	3.4
3S/6E-26Q1	3-12-85	1,300	7.4	18.5	97	26	130	2.1
4S/6E-9M1	3-13-85	612	7.8	22.0	56	17	49	2.1
4S/7E-36Q3	3-13-85	1,170	7.9	19.5	46	93	73	2.0
4S/8E-7P1	7-02-85	5,130	7.5	17.5	260	69	730	9.7
5S/7E-27B1	5-16-85	1,320	7.9	21.5	32	42	190	1.9
5S/8E-32K3	4-30-85	1,330	7.7	21.0	96	62	150	1.4
6S/7E-1R1	5-16-85	1,840	7.7	20.5	100	87	200	2.3
6S/8E-3R2	5-16-85	1,220	7.6	21.0	96	49	100	2.1
6S/9E-9A2	5-21-85	7,960	7.4	21.0	150	60	1,500	5.2
7S/8E-27Q1	5-13-85	1,170	7.8	22.5	51	26	150	4.4
7S/9E-34Q1	3-28-85	2,040	7.9	25.0	88	44	300	3.6
7S/10E-20F1	5-13-85	1,970	8.3	20.5	50	13	380	1.6
8S/9E-34Q2	3-27-85	2,280	7.5	20.0	120	92	280	2.2
9S/9E-14N2	3-28-85	3,480	7.7	23.5	160	70	570	4.1
9S/10E-32B1	4-09-85	1,450	7.6	24.0	69	33	150	2.0
9S/11E-7N4	4-10-85	2,320	8.2	20.5	33	5.1	360	1.3
9S/12E-5D1	4-10-85	618	8.1	21.0	20	3.3	110	1.4
10S/9E-14H2	4-10-85	1,780	7.8	21.0	87	48	270	1.7
10S/13E-1J1	5-14-85	282	8.4	22.5	9.1	1.5	53	1.6
12S/11E-14C1	5-14-85	1,760	8.3	25.0	70	37	240	3.1

Table 11.—Continued

[Results in milligrams per liter except where otherwise noted. µS/cm, microsiemen per centimeter at 25 °C; °C, degrees Celsius; --, no data. <, actual value is less than value shown]

Alkalinity, total (as $CaCO_3$)	Sulfate, dissolved	Chloride, dissolved	Fluoride, dissolved	Silica, dissolved	Solids, sum of constituents, dissolved	Nitrogen, nitrate, dissolved (as N)	Phosphorus, orthophosphate, dissolved (as P)	Carbon, organic, total (as C)
				Semiconfined zone--*Continued*				
--	320	420	0.1	33	1,400	9.1	<0.01	0.7
82	230	320	.1	42	1,100	6.4	.03	1.2
148	14	5.7	<.1	31	210	<.10	.06	.1
273	370	350	.1	28	1,400	.13	.03	1.1
200	15	17	.1	47	300	6.7	.04	.2
275	120	190	.2	25	750	18	.03	.3
277	1,200	280	.3	28	2,400	.90	.02	.5
327	540	140	.3	27	1,300	15	.02	.8
505	30	750	.1	27	1,700	.10	.03	1.9
433	300	700	.1	30	1,900	11	.02	.9
451	170	170	.2	27	960	5.6	.03	.6
268	29	30	.8	27	410	14	.41	3.4
319	120	160	.1	25	750	11	.01	.5
284	170	190	.3	24	840	12	.01	.5
240	67	170	.2	21	610	3.2	.03	.3
361	530	490	.1	46	1,900	1.7	.04	1.2
379	250	430	.2	32	1,400	<.10	<.01	3.6
398	140	180	.1	63	940	8.0	.03	.06
218	120	140	.1	56	660	3.9	.02	.4
219	19	27	.1	32	290	<.10	<.01	.5
171	47	74	.2	48	420	<.10	.07	.2
				Confined zone--*Continued*				
136	220	110	0.1	23	650	2.3	0.03	0.1
136	140	78	<.1	43	510	<.10	.14	<.1
239	330	130	.2	21	920	1.4	<.01	.1
252	120	160	.2	23	710	5.6	.03	.5
136	44	65	.3	24	340	9.1	.01	.1
251	120	180	.2	23	690	8.3	.03	<.1
112	7.7	1,900	<.1	36	3,100	<.10	.03	.1
229	190	140	.3	25	760	16	.02	.2
176	530	65	.4	26	1,000	4.0	.01	.2
259	630	140	.6	26	1,300	9.6	.01	.5
185	360	66	.2	32	820	6.4	.02	.6
716	180	2,000	.2	28	4,400	20	.05	3.3
273	56	170	.3	31	650	10	.01	.4
109	500	300	.1	33	1,300	<.10	.02	.2
155	490	220	.3	21	1,300	<.10	.02	<.1
336	420	370	.2	33	1,500	4.5	<.01	1.0
134	96	1,200	.2	25	2,200	.72	<.01	.2
164	280	140	.2	34	810	.33	.04	.2
170	480	180	.2	20	1,200	<.10	.05	.5
139	27	92	.3	30	370	<.10	.03	<.1
192	210	420	.3	35	1,200	5.5	.05	.7
112	6.1	17	.3	36	190	.24	.02	<.1
139	330	290	<.1	21	1,100	.22	.01	.4

Table 12. Chemical analyses of dissolved trace elements

[Dissolved trace elements in micrograms per liter. --, no data. <, actual value is less than value shown]

State well No.	Date	Aluminum	Arsenic	Boron	Cadmium	Chromium	Copper	Iron
Semiconfined zone								
2S/5E-13P1	3-28-85	10	<1	2,200	<1	10	3	30
3S/6E-7E1	3-11-85	20	1	1,600	<1	7	<1	30
3S/7E-7Q1	3-12-85	10	2	50	1	1	<1	86
4S/7E-33B1	3-12-85	20	3	900	<1	30	9	50
4S/8E-12E1	5-01-85	<10	3	60	1	2	2	<3
5S/7E-1M2	5-01-85	<10	<1	580	<1	9	1	5
5S/8E-22C1	4-30-85	<10	3	2,200	<1	<1	7	30
6S/8E-4P1	5-16-85	20	<1	510	<1	10	4	7
6S/9E-4M1	5-15-85	20	<1	290	<1	<2	3	50
7S/8E-13N1	3-26-85	10	<1	640	<1	30	2	40
7S/9E-18D1	3-26-85	10	<1	740	<1	20	1	5
7S/10E-11Q1	5-14-85	10	38	120	<1	<1	6	980
8S/8E-1H1	3-27-85	10	<1	480	<1	7	1	3
8S/9E-17B1	3-27-85	20	<1	470	<1	6	2	4
9S/9E-33C1	3-28-85	<10	<1	480	<1	3	<1	<3
9S/10E-35Q1	4-09-85	10	12	2,100	2	<1	4	30
9S/11E-34N2	4-10-85	10	4	340	<4	<1	<4	5,200
10S/10E-22H4	4-30-85	<10	4	1,000	<1	20	<1	9
10S/10E-23A2	4-11-85	10	9	740	<1	20	2	<6
10S/12E-22J1	4-29-85	<10	8	140	<1	<1	<1	82
10S/13E-29P1	4-30-85	<10	11	40	<1	<1	<1	5
Confined zone								
2S/5E-21D1	3-27-85	<10	1	1,300	<1	7	<1	<3
2S/6E-20L2	5-21-85	<10	5	570	<10	<1	1	47
3S/5E-20A2	3-28-85	20	<1	3,000	<1	4	5	5
3S/6E-26Q1	3-12-85	20	<1	790	2	4	<1	110
4S/6E-9M1	3-13-85	20	<1	430	<1	<1	<1	9
4S/7E-36Q3	3-13-85	20	<1	590	<1	9	<1	12
4S/8E-7P1	7-02-85	<10	2	480	1	<1	<1	40
5S/7E-27B1	5-16-85	<10	1	1,200	<1	10	<1	10
5S/8E-32K3	4-30-85	<10	1	670	<1	30	4	8
6S/7E-1R1	5-16-85	10	1	860	<1	1	1	10
6S/8E-3R2	5-16-85	<10	2	410	<1	10	<1	<3
6S/9E-9A2	5-21-85	<10	1	540	<1	<1	4	40
7S/8E-27Q1	5-13-85	<10	<1	470	<1	<1	2	<3
7S/9E-34Q1	3-28-85	10	1	2,900	<1	<1	<1	90
7S/10E-20F1	5-13-85	10	<1	2,900	<1	--	1	40
8S/9E-34Q2	3-27-85	10	<1	2,400	<1	<1	<1	30
9S/9E-14N2	3-28-85	10	<1	1,400	<1	<1	<1	60
9S/10E-32B1	4-09-85	10	4	1,500	<1	<1	<1	<3
9S/11E-7N4	4-10-85	10	3	2,500	<1	<1	2	10
9S/12E-5D1	4-10-85	10	6	40	<1	<1	<1	16
10S/9E-14H2	4-10-85	20	18	1,700	<10	4	<10	30
10S/13E-1J1	5-14-85	<10	15	40	<1	<1	1	4
12S/11E-14C1	5-14-85	10	5	2,800	<1	<1	2	11

Table 12.—Continued

[Dissolved trace elements in micrograms per liter. --, no data. <, actual value is less than value shown]

Lead	Lithium	Manganese	Mercury	Molybdenum	Nickel	Selenium	Silver	Vanadium	Zinc
Semiconfined zone--*Continued*									
<1	50	<10	<0.1	<1	8	4	<1	12	10
<1	70	10	<.1	1	4	2	<1	13	50
<1	<4	150	<.1	<1	<1	<1	<1	1	26
<1	70	20	<.1	<1	1	10	<1	10	50
<1	13	<1	.2	<1	<1	<1	2	23	19
<1	29	<1	<.1	<1	1	2	<1	5	79
1	120	60	.1	3	<1	13	<1	7	200
4	100	4	<.1	<1	5	4	<1	5	37
4	<10	1,000	--	1	1	<1	<1	22	10
5	70	<10	.1	<1	6	<1	<1	16	70
4	48	<1	<.1	<1	5	2	<1	1	160
1	11	1,200	<.1	4	2	<1	1	16	15
1	35	<1	<.1	<1	2	2	<1	<1	20
2	41	<1	<.1	<1	5	1	<1	1	110
<1	16	<1	<.1	<1	4	<1	<1	4	12
2	40	<10	--	5	1	6	<1	25	20
<4	20	2,300	--	7	<4	<1	<4	7	110
<1	31	5	<.1	<1	<1	1	<1	17	27
5	31	1	--	2	1	<1	<1	22	19
<1	8	580	<.1	4	1	<1	<1	<1	21
<1	8	97	<.1	5	<1	<1	<1	11	14
Confined zone--*Continued*									
<1	25	1	<0.1	2	5	3	<1	4	19
2	11	150	<.1	3	<1	<1	<1	<1	11
<1	48	2	<.1	1	6	2	<1	8	5
<1	39	13	.1	<1	<1	1	<1	4	71
<1	21	6	.8	<1	2	2	<1	2	250
1	26	1	<.1	<1	1	1	<1	5	52
4	40	1,300	.3	10	<1	<1	<1	36	20
5	130	4	<.1	1	1	5	2	7	140
<1	87	2	<.1	2	<1	11	<1	5	13
3	110	4	<.1	1	1	6	<1	8	370
3	77	<1	<.1	<1	2	8	<1	8	27
<1	20	1,000	.1	12	21	<1	<1	68	40
<1	59	12	.1	<1	4	<1	<1	8	130
1	30	120	.2	11	7	<1	<1	5	<10
4	<10	110	.3	23	4	<1	<1	4	20
<1	50	<10	<.1	<1	4	4	<1	13	50
<1	60	60	.1	6	3	<1	<1	23	20
2	27	150	--	8	<1	1	1	10	21
4	13	88	--	29	2	<1	<1	3	<3
2	6	42	--	15	2	<1	<1	15	8
30	110	<10	--	10	<10	3	<10	43	20
7	<4	13	<.1	<1	4	<1	<1	92	16
10	64	150	--	8	26	1	<2	5	56