# GEOLOGY OF THE FRESH GROUND-WATER BASIN OF THE CENTRAL VALLEY, CALIFORNIA, WITH TEXTURE MAPS AND SECTIONS

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1401–C

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*By* R. W. PAGE

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## FOREWORD

### THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of 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 have often arbitrarily been limited in the past. The broad objective for each study is 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 use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

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## CONVERSION FACTORS

**For the readers who may prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are listed below.**

| Multiply | By | To obtain |
|---|---|---|
| acres | 0.4047 | (hectares) |
| feet | 0.3048 | (meters) |
| gal/min (gallons per minute) | 0.00006309 | (cubic meters per second) |
| inches | 25.4 | (millimeters) |
| miles | 1.609 | (kilometers) |
| $mi^2$ (square miles) | 2.590 | (square kilometers) |

# GEOLOGY OF THE FRESH GROUND-WATER BASIN OF THE CENTRAL VALLEY, CALIFORNIA, WITH TEXTURE MAPS AND SECTIONS

By R. W. PAGE

## ABSTRACT

The Central Valley of California, which is about 400 miles long and averages about 50 miles wide, comprises about 20,000 square miles. Geologically, the valley is a large asymmetric trough that is bounded by granitic, metamorphic, and marine sedimentary rocks of pre-Tertiary age. The trough has been filled with as much as 6 vertical miles of sediment in the San Joaquin Valley and as much as 10 vertical miles of sediment in the Sacramento Valley; these sediments range in age from Jurassic to Holocene.

Some volcanic rocks and deposits crop out in the valley, but of those only the Tuscan Formation in the northeastern part of the Sacramento Valley is of major importance to the fresh ground-water basin.

Post-Eocene continental rocks and deposits contain most of the fresh water in the Central Valley; they crop out virtually over the whole valley and in most places overlie or contain saline water at depth.

Continental rocks and deposits of Tertiary age include the Mehrten Formation. The Mehrten is of great importance to the fresh ground-water basin of the Central Valley and yields large quantities of water to wells.

Although continental rocks and deposits of Tertiary and Quaternary age compose a number of formations and informal deposits, in total they constitute the major aquifer of the Central Valley. In most places, similarity in sediment type between the continental deposits and some underlying rocks and deposits and even between separate units of continental rocks and deposits makes mapping of subsurface geologic contacts difficult if not practically impossible. In this respect, a unit that can be mapped on the surface is difficult to delineate in the subsurface, and, although such a unit can be called an aquifer, it merges with similar units in the subsurface to form a major, widespread aquifer.

Continental rocks and deposits of Tertiary and Quaternary age include (1) the Kern River Formation; (2) the Laguna Formation; (3) the Tulare Formation; (4) the Tehama Formation; and (5) a number of younger formations, as well as some informally named deposits. These deposits and formations also include lacustrine and marsh deposits, which are much thicker and more extensive in the San Joaquin Valley than in the Sacramento Valley. These continental rocks and deposits generally crop out as wide belts along the flanks of the Central Valley and range in thickness from 0 foot along the flanks to about 15,000 feet in the extreme southern part. In general, the rocks and deposits consist of a heterogeneous mixture of generally poorly sorted clay, silt, sand, and gravel; in some places they consist of more consolidated sediments, such as mudstone and sandstone. Yields to wells from these rocks and deposits, except the lacustrine and marsh deposits, range from about 20 gallons per minute to 4,500 gallons per minute.

Lacustrine and marsh deposits crop out in the San Joaquin Valley but not in the Sacramento Valley. Beneath Tulare Lake bed in the San Joaquin Valley, the lacustrine and marsh deposits, which constitute a thick plug of clay and silt from which lenses of clay and silt emanate at irregular intervals, are in places more than 3,600 feet thick. The lens mapped as the E Clay in the San Joaquin Valley is the most extensive lacustrine clay in the entire Central Valley and includes the Corcoran Clay Member of the Tulare Formation. More recent mapping has shown that the E Clay in the extreme southern part of the valley is shallower than previous reports had indicated; therefore, in this report the clay is referred to as the modified E Clay. Perhaps the expansion of lakes and the resulting deposition of extensive clays in the San Joaquin Valley occurred principally because of a large downwarping basin beneath an area known as Tulare Lake bed, and perhaps a similar expansion and deposition did not occur in the Sacramento Valley because a similar downwarping basin probably had not developed there.

Continental deposits of Quaternary age crop out chiefly along the major rivers and streams of the valley as well as other low-lying areas; the deposits include river deposits, flood-basin deposits, and sand dunes. River deposits, including channel and flood-plain deposits, are considered to be the most permeable deposits in the valley; in general, they are not tapped by wells. Flood-basin deposits consist largely of fine-grained beds that restrict the vertical movement of water. Sand dunes are not considered important aquifers because they generally lie above the water table.

The large, asymmetrical, northwestward-trending structural trough of the Central Valley is the principal structure controlling the occurrence and movement of ground water in the area. Because the flanks of the valley are higher than its axis, recharge from tributary rivers and streams has caused heads in the ground water along the flanks to be higher than those along the axis. Therefore, the overall ground-water movement in the Central Valley is from the flanks toward the axis and from there toward the delta area. Secondary structures in the valley, such as arches and faults, also influence the occurrence and movement of ground water.

As it is used in this report, "texture" means the proportion of coarse-grained to fine-grained sediment in sedimentary rocks and deposits. In the Central Valley, most of the deposits for which data are available generally contain no more than 40 to 60 percent of coarse-grained sediment, where coarse-grained sediment includes clayey and silty sand and gravel. Texture columns, maps, and sections, in depth intervals of 300 feet, show that the alluvial deposits of the Central Valley are a heterogeneous mixture whose character ranges over short distances and depths from chiefly fine-grained to chiefly coarse-grained and vice versa. Nevertheless, some areas are underlain chiefly by fine-grained sediment and others by coarse-grained sediment; sediments of like size in an area indicate that sources and depositional environment probably were similar for long periods of time.

## INTRODUCTION

This report is the product of the Central Valley aquifer-systems analysis project, which is part of the National Regional Aquifer-System Analysis Program. Several other studies are planned for this project (Bertoldi, 1979, p. 15); a report of the geochemistry of ground water in the valley has been published (Hull, 1984).

### PURPOSE AND SCOPE

The purpose of this report is to describe the late Cenozoic subsurface geology of the Central Valley (fig. 1). Such knowledge is necessary for proper management of the ground-water resources of the valley.

The report summarizes and describes those rocks and deposits that are pertinent to the fresh ground-water basin of the Central Valley and shows the relative proportions, both laterally and vertically, of coarse-grained to fine-grained sediments in those rocks and deposits. Thus, this report pertains chiefly to the post-Eocene continental rocks and deposits of the Central Valley with a particular reference to some of their textural features. The investigation did not include any surface mapping of geologic units, so that discussion of geologic units in this report relies chiefly on the work of others.

Older rocks and deposits are discussed as they pertain to the ground-water basin. In addition, some of the general hydrologic properties of both the older and younger rocks and deposits are discussed.

### LOCATION AND GENERAL FEATURES

The Central Valley comprises about 20,000 $mi^2$ and extends from near Red Bluff on the north to near Bakersfield on the south, a distance of about 400 miles (fig. 1). The average width of the valley is about 50 miles, and the valley is bounded on the north by low-lying hills; on the northeast by a volcanic plateau of the Cascade Range; on the west by the Coast Ranges, which in places rise to altitudes of about 4,000 feet; on the east by the Sierra Nevada, which in places rise to altitudes of more than 14,000 feet; and on the south by the Coast Ranges and the Tehachapi Mountains (figs. 1 and 2). Roughly the northern one-third of the valley is known as the Sacramento Valley and the southern two-thirds as the San Joaquin Valley.

Mean annual precipitation in the Sacramento Valley ranges from about 25 inches along the flanks to about 14 inches near Sutter Buttes (Rantz, 1969). Mean annual precipitation in the San Joaquin Valley ranges from about 15 inches along the eastern flank of the valley to about 5 inches just west of Bakersfield. Mean annual precipitation in the Sierra Nevada is significantly higher, and some areas in the northern part average 90 inches (Rantz, 1969). Most of the precipitation in the Central Valley falls from late autumn through early spring. Hot and dry summers and cool and moist winters are the norm in the valley.

The Sacramento River flows southward through the Sacramento Valley to join the San Joaquin River in the delta area east of Suisun Bay (fig. 2). Major tributaries of the Sacramento River, including the Feather River, flow westward from the Sierra Nevada; smaller tributaries flow eastward from the Coast Ranges. The San Joaquin River enters the San Joaquin Valley just northeast of Fresno, and it flows westward before turning northward to join the Sacramento River in the delta area. All the major tributaries of the San Joaquin River originate in the Sierra Nevada (fig. 2). Farther south, the Kern River enters the San Joaquin Valley from the Sierra Nevada.

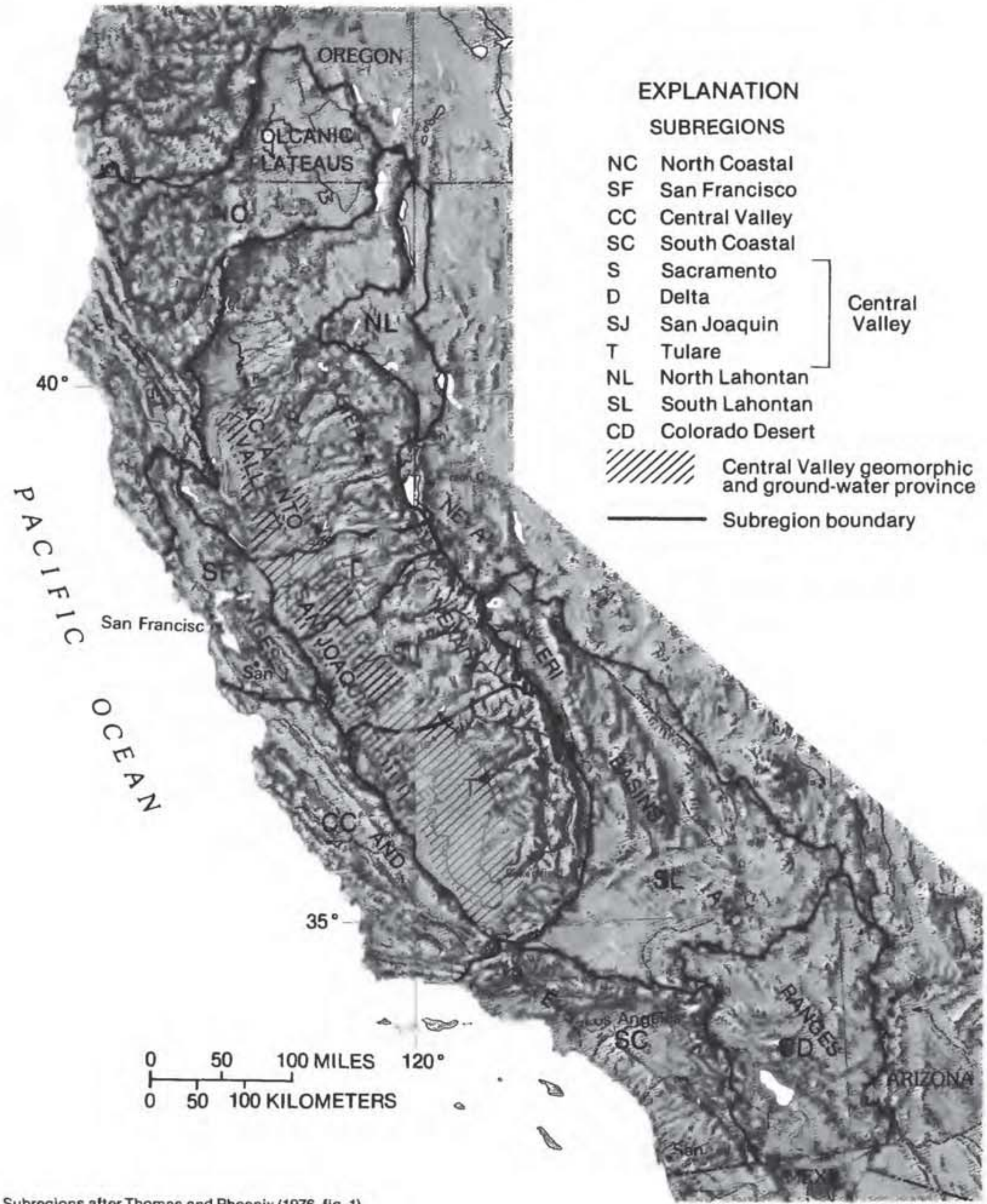
Just south of Fresno is an area of interior drainage dominated by the low-lying Tulare Lake bed; Buena Vista and Kern Lake beds are also part of this area. Because Tulare Lake bed is the largest bed in the area and lies at the lowest altitude, about 180 feet, the whole area is commonly referred to as the Tulare Lake drainage basin. In some wet years, water fills the Tulare Lake bed and spills northward toward the San Joaquin River.

Within the Central Valley the most extensive geomorphic units include (1) dissected uplands, (2) low alluvial plains and fans, (3) river flood plains and channels, and (4) overflow lands and lake bottoms (fig. 2) (Davis and others, 1959, pl. 1; Olmsted and Davis, 1961, pl. 1). The most prominent geomorphic unit is Sutter Buttes.

Dissected uplands lie along the flanks of the valley near the borders of the mountains. They commonly show forms characteristic of alluvial fans but range in form from dissected hills where relief is several hundred feet to gently rolling lands where relief is only a few feet.

Low alluvial plains and fans, which constitute the belt of coalescing alluvial fans of low relief between the dissected uplands and the valley trough, range in relief from nearly flat to slightly dissected where they merge with the dissected uplands.

River flood plains and channels lie along the trunk streams and their major tributaries (fig. 2). Some of the tributary rivers are incised below the general land surface and have well-defined flood plains; in the axial trough of the valley, the rivers are flanked by low-lying overflow lands, and natural levees confine the flood-plain and channel deposits to stream channels.




Subregions after Thomas and Phoenix (1976, fig. 1)
Base from U.S. Geological Survey Atlas (1970)

**Figure 1.** Subregions and landforms of California and adjacent areas.

Overflow lands and lake bottoms include Buena Vista, Kern, and Tulare Lake beds. They are characterized by very gentle slopes of the land surface, and during times of highest flooding they are wholly or partly inundated.

The volcanic Sutter Buttes, which seem to burst from the plain of the Sacramento Valley, are a small mountain range of sharp relief that is about 10 miles in diameter and about 2,000 feet in altitude.

## PREVIOUS REPORTS

Mendenhall and others (1916) wrote the first comprehensive report on ground water in the San Joaquin Valley, which included a brief discussion of the geology of the valley and the surrounding mountains and a discussion of the origin of land forms.

Bryan (1923) wrote the first comprehensive report on geology and ground water in the Sacramento Valley. He discussed the geology of the valley and its relation to the occurrence of ground water and yield to wells. He also discussed land forms.

Forbes (1931) discussed the geology and ground-water storage capacity of the San Joaquin Valley but did not include a geologic map.

Hoots and others (1954) wrote a geological summary of the San Joaquin Valley. The report discusses the structure and general stratigraphy of the valley. The report also includes eight paleogeographic maps that show the distribution and thickness of sediments ranging in age from Paleocene to Pleistocene.

Davis and others (1959) wrote a comprehensive report on the geology, geomorphology, and ground water of the San Joaquin Valley; they did not include a geologic map but did discuss the geologic history of the San Joaquin Valley in some detail. They also discussed the occurrence of a diatomaceous clay that underlies a large part of the San Joaquin Valley.

Repenning (1960) discussed the general stratigraphy of the Central Valley, and in his report included a map showing the thickness of sedimentary rocks in the valley and seven maps showing the distribution and thickness of sediments ranging in age from Paleocene to Pleistocene.

Olmsted and Davis (1961) wrote a comprehensive report on the geology, geomorphology, ground water, and geologic history of the Sacramento Valley. The geologic map included in their report is considered to be the best reference for the Sacramento Valley on geology pertaining to ground water.

Hackel (1966) described the general stratigraphy and structure of the Central Valley and included Repenning's maps in his report.

Croft (1972) mapped the subsurface geology of the upper Tertiary and Quaternary water-bearing deposits of the southern part of the San Joaquin Valley. He also mapped three extensive clays that function as confining beds.

Redwine (1972) discussed the subsurface geology of the Sacramento Valley and mapped geologic units on six cross sections. His discussion of some of the stratigraphic units occurring in the subsurface of the Sacramento Valley is extensive.

Page (1974) mapped the base and thickness of the post-Eocene continental deposits in the Sacramento Valley. Included in his report is a structure-contour map of the base of those deposits.

The California Department of Water Resources (1978) wrote another comprehensive report on the geology, geomorphology, and ground water of the Sacramento Valley. That report includes a discussion of soils and of geologic structures that affect the movement of ground water.

Harwood and Helley (1982) mapped the major late Cenozoic structural features and depth to the basement of the Sacramento Valley.

Numerous other reports also have been written concerning the geology of local areas in the Central Valley, including a number of recently published maps and reports. Many of those reports are listed under "Selected References".

### WELL-NUMBERING SYSTEM

Wells are identified according to their location in the rectangular system for the subdivision of public lands. For example, in the number 12N/1E-34Q1, the part of the number preceding the slash indicates the township (T. 12 N.); the number after the slash, the range (R. 1 E.); the digits after the hyphen, the section (sec. 34); and the letter after the section number, the 40-acre subdivision of the section, as indicated on the diagram below.

| | | | |
|---|---|---|---|
| D | C | B | A |
| E | F | G | H |
| M | L | K | J |
| N | P | Q | R |

Within each 40-acre tract the wells are numbered serially as indicated by the final digit of the well number. For example, well 12N/1E-34Q1 was the first well to be listed in the SW¼SE¼ sec. 34. The final digit has been omitted for wells not field located by the Geological Survey.

Most of the study area lies north or south and east or west of the Mount Diablo base line and meridian (M). A small area at the southern part of the valley lies north and west of the San Bernardino base line and meridian (S), but no wells in the study area are referred to this base line.

## GEOLOGY

The Central Valley is a large, northwestward-trending, asymmetric structural trough that has been filled with as much as 6 vertical miles of sediment in the San Joaquin Valley and as much as 10 miles of sediment in the Sacramento Valley; these sediments range in age from Jurassic to Holocene and include both marine and continental rocks and deposits (fig. 3) (Repenning, 1960, p. 7, fig. 2). The sediments beneath part of the eastern side of the valley are underlain by

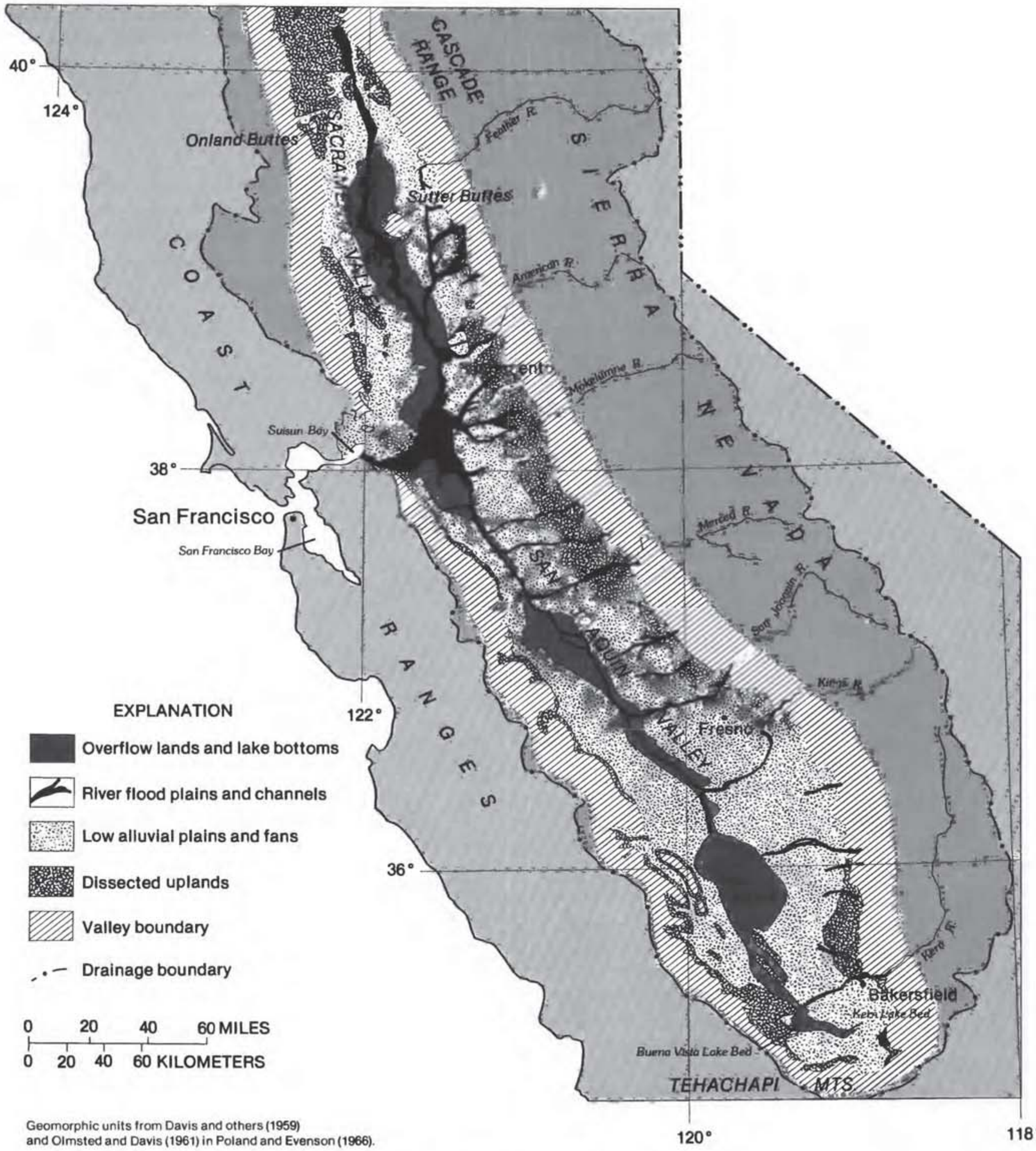



**Figure 2.** Geomorphic map of Central Valley.

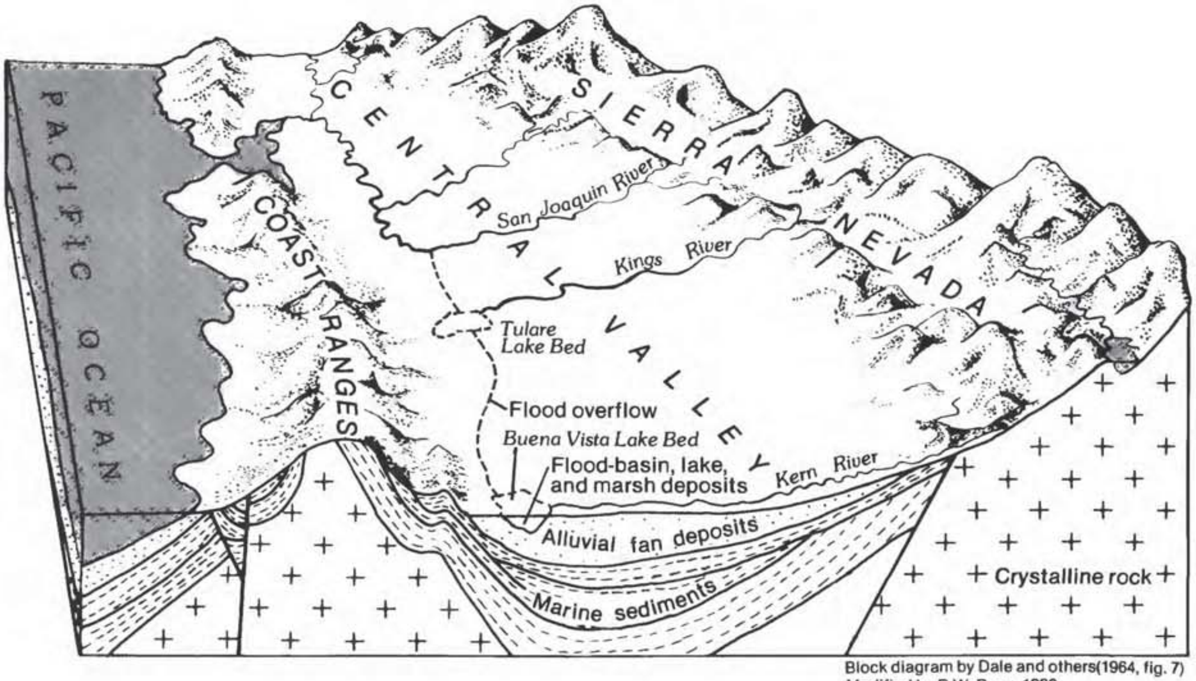



**Figure 3.** Generalized geologic section and view of part of the Central Valley.

granitic and metamorphic rocks of pre-Tertiary age. Beneath the western side and part of the eastern side, the sediments are thought to be underlain by a mafic and ultramafic complex of pre-Tertiary age (Cady, 1975, p. 17-19; and Suppe, 1978, p. 7). Granitic and metamorphic rocks crop out along most of the eastern and southeastern flank of the Central Valley (pls. 1 and 2). Marine rocks of pre-Tertiary age crop out along most of the western flank of the valley, and marine rocks and deposits of Tertiary age crop out around Sutter Buttes and along the western, southwestern, southern, and southeastern flanks of the valley (pls. 1 and 2). Volcanic rocks and deposits of Pliocene age crop out along the northeastern flank (pl. 1).

The post-Eocene continental rocks and deposits contain most of the fresh ground water in the Central Valley and crop out over virtually the whole valley (pls. 1 and 2, tables 1 and 2). In most places, the continental rocks and deposits overlie or contain saline water at depth (Berkstresser, 1973; Page, 1973); saline water, as defined here, has a minimum dissolved-solids concentration of 2,000 mg/L.

## GRANITIC AND METAMORPHIC ROCKS (PRE-TERTIARY)

The granitic and metamorphic rocks crop out mostly along the eastern flank of the valley (pls. 1 and 2). In places, some mafic intrusive rocks are included with the granitic rocks. Metamorphic rocks contain metasedimentary, metavolcanic, and undifferentiated-metamorphic rocks. These rocks form an almost impermeable boundary for the ground-water basin, but fractures and joints permit small yields of water to wells. The granitic and metamorphic rocks slope gently southwestward from the outcrops in the Sierra Nevada to depths of more than 15,000 feet in the Central Valley (Smith, 1964).

## MARINE ROCKS (PRE-TERTIARY)

Marine rocks of pre-Tertiary age crop out mostly along the western flank of the valley, although some marine rocks crop out along the eastern flank, and a small outcrop occurs in Sutter Buttes where the marine rocks were intruded by a volcanic plug (pls. 1-3). The marine rocks are composed mostly of conglomerate, sandstone, siltstone, mudstone, and shale. Where saturated, these rocks generally contain saline water and would yield only small quantities of water to wells.

Beneath the north-central part of the valley, the marine rocks, together with some lower Tertiary rocks, lie at depths of more than 1,500 feet, and from north to south they lie at generally ever greater depths and thus define the southerly tilt of the Central Valley (pls. 1-3) (Ross and McCulloch, 1979; Suppe, 1978). Marine rocks of Cretaceous age are as much as 25,000 feet thick in the Sacramento Valley, and in the San Joaquin Valley they are as much as 20,000 feet thick (Repenning, 1960, p. 10, fig. 4).

### MARINE ROCKS AND DEPOSITS (TERTIARY)

Near the close of the Late Cretaceous, tectonic movements elevated many Coast Range areas, including those adjacent to the Sacramento Valley and the northern San Joaquin Valley; these movements created the ancestral Tertiary San Juaquin and Sacramento basins as restricted troughs of deposition lying between the emerging Coast Ranges and the eastern Sierra Nevada (Hackel, 1966, p. 223). Both marine and continental rocks and deposits, ranging in age from Paleocene to Pliocene, were deposited into these continually evolving basins. As indicated by Repenning (1960, figs. 5-11), marine rocks and deposits were dominant in the Central Valley from the Paleocene to the beginning of the Miocene; during the early Miocene, marine rocks were restricted to the southern part of the San Joaquin Valley; during the middle Miocene, marine rocks and deposits were still restricted to the southern part of the San Joaquin Valley except near Suisun Bay; during the late Miocene, marine rocks and deposits were laid down around Suisun Bay along the western flank of the San Joaquin Valley and throughout most of the southern part of the valley; and, by Pliocene time, marine rocks and deposits were again restricted to the southern part of the San Joaquin Valley. During the Pleistocene and Holocene, the seas had retreated, and only continental rocks and deposits were being laid down.

Marine rocks and deposits of Tertiary age, therefore, underlie large parts of the Central Valley; they crop out around Sutter Buttes and along the southwestern flank of the Sacramento Valley as well as along the western, southwestern, southern, and southeastern flanks of the San Joaquin Valley (pls. 1 and 2).

Because of their varied history of deposition, the marine rocks and deposits differ greatly in sediment type, sorting, and thickness, and they have been given many names by petroleum geologists (Sacramento Petroleum Association, 1962, figs. 6, 7, 10, 20, and 27, table 2; Park and Weddle, 1959, pl. 3). The marine rocks and deposits were, in part, the source rocks for some of the deposits in the fresh ground-water basin; some of the saline water they contain has migrated into adjacent and overlying continental deposits (pl. 3).

In a few places in the San Joaquin Valley, however, the marine rocks and deposits have been flushed of saline water, and they now contain fresh water, which they yield to wells. In the Sacramento Valley, marine rocks and deposits have not been reported as yielding fresh water to wells, although Olmsted and Davis (1961, p. 134) said that locally marine rocks have been flushed of connate water.

Hilton and others (1961, p. 28, table 3) reported that the Vedder Sand, the overlying Pyramid Hill Sand Member of the Jewett Sand, and the Olcese Sand, which overlies the Pyramid Hill Sand Member, were potential sources of fresh ground water in the Richgrove area along the southeastern flank of the San Joaquin Valley (pl. 2, table 2). In this report area, the Vedder Sand of Oligocene age (Bartow, J. A., and McDougall, K. A., U.S. Geological Survey, written commun., 1982) and the overlying Pyramid Hill Sand Member of the Jewett Sand of Miocene age consist, in aggregate, of (1) a lower bed of alternating fine-grained marine sand and nonmarine gritty sand and gravel and (2) an upper bed of olive-brown, very clayey sand with black pebbles at the base (Hilton and others, 1961, table 3). The Vedder Sand in this area is described as being partly nonmarine (Albright and others, 1957, table 3). These sands range in thickness from 0 to about 300 feet. The Vedder Sand and the Pyramid Hill Sand Member of the Jewett Sand are separated from the Olcese Sand by the Freeman Silt of Miocene age. This silt consists of a hard, compact siltstone and silty sand, and in the Richgrove area it ranges in thickness from 0 to about 1,100 feet (Hilton and others, 1961, table 3). The Olcese Sand of Miocene age consists of unconsolidated medium- to coarse-grained sand containing few pebble and siltstone beds; it crops out near Poso Creek and ranges in thickness from 0 to about 600 feet. In the Richgrove area, the Round Mountain Silt of Miocene age overlies the Olcese Sand. The Round Mountain Silt consists mostly of a firm gray and brown siltstone that contains beds of diatomite and silty sand (Hilton and others, 1961, table 3; Albright and others, 1957, table 1). In the Richgrove area, this silt ranges in thickness from 0 to about 200 feet.

Overlying the Round Mountain Silt is the Santa Margarita Formation of Diepenbrock (1933) of Miocene age as used by Hilton and others (1961), which in the Richgrove area is a major aquifer that reportedly yields as much as 1,950 gal/min to wells (Hilton and others, 1961, p. 51). Croft (1972, p. 13) reported that the formation also yields water to wells in the foothills southeast of Bakersfield, where it has been mapped as the Santa Margarita Formation of Hoots (1930) (Bartow and Doukas, 1978). In the Richgrove area, the formation, which ranges in thickness from 0 to about 600 feet (Hilton and others, 1961, table 3), consists of an upper bed of fine, silty, fairly well-sorted to well sorted gray sand and a lower bed of brownish-gray and brown fossiliferous micaceous sandy siltstone.

All marine beds in this area thicken and dip gently in a westerly direction (Lofgren and Klausing, 1969, figs. 4 and 5).

## CONTINENTAL AND MARINE ROCKS AND DEPOSITS (TERTIARY)

During the time of deposition of marine sediments of Tertiary age in the Central Valley, continental rocks and deposits also were laid down. As the seas advanced and retreated, some rocks and deposits became a mix of both continental and marine sediments. In general, these types of rocks and deposits are not important to the fresh ground-water basin of the Central Valley, but locally in the San Joaquin Valley some of them yield large quantities of fresh water to wells.

As mentioned in the previous section, the Vedder Sand contains some continental and marine sediments that are potential sources of water along the southeastern flank of the San Joaquin Valley. On the northwestern side of the San Joaquin Valley in the Tracy-Dos Palos area (pl. 2), a few wells reportedly yield fresh water from the upper part of the San Pablo Formation or Group of Miocene age (Hotchkiss and Balding, 1971, p. 15). The San Pablo Formation, which unconformably overlies the marine Kreyenhagen Formation of Eocene age, consists of volcanic gravel, sand, and clay. Much of the San Pablo in the northwestern part of the valley was deposited in a fresh water or subaerial environment; locally, marine fossils are found in the formation (Miller and others, 1971, p. 13). Farther south in the Los Banos-Kettleman City area, the Etchegoin Formation of Miocene and Pliocene age and the overlying San Joaquin Formation of Pliocene age are also partly continental and partly marine. Both of these formations crop out along the hills in the area and dip gently northeastward beneath the valley (pl. 2, table 2). Miller and others (1971) made a detailed study of the geology in the area, and the following discussion is based largely on their work.

The sediment type of the Etchegoin Formation varies considerably, ranging from clay and silt to sand, gravel, and sandstone. It ranges in thickness from a few tens of feet to more than 2,000 feet. Further, marine fossils in the formation are more abundant in the southern part of the Los Banos-Kettleman City area than in the northern part. Several wells near the foothills and a few deep wells in the valley derive fresh water from the Etchegoin; however, its depth of more than 3,000 feet beneath most of the valley prevents it from being considered an important source of water.

The San Joaquin Formation also has different sediment types, but much of it contains silt and silty sandstone; in the Kettleman Hills, a basal conglomerate is part of the formation. In the deep subsurface of the valley northeast of the Kettleman Hills, the deposits are considered a shoreline phase of the San Joaquin Formation. The formation there is coarser and more permeable than in the Kettleman Hills and yields fresh water to many wells. Southeast of the area in T. 23 S., Rs. 21 and 22 E., at depths of about 2,700 feet, the San Joaquin Formation is considered marine rather than a mix of continental and marine sediments (Hill, 1964a, b). The San Joaquin is the youngest formation in the Central Valley that contains deposits of marine origin.

## VOLCANIC ROCKS AND DEPOSITS

In the Sacramento Valley, volcanic rocks and deposits of Miocene and Pliocene age (table 1) crop out in the northeastern and western parts (pl. 1), and volcanic rocks and deposits of Pliocene and Pleistocene age (table 1) crop out around Sutter Buttes. In the San Joaquin Valley, volcanic rocks of Miocene and Pliocene age (table 2) crop out in the northeastern and southern parts (pl. 2).

The volcanic rocks and deposits around Sutter Buttes are similar to both the Mehrten Formation of Miocene to late Pliocene age (see "Mehrten Formation") and the Tuscan Formation of Pliocene age; they are locally important sources of water (California Department of Water Resources, 1978, p. 21). These rocks and deposits are not discussed further in the present report. Of all the other volcanic rocks and deposits, only the Tuscan Formation in the northeastern part of the Sacramento Valley is of major importance to the fresh ground-water basin of the Central Valley.

### TUSCAN FORMATION

The Tuscan Formation crops out virtually continuously from northeast of Red Bluff to just north of Oroville (pl. 1, table 1). Harwood and others (1981) mapped the Tuscan in the northeastern part of the Sacramento Valley. Furthermore, Olmsted and Davis (1961, p. 67-72) and the California Department of Water Resources (1978, p. 22-25) discussed the Tuscan in detail with respect to ground water, and the following discussion is based largely on their work.

The major part of the Tuscan Formation lies east of the Sacramento Valley beneath a volcanic plateau of the Cascade Range. West of the Chico monocline, the formation continues to dip southwestward and underlies the Sacramento Valley, where it extends in the subsurface to a distance of about 5 miles west of the Sacramento River. Throughout much of the subsurface in this part of the valley, the Tuscan is separated from marine rocks by a dense, impervious basalt flow (Ellsworth, 1948). Unlike most other rocks and deposits on the eastern side of the valley, the Tuscan Formation thins from east to west; in the Cascade Range its maximum thickness is about 1,600 feet (Lydon, 1969), and beneath the valley it thins to about 300 feet; west of the Chico Monocline it is about 1,000 feet thick (California Department of Water Resources, 1978, table 1). There, the Tuscan consists largely of black volcanic sand, gravel, and tuffaceous clay, which probably were derived from beds of tuff breccia reworked by streams. Some beds of tuff breccia underlie the valley at distances of 5 to 10 miles from the outcrop of the Tuscan.

The Tuscan Formation yields large quantities of fresh water to wells; reported yields range from 900 gal/min to more than 3,000 gal/min (California Department of Water Resources, 1978, p. 25; Olmsted and Davis, 1961, p. 72). Because the Tuscan contains beds of clay and tuff breccia, most ground water in the Tuscan is confined (California Department of Water Resources, 1978, p. 25).

## CONTINENTAL ROCKS AND DEPOSITS

From the Paleocene through the Oligocene, continental rocks and deposits were restricted chiefly to the northern, eastern, and southeastern parts of the Central Valley; during the early and middle Miocene, continental rocks and deposits occupied most of the valley north of Fresno as well as narrow belts along the southeastern and southern parts of the San Joaquin Valley (Repenning, 1960, figs. 5-8). During the late Miocene, continental rocks and deposits occupied the central and eastern parts of the valley north of Merced and a narrow belt along the eastern side of the valley from Merced to just south of Fresno; they also occupied an area on the western side of the valley opposite Fresno and part of the southeastern San Joaquin Valley (Repenning, 1960, fig. 10). By Pliocene time, continental rocks and deposits occupied all of the Sacramento Valley and most of the northern part of the San Joaquin Valley, as well as wide belts along its eastern and southern parts (Repenning, 1960, fig. 10). After the Pliocene, only continental rocks and sediments were deposited in the valley. Further, after a major uplift of the surrounding area during the middle Pleistocene, the valley evolved to its present-day form, which has contributed to erosion of many of the older rocks and deposits and a more restricted area of deposition for the younger deposits.

The older continental rocks and deposits crop out along the flanks of the Central Valley, and the younger deposits crop out along streams and along the flanks and throughout the rest of the valley (pls. 1 and 2).

Because of their depositional history, these rocks and deposits also differ greatly in sediment type, sorting, and thickness. The types of deposit include alluvial fan, deltaic, flood basin, lacustrine, marsh, and river, as well as sand dunes. In places, volcanic rocks and deposits of Tertiary age are associated with the continental rocks and deposits. The continental rocks and deposits range in thickness from 0 foot along the flanks of the valley to more than 15,000 feet just north of Wheeler Ridge in the southern part of the San Joaquin Valley. There, rapid downwarping contributed to this very thick section of post-middle Pliocene continental rocks and deposits (de Laveaga, 1952, p. 102). In this part of the valley, however, the base of fresh water lies at a maximum depth of about 4,700 feet (Page, 1973); this is therefore the thickest section that contains fresh water in the Central Valley.

### CONTINENTAL ROCKS AND DEPOSITS (TERTIARY)

This part of the report includes a discussion of (1) four units of continental rocks and deposits of Tertiary age in the Sacramento Valley and (2) four units in the San Joaquin Valley. The units are grouped by age and some lithologic similarity; some units include more than one formation or informal unit. Symbols of map units (pls. 1 and 2) are included for clarity.

One of the units, continental rocks and deposits of uncertain age (Tcu), occurs only in the Sacramento Valley, and one, continental rocks and deposits of Eocene to Miocene(?) age (Tcme), occurs only in the San Joaquin Valley (pls. 1 and 2). Three of the units of continental rocks and deposits in the Sacramento Valley are also present in the San Joaquin Valley; they are (1) of Eocene age (Tce), (2) of Oligocene and Miocene age (Tcmo), and (3) of Miocene and Pliocene age (Tcpm) (pls. 1 and 2; tables 1 and 2).

Older Tertiary continental rocks and deposits yield some water to wells, but they are not important to the fresh ground-water basin of the Central Valley. On the other hand, some of the younger Tertiary rocks and deposits yield large quantities of ground water to wells.

Some of the older continental rocks and deposits of Tertiary age are not of great importance to the fresh ground-water basin of the Central Valley because they contain saline water, or the nature of their sediments prevents large yields to wells, or both. Included in this group are the Ione Formation of Eocene age (Tce) and the Valley Springs Formation of Oligocene and Miocene age (Tcmo). The Oligocene and Miocene age of the Valley Springs is based on the work of Marchand and Allwardt (1981, p. 10). Brief discussions of these formations are included herein.

Other Tertiary continental rocks and deposits are generally of such limited extent that they are not of great importance to the ground-water basin and are therefore not discussed further in this report; these include, for example, the continental rocks and deposits of uncertain age (Tcu) in the eastern part of the Sacramento Valley and the Bena Gravels of Miocene age (Tcmo) in the southern part of the San Joaquin Valley. Also omitted from discussion are rocks and deposits that generally are not penetrated by water wells, lie at extreme depths, and at depth contain saline water—such as the Walker Formation of late Eocene through early Miocene age (Tcme) and the Zilch formation of informal subsurface usage, which is considered to be the widespread continental equivalent of the Temblor Formation of Oligocene and Miocene age (Tm) (Hunter, 1952, p. 21; Repenning, 1960, fig. 8). The Chanac Formation of Miocene age (Tcpm) (Bartow, J. A., and McDougall, K. A., written commun., 1982) probably belongs in this group, too, because it is reportedly penetrated only by oil wells in the subsurface of the southern San Joaquin Valley (Wood and Dale, 1964, p. 37).

On the other hand, the Mehrten Formation of Miocene to late Pliocene age (Tcpm) is a unit of continental rocks and deposits of Tertiary age that is of great importance to the fresh ground-water basin of the Central Valley.

### Ione Formation

The Ione Formation crops out discontinuously along the eastern flank of the valley from just south of Chico to just north of Fresno (pls. 1 and 2, tables 1 and 2). In most areas of outcrop, it lies unconformably on pre-Tertiary rocks and dips gently southwestward beneath the Central Valley. The Ione is composed of clay, sand, sandstone, and conglomerate. Where exposed, it ranges in thickness from 0 to about 400 feet in the Sacramento Valley and from 0 to 200 feet in the San Joaquin Valley (California Department of Water Resources, 1978, p. 20; Davis and Hall, 1959, p. 8). Allen (1929) considered it largely deltaic in origin; Piper and others (1939, p. 84) considered it largely fluviatile with some lacustrine and lagoonal deposits. Large parts of the Ione, however, were considered marine by Redwine (1972, p. 100-104). Because of the clay and consolidated rocks, the Ione Formation yields only small quantities of water to wells, and in places it reportedly yields saline water (California Department of Water Resources, 1978, p. 21; Davis and Hall, 1959, p. 8).

### Valley Springs Formation

The Valley Springs Formation crops out discontinuously along the eastern flank of the valley from just south of the Bear River to just north of the Chowchilla River (pls. 1 and 2, tables 1 and 2). In most areas, the formation lies unconformably over the Ione Formation or the pre-Tertiary rocks and dips gently southwestward beneath the valley. The Valley Springs is a mostly fluvial sequence of chiefly sandy clay, quartz sand, rhyolitic ash, and siliceous gravel (Davis and Hall, 1959, p. 8-9); east of Modesto the Valley Springs was believed by Page and Balding (1973, p. 17) and the U.S. Bureau of Reclamation (written commun., 1958 and 1959) to be composed chiefly of rhyolitic tuff and some siltstone and claystone. Bartow (1982) considered the Valley Springs to have been deposited on a poorly drained coastal plain that was occasionally blanketed by ash deposits. Where exposed or where recorded on well logs, the Valley Springs ranges in thickness from 0 to about 200 feet in the Sacramento Valley and from 0 to about 450 feet in the San Joaquin Valley (California Department of Water Resources, 1978, p. 78; Piper and others, 1939, p. 77).

Because of its fine ash and clay matrix, the Valley Springs is generally a small-yield aquifer, although one well in the Modesto area yielded 710 gal/min (Page and Balding, 1973, p. 17).

### Mehrten Formation

The Mehrten Formation crops out discontinuously along the eastern flank of the valley from just south of the Bear River to just south of the Chowchilla River (pls. 1 and 2; tables 1 and 2). It overlies the Valley Springs Formation and in places lies uncomformably on pre-Tertiary rocks (pls. 1 and 2). The Mehrten dips gently southwestward beneath the valley, and there it is considered to interfinger with marine and nonmarine facies of the Neroly Formation of Miocene age (Davis and Hall, 1959, p. 10).

Piper and others (1939, p. 61-71) were the first to describe the Mehrten Formation; they designated its type section as being in the NE¼ SW¼ sec. 5, T. 4 N., R. 9 E. There, the Mehrten is composed of about 190 feet of clay and silt and andesitic sandstone and breccia (Piper and others, 1939, p. 62).

In the Sacramento Valley, the Mehrten can be divided into two units: (1) an overlying unit composed mostly of unconsolidated black sands interbedded with blue-to-brown clay and (2) an underlying unit of hard, very dense tuff breccia (California Department of Water Resources, 1978, p. 21). Where exposed in the Sacramento Valley, the Mehrten is as much as 200 feet thick, and in the subsurface it ranges in thickness from 400 to 500 feet. In the northeastern part of the San Joaquin Valley, Davis and Hall (1959, p. 10) divided the Mehrten into three units: a lower unit of scoriaceous and pumiceous sand and conglomerate that has a maximum thickness of about 40 feet where exposed; a middle unit of alternating andesitic gravel, sand, and silt that has an estimated thickness of about 400 feet where exposed; and an upper unit of soft clay, silt, sand, and minor amounts of gravel that has an aggregate thickness of about 300 feet where exposed. Further, they indicated that the Mehrten attains a maximum thickness of about 1,200 feet in the western part of the Modesto area where it lies at a depth of about 1,100 feet (Davis and Hall, 1959, pl. 3). There, however, the Mehrten contains saline water (Page and Balding, 1973, fig. 6). Marchand and Allwardt (1981, p. 10) stated that the Mehrten in the Modesto-Merced area consists of claystone, siltstone, sandstone, and conglomerate; they also observed a general decrease in mean grain size in the Mehrten from the Stanislaus River on the north to near the Fresno River on the south. The Mehrten Formation is considered to have been laid down by streams carrying andesitic debris from the Sierra Nevada (Marchand and Allwardt, 1981, p. 10).

Generally, the Mehrten Formation yields large quantities of water to wells, although hydraulic conductivity in the Mehrten varies from place to place (Page and Balding, 1973, p. 22). Ground water in the Mehrten is probably confined in places by consolidated rocks.

## CONTINENTAL ROCKS AND DEPOSITS (TERTIARY AND QUATERNARY)

Although continental rocks and deposits of Tertiary and Quaternary age (tables 1 and 2) constitute a number of formations and informal units, in total they compose the major aquifer in the Central Valley, and in general consolidated sediments are fewer than in the Tertiary continental rocks and deposits. For example, Croft (1972, p. 13) said that in the San Joaquin Valley a gradational change probably occurs between the consolidated rocks and the overlying, unconsolidated deposits.

In most places in the Central Valley, the similarity in sediment type of the continental rocks and deposits of Tertiary and Quaternary age and some underlying rocks and deposits, and even between separate units of continental rocks and deposits, makes mapping of subsurface contacts with any degree of certainty difficult if not practically impossible. In this respect, a unit that can be mapped on the subsurface is difficult to delineate in the subsurface, and although in the Central Valley such a unit can be considered a separate aquifer, in the subsurface it merges with similar units to form a major widespread aquifer. In places, this aquifer is separated by confining beds (see "Lacustrine and Marsh Deposits"), and there ground water occurs under both unconfined and confined conditions.

Dale and others (1966, p. 21) in their report on the Kern River area indicated that, although units of continental rocks and deposits could be differentiated and mapped on the surface by using physiographic and weathering criteria, the subsurface equivalents of these units could not be mapped because there was no apparent difference in lithology. Furthermore, E. J. Helley of the U.S. Geological Survey (oral commun., 1982) said that new geologic maps of the valley differ significantly from the old maps because of recent dating of tuffs and new mapping of the continental rocks and deposits in the Central Valley; subsurface equivalents of these newly mapped units, however, are still difficult to determine. Some of these new maps are available (see "Previous Reports").

For this report, continental rocks and deposits of Tertiary and Quaternary age and some of the deposits of Quaternary age have been grouped as the continental rocks and deposits of Tertiary and Quaternary age (QTc) (pls. 1 and 2; tables 1 and 2). They are discussed as a group because (1) some of the new maps, correlations, and interpretations are not yet available; (2) subsurface contacts between units of the group are difficult to determine; and (3) they compose in total the major, widespread aquifer of the Central Valley. Lacustrine and marsh deposits are discussed separately in this report.

The continental rocks and deposits of Tertiary and Quaternary age crop out virtually continuously along the flanks of the Central Valley and dip gently toward the valley trough (pls. 1 and 2). They include the Kern River Formation of Miocene to Pleistocene(?) age, which crops out in the Bakersfield area; the Laguna Formation of Pliocene age, as mapped by Marchand and Allwardt (1981, p. 19, pl. 1); the Tulare Formation of Pliocene and Pleistocene age, which crops out along the western part of the San Joaquin Valley; the Tehama Formation[1] of Pliocene to Pleistocene age (Page and Bertoldi, 1983, p. 17), which crops out along the western and northwestern part of the Sacramento Valley; and the Red Bluff Formation of Pleistocene age, which crops out in the Sacramento Valley. They also include the Turlock Lake Formation, the Riverbank Formation, and the Modesto Formation, all of Pleistocene age, which crop out in both the Sacramento and San Joaquin Valleys. In addition, they include informal units, such as continental deposits of Tertiary and Quaternary age, older alluvium of Pleistocene and Holocene(?) age, and probably younger alluvium of Holocene age. These informal units undoubtedly contain some of the formal units that already have been mentioned.

[1] The Pliocene and Pleistocene age of the Tehama Formation as used in this report does not conform to the Pliocene age of the Tehama as used by the U.S. Geological Survey.

In the northeastern part of the Sacramento Valley, the continental rocks and deposits of Tertiary and Quaternary age are chiefly of Pleistocene age (Harwood and others, 1981) and were derived largely from the Tuscan Formation. The continental rocks and deposits in this area dip gently southwestward. They consist in part of a heterogeneous mix of gravel, sand, silt, and clay, and in large part they have been designated as fanglomerate because they are cemented in places and contain beds of sandstone and conglomerate (California Department of Water Resources, 1978, p. 26, pl. 2; Olmsted and Davis, 1961, p. 89). Thickening from east to west, the fanglomerate ranges in thickness from less than 150 feet north of Pine Creek to more than 600 feet west of Chico (Olmsted and Davis, 1961, p. 88-89). For wells pumped exclusively from the fanglomerate, yields ranged from 400 to 2,800 gal/min, although overall the fanglomerate is not very permeable (California Department of Water Resources, 1978, p. 26; Olmsted and Davis, 1961, p. 90).

Along the eastern flank of the Central Valley, from near Oroville to near Merced, the continental rocks and deposits dip gently southwestward (pls. 1 and 2) and in places successively overlie the pre-Tertiary rocks, the Ione, the Valley Springs, and the Mehrten Formations. Derived in large part from the pre-Tertiary rocks of the Sierra Nevada, they include the Laguna Formation and consist of a heterogeneous mix of generally poorly sorted clay, silt, sand, and gravel. Olmsted and Davis (1961, p. 84) said that in the Sacramento Valley the Laguna Formation contains abundant beds of somewhat clayey silt to silty fine sand, some well-sorted sand in relatively thin zones, and scarce, poorly sorted gravel beds. Marchand and Allwardt (1981, p. 21-28), however, noted that in the northeastern part of the San Joaquin Valley the Laguna contains a number of coarse-grained beds.

The California Department of Water Resources (1978, fig. 6) showed that near the Sacramento River in the southeastern part of the Sacramento Valley the continental rocks and deposits overlie the Mehrten Formation and attain a maximum thickness of more than 2,500 feet. In the Modesto-Merced area of the San Joaquin Valley, the continental rocks and deposits range in thickness from less than 50 feet to more than 1,000 feet, where they are considered as equivalent to the older alluvium and the continental deposits of Page and Balding (1973, fig. 6). Moreover, in the western parts of these areas, the continental rocks and deposits in part contain saline water (pl. 3) (Page and Balding, 1973, fig. 6).

In the Sacramento Valley, yields to wells in this area ranged from about 100 to 3,700 gal/min and, in the San Joaquin Valley, from about 20 to about 4,500 gal/min (Page and Balding, 1973, p. 28). In the Modesto-Merced area, both the mean and median yield to 96 large wells in the unit mapped as older alluvium was 1,900 gal/min (Page and Balding, 1973, fig. 5, p. 28).

From near Merced to near Richgrove, the continental rocks and deposits along the eastern flank of the valley lie unconformably over the pre-Tertiary rocks of the Sierra Nevada; south of Richgrove to the extreme southeastern part of the valley, they lie unconformably over pre-Tertiary rocks and also over marine rocks and deposits of Tertiary age (pl. 2). In the subsurface the continental rocks and deposits dip gently southwestward and overlie pre-Tertiary rocks, marine rocks and deposits of Tertiary age, undifferentiated marine and continental rocks and deposits of Tertiary age, and such continental rocks and deposits of Tertiary age as the Mehrten Formation (Croft, 1972, pls. 1 and 3; Croft and Gordon, 1968, pls. 4 and 7; Lofgren and Klausing, 1969, figs. 4 and 5; Mitten and others, 1970, pl. 1; Page and Balding, 1973, fig. 6).

In this area, the continental rocks and deposits of Tertiary and Quaternary age consist of lenses of clay, silt, sand, and gravel that were derived chiefly from the Sierra Nevada and that are largely arkosic, generally poorly sorted, and in places cemented; they also consist of mudstone, sandstone, and conglomerate (Bartow and Doukas, 1978). Croft and Gordon (1968, pl. 4) showed that in the Hanford-Visalia area (pl. 2) the continental rocks and deposits grade from oxidized deposits of brown and reddish-brown beds to reduced deposits of bluish-green beds, which indicates a change from subaerial to subaqueous deposition. In the Fresno area and in part of the Hanford-Visalia area, an abrupt change on electrical logs from high resistivities in the upper part of the continental rocks and deposits to low resistivities in the lower part was interpreted as a change from mostly coarse-grained sediment in the upper part to mostly fine-grained sediment, respectively (Page and LeBlanc, 1969, fig. 4). In these areas, the coarser sediment was mapped as older alluvium, and the finer sediment as continental deposits by Croft and Gordon (1968, p. 23, pls. 4-7) and Page and LeBlanc (1969, p. 14-15, pls. 4 and 6).

In the Fresno area (pl. 2), yields to wells in the upper part of the continental rocks and deposits—mapped as older alluvium by Page and LeBlanc (1969, p. 21, pls. 4 and 6)—ranged from about 20 to 3,500 gal/min and averaged about 900 gal/min. In this area, water wells generally do not penetrate the lower part of the continental rocks and deposits, which were mapped as continental deposits by Page and LeBlanc (1969, p. 14, pls. 4 and 6). In the Hanford-Visalia area, yields to wells in the upper part of the continental rocks and deposits were not estimated, but yields to wells in the lower part reportedly ranged from 500 to 2,500 gal/min in the reduced parts and from 100 to 500 gal/min in the oxidized parts (Croft and Gordon, 1968, p. 18-19). In the Richgrove area, the continental rocks and deposits—mapped as continental deposits by Hilton and others (1961)—were reported as moderately to highly permeable and a major source of water; farther south, they were reported as only moderately permeable (Hilton and others, 1961, table 2; Wood and Dale, 1964, p. 38).

In the extreme southwestern part of the San Joaquin Valley and along most of its western flank, the continental rocks and deposits make up the Tulare Formation, which in many places is overlain by younger deposits (pl. 2, table 2). There, the continental rocks and deposits dip gently northeastward beneath the valley.

Woodring and others (1940, p. 13) defined the Tulare Formation as the youngest folded strata exposed in the Kettleman Hills. They defined the base of the Tulare Formation as the layer just above the upper *Mya* zone of the San Joaquin Formation (Woodring and others, 1940, p. 13-14). Upper *Mya* zone refers to the uppermost strata in which the burrowing pelecypod (clam, *Mya*) occurs in the San Joaquin Formation. The folded strata and upper *Mya* zone have been used by other workers for mapping the Tulare either along the western flank of the valley or in the subsurface, but where these criteria are absent most workers have found it very difficult to map either the upper or the lower contact of the Tulare Formation (Hotchkiss and Balding, 1971, p. 18-19; Miller and others, 1971, p. 21; Wood and Dale, 1964, p. 38-39; Wood and Davis, 1959, p. 22-23).

The Tulare Formation conformably overlies the San Joaquin Formation just above the upper *Mya* zone in the Kettleman Hills and in the subsurface east of the Hills, but where it is exposed elsewhere in the Coast Ranges, it generally lies unconformably on Pliocene and older formations. In the southwestern part of the San Joaquin Valley, the exposed Tulare ranges in thickness from a few tens of feet to more than 4,000 feet (Wood and Dale, 1964, p. 39); beneath the valley in this area, the thickness of the Tulare Formation and overlying deposits was not estimated. Northward from the Elk Hills to the Kettleman Hills, the exposed Tulare ranges in thickness from a few tens of feet along the western flank of the valley to about 3,500 feet in the Kettleman Hills (Wood and Davis, 1959, p. 23; Woodring and others, 1940, p. 14). Beneath the valley in this area, the thickness of the Tulare Formation and overlying deposits is not well known, but data compiled by Wood and Davis (1959, table 4) indicate that the thickness of the Tulare Formation ranges from about 200 feet at North Belridge to about 5,000 feet beneath the Kettleman Plains. Beneath the Kettleman Plains, the Tulare Formation and overlying deposits are as much as 6,500 feet thick (Woodring and others, 1940, p. 51). Miller and others (1971, p. 23) said that the exposed Tulare has a maximum thickness of about 2,600 feet in the northern part of the Kettleman Hills and that north of the Hills the thickness of the exposed Tulare does not exceed 350 feet. In the subsurface, the Tulare Formation, together with overlying deposits and some interbedded deposits from the Sierra Nevada, ranges in thickness from about 3,300 feet in the southern part of the Los Banos-Kettleman City area to about 900 feet in the northern part (Miller and others, 1971, pl. 3). Hotchkiss and Balding (1971, p. 18-19, pl. 1) estimated that in the Tracy-Dos Palos area the Tulare Formation and overlying deposits range in thickness from 0 to about 1,100 feet.

Most of the continental rocks and deposits along the western flank of the San Joaquin Valley consist of reworked sedimentary material that was derived from the older rocks of the Coast Ranges and deposited as alluvial-fan, flood-basin, deltaic, or lacustrine and marsh deposits. Miller and others (1971, pl. 4) showed that in the Los Banos-Kettleman City area the continental rocks and deposits derived from the Coast Ranges overlie and are interbedded with arkosic continental rocks and deposits from the Sierra Nevada. In the Los Banos-Kettleman City area and perhaps other parts of the valley, the gradual eastern extension of sediments from the Coast Ranges indicates that the topographic axis migrated eastward (Miller and others, 1971, p. 24, pl. 4).

The continental rocks and deposits in this part of the San Joaquin Valley consist principally of unconsolidated, generally poorly sorted deposits of clay, silt, sandy clay and silt, sand, clayey sand and silty sand, gravel, and clayey, silty, and sandy gravel. Locally, the Tulare Formation consists of consolidated sediment such as conglomerate and sandstone, and the lower part of the formation in the Kettleman Hills contains abundant pyroclastic material (Woodring and others, 1940, p. 13). Furthermore, the continental rocks and deposits consist in part of widespread silt and clay deposits of chiefly lacustrine origin (see "Lacustrine and Marsh Deposits").

Along the western side of the valley south of the Tulare Lake bed, the continental rocks and deposits contain mostly saline water, and north of Tulare Lake bed they contain mostly fresh water (Hotchkiss and Balding, 1971, p. 18; Miller and others, 1971, pls. 3 and 4; Page, 1973). As a consequence, in the southwestern part of the San Joaquin Valley, few deep-water wells penetrate the continental rocks and deposits, and not much is known about yields to wells.

Nevertheless, 344 water wells were investigated in this area, and the reported average yield to irrigation wells was about 600 gal/min from alluvium of Pleistocene and Holocene age as mapped by Wood and Davis (1959, p. 28 pl. 1).

Along the western flank of the valley, from Anticline Ridge to Cantua Creek in the Los Banos-Kettleman City area, alluvial-fan deposits of the Tulare Formation were drilled through as much as 2,800 feet in order to tap more permeable deposits in the underlying San Joaquin and Etchegoin Formations (Miller and others, 1971, p. 28). Northwest and southeast of this area the deposits are coarser grained and more permeable. In the Tracy-Dos Palos area (pl. 2), yields to wells, mostly from the Tulare Formation, ranged from about 40 gal/min to 3,300 gal/min; most wells in the area averaged much more than 1,000 gal/min (Hotchkiss and Balding, 1971, fig. 7).

In the northern, northwestern, and western Sacramento Valley, most of the continental rocks and deposits constitute the Tehama Formation. In turn, the Tehama is overlain in many places by younger and much thinner deposits, including the Red Bluff Formation. As in most other areas in the Central Valley, the subsurface contact between these units is difficult to determine. Near its base, however, the Tehama Formation, as well as the Tuscan Formation (see "Tuscan Formation"), in places contains the Nomlaki Tuff Member of late Pliocene age. Where present, the tuff serves as an excellent marker bed. Nevertheless, because the lithology of the Tehama is similar to that of some older rocks and deposits in the valley, the basal part of the Tehama as mapped in the subsurface probably contains some of these older units. The maximum thickness of the continental rocks and deposits is more than 2,000 feet in the northern part of the Sacramento Valley and about 3,000 feet in the south-central part; in these areas, the Tehama Formation constitutes the thickest part (California Department of Water Resources, 1978, fig. 6). Throughout most of the western side of the Sacramento Valley, the Tehama averages about 2,000 feet in thickness (California Department of Water Resources, 1978, p. 25). At depth, the continental rocks and deposits, including the Tehama Formation, contain saline water (pl. 3) (Berkstresser, 1973; California Department of Water Resources, 1978, fig. 6).

Russell (1931, p. 27 and 31) considered the Tehama Formation to be of fluvial origin, and, because the fine-grained beds dominate, he concluded that the sediments were deposited under flood-plain conditions. The Tehama consists of poorly sorted deposits of clay, silt, clayey silt, sandy silt and clay, and silty sand containing generally thin lenses of gravel and sand; in areas of outcrop, it consists chiefly of siltstone, sandstone, and conglomerate (Helley and others, 1981, p. 11). However, in U.S. Geological Survey test hole 12N/1E-34Q1, which was drilled to a depth of 2,500 feet and which probably penetrated the total thickness of the Tehama Formation, virtually no consolidated sediments were found above a depth of 2,000 feet (French and others, 1982, table 2). This difference in consolidation between beds in areas of outcrop and beds in the deep subsurface indicates that, for some beds at least, consolidation probably was the result of exposure and weathering; however, farther out in the valley, beds in the subsurface generally have not had as much exposure or weathering. A simple example is shown by cores of clay taken from well 34Q1. When these cores were examined as they came from the borehole, the clays were saturated and plastic, but after a few months in storage they were dry and hard.

Younger deposits within the continental rocks and deposits consist of heterogeneous mixes of clay, silt, sand, and gravel, which in places are cemented and contain hardpan. Alluvial deposits underlying the Stony Creek alluvial fan are coarser grained than in any other place in the Sacramento Valley (California Department of Water Resources, 1978, p. 30), and the proportion of sand and gravel to depths of 200 feet averages about one-third (Olmsted and Davis, 1961, p. 106). Between Willows and Williams (pl. 1), alluvial-fan deposits are finer grained than those to the north, and wells must penetrate the underlying Tehama to get significant yields of water (California Department of Water Resources, 1978, p. 30). South of Williams to Cache Creek, the alluvial-fan deposits consist mostly of fine-grained sediments containing some lenses of poorly sorted sand and gravel. Farther south, both Cache and Putah Creeks have deposited extensive beds of sand and gravel, but, even in these areas, sand and gravel in the upper 200 feet make up only 25 to 30 percent of the deposits (Olmsted and Davis, 1961, p. 106-107).

In the Sacramento Valley, yields to wells from the Tehama Formation differ considerably. The California Department of Water Resources (1978, p. 25) reported the following yields: west of Red Bluff and Corning, yields to wells ranged from about 500 to 950 gal/min; in T. 25 N., R. 3 W., from about 500 to 2,200 gal/min; west of Artois, from about 950 to 1,900 gal/min; and, near Arbuckle, irrigation wells were reported to yield from about 1,900 to 4,000 gal/min. Yields to wells from the overlying deposits also differ, and, in places along the western flank of the Sacramento Valley, some of the deposits are unsaturated. Average yields to wells in the Stony Creek area are about 2,000 gal/min. One well in the Cache Creek area yielded 1,400 gal/min from the alluvial-fan deposits; this yield was not considered to be unusual (Olmsted and Davis, 1961, p. 106).

### Lacustrine and marsh deposits

Lacustrine and marsh deposits crop out in the San Joaquin Valley beneath Buena Vista, Kern, and Tulare Lake beds, and also along the western flank of the valley just west of Los Banos (pl. 2, table 2). They do not crop out in the Sacramento Valley.

If it were possible to open the earth and look at the lacustrine and marsh deposits beneath Tulare Lake bed, they would appear as a thick plug of mostly blue-green or gray clay and silt, from which lenses of clay and silt emanate at irregular intervals (pl. 3). Sediment from test holes less than 100 feet deep indicated that at least one fine-grained deposit beneath Tulare Lake bed is a distal part of an alluvial-fan deposit derived from the Coast Ranges (B. F. Atwater, U.S. Geological Survey, oral commun., 1983). Some fine-grained beds probably include flood-basin deposits. Nevertheless, this plug of chiefly lacustrine and marsh deposits and its related lenses probably warrant formational status. If recognized as a formation, the various lenses would be members, and instead of the Corcoran Clay Member (Pleistocene) being a member of both the Tulare Formation (Pliocene and Pleistocene) and the Turlock Lake Formation (Pleistocene), as indicated below, it would be a member of only one formation. Furthermore, instead of the other lenses possibly being named members of various formations, these lenses would be members of only one formation, and their origin would be more readily apparent.

In the SW¼ T. 23 S., R. 20 E., the lacustrine and marsh deposits are more than 3,600 feet thick. Croft (1972, pls. 1-6, p. 17-21) mapped six of the lenses and designated them from youngest to oldest by the letters A through F. The A, C, and E clays of Quaternary age are the more extensive. In fact, the E clay in the San Joaquin Valley is the most extensive lacustrine clay in the entire Central Valley.

Beneath Buena Vista and Kern Lake beds, flood-basin deposits and fine-grained facies of alluvium have been included with the lacustrine and marsh deposits; those deposits are composed chiefly of silt, silty clay, sandy clay, and clay, interbedded with some sand lenses (Wood and Dale, 1964, p. 43). In that area, such deposits are considered to be at least 1,000 feet thick.

Elsewhere in the Central Valley, aside from the widespread A, C, and E clays and the deposits beneath Tulare Lake bed, lacustrine and marsh deposits are considerably thinner and are reported only in local areas (Redwine, 1972, p. 157; Russell, 1931, p. 27; Page and Bertoldi, 1983, p. 16-17).

Modified E clay—The E clay of Pleistocene age includes the diatomaceous clay of Davis and others (1959, pl. 14) and an extension of that clay mapped by Croft (1972, p. 19, pl. 4) in the area of Buena Vista and Kern Lake beds. In turn, the diatomaceous clay is considered equivalent to the Corcoran Clay Member of the Tulare Formation. In the northeastern part of the San Joaquin Valley, where virtually all the continental deposits were derived from the Sierra Nevada, Marchand and Allwardt (1981, p. 34) considered the Corcoran Clay Member of the Tulare Formation also to be a member of the Turlock Lake Formation. Janda and Croft (1967, p. 164) reported that a volcanic ash and pumice, the Friant Pumice Member of the Turlock Lake Formation (Marchand and Allwardt, 1981, p. 34), can be traced discontinuously from near Friant, where it is exposed, to beneath the axis of the San Joaquin Valley, where it conformably overlies the Corcoran Clay Member. G. B. Dalrymple (Marchand and Allwardt, 1981, p. 34) dated two separate collections of the Friant Pumice Member as 612,000±31,000 years and 618,000±31,000 years before the present.

Croft (1972, p. 19, pl. 4) mapped the E clay in the area around Buena Vista and Kern Lake beds. Diatoms in that area have not been reported in the clay. Later, R. E. Brown (California Department of Water Resources, written commun., 1981) compiled eight geologic sections for the area at and around Buena Vista and Kern Lake beds and correlated an extensive clay bed by using electric logs and by intensive checking of his sections and Croft's mapping. Brown concluded that, in the area at and around Buena Vista Lake bed, the E clay lies from 100 to 300 feet above the depth that Croft mapped it. Inasmuch as a great many more electric logs, as well as additional drillers' logs, were available to Brown than to Croft, Brown's data were used in mapping the depth to his E clay, herein called the modified E clay at and around Buena Vista and Kern Lake beds (pl. 4).

The modified E clay ranges in depth from 0 foot at the outcrop along the western flank of the valley to about 900 feet beneath Tulare Lake bed (pl. 4). In some areas, such as near Little Panoche Creek and the Fresno River, the modified E clay may have been eroded, as indicated by the truncated depth contours. Although the depth map properly cannot be used as a structural contour map, the gentle relief of the San Joaquin Valley permits some structural interpretation of the map. The most striking features shown on plate 4 are (1) the number of basins in the clay, (2) a general deepening from north to south, and (3) a trough that underlies virtually the entire western part of the San Joaquin Valley. Some of the deeper parts of the ancient lake probably are indicated in areas where the basins approximately coincide with thicker sections of the clay, such as near Cantua and Panoche Creeks and beneath parts of Tulare Lake bed (pls. 4 and 5); these and other basins may also be the result of structural deformation. The trough reflects the syncline that underlies the western part of the San Joaquin Valley (Hoots and others, 1954, pl. 5).

The modified E clay ranges in thickness from less than 10 feet in places near its edge to more than 160 feet beneath the western part of Tulare Lake bed (pl. 5). Where the modified E clay is bifurcated (pl. 5), an upper bed of clay or silty clay is separated from a similar lower bed by a bed of coarser grained sediment that ranges in thickness from about 5 to 70 feet and averages about 20 feet.

The E clay, or modified E clay, may have been deposited in a large lake that was coeval with glaciation in the Sierra Nevada (Janda and Croft, 1967, p. 168), but Davis and others (1977, p. 389) suggested that the E clay may represent an interglacial stage.

A AND C CLAYS—The C clay of Pleistocene age was mapped as being beneath the San Joaquin Valley from about Mendota on the north to Goose Lake bed on the south (Croft, 1972, pl. 5; Page and LeBlanc, 1969, pl. 9). It underlies the topographic axis of the valley and ranges in depth from about 100 to 330 feet and in thickness from about 5 to 45 feet. The C clay may have been deposited in a large lake in the valley coeval with a glacial stage in the Sierra Nevada (Janda and Croft, 1967, p. 168; U.S. Geological Survey, 1965, p. A100).

The A clay of Pleistocene and Holocene(?) age (Croft, 1972, p. 21) was mapped as being beneath the San Joaquin Valley from near Mendota on the north to Kern Lake bed on the south (Croft, 1972, pl. 6; Page and LeBlanc, 1969, pl. 9); it also underlies the topographic axis of the valley. The A clay ranges in depth from less than 10 to about 70 feet and in thickness from about 5 to 70 feet. Janda and Croft (1967, p. 168) considered the A clay to have been deposited in a large lake coeval with the Wisconsin glaciation. Radiocarbon dates for wood collected 3 feet beneath the A clay and for wood within the upper part of the clay are 26,780±600 years and 9,040±300 years, respectively (U.S. Geological Survey, 1965, p. A99-A100; Croft, 1972, p. 20-21).

Fine-grained beds, such as the A, C, and E clays, do not yield much water to wells, unless compacted; instead, they impede the vertical movement of water and function as confining beds—that is, where underlying sediments are fully saturated, ground water is at greater than atmospheric pressure.

LACUSTRINE-CLAY DISTRIBUTION—As mentioned, at least two extensive lacustrine clays (E and C clays) of Pleistocene age and one (A clay) of Pleistocene and Holocene(?) age underlie the San Joaquin Valley; similar extensive clays have not been found in the Sacramento Valley. Probably the absence of an active basin-forming structural depression similar to that underlying the Tulare Lake bed area of the San Joaquin Valley accounts for the lack of widespread lacustrine deposits in the Sacramento Valley. Three major structural depressions, however, have been designated as the three Tertiary depocenters of the Central Valley; they underlie the Tulare Lake bed and Buttonwillow area, the Kern Lake bed area, and the delta area (Zieglar and Spotts, 1978, fig. 7). Only the depocenter underlying the Tulare Lake bed area contains a thick—more than 3,600 feet—virtually continuous section of continental sediments of silt and clay. Depocenters underlying the other areas contain fine-grained sediments that are not nearly as thick and that are interbedded with coarse-grained sediments.

Many workers have suggested that, in the Tulare Lake bed area, damming by the growth of alluvial fans from the Kings River on the east and Los Gatos Creek on the west was the cause of the interior drainage there (Mendenhall and others, 1916, p. 21; Davis, 1933, p. 224; Hinds, 1952, p. 150). Davis and Green (1962, p. 82-91), however, showed that Tulare Lake bed is an area of structural downwarping and that active tectonic subsidence is the cause of the basin. That basin is underlain chiefly by fine-grained lacustrine and marsh deposits more than 3,600 feet thick. Those deposits range in age from late Pliocene to Holocene (Croft, 1972, p. 18); therefore, lakes and marshes have existed in this area for more than 2 million years. Being structurally downwarped, the area has been and is a basin to which water flows through large and small streams from the surrounding area. Deltaic deposits in the deep subsurface are further evidence that this basin has been receiving water from surrounding areas for an extremely long time. For example, Miller and others (1971, p. 28, pl. 4) mentioned that deltaic deposits just north of Tulare Lake bed begin 350 feet below the surface and are about 2,000 feet thick. In the past, and even today, lakes in the area have expanded and contracted, as indicated by the A, C, and E clays and by flooding of the lake bed in recent times. These clays probably represent times when large quantities of water drained into the ancient Tulare Lake bed area and expanded the existing lake.

The expansion of the lakes and the resulting clays might have occurred in two ways: (1) as water from the surrounding area drained into the ancient basin, the lake expanded; and (2) streams to the north formed, or had already formed, dams by building alluvial fans out into the axis of the valley, so that an expanding lake may have been dammed by alluvial fans. Recently, B. F. Atwater, W. R. Lettis, and David Adam of the U.S.

Geological Survey (written commun., 1982) suggested that large lakes in the basin may have formed as a result of high dams (50 feet) built by brief pulses (less than 10,000 years) of aggradation by large rivers, and that smaller lakes may have resulted from lesser aggradational events, perhaps with the aid of tectonic subsidence at the lake site. Shlemon (1971, p. 436) said that studies of alluvial sequences in the Central Valley have shown that periods of alluvial-fan formation probably correlate with glacial advances in the Sierra Nevada, and that relative landscape stability and soil formation occurred during interglacial time. Atwater, Lettis, and Adam (written commun., 1982) said that glacially induced dams apparently persisted into interglacial periods.

Shlemon (1971, fig. 13) mapped three Pleistocene river channels in the Mokelumne River area (pl. 1). He inferred that the oldest channel deposits could be correlated with sediments 100 miles to the south that were dated as approximately 600,000 years old (Shlemon, 1971, p. 433); those sediments are undoubtedly the Friant Pumice Member of the Turlock Lake Formation. Shlemon (1971, p. 434, fig. 3) said that at Lodi the channel deposits lie at a depth of about 250 feet, and he inferred that about 20 miles west of Lodi the channel deposits lie at a depth of about 380 feet. The inferred age of the channel deposits, of course, correlates with the approximate age of the modified E clay (see "Modified E Clay"), and the depths of the channel deposits approximate those of the modified E clay near Tracy (pl. 4). While the ancient Mokelumne River was building its fan out toward the delta area, other rivers in the Central Valley probably were building fans, too. Thus, alluvial dams probably were present in the axis of the Central Valley when the modified E clay was being deposited in the lake that was expanding northward from the Tulare Lake bed area. Perhaps northward-flowing rivers breached the alluvial dams of rivers south of Tracy and north of the Kings River, or perhaps the expanding lake captured the water from these rivers, breached a dam, and continued its northward expansion.

Shlemon (1971) mapped a second channel in the Mokelumne River area. The deposits of this channel lie at a depth of about 90 feet beneath Lodi; 4 miles west, the depth is about 120 feet. These deposits are inferred to be between 75,000 and 300,000 years old (Shlemon, 1971, p. 434, fig. 3). The depths of these channel deposits approximate those of the C clay, and the deposits and the clay may be similar in age.

The third channel mapped by Shlemon (1971, p. 434-435, fig. 3) lies at a depth of about 40 feet beneath Lodi; 3 miles west, the depth is about 50 feet. Shlemon (1971, p. 435) considered the deposits of this channel to be somewhat older than 27,000 years and perhaps correlative with the age-dated lacustrine sediments of Janda and Croft (1967, p. 168), the A clay. Both the A and C clays were mapped chiefly south of Mendota, and there the lakes in which those clays were deposited could have been dammed by alluvial fans of the ancient San Joaquin or Kings Rivers.

The earliest indication that the Sacramento Valley probably is not underlain by a widespread fine-grained bed was given by Bryan (1923, p. 91), who said, "Only a small number of flowing wells have been obtained in Sacramento Valley, and of these only a few have strong flows. There is no large area of artesian flow, as in San Joaquin Valley." Before Bryan's study, Mendenhall and others (1916, pl. 1) had mapped a large area in the San Joaquin Valley that was underlain by confined ground water and that is roughly comparable to the area underlain by the modified E clay (pl. 4). This lack of a "large area of artesian flow" in the Sacramento Valley indicates the absence of a widespread confining bed.

Between February 1979 and October 1980, the U.S. Geological Survey drilled seven test holes in the Sacramento Valley (pl. 1); well 5N/1E-34A was drilled by the U.S. Army Corps of Engineers. The holes ranged in depth from 900 to 2,500 feet. At test holes 12N/1E-34Q1, 12N/3E-2G1, and 19N/1E-32G1, three potentiometric tubes were placed in each hole and bottomed at three different depths (French, Page, and Bertoldi, 1982 and 1983; French, Page, Bertoldi, and Fogelman, 1983). Fluctuations of water levels in those tubes indicated that ground water was confined at most depths. As numerous fine-grained beds underlie the test-hole sites, landing a tube beneath any one of the beds probably would result in recording some confinement. If a fine-grained bed could have been correlated from one test-hole site to another, then it could have been shown that a widespread fine-grained bed existed in the Sacramento Valley and that confinement of ground water is of more than local extent.

One of the purposes of drilling the test holes was to determine whether a diatomaceous clay of Pleistocene age, cored in test hole 12N/1E-34Q1 near Zamora from depths of 534 to 544 feet (Page and Bertoldi, 1983, table 1), could be correlated with a diatomaceous clay found at depths of 18 to 22 feet in test hole 5N/1E-34A near the northern edge of the Montezuma Hills (pl. 1). The diatomaceous clay near the Montezuma Hills was thought to be comparable in age and deposited in an environment similar to that of the Corcoran Clay Member of the Tulare Formation (Olmsted and Davis, 1961, p. 74). It is not known whether the clay near the Montezuma Hills is a northern extension of the Corcoran Clay Member.

Because no diatoms were found in any of the cores taken from four test holes drilled between test holes

12N/1E-34Q1 and 5N/1E-34A (pl. 2), the diatomaceous clay found in 34Q1 was considered a separate clay rather than an extension of the clay found near the Montezuma Hills (Page and Bertoldi, 1983, p. 17). Nor were diatoms found in test holes 12N/3E-2G1 near Nicolaus and 19N/1W-32G1 near Butte City. Therefore, the Pleistocene diatomaceous clay found in 12N/1E-34Q1 was considered to be of only local extent.

Furthermore, examination of more than 900 electric logs indicated that thick, fine-grained lacustrine deposits like those underlying the Tulare Lake bed area probably do not exist in the Sacramento Valley. Thomasson and others (1960, p. 85), however, mentioned dominantly fine-grained zones underlying T. 8 N., R. 1 E., which they said represent possible lake or flood-basin deposits; these zones also contain many coarse-grained beds (Thomasson and others, 1960, pl. 8). Olmsted and Davis (1961) and the California Department of Water Resources (1978) do not mention any thick, fine-grained lacustrine deposits in the Sacramento Valley. Redwine (1972, p. 156-157) considered the Tehama Formation to have been deposited chiefly on the west side of a broad, low-lying Sacramento Valley in flood plains and streams and locally in small, shallow, intermittent lakes, where diatomaceous claystone accumulated. Considering these data, a structural basin comparable to that beneath Tulare Lake Bed in the San Joaquin Valley probably is not present in the Sacramento Valley.

Although a structural depression exists in the delta area (Zieglar and Spotts, 1978, fig. 9), available data indicate that it probably did not contribute to the forming of widespread lakes, as is inferred for the structural depression in the Tulare Lake bed area. Large lakes may not have formed in the delta area because drainage from the Central Valley to the ocean probably took place near there between 0.6 and 3.3 million years ago (SarnaWojcicki, 1976, p. 25).

In the Sacramento Valley, then, water from the rivers of the surrounding area probably did not accumulate in a large, downwarping basin like the one in the Tulare Lake bed area because such a basin, in which large lakes could form and then expand, probably had not developed there. Instead, probably only small lakes existed in the valley. Before any large lakes could form, alluvial dams in the Sacramento Valley probably were breached by a throughflowing trunk stream comparable to the present-day Sacramento River. Consequently, at a time when widespread lacustrine clays were being deposited in large lakes in the San Joaquin Valley, lacustrine clays of only local extent probably were being deposited in relatively small lakes in the Sacramento Valley.

## CONTINENTAL DEPOSITS (QUATERNARY)

Quaternary deposits are largely of Holocene age; along their outer margins, however, some may be of Pleistocene age. The deposits crop out chiefly along the major rivers and streams of the valley, as well as in other low-lying areas (pls. 1 and 2), and include river deposits, flood-basin deposits, and sand dunes, all of Holocene age. In places, they may include such deposits as the Modesto Formation of Pleistocene age.

### River deposits (Holocene)

The river deposits crop out along the major rivers and streams of the Central Valley (pls. 1 and 2, tables 1 and 2) and include channel and flood-plain deposits. The river deposits are still accumulating, except where human activity intervenes. Channel deposits, which consist chiefly of sand and gravel, range in width from a few feet to nearly 1,000 feet. Flood-plain deposits generally are finer grained than channel deposits and consist chiefly of sand and silt, and they range in width from a few hundred feet to more than 3 miles. Because soil development and topography were the criteria for mapping river deposits, subsurface contact with underlying deposits is poorly defined. Olmsted and Davis (1961, p. 109) defined the river deposits as the predominantly coarse-grained deposits at relatively shallow depth that appear to be hydraulically continuous with the present stream channels, flood plains, and natural levees. The California Department of Water Resources (1978, p. 33) believed that the river deposits attain a maximum thickness of about 115 feet and that they are the most permeable deposits in the Sacramento Valley.

### Flood-basin deposits (Holocene)

Flood-basin deposits crop out in low-lying areas throughout the Central Valley (pls. 1 and 2; tables 1 and 2). They result from flood waters entering low-lying basins and depositing mostly fine silt and clay and some fine sand. Flood-basin deposits grade into river deposits, rocks, and deposits of Tertiary and Quaternary age, and lacustrine and marsh deposits. As with most deposits of Quaternary age in the valley, contact with underlying deposits is difficult to determine. The California Department of Water Resources (1978, p. 32) stated, however, that the flood-basin deposits in the Sacramento Valley consist of as much as 160 feet of fine-grained sediments in the area west and south of Sacramento and that the deposits north of the Sutter Buttes appear to be thinner, about 50 feet thick. In the San Joaquin Valley, the deposits were estimated to be as much as 100 feet thick (Page and Balding, 1973, p. 37). Because of their fine-grained nature, the flood-basin deposits would not yield much water to wells and would impede the vertical movement of water.

### Sand dunes (Holocene)

Sand dunes crop out chiefly in the eastern part of the San Joaquin Valley (pl. 2, table 2). They range in thickness from 0 to about 140 feet and consist of generally cross-bedded, well-sorted, medium-to-coarse sand and some very fine to fine sand and silt (Page and LeBlanc, 1969, p. 25; Wood and Dale, 1964, p. 44-45). In most places, the sand dunes lie above the saturated zone, but their permeability permits recharge from stream runoff, precipitation, or irrigation return.

## GEOLOGIC STRUCTURE

The large, asymmetrical, northwestward-trending trough of the Central Valley is the principal structure controlling the occurrence and movement of ground water in the area. Along the flanks of the valley, which are the flanks of the trough, deposits generally are much thinner than those underlying either the topographic axis of the valley or the more westerly structural axis of the trough. In general, most of the confinement of ground water occurs near the axis of the valley as a result of more extensive confining beds deposited there. Furthermore, because the flanks of the valley are higher than its axis, recharge from tributary rivers and streams, as well as from irrigation return, has caused heads in the ground water along the flanks to be higher than those along the axis, so that, overall, ground water moves from the flanks toward the axis and thence northward (San Joaquin Valley) or southward (Sacramento Valley) toward the delta area and points of ultimate discharge. And since development, some ground water moves toward large pumping depressions in various parts of the valley.

A number of secondary geologic structures in the Central Valley also influence the occurrence and movement of ground water. The Red Bluff arch at the northern end of the Sacramento Valley is a series of northeastward-trending anticlines and synclines that result in a structural barrier to ground-water movement (pl. 1) (California Department of Water Resources, 1978, p. 39). Faulting in the area (Harwood and Helley, 1982) may also affect ground-water movement. Although it probably is not a barrier to ground-water movement, the Chico monocline on the northeastern flank of the valley accounts for the nearly straight basin boundary that lies north of Pine Creek. The northward-trending structure, which lies south of the Red Bluff arch and which has been mapped as the Corning anticline, is expressed on the surface by a series of low-lying hills; in the subsurface it consists of two domes (Harwood and Helley, 1982). An extension of this structure is thought to have uplifted the Tuscan Formation near the Red Bluff Diversion Dam because the Tuscan lies at a shallower depth there than in nearby areas (California Department of Water Resources, 1978, p. 34). In the northwestern part of the valley, pre-Tertiary marine rocks have been uplifted along a fault at Orland Buttes; the fault and the rocks are probably barriers to ground-water movement. The Willows fault, which lies just southeast of the Orland Buttes, has no surface expression, but its presence has been inferred from changes in water level across the structure (California Department of Water Resources, 1978, p. 39). In the central part of the valley, ground water is diverted around the Sutter Buttes. Curtin (1971, p. 51-53) suggested that the mound of saline water on the south side of the Buttes (pl. 3) resulted from saline water migrating upward along a fault from underlying marine rocks. On the western side of the Sacramento Valley, the Tehama Formation has been folded by the uplift of the Dunnigan Hills anticline (pl. 1). Bryan (1923, p. 79, pl. 3) mapped a fault along the east limb of this anticline, as did Harwood and Helley (1982). The anticline and perhaps the fault extend northwestward. Near Arbuckle, one or both of these structures probably are barriers to ground-water movement (California Department of Water Resources, 1978, p. 39). The Plainfield Ridge lies south of the Dunnigan Hills anticline and is an anticlinal structure, the surface expression of which is a series of low hills; it lies parallel to the Dunnigan Hills anticline. This structure is a barrier to the eastward movement of ground water (California Department of Water Resources, 1978, p. 39). The Montezuma Hills in southwestern Sacramento Valley represent a broad, gentle uplift, which is reportedly modified by faulting (Olmsted and Davis, 1961, p. 130-131). It is not known whether the faults affect ground-water movement.

In the San Joaquin Valley, anticlinal folds such as Anticline Ridge, Guijarral Hills, Kettleman Hills, and Lost Hills restrict the movement of ground water from Pleasant Valley, Kettleman Plain, and Antelope Plain (pl. 2). Farther south, the Elk Hills and the Buena Vista Hills restrict the movement of ground water from Buena Vista Valley. In the southern part of the valley, the White Wolf fault is a barrier to ground-water movement, as is the Edison fault along the southeastern part of the valley (Wood and Dale, 1964, p. 28-29). Other faults are present throughout the San Joaquin Valley, but they have not been shown definitely to restrict ground-water movement.

## TEXTURE

"Texture," as used in the illustrations of this report, means the proportion of coarse-grained to fine-grained sediment in sedimentary rocks and deposits. Texture was mapped only above the base of fresh water. In this report, coarse-grained sediment is considered to consist principally of sand, clayey and silty sand, gravel, and clayey, silty, and sandy gravel; fine-grained sediment consists principally of clay, silt, and sandy clay and silt. In order to determine texture, 685 geophysical logs mostly from oil and gas wells were used. These logs show properties of sedimentary material and their included fluid, such as resistivity and spontaneous potential. The texture of sediments, as well as their depth and thickness, can be determined from geophysical logs (Schlumberger Ltd., 1972). In the sediments of the Central Valley, for example, high resistivities are interpreted as representing coarse-grained sediment and low resistivities as representing fine-grained sediment (fig. 4). The spontaneous potential also is a guide in determining coarse-grained and fine-grained sediment. Opposite a coarse-grained bed, the spontaneous-potential line, depending on water salinity in the bed and fluid salinity in the borehole, moves either to the right or left of a base line representing fine-grained sediment. Although coarse-grained and fine-grained sediment can be determined from geophysical logs, the logs cannot be used to determine whether the coarse-grained sediment is gravel or sand or whether a fine-grained sediment is silt or clay. Furthermore, geophysical logs cannot be used to determine the degree of cementation or sorting in a deposit; thus, some of the coarse-grained sediment may consist of conglomerate or sandstone, and some of the fine-grained sediment may consist of siltstone or claystone.

Using geophysical logs and a computer program written by H. T. Mitten of the Geological Survey (written commun., 1980), texture maps of the sediments beneath the Central Valley were made by computing and plotting the percentage of coarse-grained sediment by quarter townships in depth intervals of 300 feet (figs. 5-21). Also, texture columns and sections for selected areas and graphs of the frequency of occurrence of coarse-grained sediment by depth zones were made for both the Sacramento and San Joaquin Valleys (figs. 22-35). Many of the computations for texture were for depths below 300 feet because the

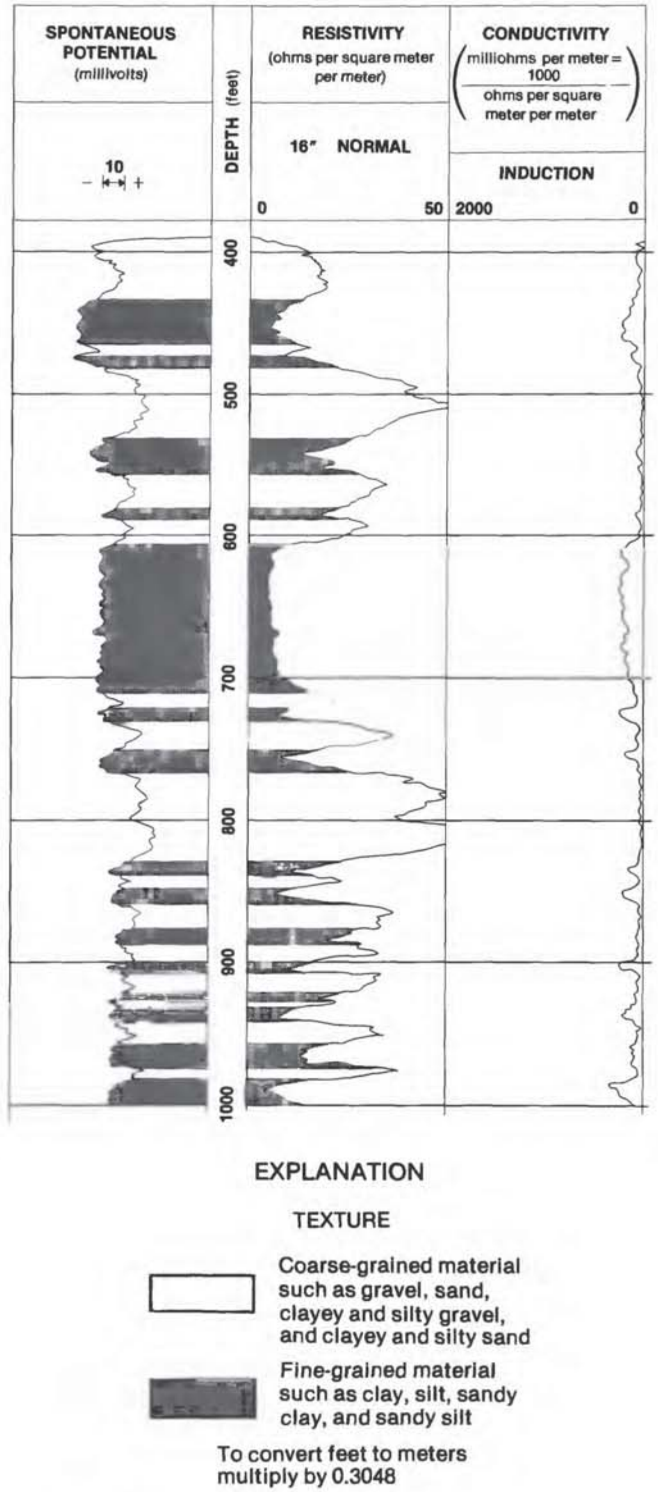



**Figure 4.** Geophysical logs for part of well 23S/23E-25E.

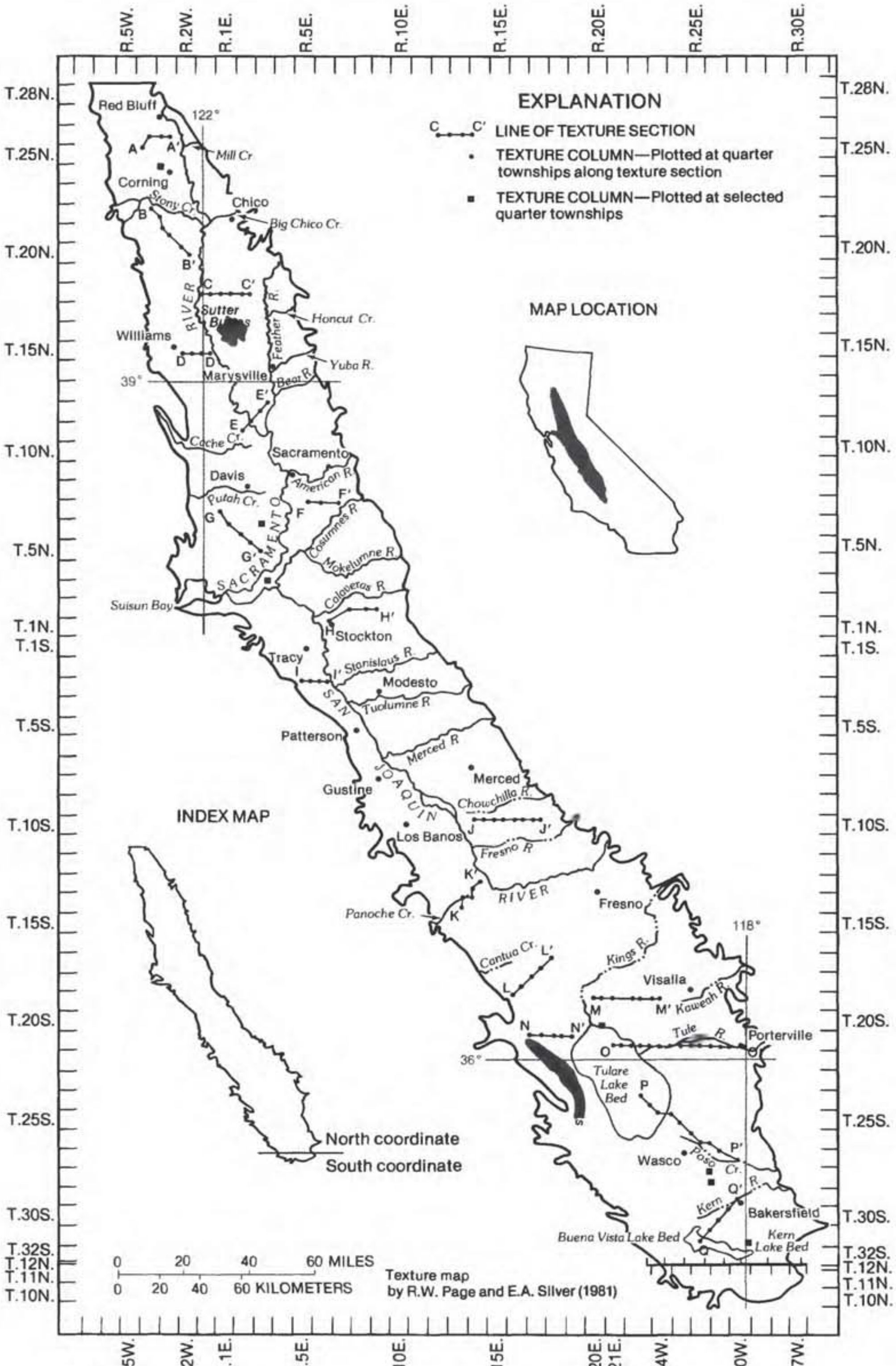



**Figure 5.** Location of texture columns and sections.

California Division of Oil and Gas requires that, before an oil or gas well may be drilled, a casing must be set in the ground from the surface to 10 percent of the total depth of the well. This casing blocks the recording of resistivity and spontaneous potential.

The maps and sections show texture down to the base of fresh water (Berkstresser, 1973; Page, 1973). They are not maps and sections for only one formation, and undoubtedly many of the indicated depth zones transgress formation contacts. In figure 35, the Sacramento Valley is considered to include all the area in the Central Valley from T. 1 N.(M) to T. 28 N(M), and the San Joaquin Valley, all the area from T. 1 S.(M) to T. 10 N.(S) (fig. 5).

The alluvial deposits of the Central Valley are a heterogeneous mixture of sediments, which, over short distances and depths, range from chiefly fine-grained sediments to chiefly coarse-grained sediments, and vice versa (figs. 6-34). Furthermore, the deposits do not always grade from chiefly coarse-grained sediments near the flanks of the valley to chiefly fine-grained sediments near its axis, although more gravel is likely to be found along the flanks of the valley and more sand near its axis. Nevertheless, some areas are underlain chiefly by coarse-grained sediment and others by fine-grained sediment, which indicates that sources and depositional environment for areas containing sediment of like size probably were similar for long periods of time.

In the San Joaquin Valley near Tulare Lake bed, the thick deposits of chiefly coarse-grained sediments at depths ranging from less than 300 feet to about 3,000 feet (figs. 5-15) probably are largely of deltaic origin (see "Lacustrine-Clay Distribution") and were formed where the streams of the alluvial fan dropped most of their remaining coarse-grained load as they entered lakes and marshes. West and southwest of Bakersfield, the chiefly coarse-grained sediments were deposited at depths ranging from less than 300 feet to about 3,900 feet (figs. 6-18) by the Kern River, its antecedents, and other streams in an area of rapid downwarping (de Laveaga, 1952, p. 102). Probably the sediments are largely alluvial-fan deposits, but near Buena Vista and Kern Lake beds some of the coarse-grained sediments are probably deltaic. Along the southeastern flank of the San Joaquin Valley from north of Bakersfield to T. 22 S., the mostly coarse-grained sediments indicated at depths greater than about 1,500 feet (figs. 11-15) are largely flushed marine rocks and deposits, such as the Santa Margarita Formation of various authors (see "Marine Rocks and Deposits (Tertiary)").

Some thick, mostly coarse-grained sediments underlie the southeastern Sacramento Valley from the American River south to the Calaveras River at depths ranging from less than 300 feet to about 2,100 feet (figs. 7-12). The sediments generally grade in a westerly direction from coarser to finer grained sediments and in large part are probably alluvial-fan deposits laid down by the American, Cosumnes, Mokelumne, and Calaveras Rivers and their antecedents. Furthermore, the great thickness of the mostly coarse-grained sediments, which extend from the basal part of the continental rocks and depostis to near land surface, indicates that they have been deposited in parts of this area for an extremely long time, probably much more than 1 million years (pl. 3). Farther north, at depths ranging from less than 300 feet to about 1,200 feet (figs. 6-9), the mostly coarse-grained sediments underlying the immediate area around Sutter Buttes probably were derived for the most part from streams draining the Buttes, where the carrying power of the streams increased as the rocks and deposits of the Buttes were uplifted. North of Sutter Buttes, the distribution of the mostly coarse-grained sediments at depths ranging from less than 300 feet to about 1,200 feet (figs. 6-9) indicates that Big Chico Creek, Stony Creek, the Feather River, and their antecedents probably have contributed proportionally more coarse-grained sediment to the Sacramento Valley than has the Sacramento River.

In the Central Valley, the thickest and most extensive sections of fine-grained sediment underlie Tulare Lake bed. There, the fine-grained sediments are more than 3,600 feet thick in places and contain very few coarse-grained beds. At depth, the sediments underlie an area of nearly 1,000 $mi^2$. For the most part, these chiefly lacustrine and marsh deposits are not shown on the texture maps because they generally lie below the base of fresh water and have been mapped for other reports (Croft, 1972, pls. 3 and 4; Page, 1983b, fig. 10) (pl. 3).

Other areas in the Central Valley are also underlain by mostly fine-grained sediments, but in those areas the fine-grained sediments are interbedded with coarse-grained sediments and are not nearly as thick or homogeneous as the fine sediments underlying Tulare Lake bed. Mostly fine-grained sediments lie along the southeastern flank of the San Joaquin Valley between Bakersfield and Portersville, at depths ranging from less than 300 feet to about 1,500 feet (figs. 6-10); along the western flank from north of the Kettleman Hills to Los Banos and the area just to the east, at depths ranging from less than 300 feet to about 2,700 feet (figs. 6-14); and on the northwestern flank just west and south of Tracy, at depths ranging from less than 300 feet to about 1,800 feet (figs. 6-11). Even in these areas, however, some mostly coarse-grained sediments are present (figs. 6-11). Many of these sediments probably were deposited in distal parts of alluvial fans or along flood plains, and in some areas they may have been deposited in small lakes and marshes. Furthermore, sediments derived from the Coast Ranges, such as most of those along the western side of the valley, generally are finer grained than those derived from the Sierra Nevada (Croft, 1972, p. 15) (figs. 6-12).

In the Sacramento Valley, mostly fine-grained sediments underlie areas along its northeastern flank just south of Chico at depths ranging from about 600 feet to about 900 feet (fig. 8) and along its southwestern flank from just north of Cache Creek to T. 3 N. at depths ranging from less than 600 feet to about 2,700 feet (figs. 8-12, and 14). The mostly fine-grained sediments near Chico may consist in part of tuffaceous clay of the Tuscan Formation. As noted previously, the Tehama Formation, which underlies most of the western part of the Sacramento Valley, is composed of chiefly fine-grained sediments that for the most part were probably deposited under flood-plain conditions.

Selected texture columns also indicate the heterogeneity of the continental rocks and deposits (fig. 22). In the NW¼, T. 24 N., R. 3 W., the percentage of coarse-grained sediments increases below depths of about 600 feet; in the NW¼, T. 6 N., R. 3 E., the distribution of sediments has a more random pattern but shows a general increase in mostly coarse-grained sediment from depths of about 1,200 to 2,700 feet; and in the delta area in the NE¼, T. 3 N., R. 3 E., the percentage of coarse-grained sediments decreases below a depth of about 1,200 feet. In the San Joaquin Valley, the distribution of coarse-grained sediment is fairly uniform in the SE¼, T. 20 S., R. 20 E., but the percentage of coarse-grained sediment increases somewhat at depths between 1,500 and 2,400 feet; distribution of coarse-grained sediment also is fairly uniform in the NW¼, T. 28 S., R. 26 E., except for the smaller percentage of coarse-grained sediment between depths of 300 and 600 feet; distribution of coarse-grained sediment in the SW¼, T. 28 S., R. 26 E., is fairly uniform except for the very large percentage of coarse-grained sediment between depths of 300 and 600 feet; and in the SW¼, T. 31 S., R. 28 E., the distribution of coarse-grained sediment is fairly uniform to a depth of about 3,000 feet; below 3,000 feet the distribution is fairly uniform, but the percentage of coarse-grained sediment is smaller.

Obviously, local depositional environments have had a great effect on the distribution of coarse- and fine-grained sediments, as is indicated by the disparate patterns of sediment distribution in the texture columns for both the Sacramento and San Joaquin Valleys. The effect of local depositional environments also is indicated by changes in distribution over relatively small areas; for example, note the smaller percentage of coarse-grained sediment in the NW¼, T. 28 S., R. 26 E., compared with the percentage in the SW¼, T. 28 S., R. 26 E. (fig. 22). On the other hand, the effects of regional events, such as glaciation in the Sierra Nevada, are not readily apparent in these columns, maps, and sections (figs. 6-34).

Texture sections also indicate the lateral and vertical heterogeneity of the alluvial deposits in the Central Valley (figs. 22-34). Most of the sections were drawn to show changes in the percentage of coarse-grained sediment from high areas of present-day alluvial fans to low areas. Section E-E' (fig. 25) indicates the percentage of coarse-grained sediment in a low-lying area of the Sacramento Valley, where the percentage of coarse-grained sediment is generally small. In using the sections, it should be kept in mind that sediments in zones of equal depth were not necessarily deposited during the same time periods because depths of a given bed can differ greatly, as indicated by the modified E clay (pl. 4).

Many of the sections do not indicate a general decrease in the percentage of coarse-grained sediment from high to low areas, although deposits underlying high areas generally contain more gravel, and those underlying low areas, more sand. In both high and low areas many of the deposits probably are poorly sorted and are composed of clayey and silty sand or clayey, silty, and sandy gravel. Some of the coarse-grained sediment near the lower side of some sections probably was deposited by either the Sacramento River or the San Joaquin River, as in the SE¼, T. 26 N., R. 3 W., in section A-A' (fig. 23) or the NE¼, T. 1 N., R. 6 E., in section H-H' (fig. 26). Near the lower side of some sections, some of the fine-grained sediments are largely lacustrine and marsh deposits, as in the SW¼, T. 21 S., R. 21 E., and the SE¼, T. 21 S., R. 2 E., in secton O-O' (fig. 32) and in the SE¼, T. 24 S., R. 22 E., in section P-P' (fig. 33).

In the Central Valley, most of the deposits for which data are available contain no more than 40 to 60 percent of coarse-grained sediment (fig. 35), where coarse-grained sediment includes clayey and silty sand and gravel. Bar graphs are shown for only those depth zones that had 20 or more geophysical logs available. For the most part, data for the thick fine-grained sections underlying Tulare Lake bed were not included in the computations (see "Lacustrine and Marsh Deposits"). By comparing depth zones in figure 35 with the appropriate texture map (figs. 6-16), the areal distribution of the data used for the graphs can be determined. For example, in the San Joaquin Valley, a general increase in the percentage of coarse-grained sediment between the depths of 1,500 and 2,700 feet reflects in large part the influence of the mostly coarse-grained sediment around Tulare Lake bed and the Bakersfield area (figs. 11-14 and 35).

These maps and sections could be used by ground-water managers as a general guide for selecting test-hole sites and by modelers for assigning values for transmissivity and coefficient of storage with smaller values being assigned to the fine-grained sediments.

The maps and sections could also be used as a general guide for locating areas and depths of potential land subsidence. In alluvial basins where thick beds of fine-grained sediment have been deposited, as in the Central Valley, compaction of such beds results in land subsidence. For example, the greatest subsidence in the Central Valley has been in the Los Banos-Kettleman City area on the western side of the San Joaquin Valley (Poland and others, 1975, fig. 5). There, the maximum subsidence as of 1977 was 29.6 feet in an area about 10 miles southwest of Mendota (Ireland and others 1984, p. 7). Very little compaction has taken place in the upper 300 feet of the deposits in the Los Banos-Kettleman City area; most of the compaction has been between depths below land surface of about 300 and 1,100 feet. In this area, largely fine-grained sediments occur at those depths (figs. 7-9). Land has subsided in areas underlain by relatively coarse-grained sediment, as in the extreme southern part of the San Joaquin Valley, where a maximum subsidence of about 9 feet occurred between 1926 and 1970 (Ireland and others, 1982, fig. 30; Lofgren, 1975, pl. 4). There, however, some thick beds of clay and silt lie below depths of about 400 feet (Lofgren, 1975, tables 2 and 3). Land subsidence has also taken place along the western flank of the Sacramento Valley; from 1949 to 1964, for example, land at Zamora subsided more than 0.6 foot (Lofgren and Ireland, 1973, p. 18). Mostly fine-grained deposits underlie this part of the valley from depths of about 300 to at least 2,700 feet (figs. 7-14). Of course, other factors contribute to the amount and rate of compaction, such as water-level decline and the compressibility of the silt and clay beds.

## SUMMARY AND CONCLUSIONS

The Central Valley of California comprises about 20,000 $mi^2$ and is about 400 miles long and averages about 50 miles wide. The valley contains the Sacramento Valley on the north and the San Joaquin Valley on the south. Within the Central Valley, the most extensive geomorphic units are (1) dissected uplands, (2) low alluvial plains and fans, (3) river flood plains and channels, and (4) overflow lands and lake bottoms. The most prominent geomorphic unit is Sutter Buttes.

Geologically, the Central Valley is a large, northwestward-trending, asymmetric structural trough that has been filled with as much as 6 miles of sediment in the San Joaquin Valley and as much as 10 miles of sediment in the Sacramento Valley; these sediments range in age from Jurassic to Holocene. Granitic and metamorphic rocks crop out along most of the eastern and southeastern flanks of the Central Valley. Marine rocks of pre-Tertiary age crop out along most of the western flank of the valley, and marine rocks and deposits of Tertiary age crop out around Sutter Buttes and along the western, southwestern, southern, and southeastern flanks of the valley. Volcanic rocks and deposits of Pliocene age crop out chiefly along the northeastern flank.

In a few places in the San Joaquin Valley, marine rocks and deposits have been flushed of saline water and contain fresh water, which they yield to wells. In the Sacramento Valley, marine rocks and deposits have not been reported as yielding fresh water to wells.

Of all the volcanic rocks and deposits, only the Tuscan Formation, which crops out in the northeastern part of the Sacramento Valley, is of major importance to the fresh ground-water basin of the Central Valley.

The post-Eocene continental rocks and deposits contain most of the fresh ground water in the Central Valley and crop out over virtually the whole valley. In most places, these rocks and deposits are underlain by or contain saline water at depth. They range in thickness from 0 along the flanks of the Central Valley to more than 15,000 feet in the extreme southern part. In the southern part, however, the base of fresh water lies at a maximum depth of about 4,700 feet—the thickest section of fresh water in the Central Valley.

Some of the continental rocks and deposits of Tertiary age are not of great importance to the ground-water basin of the Central Valley because they commonly contain saline water, or the nature of their sediments prevents large yields to wells, or both. Included in this group are the Ione Formation and the Valley Springs Formation.

On the other hand, the Mehrten Formation is a unit of continental rocks and deposits of Tertiary age that is of great importance to the fresh ground-water basin of the Central Valley. The Mehrten crops out along the eastern side of the Central Valley and yields large quantities of water to wells.

Although continental rocks and deposits of Tertiary and Quaternary age compose a number of formations and informal deposits, in total they make up the major aquifer of the Central Valley. In most places, the similarity of sediment type between the continental rocks and some underlying rocks and deposits and even between separate units of continental rocks and deposits makes mapping of subsurface geologic contacts, with any degree of certainty, difficult. In this respect, a unit that can be mapped on the surface is difficult to delineate in the subsurface, and although such a unit can be called an aquifer, it merges with other units in the subsurface to form a major, widespread aquifer. In places, the aquifer is separated by confining beds which include lacustrine and marsh deposits that are much thicker and more extensive in the San Joaquin Valley than in the Sacramento Valley.

In the Central Valley, the continental rocks and deposits consist of heterogeneous mixes of gravel, sand, silt, and clay, and in places they contain beds of claystone, siltstone, sandstone, and conglomerate. Yields to wells from these rocks and deposits, except from the lacustrine and marsh deposits, differ greatly from place to place and range from about 20 to 4,500 gal/min.

Lacustrine and marsh deposits crop out in the San Joaquin Valley beneath Buena Vista, Kern, and Tulare Lake beds; they do not crop out in the Sacramento Valley. The expansion of the lakes and resulting deposition of extensive clays in the San Joaquin Valley might have occurred in two ways: (1) as water drained into the ancient structural basin beneath Tulare Lake bed, the existing lake or lakes expanded; and (2) streams to the north formed, or had formed, dams by building alluvial fans out into the axis of the valley, so that an expanding lake in the San Joaquin Valley could have been dammed by alluvial fans. In the Sacramento Valley, water from the rivers of the surrounding area probably did not accumulate in a large, downwarping basin like the one in the Tulare Lake bed area because such a basin, in which large lakes could form and expand, probably had not developed there. Before any large lakes could form behind alluvial dams, the dams in the Sacramento Valley probably were breached by a through-flowing trunk stream comparable to the present-day Sacramento River. Consequently, while widespread lacustrine clays were being deposited in large lakes in the San Joaquin Valley, lacustrine clays of only local extent probably were being deposited in relatively small lakes in the Sacramento Valley.

Continental deposits of Quaternary age include river deposits, flood-basin deposits, and sand dunes. The deposits crop out chiefly along the major rivers and streams of the valley as well as in other low-lying areas. River deposits include channel and flood-plain deposits; channel deposits consist chiefly of sand and gravel; and flood-plain deposits consist chiefly of sand and silt. River deposits are among the more permeable in the valley. Flood-basin deposits consist chiefly of fine silt and clay with some fine sand. Because of their fine-grained nature, the flood-basin deposits would not yield much water to wells and would impede the vertical movement of water. Sand dunes, which crop out chiefly in the eastern part of the San Joaquin Valley, consist of medium-to-coarse sand and some sand and silt that is very fine to fine. In general, the dunes are unsaturated, but they permit recharge from stream runoff, precipitation, or irrigation return.

The large structural trough of the Central Valley is the principal structure controlling the occurrence and movement of ground water in the area. As the flanks of the valley are higher than its axis, recharge from tributary rivers and streams, as well as from irrigation return, has caused heads in the ground water along the flanks to be higher than those along the axis. In the Central Valley, therefore, the overall ground-water movement is from the flanks toward the axis and from there toward the delta area. Secondary structures in the valley also influence the occurrence and movement of ground water, for example the Red Bluff arch at the northern end of the valley and the White Wolf fault at the southern end.

Texture columns, maps, and sections in depth intervals of 300 feet show that thick, chiefly coarse-grained sediments lie just north of Tulare Lake and that largely coarse-grained sediments lie in the central-eastern part of the valley and in the extreme southern part of the valley, as well as around and north of Sutter Buttes.

The thickest and most extensive sections of fine-grained sediment underlie Tulare Lake bed. There, the fine-grained sediments are more than 3,600 feet thick in places, and at depth underlie an area of nearly 1,000 $mi^2$. Other areas in the valley are also underlain by mostly fine-grained sediments, but in those areas the fine-grained sediments are interbedded with coarse-grained sediments and are not nearly as thick and homogeneous as the fine sediments underlying Tulare Lake bed. Such areas of mostly fine-grained sediments lie along the southeastern, northeastern, and western flanks of the valley.

The post-Eocene continental rocks and deposits of the Central Valley, therefore, constitute a heterogeneous mixture in which texture differs over short distances and depths from chiefly fine-grained to chiefly coarse-grained sediments and vice versa. Obviously, local depositional environments have had a great effect on the distribution of coarse- and fine-grained sediments, as indicated by the disparate patterns of sediment distribution in the texture columns, maps, and sections. On the other hand, the effects of regional events, such as glaciation in the Sierra Nevada, are not readily apparent in these illustrations.

Although the texture of the continental rocks and deposits differs greatly over short distances and depths, some areas in the Central Valley are underlain chiefly by coarse-grained sediment and others by fine-grained sediment; for those areas that have like sediment size, sources and depositional environments probably were similar for long periods of time. The thick section of fine-grained sediments underlying

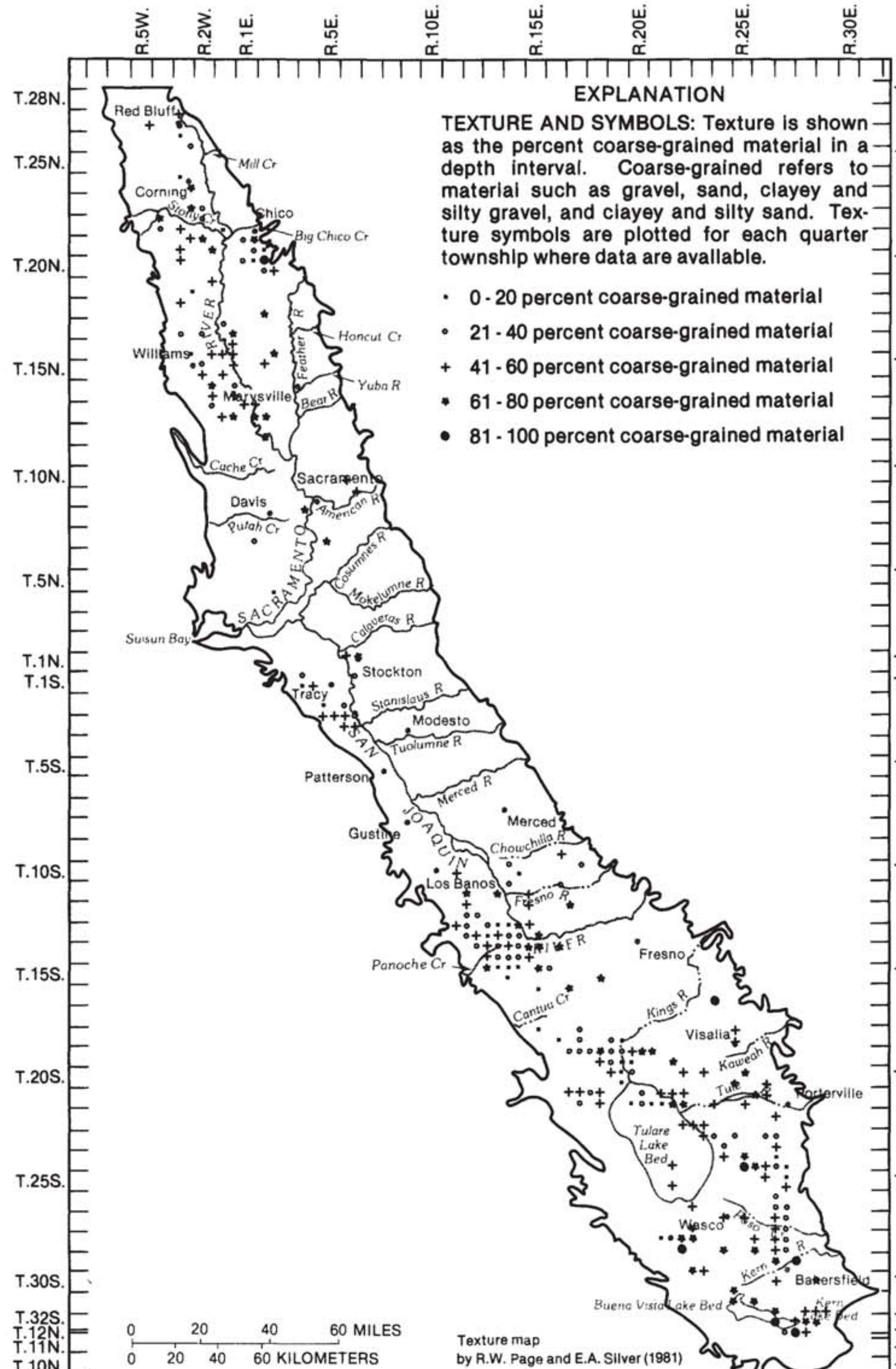



**Figure 6.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 0 to 300 feet.

Tulare Lake bed is an example. The distribution of thick, coarse-grained sediments north of Sutter Buttes indicates that through time Big Chico Creek, Stony Creek, the Feather River, and their antecedents probably have contributed proportionally more coarse-grained sediment to the Sacramento Valley than has the Sacramento River.

In the Central Valley, most of the rocks and deposits contain no more than 40 to 60 percent coarse-grained sediment, where coarse-grained sediment in-

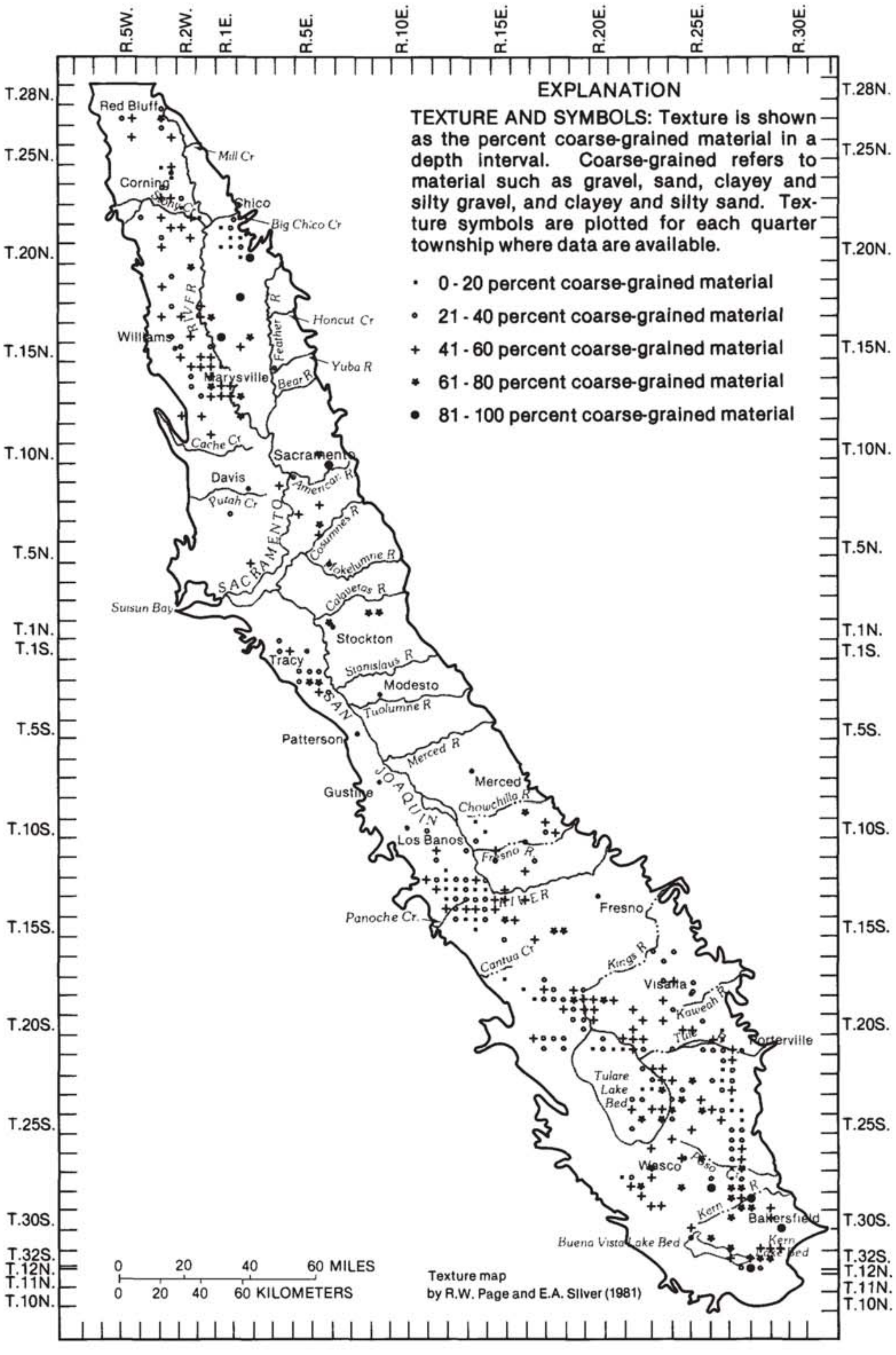



**Figure 7.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 300 to 600 feet.

cludes clayey and silty sand and clayey and silty gravel.

The texture maps and sections could prove useful to ground-water managers as a general guide for selecting test-hole sites and to modelers for assigning values for transmissivity and coefficient of storage with smaller values being assigned to the fine-grained sediments. The maps and sections also could be used as a general guide for locating areas and depths of potential land subsidence.

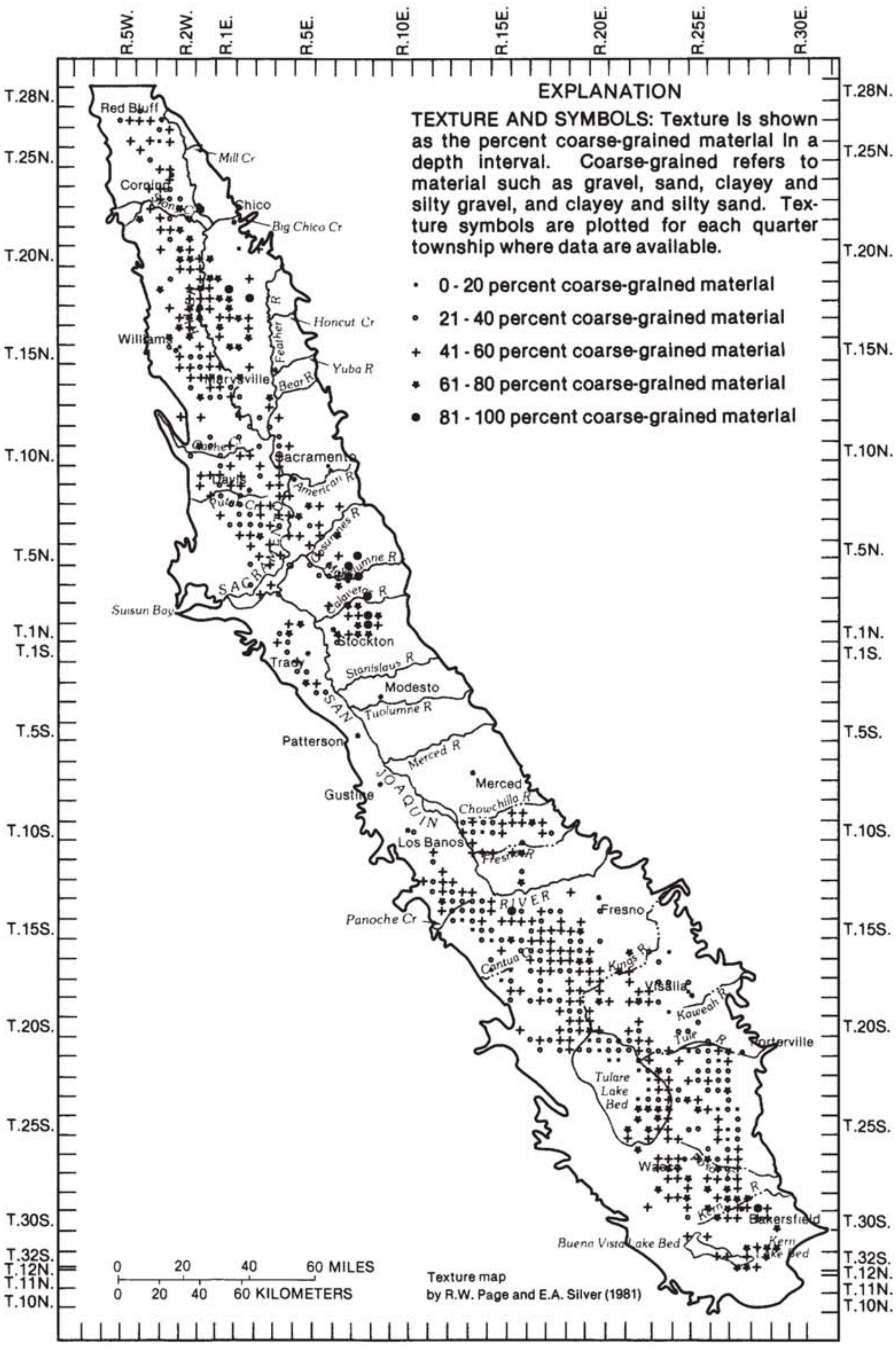



**Figure 8.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 600 to 900 feet.

Although widespread lacustrine clays have been deposited in the San Joaquin Valley, similar widespread clays probably have not been deposited in the Sacramento Valley. As a result, ground water in the San Joaquin Valley is confined over large areas beneath widespread clays, in addition to unconfined and locally confined conditions, but ground water in the Sacramento Valley is confined probably over relatively small areas beneath clays of only local extent.

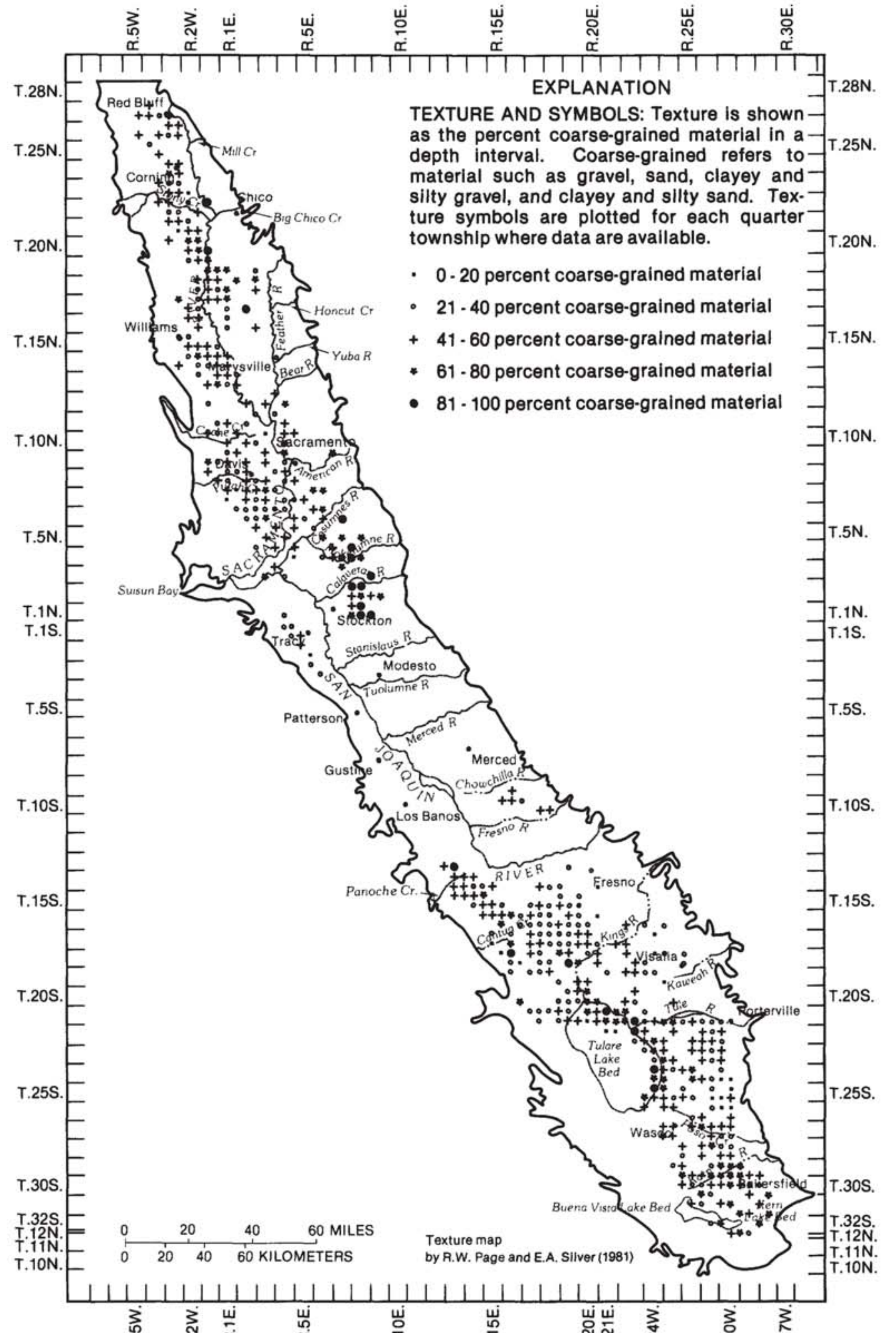



**Figure 9.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 900 to 1,200 feet.

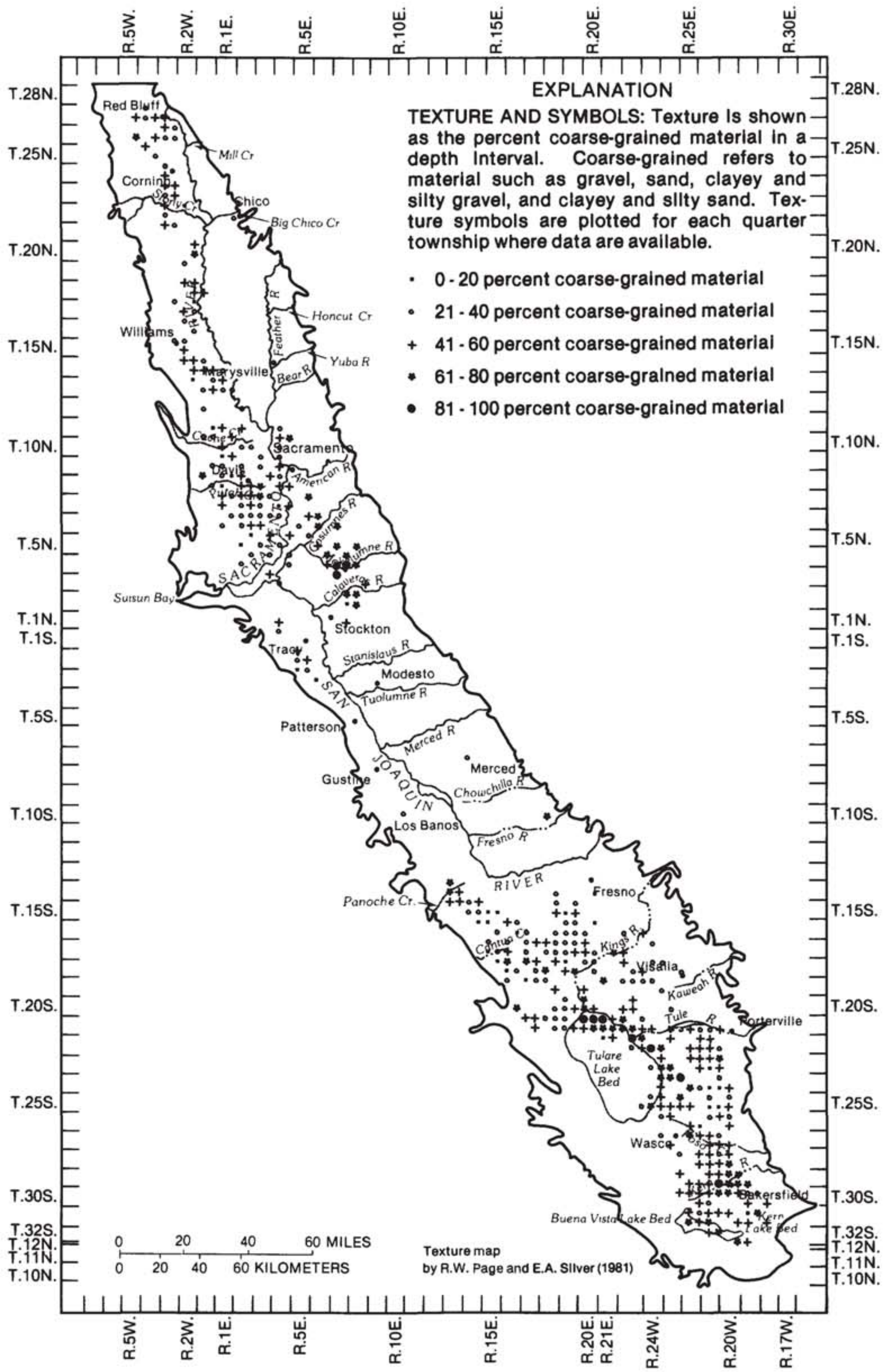



**Figure 10.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 1,200 to 1,500 feet.

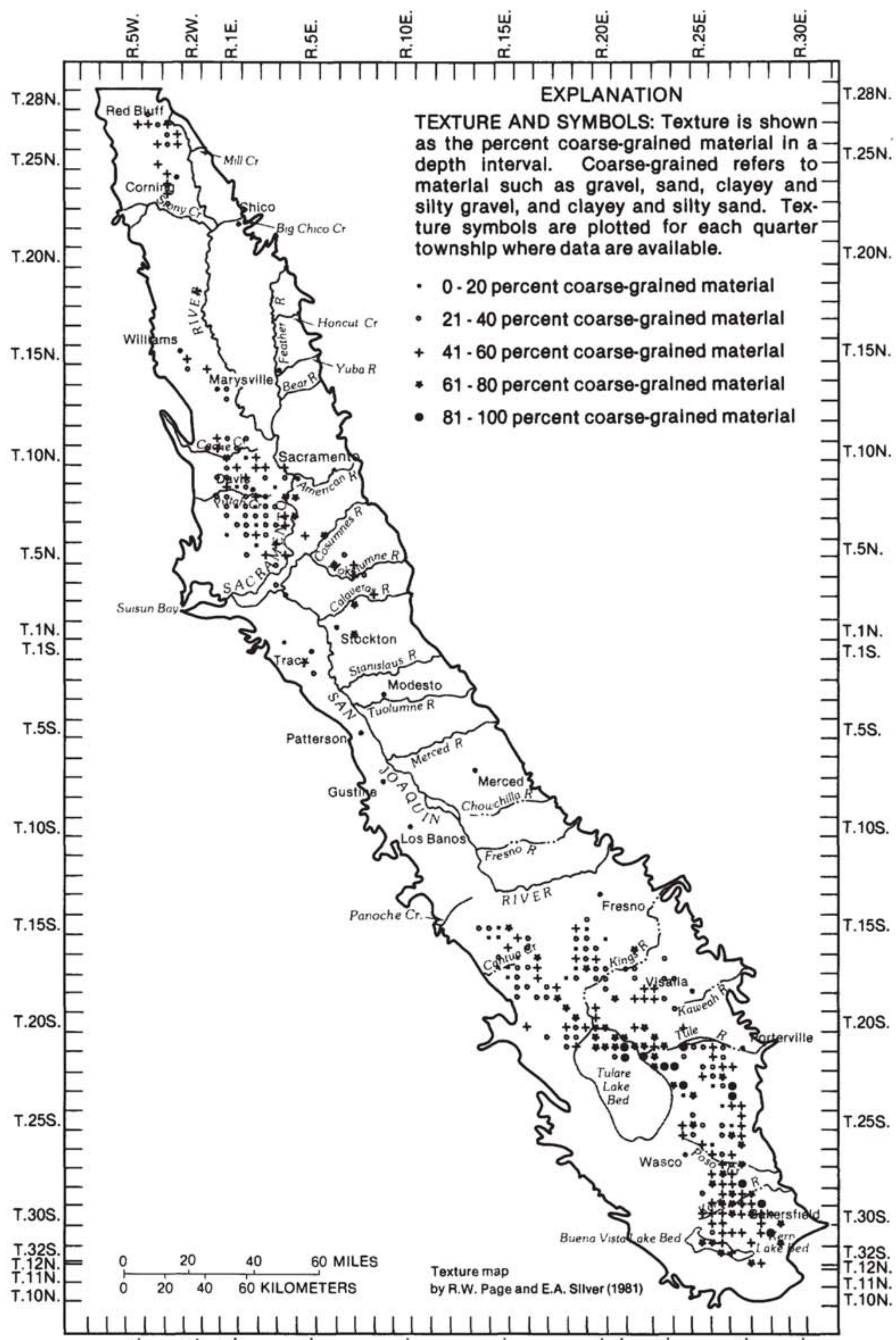



**Figure 11.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 1,500 to 1,800 feet.

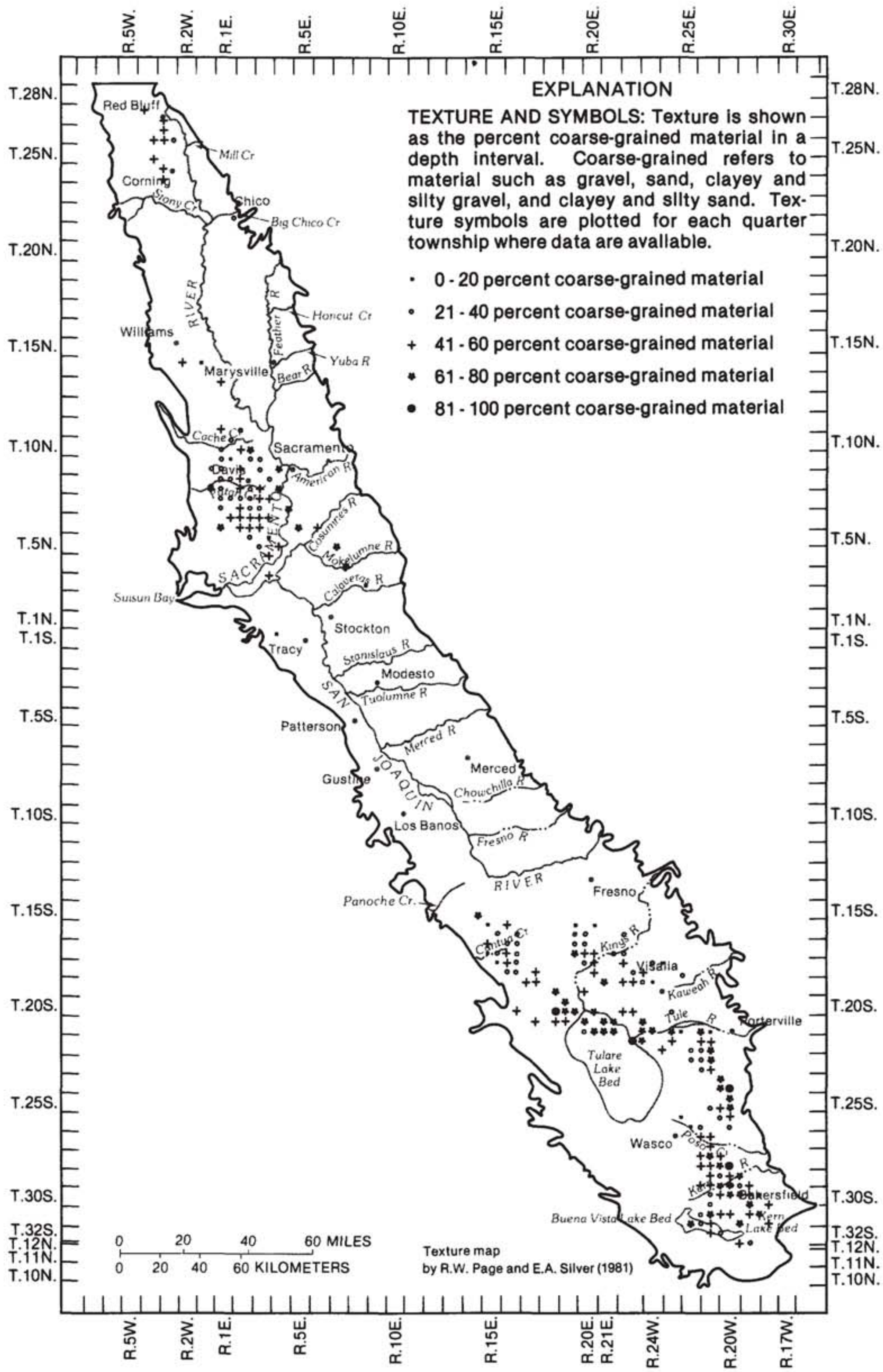



**Figure 12.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 1,800 to 2,100 feet.

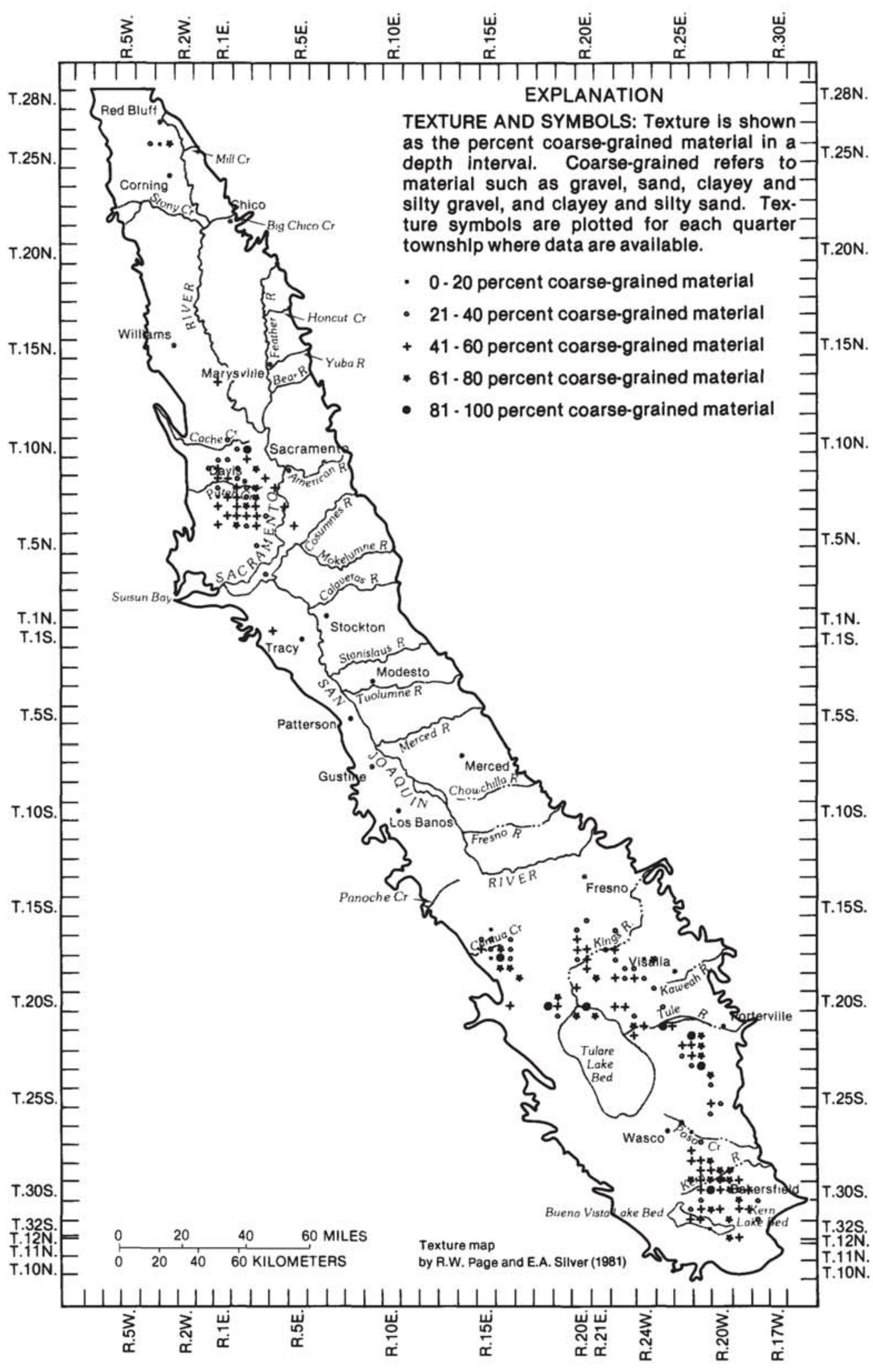



**Figure 13.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 2,100 to 2,400 feet.

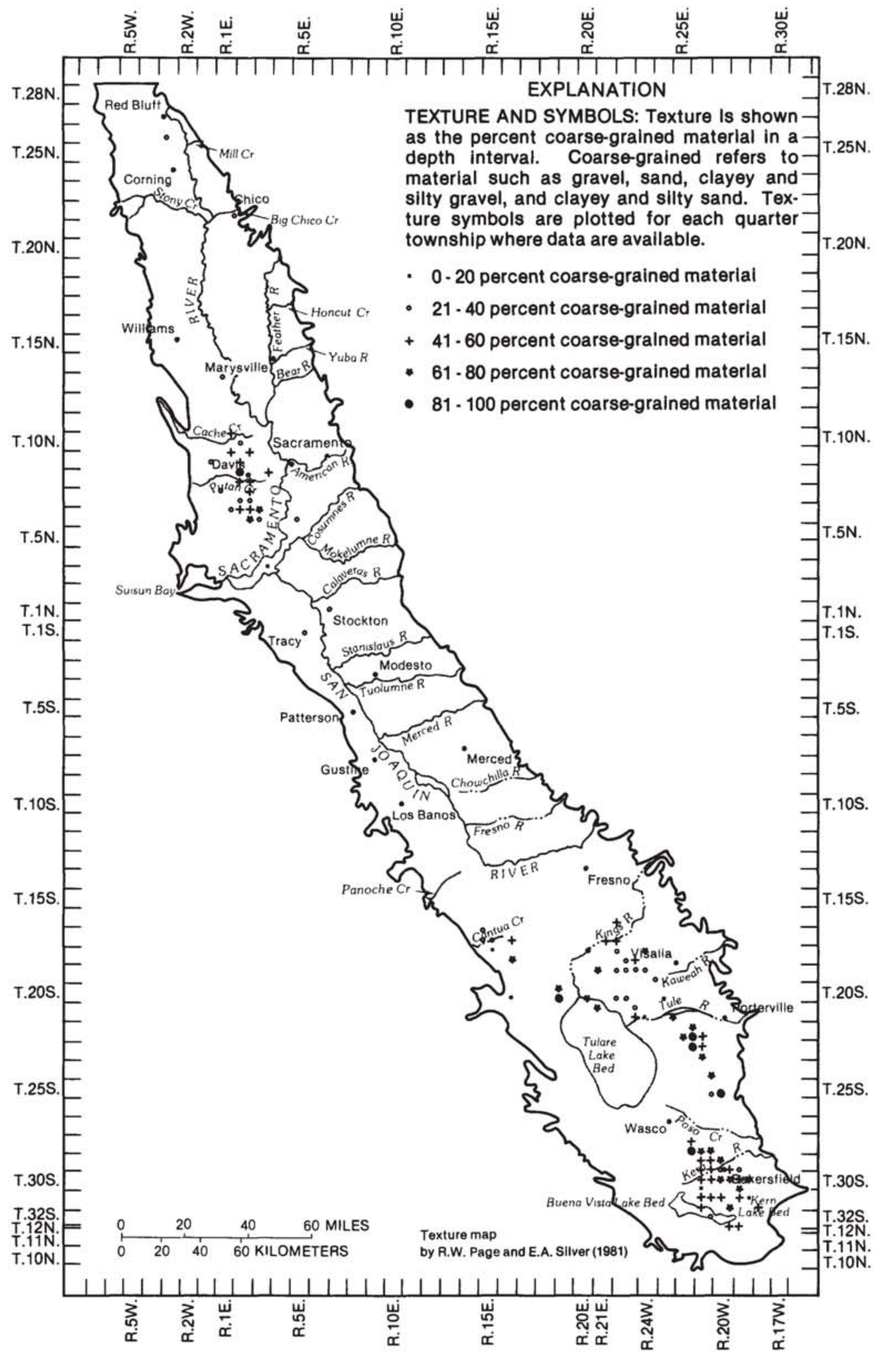



**Figure 14.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 2,400 to 2,700 feet.

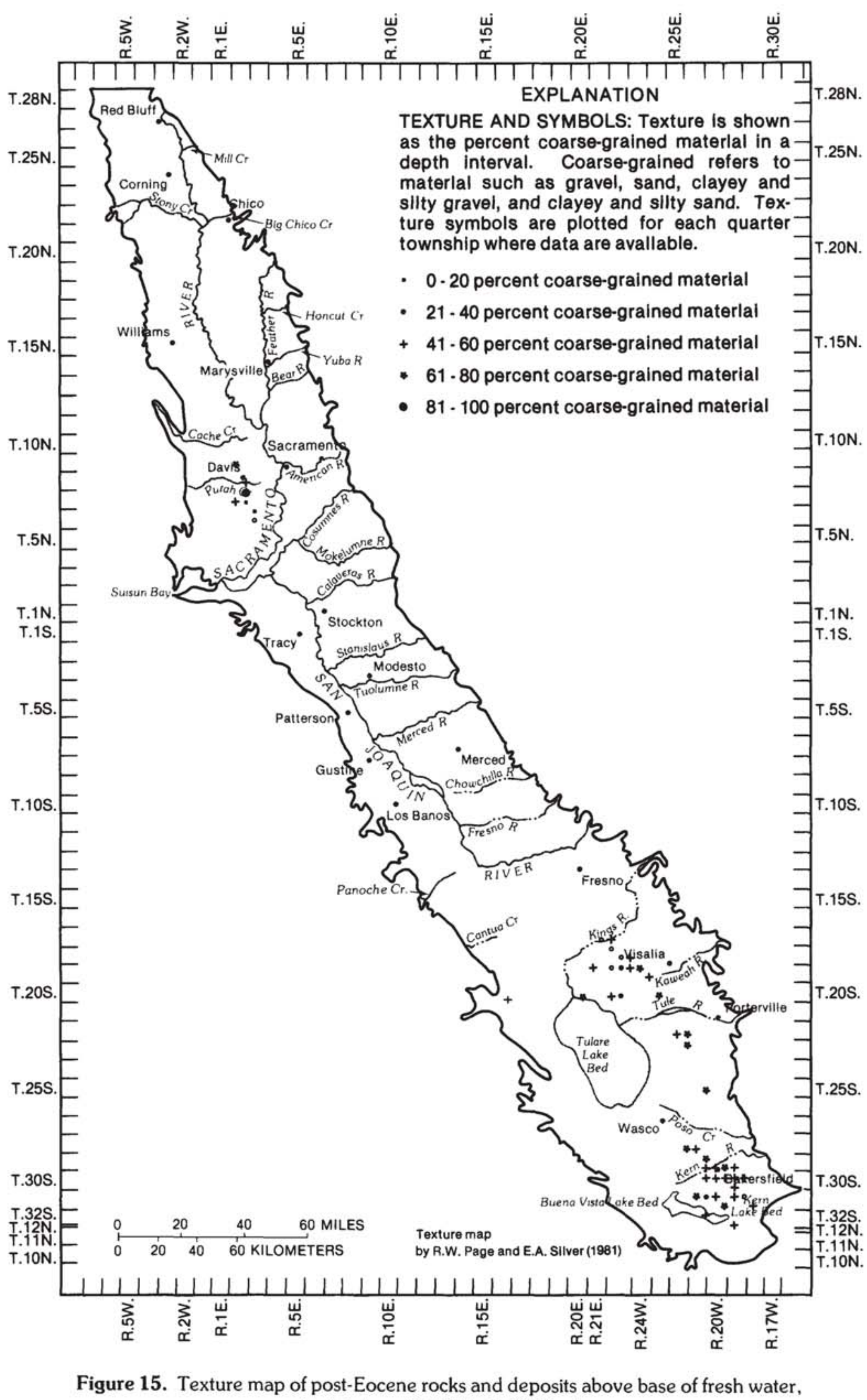



**Figure 15.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 2,700 to 3,000 feet.

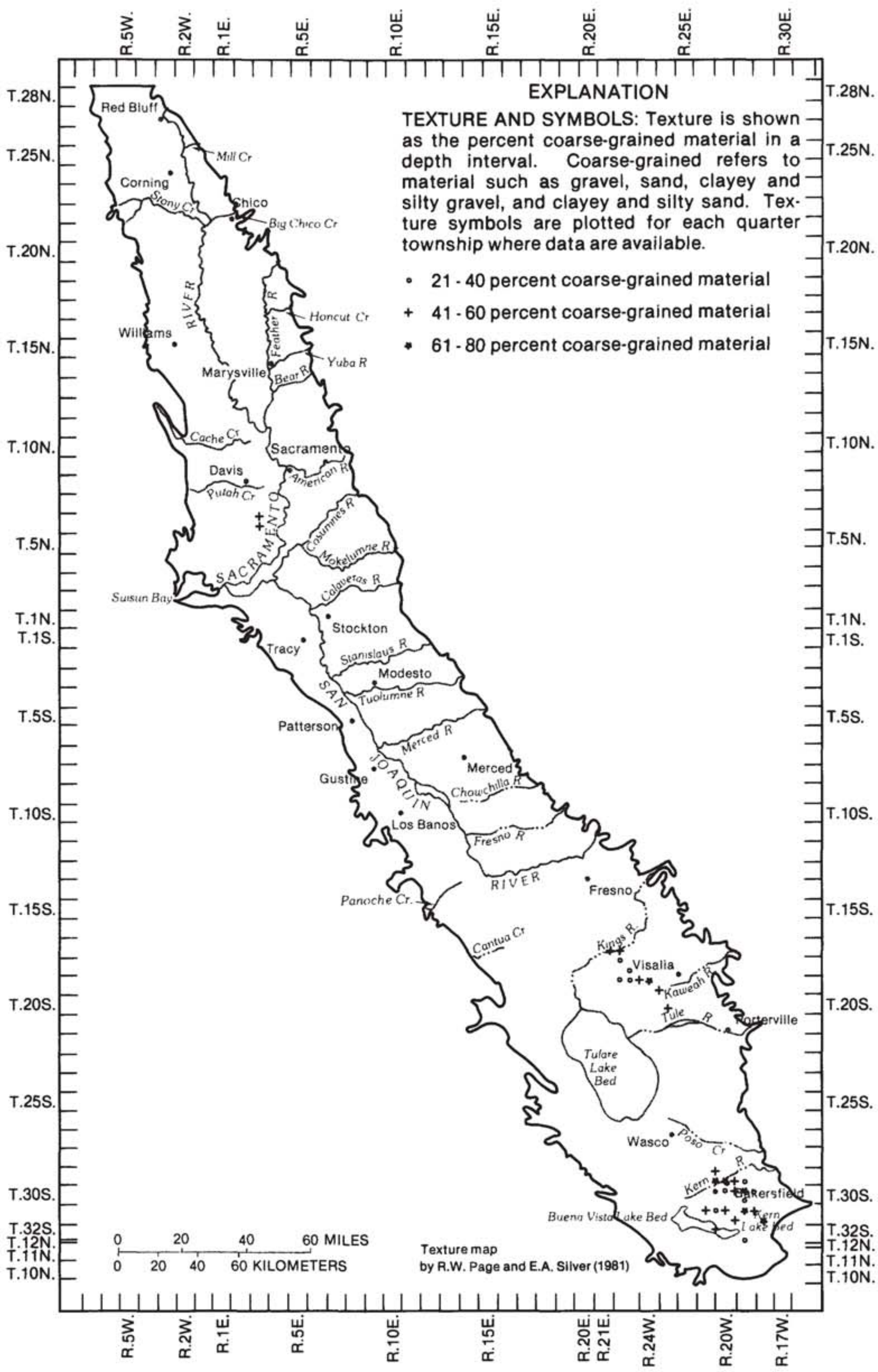



**Figure 16.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 3,000 to 3,300 feet.

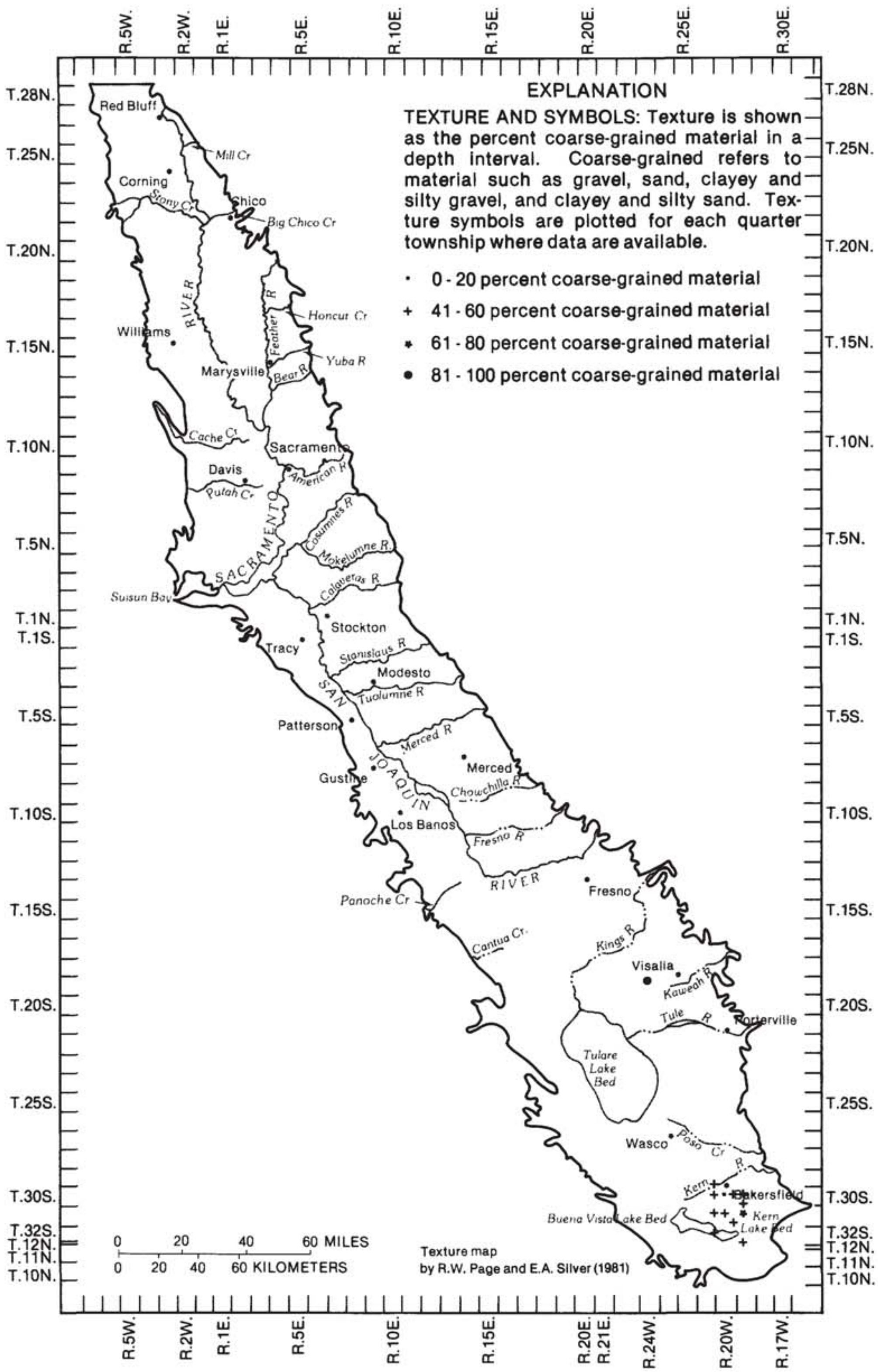



**Figure 17.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 3,300 to 3,600 feet.

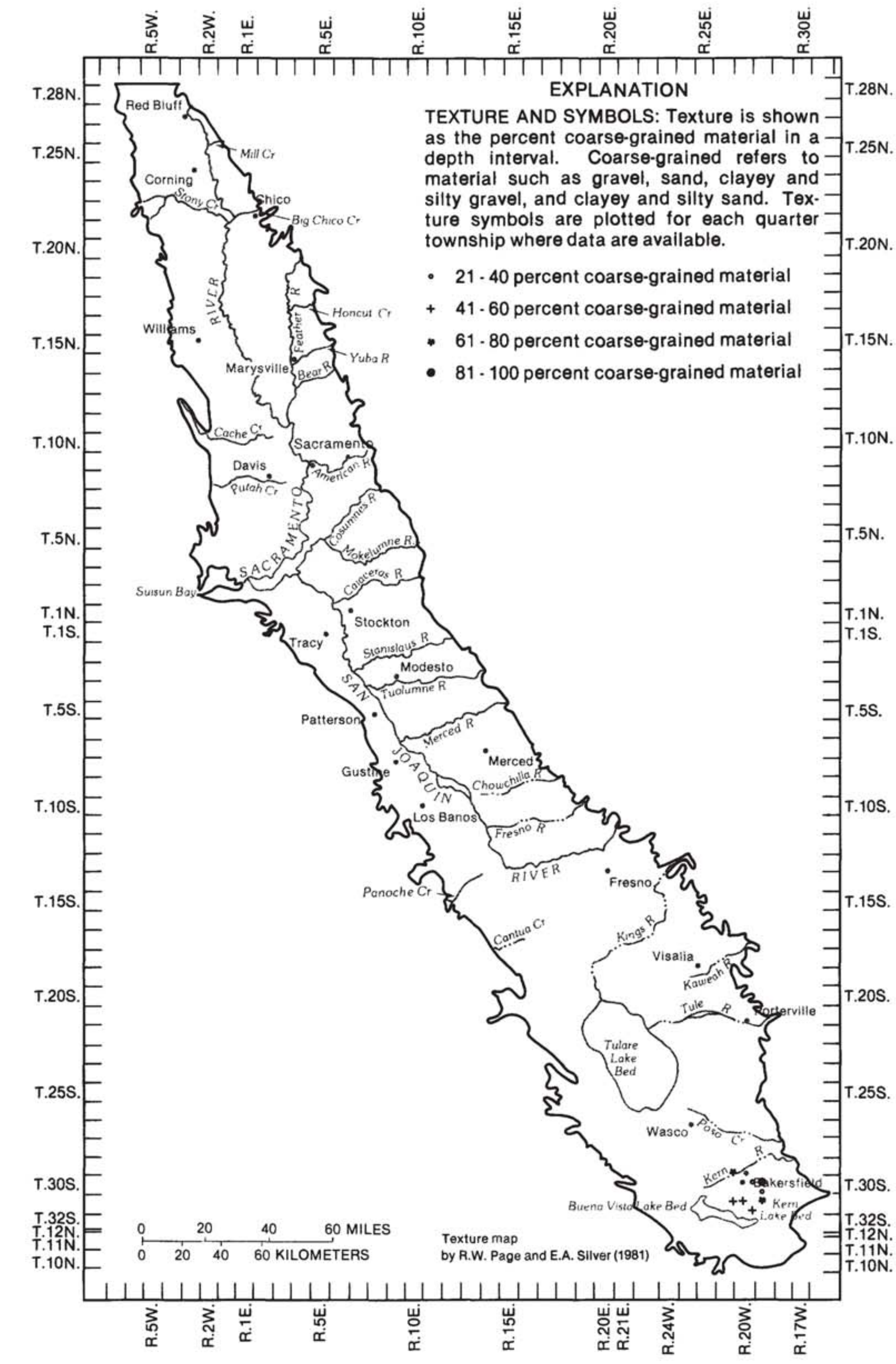



**Figure 18.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 3,600 to 3,900 feet.

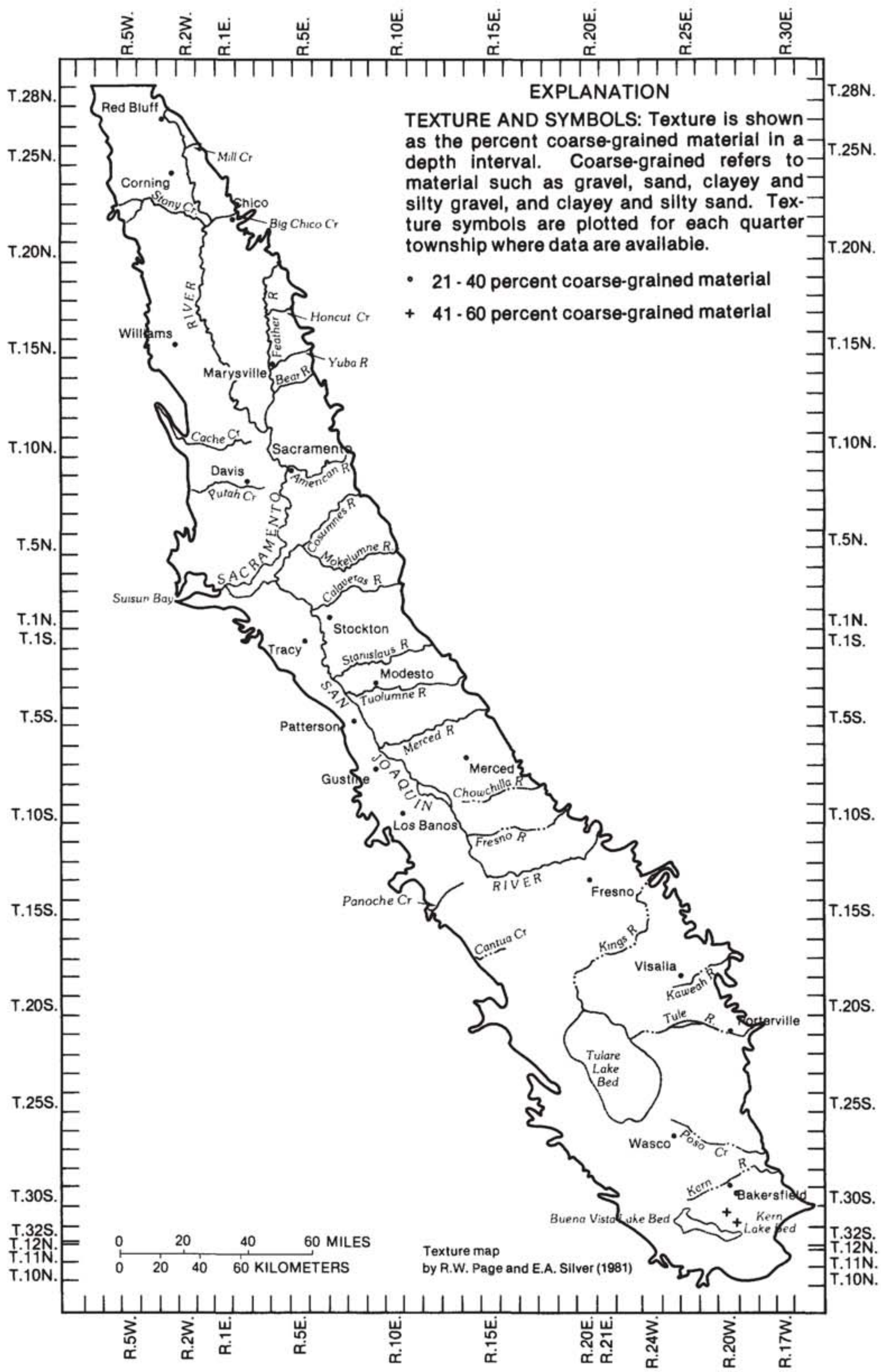



**Figure 19.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 3,900 to 4,200 feet.

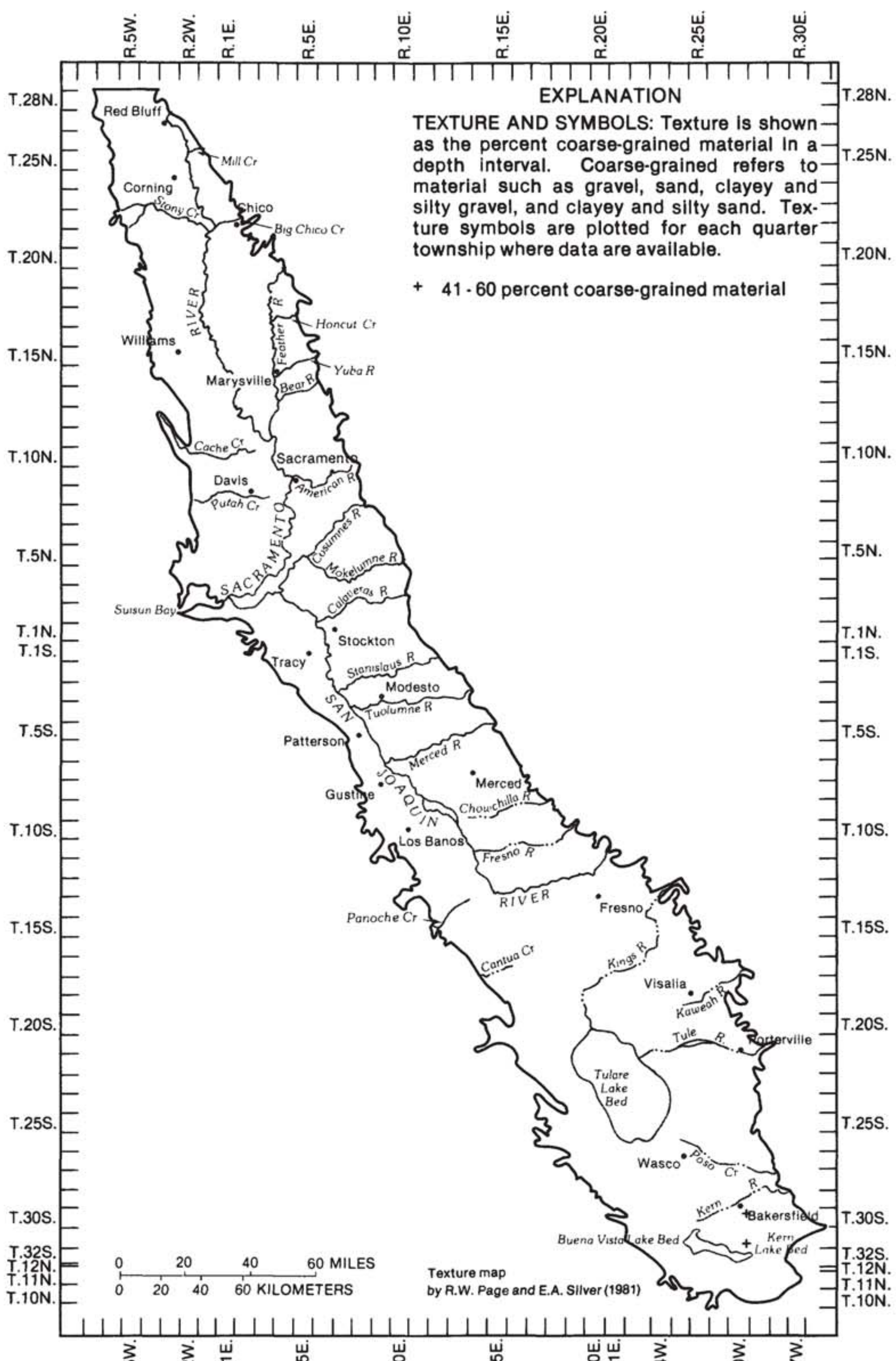



**Figure 20.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 4,200 to 4,500 feet.

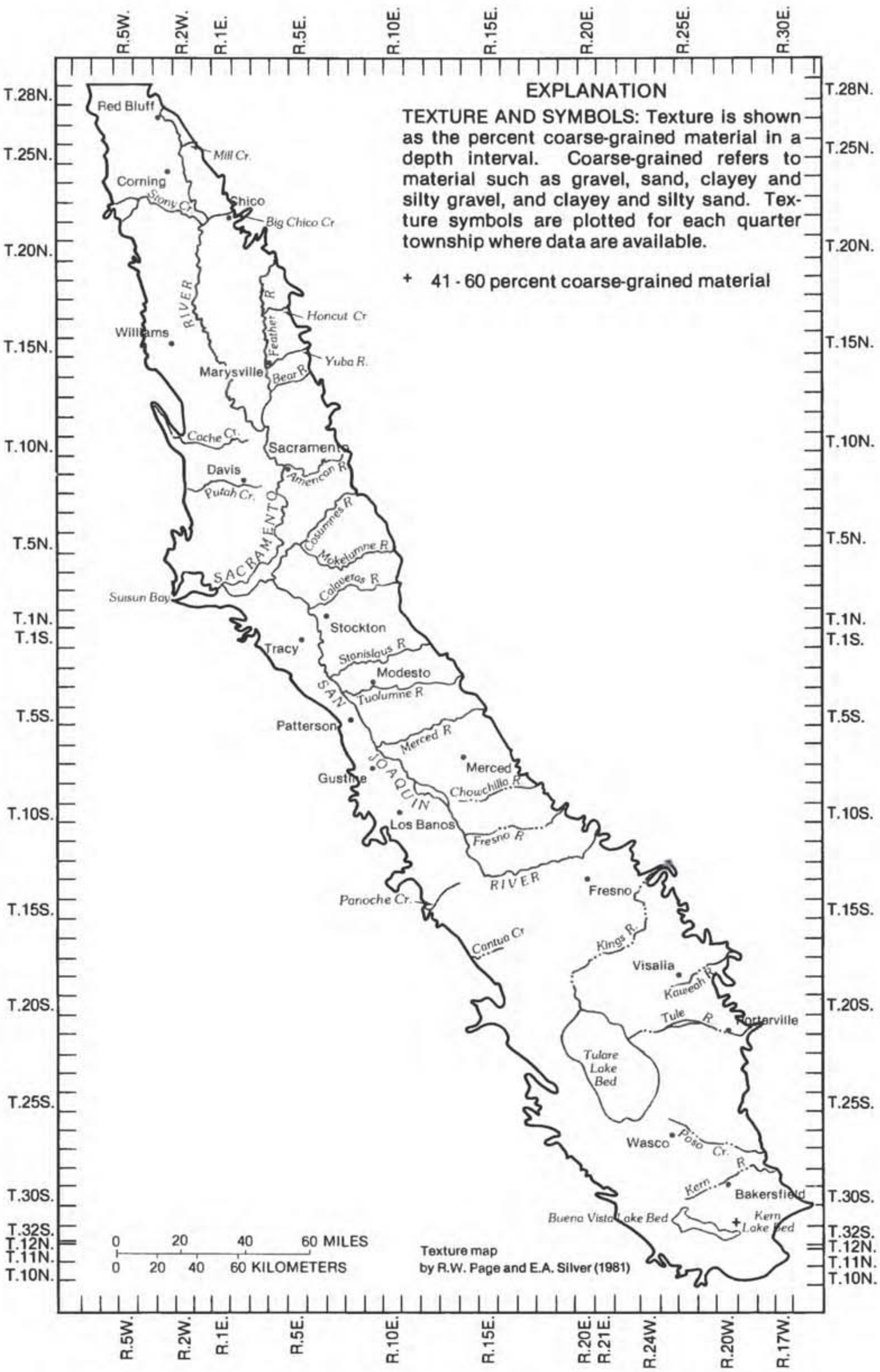



**Figure 21.** Texture map of post-Eocene rocks and deposits above base of fresh water, depth interval 4,500 to 4,800 feet.

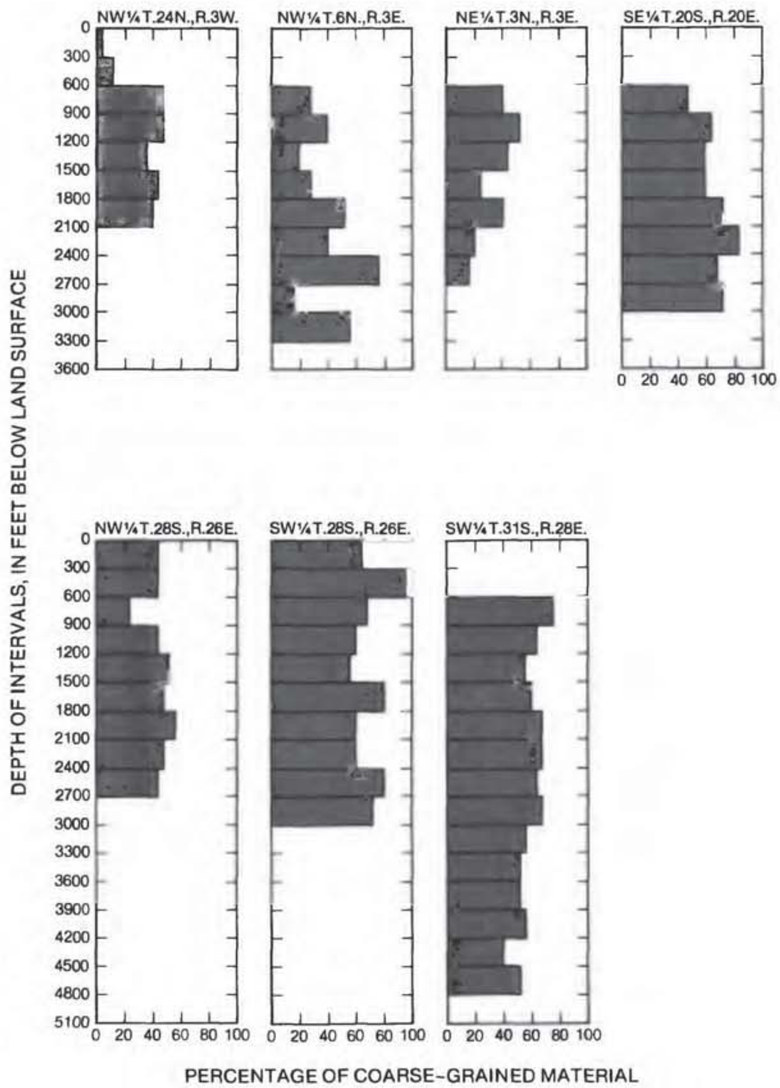



**Figure 22.** Selected texture columns.

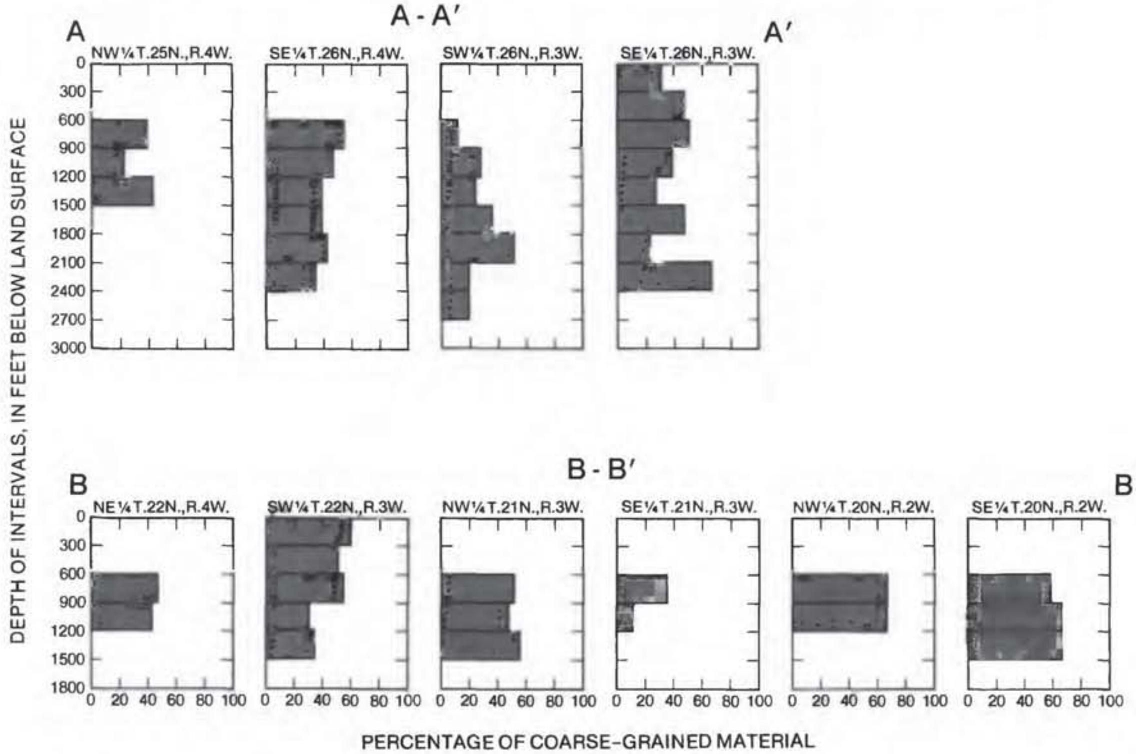



**Figure 23.** Texture sections A-A′ and B-B′.

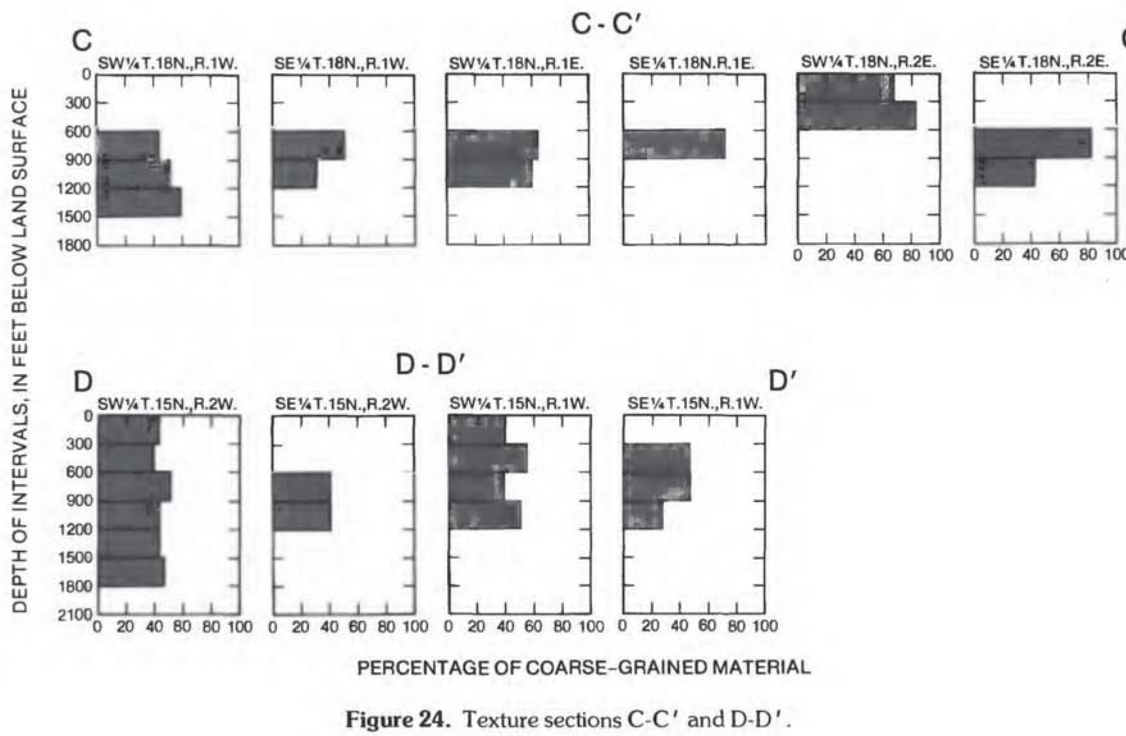



**Figure 24.** Texture sections C-C′ and D-D′.

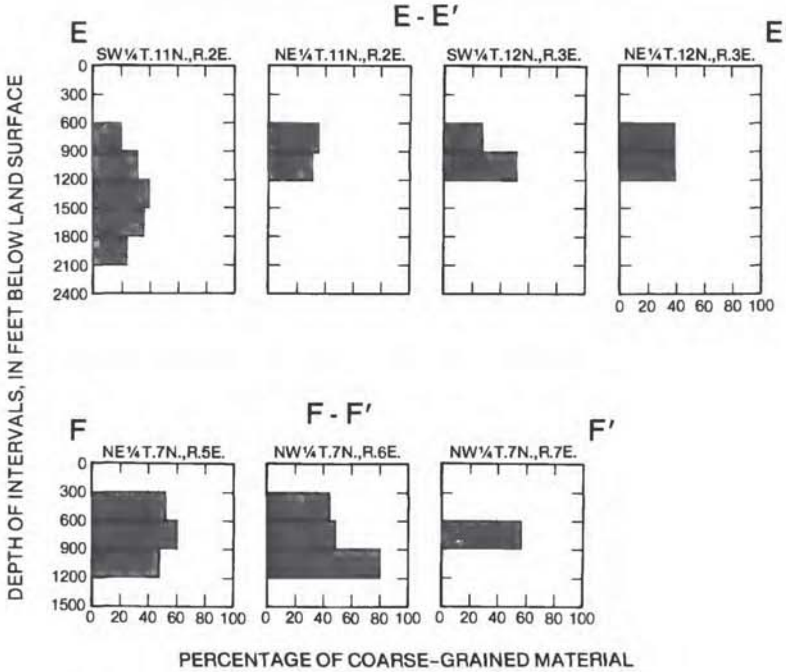



**Figure 25.** Texture sections E-E' and F-F'.

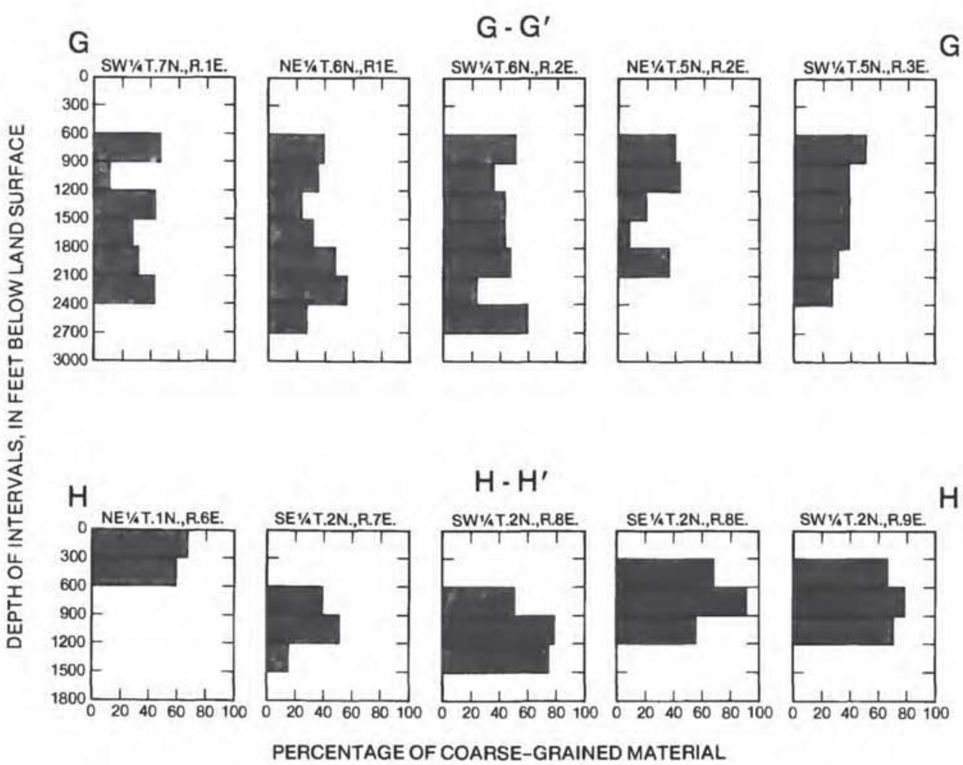



**Figure 26.** Texture sections G-G' and H-H'.

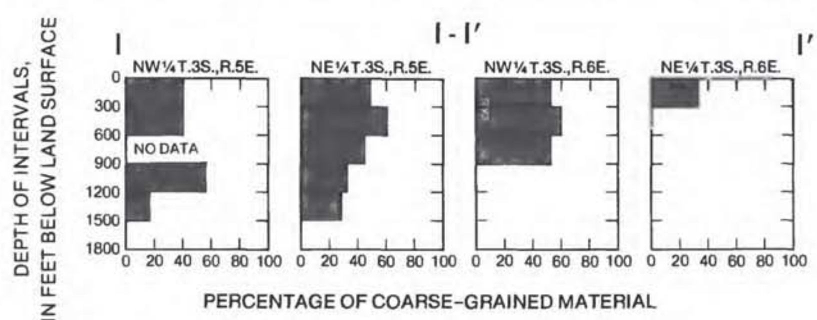



**Figure 27.** Texture section I-I′.

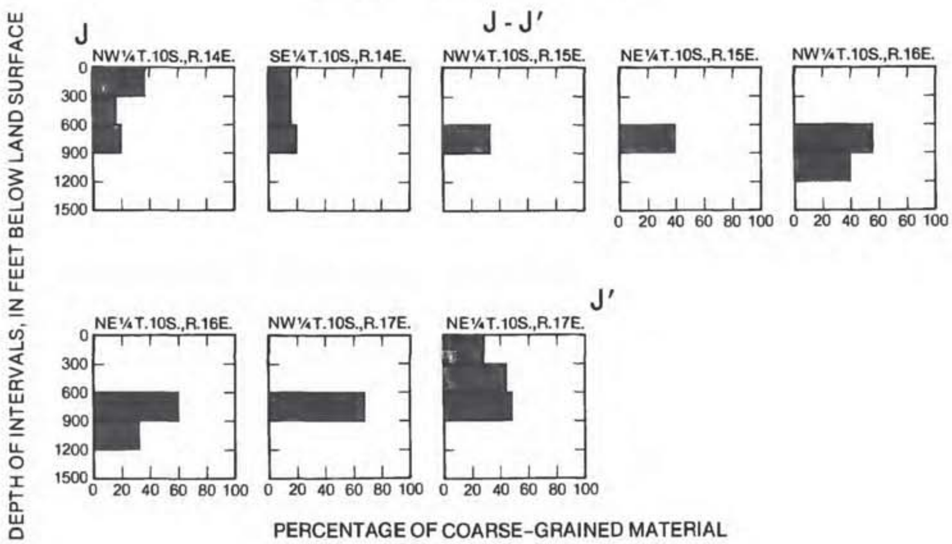



**Figure 28.** Texture section J-J′.

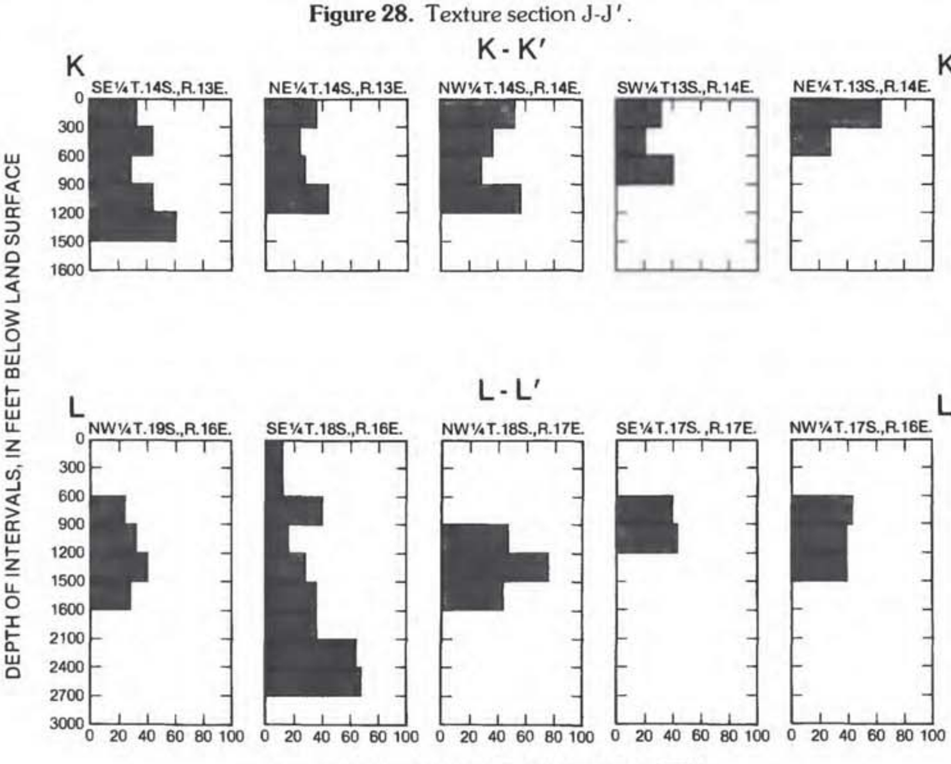



**Figure 29.** Texture sections K-K′ and L-L′.

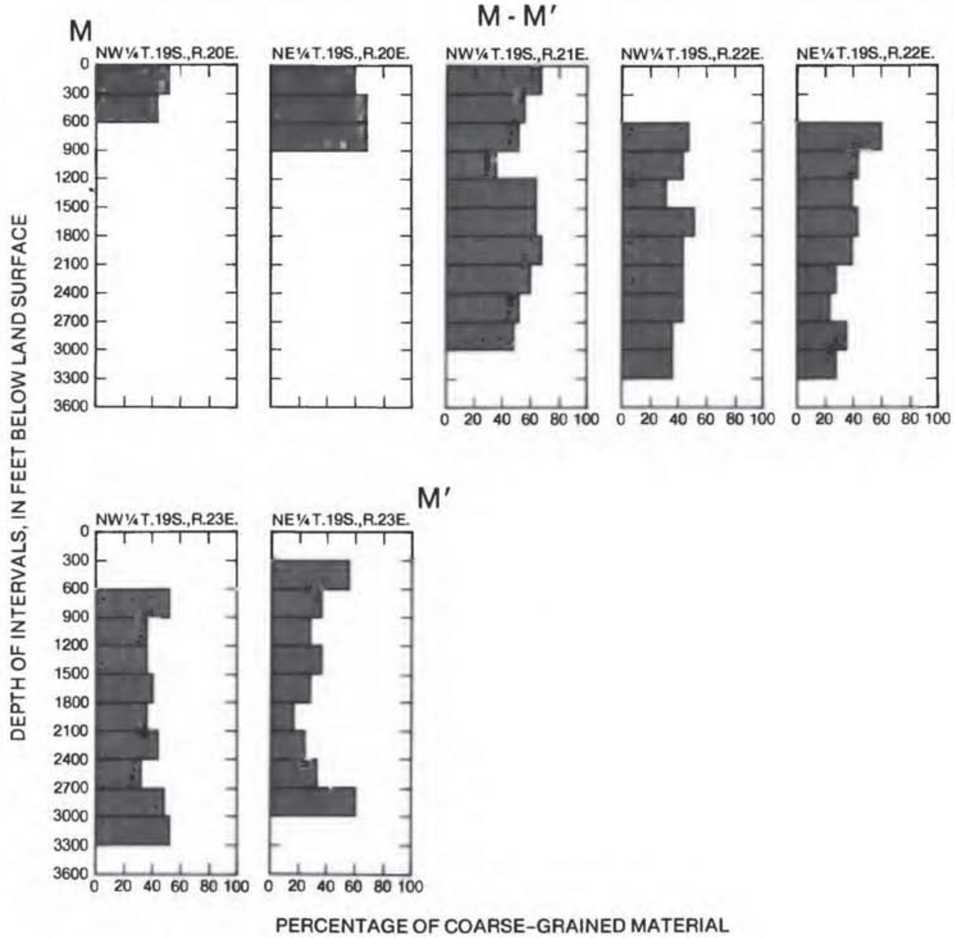



**Figure 30.** Texture section M-M'.

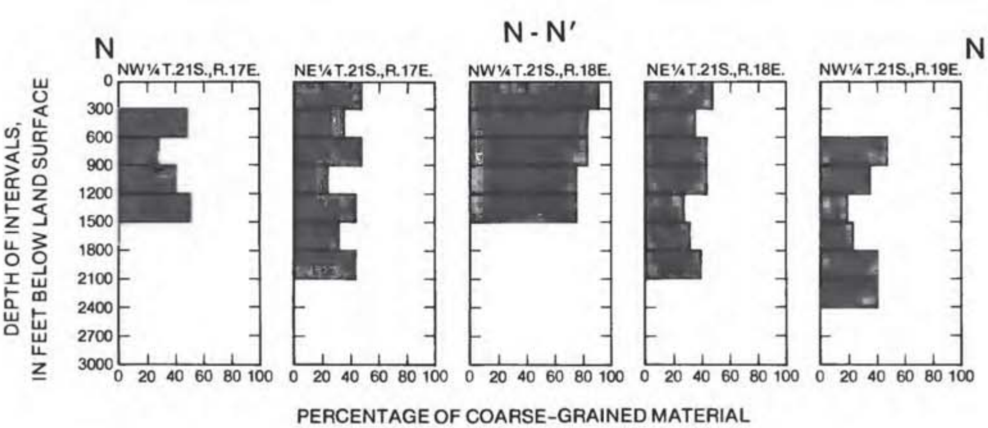



**Figure 31.** Texture section N-N'.

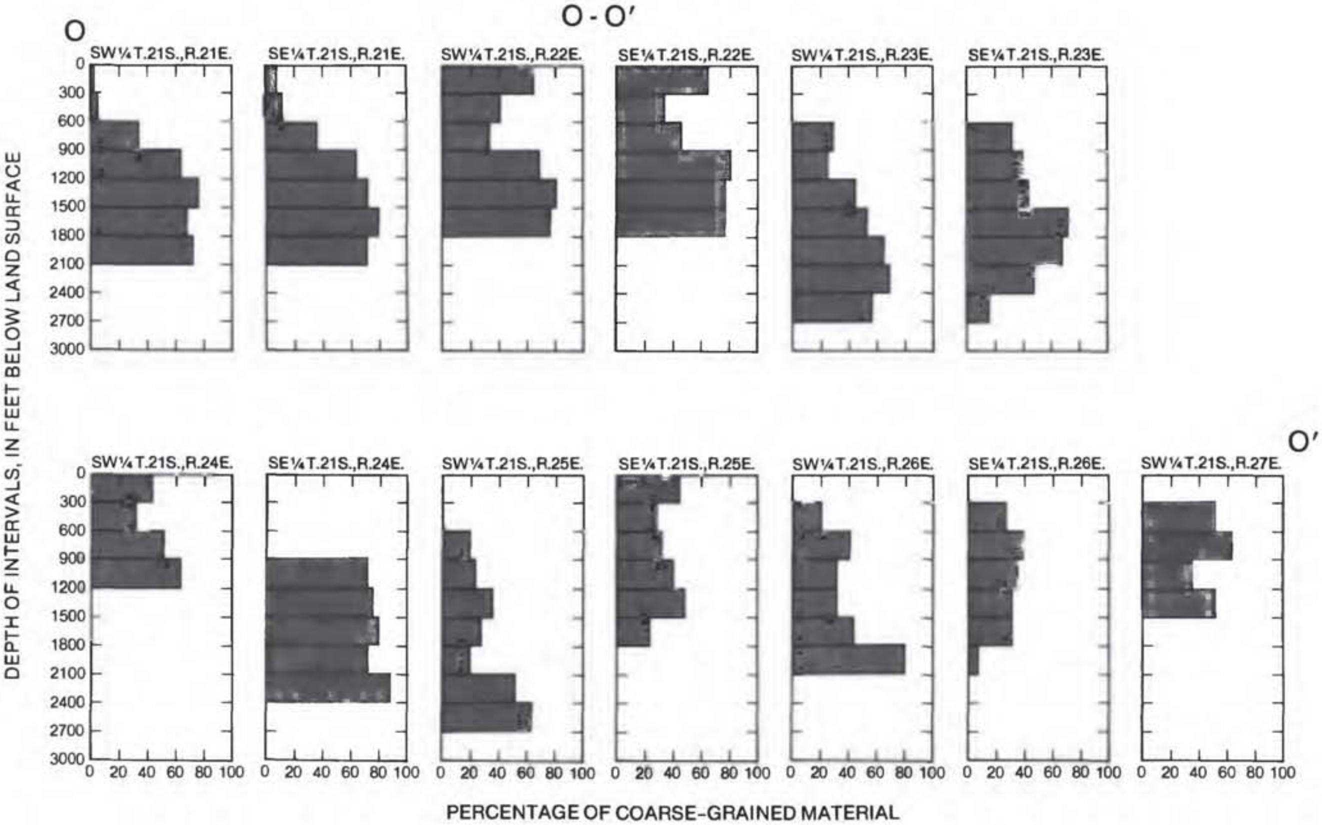



**Figure 32.** Texture section O-O′.

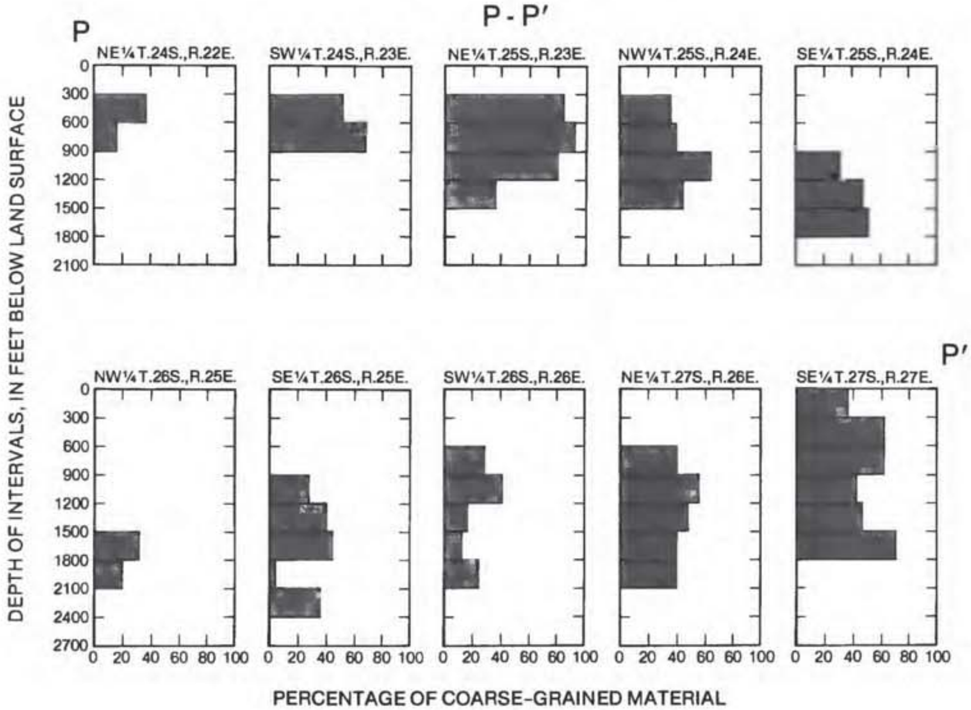



**Figure 33.** Texture section P-P′.

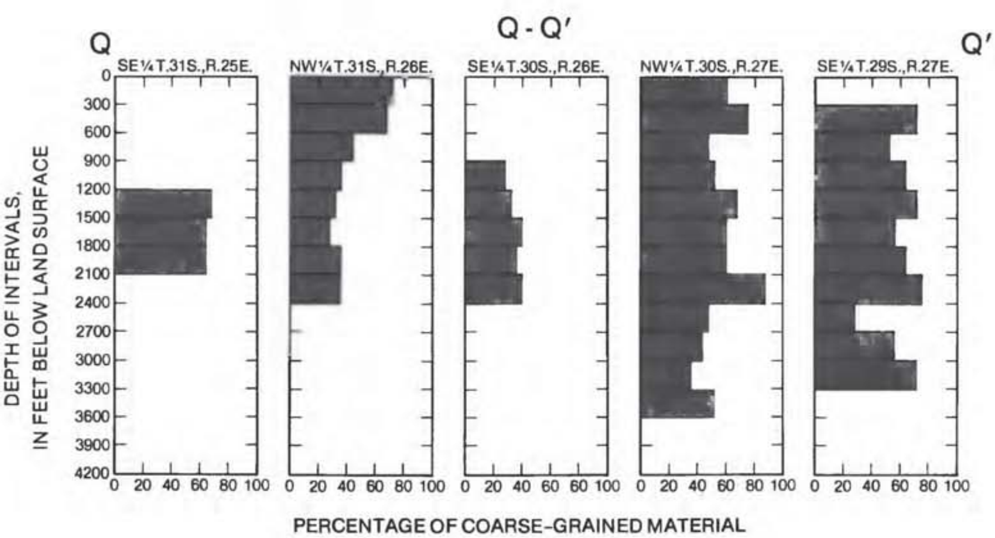



**Figure 34.** Texture section Q-Q′.

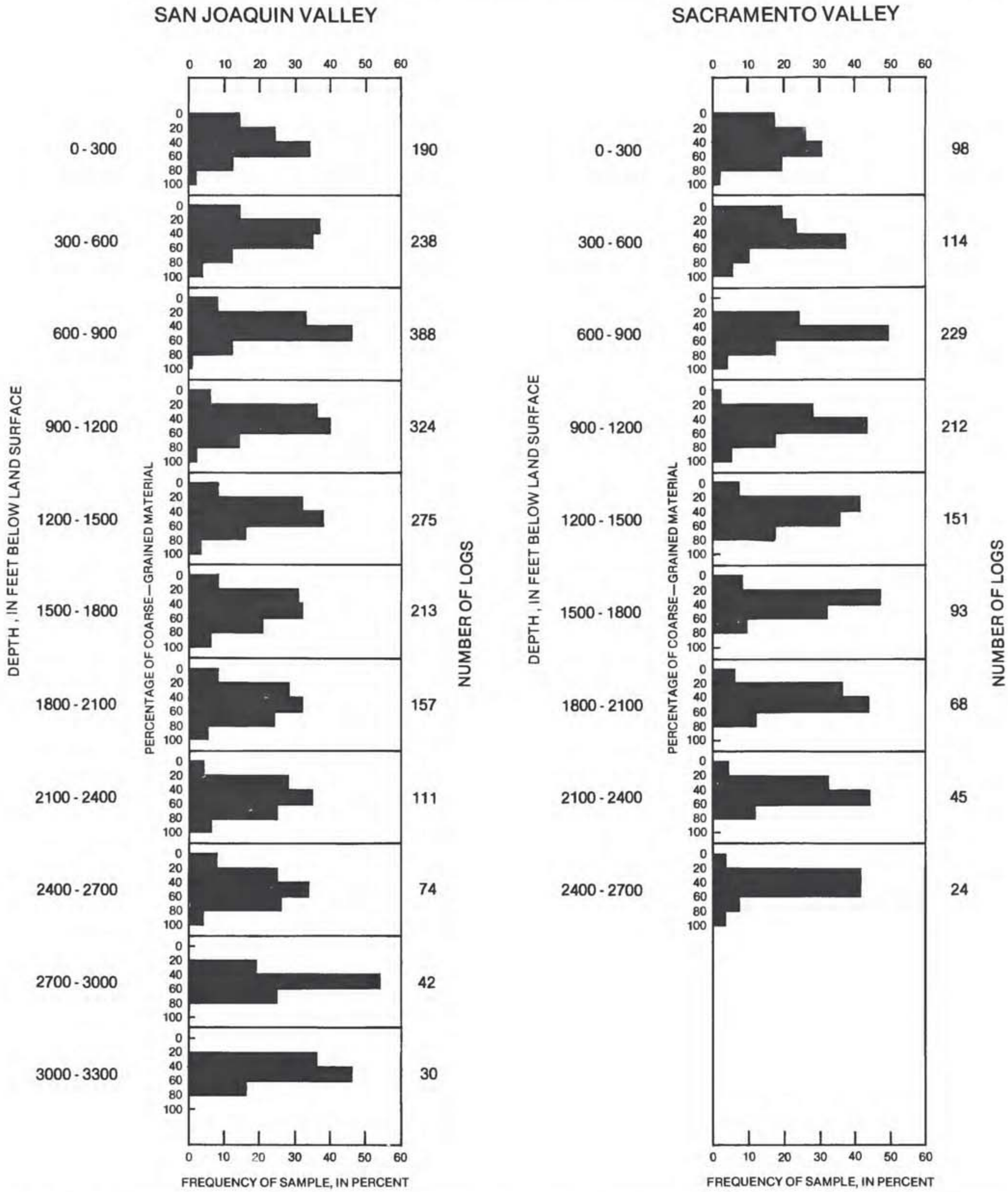



**Figure 35.** Bar graphs showing frequency of occurrence of coarse-grained sediment by depth, Sacramento and San Joaquin Valleys.

## SELECTED REFERENCES


Addicott, W. O., 1970, Miocene gastropods and biostratigraphy of the Kern River area, California: U.S. Geological Survey Professional Paper 642, 174 p.

Albright, M. B., Hluza, A. G., and Sullivan, J. C., 1957, Mount Poso oil field: California Department of Natural Resources, Division of Oil and Gas, Summary of Operations, California Oil Fields, v. 42, no. 2, p. 5-21.

Allen, V. T., 1929, The Ione Formation of California: California University Pubs., Department of Geological Science Bulletin, v. 18, no. 14, p. 347-448.

American Association of Petroleum Geologists, 1951, Cenozoic correlation section from northside Mt. Diablo to eastside Sacramento Valley, through Rio Vista-Thorton-Lodi gas fields, California: Pacific Section, American Association of Petroleum Geologists, 2 sheets.

———1957, Correlation section across central San Joaquin Valley from San Andreas fault to Sierra Nevada foot hills: Pacific Section, American Association of Petroleum Geologists, 1 sheet.

———1958a, Correlation sections longitudinally north-south through Central San Joaquin Valley from Rio Vista through Riverdale (10 North), California: Pacific Section, American Association of Petroleum Geologists, 1 sheet.

———1958b, Correlation sections longitudinally north-south through Central San Joaquin Valley from Riverdale through Tejon Ranch area (10 South), California: Pacific Section, American Association of Petroleum Geologists, 1 sheet.

———1960, Correlation section longitudinally north-south through Sacramento Valley from Red Bluff to Rio Vista, California: Pacific Section, American Association of Petroleum Geologists, 1 sheet.

Anderson, Robert, and Pack, R. W., 1915, Geology and oil resources of the west border of the San Joaquin Valley north of Coalinga, California: U.S. Geological Survey Bulletin 603, 220 p.

Atwater, B. F., 1979, Generalized geologic map of the Rio Vista 15-minute quadrangle, California: U.S. Geological Survey Open-File Report 79-853, scale 1:62,500.

———1982, Geological maps of the Sacramento-San Joaquin Delta, California: U.S. Geological Survey Miscellaneous Field Studies Maps MF-1401, 21 sheets, scale 1:24,000.

Atwater, B. F., and Marchand, D. E., 1980, Preliminary geologic maps showing late Cenozoic deposits of the Braceville, Elk Grove, Florin, and Galt 7.5-minute quadrangles, Sacramento and San Joaquin Counties, California: U.S. Geological Survey Open-File Report, scale 1:24,000.

Axelrod, D. I., 1944, The Oakdale flora: Washington, Carnegie Institute Publication 553, p. 147-165.

Bandy, O. L., and Arnal, R. E., 1969, Middle Tertiary basin development, San Joaquin Valley, California: Geological Society of America Bulletin, v. 80, no. 5, p. 783-819.

Barbat, W. F., and Galloway, John, 1934, San Joaquin Clay, California: American Association of Petroleum Geologists Bulletin, v. 18, no. 4, p. 476-499.

Bartow, J. A., 1981, Geologic map of the Rio Bravo Ranch quadrangle, California: U.S. Geological Survey Open-File Report 81-152, scale 1:24,000.

———1982, Sedimentology of a middle Tertiary paludal deposit, northern San Joaquin Valley, California: Fifty-seventh annual meeting, Pacific Sections, American Association of Petroleum Geologists, Society of Exploration Geophysicists, and Society of Economic Paleontologists and Mineralogists, p. 46.

Bartow, J. A., and Dibblee, T. W., Jr., 1981, Geology of the Tejon Hills area-Arvin and Tejon Hills quadrangles, Kern County, California: U.S. Geological Survey Open-File Report 81-297, 5 p., scale 1:24,000.

Bartow, J. A., and Doukas, M. P., 1978, Preliminary geologic map of the southeastern border of the San Joaquin Valley, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-944, scale 1:125,000.

Bartow, J. A., and Helley, E. J., 1979a, Preliminary geologic maps of Cenozoic deposits of the Auburn quadrangle, California: U.S. Geological Survey Open-File Report 79-386, scale 1:62,500.

———1979b, Preliminary geologic map of Cenozoic deposits of the Folsom area, California: U.S. Geological Survey Open-File Report 79-550, scale 1:62,500.

Bartow, J. A., and Marchand, D. E., 1979a, Preliminary geologic maps of Cenozoic deposits of the Sutter Creek and Valley Springs quadrangles, California: U.S. Geological Survey Open-File Report 79-436, scale 1:62,500.

———1979b, Preliminary geologic map of Cenozoic deposits of the Clay area, California: U.S. Geological Survey Open-File Report 79-667, scale 1:62,500

Bartow, J. A., Marchand, D. E., and Shipley, S., 1981, Preliminary geologic map of Cenozoic deposits of the Copperopolis quadrangle, California: U.S. Geological Survey Open-File Report 81-1048, scale 1:62,500.

Berkstresser, C. F., Jr., 1973, Base of fresh ground water—approximately 3,000 micromhos—in the Sacramento Valley and Sacramento-San Joaquin Delta, California: U.S. Geological Survey Water-Resources Investigations 40-73, 1 map.

Bertoldi, G. L., 1974, Estimated permeabilities for soils in the Sacramento Valley, California: U.S. Geological Survey Water-Resources Investigations 51-73, 17 p.

———1979, A plan to study the aquifer system of the Central Valley, California: U.S. Geological Survey Open-File Report 79-1480, 48 p.

Bryan, Kirk, 1923, Geology and ground-water resources of Sacramento Valley, California: U.S. Geological Survey Water-Supply Paper 495, 285 p.

Bull, W. B., 1964, Geomorphology of segmented alluvial fans in western Fresno County, California: U.S. Geological Survey Professional Paper 352-E, p. 89-128.

Bull, W. B., and Miller, R. E., 1975, Land subsidence due to ground-water withdrawal in the Los Banos-Kettleman City area, California, Part I. Changes in the hydrologic environment conducive to subsidence: U.S. Geological Survey Professional Paper 437-E, 71 p.

Cady, J. W., 1975, Magnetic and gravity anomalies in the Great Valley and western Sierra Nevada metamorphic belt, California: Geological Society of America Special Paper 168, 56 p.

California Department of Water Resources, 1967, San Joaquin County ground-water investigation: California Department of Water Resources Bulletin 146, 177 p.

———1978, Evaluation of ground-water resources: Sacramento Valley: California Department of Water Resources Bulletin 118-6, 136 p.

California Division of Mines and Geology, 1959a, Geologic map of California, San Luis Obispo sheet: California Department of Conservation, 2 sheets.

———1959b, Geologic map of California, Santa Cruz sheet: California Department of Conservation, 2 sheets.

———1960, Geologic map of California, Ukiah sheet: California Department of Conservation, 2 sheets.

———1962a, Geologic map of California, Chico sheet: California Department of Conservation, 2 sheets.

———1962b, Geologic map of California, Redding sheet: California Department of Conservation, 2 sheets.

———1963, Geologic map of California, Santa Rosa sheet: California Department of Conservation, 2 sheets.

———1965, Geologic map of California, Bakersfield sheet: California Department of Conservation, 2 sheets.

———1966a, Geologic map of California, Sacramento sheet: California Department of Conservation, 2 sheets.

———1966b, Geologic map of California, Fresno sheet: California Department of Conservation, 2 sheets.

———1966c, Geologic map of California, San Jose sheet: California Department of Conservation, 2 sheets.

———1969, Geologic map of California, Los Angeles sheet: California Department of Conservation, 2 sheets.

Cehrs, David, Soenke, Stephen, and Bianchi, W. C., 1980, A geologic approach to artificial recharge site selection in the Fresno-Clovis area, California: U.S. Department of Agriculture Technical Bulletin 1604, 73 p.

Clark, B. L., and Anderson, C. A., 1938, Upper Eocene Wheatland Formation of California and its relation to early Tertiary andesites in the Sierra Nevada: Geological Society of America Bulletin, v. 49, p. 931-956.

Croft, M. G., 1965, Data for three lacustrine clay deposits in the southern part of the San Joaquin Valley, California: U.S. Geological Survey Open-File Report, 53 p.

———1968, Geology and radiocarbon ages of late Pleistocene lacustrine clay deposits, southern part of San Joaquin Valley, *in* U.S. Geological Survey Research 1968: U.S. Geological Survey Professional Paper 600-B, p. 151-155.

———1972, Subsurface geology of the late Tertiary and Quaternary water-bearing deposits of the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1999-H, 29 p.

Croft, M. G., and Gordon, G. V., 1968, Geology, hydrology, and quality of water in the Hanford-Visalia area, San Joaquin Valley, California: U.S. Geological Survey Open-File Report, 170 p.

Curtin, George, 1971, Hydrogeology of the Sutter Basin, Sacramento Valley, California: Phoenix, Arizona University, Master's thesis, 83 p.

Dale, R. H., French, J. J., and Gordon, G. V., 1966, Ground-water geology and hydrology of the Kern River alluvial-fan area, California: U.S. Geological Survey Open-File Report, 92 p.

Dale, R. H., French, J. J., and Wilson, H. D., Jr., 1964, The story of ground water in the San Joaquin Valley, California: U.S. Geological Survey Circular 459, 11 p.

Davis, G. H., and Green, J. H., 1962, Structural control of interior drainage, southern San Joaquin Valley, California, *in* Geological Survey Research 1962: U.S. Geological Survey Professional Paper 450-D, p. 89-91.

Davis, G. H., Green, J. H., Olmsted, F. H., and Brown, D. W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1469, 287 p.

Davis, G. H., Lofgren, B. E., and Mack, Seymour, 1964, Use of ground-water reservoirs for storage of surface water in the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1618, 125 p.

Davis, G. H., and Poland, J. F., 1957, Ground-water conditions in the Mendota-Huron area, Fresno and Kings Counties, California: U.S. Geological Survey Water-Supply Paper 1360-G, p. 409-588.

Davis, P., Smith, J., Kukla, G. J., and Opdyke, N. D., 1977, Paleomagnetic study at a nuclear power plant site near Bakersfield, California: Quaternary Research, v. 7, p. 380-397.

Davis, S. N., and Hall, F. R., 1959, Water quality of eastern Stanislaus and northern Merced Counties, California: Stanford University Publications, Geological Science, v. 6, no. 1, 112 p.

Davis, W. M., 1933, The lakes of California: California Journal of Mines and Geology, v. 29, nos. 1 and 2, p. 175-236.

de Laveaga, Miguel, 1952, Oil fields of central San Joaquin province, *in* AAPG-SEPM-SEG Guidebook field trip routes, Joint Annual Meeting, American Association of Petroleum Geologists, Society of Economic Paleontologists and Mineralogists, and Society of Exploration Geophysicists: p. 99-103.

Dibblee, T. W., Jr., 1982a, Preliminary geologic map of the Wilcox Ridge quadrangle, Stanislaus County, California: U.S. Geological Survey Open-File Report 82-0392, scale 1:24,000.

———1982b, Preliminary geologic map of the Copper Mountain quadrangle, Stanislaus County, California: U.S. Geological Survey Open-File Report 82-0393, scale 1:24,000.

———1982c, Preliminary geologic map of the Patterson quadrangle, Stanislaus County, California: U.S. Geological Survey Open-File Report 82-0394, scale 1:24,000.

———1982d, Preliminary geologic map of the Orestimba Peak quadrangle, Stanislaus County, California: U.S. Geological Survey Open-File Report 82-0395, scale 1:24,000.

Dibblee, T. W., Jr., and Chesterman, C. W., 1953, Geology of the Breckenridge Mountain quadrangle, California: California Department of Natural Resources, Division of Mines, Bulletin 168, 55 p.

Dibblee, T. W., Jr., and Oakeshott, G. B., 1953, White Wolf fault in relation to geology of the southeastern margin of San Joaquin Valley, California [abs.]: Geological Society of America Bulletin, v. 64, p. 1502-1503.

Diepenbrock, Alex, 1933, Mount Poso oil field, *in* Summary of Operations, California oilfields: California Division of Oil and Gas, v. 19, no. 2, p. 4-35.

Ellsworth, T. P., 1948, Multiple reflections: Geophysics, v. 13, no. 1, p. 1-18.

Forbes, Hyde, 1931, Geology and underground water storage capacity of San Joaquin Valley, Appendix B, *in* San Joaquin River basin: California Division of Water Resources Bulletin 29, p. 531-550.

———1941, Geology of the San Joaquin Valley as related to the source and the occurrence of the ground-water supply: Transactions of the American Geophysical Union, pt. 1, p. 8-20.

Foss, C. D., 1972, A preliminary sketch of the San Joaquin Valley stratigraphic framework *in* E. W. Rennie, Jr., Guidebook, geology and oil fields, west side central San Joaquin Valley: American Association of Petroleum Geologists, Pacific Section, p. 40-50.

French, J. J., Page, R. W., and Bertoldi, G. L., 1982, Data for ground-water test hole near Zamora, Central Valley Aquifer Project, California: U.S. Geological Survey Open-File Report 82-510, 72 p.

———1983, Data for ground-water test hole near Nicolaus, Central Valley Aquifer Project, California: U.S. Geological Survey Open-File Report 83-273, 60 p.

French, J. J., Page, R. W., Bertoldi, G. L., and Fogelman, R. P., 1983, Data for ground-water test hole near Butte City, Central Valley Aquifer Project, California: U.S. Geological Survey Open-File Report 83-697, 54 p.

Frink, J. W., and Kues, H. A., 1954, Corcoran clay—A Pleistocene lacustrine deposit in San Joaquin Valley, California: American Association of Petroleum Geologists Bulletin, v. 38, p. 2357-2371.

Hackel, Otto, 1966, Summary of the geology of the Great Valley, chapter 5 *of* Geology of northern California: California Division of Mines Bulletin 190, p. 217-238.

Harding, S. T., 1927, Ground-water resources of the southern San Joaquin Valley: California Division of Engineering and Irrigation and Water Rights Bulletin 11, 146 p.

Harwood, D. S., and Helley, E. J., 1982, Preliminary structure contour map of the Sacramento Valley, California, showing major late

Cenozoic structural features and depth to basement: U.S. Geological Survey Open-File Report 82-737, 19 p.

Harwood, D. S., Helley, E. J., Barker, J. A., and Griffin, E. A., 1980, Preliminary geologic map of the Battle Creek fault zone, Shasta and Tehama Counties, California: U.S. Geological Survey Open-File Report 80-474, scale 1:24,000.

Harwood, D. S., Helley, E. J., and Doukas, M. P., 1981, Geologic map of the Chico Monocline and northeastern part of the Sacramento Valley: U.S. Geological Survey Miscellaneous Investigations Series Map I-1238, scale 1:62,500.

Helley, E. J., 1978, Geologic map of the alluvial fan of the Chowchilla River and adjacent foothill area, Mariposa, Merced, and Madera Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-927, scale 1:62,500.

———1979, Preliminary geologic map of Cenozoic deposits of the Davis, Knights Landing, Fair Oaks, and Lincoln 15-minute quadrangles, California: U.S. Geological Survey Open-File Report 79-583.

Helley, E. J., and Barker, J. A., 1979a, Preliminary geologic map of the Cenozoic deposits of the Dunnigan quadrangle, California: U.S. Geological Survey Open-File Report 79-1606, scale 1:62,500.

———1979b, Preliminary Geologic map of the Cenozoic deposits of the Woodland quadrangle, California: U.S. Geological Survey Open-File Report 79-1606, scale 1:62,500.

———1979c, Preliminary geologic map of the Cenozoic deposits of the Guinda quadrangle, California: U.S. Geological Survey Open-File Report 79-1606, scale 1:62,500.

———1979d, Preliminary geologic map of the Cenozoic deposits of the Lake Berryessa quadrangle, California: U.S. Geological Survey Open-File Report 79-1606, scale 1:62,500.

Helley, E. J., Harwood, D. S., Barker, J. A., and Griffin, E. A., 1981, Geologic map of the Battle Creek fault zone and adjacent parts of the Sacramento Valley, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1298, scale 1:62,500, 12 p.

Hill, F. L., 1964a, Harvester gas field: California Department of Conservation, Division of Oil and Gas, Summary of Operations, California, Oil Fields, v. 50, no. 1, p. 11-15.

———1964b, Northwest Trico gas field: California Department of Conservation, Division of Oil and Gas, Summary of Operations, California Oil Fields, v. 50, no. 1, p. 17-20.

Hilton, G. S., Kunkel, Fred, and Klausing, R. L., 1961, Water-use problems in the Terra Bella-Lost Hills area, San Joaquin Valley, California, pt. A—Geology: U.S. Geological Survey Open-File Report, 64 p.

Hinds, N. E. A., 1952, Evolution of the California landscape: California Division of Mines Bulletin 158, 240 p.

Hoots, H. W., 1930, Geology and oil resources along the southern border of the San Joaquin Valley, California: U.S. Geological Survey Bulletin 812-D, p. 243-332.

Hoots, H. W., Bear, T. L., and Kleinpell, W. D., 1954, Geological summary of the San Joaquin Valley, California, *in* Geology of the natural provinces, chapter 2 *of* Geology of southern California: California Division of Mines Bulletin 170, p. 113-131.

Hotchkiss, W. R., 1972a, Basic data for the Corcoran Clay Member of the Tulare Formation in the northern part of the San Joaquin Valley, California: U.S. Geological Survey Open-File Report, 6 p.

———1972b, Generalized subsurface geology of the water-bearing deposits, northern San Joaquin Valley, California: U.S. Geological Survey Open-File Report, 18 p.

Hotchkiss, W. R., and Balding, G. O., 1971, Geology, hydrology, and water quality of the Tracy-Dos Palos area, San Joaquin Valley, California: U.S. Geological Survey Open-File Report, 107 p.

Huey, A. S., 1948, Geology of the Tesla quadrangle: California Division of Mines Bulletin 140, 75 p.

Hull, L. C., 1984, Geochemistry of ground water in the Sacramento Valley, California: U.S. Geological Survey Professional Paper 1401-B, 36 p.

Hunter, G. W., 1952, Riverdale oilfield: California Department of Natural Resources, Division of Oil and Gas, Summary of Operations, California Oil Fields, v. 38, no. 2, p. 19-24.

Ireland, R. L., Poland, J. F., and Riley, F. S., 1984, Land subsidence in the San Joaquin Valley, California, as of 1980: U.S. Geological Survey Professional Paper 437-I, 93 p.

Janda, R. J., 1965, Quaternary alluvium near Friant, California: International Association for Quaternary Research Guidebook for Field Conference I, northern Great Basin and California, p. 128-133.

———1966, Pleistocene history and hydrology of the upper San Joaquin River, California: Berkeley, California University, Ph.D. dissertation, 425 p.

Janda, R. J., and Croft, M. G., 1967, The stratigraphic significance of a sequence of noncalcic brown soils formed on the Quaternary alluvium of the northeastern San Joaquin Valley, *in* International Association for Quaternary Research, Quaternary Soils: International Association for Quaternary Research, VII Congress, Reno, Nevada, Proceedings, v. 9, p. 158-190.

Lettis, W. R., 1981, Late Cenozoic landscape evolution in the west-central San Joaquin Valley, California [abs.]: Geological Society of America Abstracts with Programs, v. 14, no. 4, p. 180.

———1982, Late Cenozoic stratigraphy and structure of the western margin of the central San Joaquin Valley, California: U.S. Geological Survey Open-File Report 82-526, 203 p.

Lofgren, B. E., 1975, Land subsidence due to ground-water withdrawal, Arvin-Maricopa area, California: U.S. Geological Survey Professional Paper 437-D, 55 p.

Lofgren, B. E., and Ireland, R. L., 1973, Preliminary investigation of land subsidence in the Sacramento Valley, California: U.S. Geological Survey Open-File Report, 32 p.

Lofgren, B. E., and Klausing, R. L., 1969, Land subsidence due to ground-water withdrawal, Tulare-Wasco area, California: U.S. Geological Survey Professional Paper 437-B, 103 p.

Lydon, P. A., 1968, Geology of the Butte Mountain area, a source of the Tuscan Formation in northern California: Eugene, Oregon University, Ph.D. dissertation, 198 p.

———1969, Geology and lahars of the Tuscan Formation, northern California: Geological Society of America Memoir 116, p. 441-475.

Marchand, D. E., 1976a, Preliminary geologic maps showing Quaternary deposits of the northern Merced area, eastern San Joaquin Valley, Merced and Stanislaus Counties, California: U.S. Geological Survey Open-File Report 76-836 (8 quadrangles); scale 1:24,000.

———1976b, Preliminary geologic maps showing Quaternary deposits of the Merced area, eastern San Joaquin Valley, Merced County, California: U.S. Geological Survey Open-File Report 76-837 (7 quadrangles); scale 1:24,000.

———1976c, Preliminary geologic maps showing Quaternary deposits of the southern Merced area, eastern San Joaquin Valley, Merced and Madera Counties, California; U.S. Geological Survey Open-File Report 76-838 (7 quadrangles); scale 1:24,000.

———1976d, Preliminary geologic maps showing Quaternary deposits of the Chowchilla area, eastern San Joaquin Valley, Merced and Madera Counties, California: U.S. Geological Survey Open-File Report 76-839 (5 quadrangles); scale 1:24,000.

———1976e, Preliminary geologic maps showing Quaternary deposits of the Daulton area, eastern San Joaquin Valley, Madera County, California: U.S. Geological Survey Open-File Report 76-840 (4 quadrangles); scale 1:24,000.

———1976f, Preliminary geologic map of the Madera area, Madera County, California: U.S. Geological Survey Open-File Report

76-841 (8 quadrangles); scale 1:24,000.

———1976g, Late Cenozoic stratigraphy and history of the northeastern San Joaquin Valley: some early results of a regional study (abs): Geological Society of America Abstracts with Programs, v. 8, no. 3, p. 393-394.

———1980, Preliminary geologic map showing late Cenozoic deposits of the Ceres, Denair, and Montpelier quadrangles, Stanislaus and Merced Counties, California: U.S. Geological Survey Open-File Report 80-607, scale 1:24,000 (3 quadrangles).

———1981, Preliminary geologic map showing late Cenozoic deposits of the Snelling and Merced Falls quadrangles, Merced and Stanislaus Counties, California: U.S. Geological Survey Open-File Report 81-107, scale 1:24,000.

Marchand, D. E., and Allwardt, Alan, 1978, Preliminary geologic map showing Quaternary deposits of the northeastern San Joaquin Valley in parts of Stanislaus, Merced, Madera, Fresno, and Mariposa Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-945.

———1981, Late Cenozoic stratigraphic units, northeastern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1470, 70 p.

Marchand, D. E., and Atwater, B. F., 1979, Preliminary geologic map showing Quaternary deposits of the Lodi quadrangle, California: U.S. Geological Survey Open-File Report 79-933, scale 1:62,500.

Marchand, D. E., and Bartow, J. A., 1979, Preliminary geologic map of Cenozoic deposits of the Bellota quadrangle, California: U.S. Geological Survey Open-File Report 79-664, scale 1:62,500.

Marchand, D. E., Bartow, J. A., and Shipley, S., 1981a, Preliminary geologic maps showing Cenozoic deposits of the Cooperstown and La Grange quadrangles, Stanislaus and Tuolumne Counties, California: U.S. Geological Survey Open-File Report 81-1049, scale 1:24,000.

———1981b, Preliminary geologic maps showing Cenozoic deposits of the Farmington and Bachelor Valley quadrangles, San Joaquin, Stanislaus, and Calaveras Counties, California: U.S. Geological Survey Open-File Report 81-1050.

Marchand, D. E., and Harden, J. W., 1978, Preliminary geologic map showing Quaternary deposits of the lower Tuolumne and Stanislaus alluvial fans and the lower San Joaquin River, Stanislaus County, California: U.S. Geological Survey Open-File Report 76-656, scale 1:24,000, 4 quadrangles.

Marchand, D. E., and Wagner, Hugh, 1980, Preliminary geologic map of the Cenozoic deposits of the Turlock Lake quadrangle, Merced and Stanislaus Counties, California: U.S. Geological Survey Open-File Report 80-913, scale 1:24,000.

Meade, R. H., 1968, Compaction of sediments underlying areas of land subsidence in central California: U.S. Geological Survey Professional Paper 497-D, 39 p.

Mendenhall, W. C., 1908, Preliminary report on the ground waters of the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 222, 52 p.

Mendenhall, W. C., Dole, R. B., and Stabler, Herman, 1916, Ground water in San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 398, 310 p.

Miller, R. E., Green, J. H., and Davis, G. H., 1971, Geology of the compacting deposits in the Los Banos-Kettleman City subsidence area, California: U.S Geological Survey Professional Paper 497-E, 46 p.

Mitten, H. T., LeBlanc, R. A., and Bertoldi, G. L., 1970, Geology, hydrology, and quality of water in the Madera area, San Joaquin Valley, California: U.S. Geological Survey Open-File Report, 49 p.

Olmsted, F. H, and Davis, G.H., 1961, Geologic features and ground-water storage capacity of the Sacramento Valley, California: U.S. Geological Survey Water-Supply Paper 1497, 241 p.

Page, B. M., 1966, Geology of the Coast Ranges of California, *in* Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 255-276.

Page, R. W., 1973, Base of fresh ground water (approximately 3,000 micromhos) in the San Joaquin Valley, California: U.S. Geological Survey Hydrologic Investigations Atlas HA-489.

———1974, Base and thickness of the post-Eocene continental deposits in the Sacramento Valley, California: U.S. Geological Survey Water-Resources Investigations 45-73, 16 p.

———1980, Ground-water conditions at Beale Air Force Base and vicinity, California: U.S. Geological Survey Open-File Report 80-204, 36 p.

———1981, Data on depths to the Upper *Mya* zone of the San Joaquin Formation in the Kettleman City area, San Joaquin Valley, California: U.S. Geological Survey Open-File Report 81-699, 12 p.

———1983a, Texture maps, a guide to deep ground-water basins, Central Valley, California: American Society of Civil Engineers, Proceedings, Water Forum '81', August 10-14, 1981, 10 p.

———1983b, Geology of the Tulare Formation and other continental deposits, Kettleman City area, San Joaquin Valley, California, with a section on ground-water management considerations and use of texture maps: U.S. Geological Survey Water-Resources Investigation 83-4000, 24 p.

Page, R. W., and Balding, G. O., 1973, Geology and quality of water in the Modesto-Merced area, San Joaquin Valley, California, with a brief section on hydrology: U.S. Geological Survey Open-File Report, 85 p.

Page, R. W., and Bertoldi, G. L., 1983, A Pleistocene diatomaceous clay and a pumiceous ash, Sacramento Valley, California: California Geology, January 1983, p. 14-20.

Page, R. W., and LeBlanc, R. A., 1969, Geology, hydrology, and water quality in the Fresno area, California: U.S. Geological Survey Open-File Report, 70 p.

Park, W. H., and Weddle, J. R., 1959, Correlation study of southern San Joaquin Valley: California Department of Natural Resources, Division of Oil and Gas, Summary of Operations, California Oil Fields, v. 45, no. 1, p. 33 and 34.

Piper, A. M., Gale, H. S., Thomas, H. E., and Robinson, T. W., 1939, Geology and ground-water hydrology of the Mokelumne area, California: U.S. Geological Survey Water-Supply Paper 780, 230 p.

Poland, J. F., and Evenson, R. E., 1966, Hydrogeology and land subsidence, Great Central Valley, California, *in* Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 239-247.

Poland, J. F., Lofgren, B. E., Ireland, R. L., and Pugh, R. G., 1975, Land subsidence in the San Joaquin Valley, California, as of 1972: U.S. Geological Survey Professional Paper 437-H, 78 p.

Rantz, S. E., 1969, Mean annual precipitation in the California region: U.S. Geological Survey Open-File maps, 2 sheets.

Redwine, L. E., 1972, The Tertiary Princeton submarine valley system beneath the Sacramento Valley, California: Los Angeles, California University, Ph.D. dissertation, 480 p.

Repenning, C. A., 1960, Geologic summary of the Central Valley of California with reference to disposal of liquid radioactive waste: U.S. Geological Survey Open-File Report, 69 p.

Ross, D. C., and McCulloch, D. S., 1979, Cross section of the southern Coast Ranges and San Joaquin Valley from offshore Point Sur to Madera, California: Geological Society of America, MC-28B, 4 p.

Russell, R. D., 1931, The Tehama Formation of California: Berkeley, California University, Ph.D. dissertation, 133 p.

Russell, R. D., and Vanderhoof, V. L., 1931, A vertebrate fauna from a new Pliocene formation in northern California: California University, Department of Geological Science, Bulletin 20, p. 11-21.

Sacramento Petroleum Association, 1962, Typical gas fields of the Sacramento Valley, California, *in* Geologic guide to the gas and oil fields of northern California: California Division of Mines and Geology Bulletin 181, p. 99-148.

Sarna-Wojcicki, A. M., 1976, Correlation of late Cenozoic tuffs in the central Coast Ranges of California by means of trace- and minor-element chemistry: U.S. Geological Survey Professional Paper 972, 30 p.

Schlumberger Ltd., 1972, Log interpretation, v. 1—Principles: New York, Schlumberger Limited, 113 p.

Shlemon, R. J., 1971, The Quaternary deltaic and channel system in the Central Great Valley, California: Annals of the Association of American Geographers, v. 61, no. 3, p. 427-440.

Shlemon, R. J., and Begg, E. L., 1975, Late Quaternary evolution of the Sacramento-San Joaquin Delta, California: Quaternary Studies, The Royal Society of New Zealand, p. 259-266.

Smith, M. B., 1964, Map showing distribution and configuration of basement rocks in California, north half, south half: U.S. Geological Survey Oil and Gas Investigations Map OM-215, 2 sheets.

Suppe, John, 1978, Cross section of southern part of northern Coast Ranges and Sacramento Valley, California: Geological Society of America, MC-28B, 8 p.

Taliaferro, N. L., 1943, Geologic history and structure of the Central Coast Ranges of California: California Division of Mines Bulletin 118, p. 119-163.

Thomas, H. E., and Phoenix, D. A., 1976, Summary appraisals of the Nation's ground-water resources—California region: U.S. Geological Survey Professional Paper 813-E, 51 p.

Thomasson, H. G., Jr., Olmsted, F. H., and LeRoux, E. F., 1960, Geology, water resources, and usable ground-water storage capacity of part of Solano County, California: U.S. Geological Survey Water-Supply Paper 1464, 693 p.

U.S. Geological Survey, 1965, Geological Survey Research, 1965: U.S. Geological Survey Professional Paper 525-A, 376 p.

Vaughn, F. E., 1943, Geophysical studies in California, *in* Geologic Formations and economic development of the oil and gas fields of California: California Division of Mines Bulletin 118, p. 67-70.

Weaver, C. E., 1949, Geology of the Coast Ranges immediately north of the San Francisco Bay region, California: Geological Society of America Memoir 35, 242 p.

Wilhelm, V. H., and Saunders, L. W., 1927, Report on the Mount Poso oil field: California Oil Fields, v. 12, no. 7, p. 5-12.

Williams, Howel, and Curtis, G. H., 1977, The Sutter Buttes of California: University of California Publications in Geological Sciences, v. 116, 56 p.

Wood, P. R., and Dale, R. H., 1964, Geology and ground-water features of the Edison-Maricopa area, Kern County, California: U.S. Geological Survey Water-Supply Paper 1656, 103 p.

Wood, P. R., and Davis, G. H., 1959, Ground-water conditions in the Avenal-McKittrick area, Kings and Kern Counties, California: U.S. Geological Survey Water-Supply Paper 1457, 141 p.

Woodring, W. P., Stewart, Ralph, and Richard, R. W., 1940, Geology of the Kettleman Hills oil field, California: U.S. Geological Survey Professional Paper 195, 170 p.

Zieglar, D. L., and Spotts, J. H., 1978, Reservoir and sourcebed history of Great Valley, California: American Association of Petroleum Geologists Bulletin, v. 62, p. 813-826.