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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1999-H

*Prepared in cooperation with the*
*California Department of*
*Water Resources*

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

# Subsurface Geology of the Late Tertiary and Quaternary Water-Bearing Deposits of the Southern Part of the San Joaquin Valley, California

By M. G. CROFT

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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# CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

# SUBSURFACE GEOLOGY OF THE LATE TERTIARY AND QUATERNARY WATER-BEARING DEPOSITS OF THE SOUTHERN PART OF THE SAN JOAQUIN VALLEY, CALIFORNIA

By M. G. CROFT

## ABSTRACT

The study area, which includes about 5,000 square miles of the southern part of the San Joaquin Valley, is a broad structural trough of mostly interior drainage. The Sierra Nevada on the east is composed of consolidated igneous and metamorphic rocks of pre-Tertiary age. The surface of these rocks slopes 4°–6° southwestward from the foothills and underlies the valley. The Coast Ranges on the west consist mostly of complexly folded and faulted consolidated marine and nonmarine sedimentary rocks of Jurassic, Cretaceous, and Tertiary age, which dip eastward and overlie the basement complex. Unconsolidated deposits, of late Pliocene to Holocene age, blanket the underlying consolidated rocks in the valley and are the source of most of the fresh ground water. The unconsolidated deposits, the subject of this report, are divided into informal stratigraphic units on the basis of source of sediment, environment of deposition, and texture.

Flood-basin, lacustrine, and marsh deposits are fine grained and underlie the valley trough. They range in age from late Pliocene to Holocene. These deposits, consisting of nearly impermeable gypsiferous fine sand, silt, and clay, are more than 3,000 feet thick beneath parts of Tulare Lake bed. In other parts of the trough, flood-basin, lacustrine, and marsh deposits branch into clayey or silty clay tongues designated by the letter symbols A to F. Three of these tongues, the E, C, and A clays, lie beneath large areas of the southern part of the valley.

The E clay includes the Corcoran Clay Member of the Tulare Formation, the most extensive hydrologic confining layer in the valley. The E clay underlies about 3,500 square miles of bottom land and western slopes. The beds generally are dark-greenish-gray mostly diatomaceous silty clay of Pleistocene age. Marginally, the unit bifurcates into an upper and a lower stratum that contains thin beds of moderately yellowish-brown silt and sand.

The E clay is warped into broad, gentle northwesterly trending anticlines and synclines.

The C clay, of Pleistocene age, is a fine-grained lacustrine or paludal deposit occurring 220–300 feet beneath Tulare Lake bed and parts of Fresno Slough. The beds consist of bluish-gray silty clay. Structural contours indicate that the C clay has been extensively warped and folded.

The A clay of Pleistocene and Holocene(?) age is a fine-grained lacustrine or paludal deposit occurring 10–60 feet beneath Buena Vista, Kern, and Tulare Lake beds, and parts of Fresno Slough. The clay is mainly blue or dark greenish gray, plastic, and highly organic. In some areas the unit is separated into an upper and a lower stratum by several feet of sand. A radiocarbon date of 26,780 ± 600 years was obtained from wood cored 3 feet beneath the clay.

Continental deposits are arkosic beds of late Pliocene and Pleistocene(?) age and were derived from the Sierra Nevada, Tehachapi, and San Emigdio Mountains. In places, a reduced-oxidized contact transgresses the deposits derived from the Sierra Nevada. The reduced deposits consist of moderately permeable bluish-green or bluish-gray fine to medium sand, silt, and clay. The oxidized deposits consist mainly of poorly permeable yellowish-brown silt and fine sand. Deposits derived from the Tehachapi and the San Emigdio Mountains consist of poorly to moderately permeable yellowish-brown sand and silt. Continental and alluvial deposits of Tertiary and Quaternary age that were derived from the Coast Ranges consist mainly of poorly to moderately permeable yellowish-brown gravel, sand, silt, and clay. They include the Tulare Formation and overlying alluvial deposits.

Alluvium is composed of coarse arkosic deposits derived from the Sierra Nevada, Tehachapi, and San Emigdio Mountains. A reduced-oxidized contact also transgresses the alluvial deposits derived from the Sierra Nevada. The oxidized deposits consist of poorly to highly permeable yellowish-brown gravel, sand, silt, and clay. The reduced deposits are moderately permeable bluish-green fine to coarse sand, silt, and clay. Deposits from the Tehachapi and the San Emigdio Mountains consist of poorly to highly permeable yellowish-brown gravel, sand, and silt.

The coarse oxidized deposits of the alluvium are the most permeable beds, or aquifers, along the eastern and southern margins of the valley. The coarse oxidized continental and alluvial deposits are the most permeable strata along the western margin of the valley and contain most of the fresh-water body. Artificial recharge will be more successful if sites are located in areas underlain by these deposits. Flood-basin, lacustrine, and marsh deposits, which are nearly impermeable, are chiefly aquicludes and do not transmit water fast enough to furnish an appreciable supply for a well. Lacustrine clay tongues are virtually impermeable horizons that separate the alluvial sequence into several aquifers.

## INTRODUCTION

### LOCATION AND GENERAL FEATURES

The Central Valley of California consists of the San Joaquin and the Sacramento Valleys (fig. 1). The San Joaquin Valley,

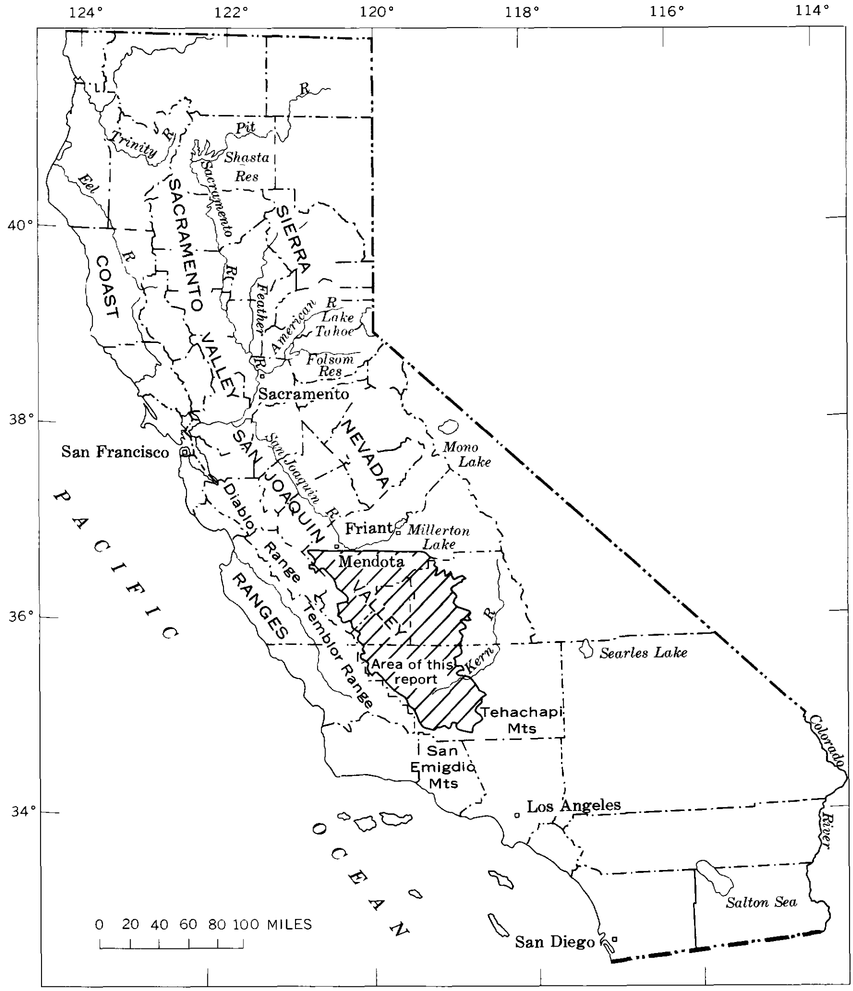


FIGURE 1.—Location of the southern part of the San Joaquin Valley.

forming the southern two-thirds of the Central Valley, is a broad structural trough. It is bordered on the east by the Sierra Nevada and on the west by the Diablo and the Temblor Ranges, which are a part of the Coast Ranges. The valley extends 250 miles southeastward from the confluence of the San Joaquin and the Sacramento Rivers to the Tehachapi and the San Emigdio Mountains. The width of the valley ranges from 25 miles near the Kern River to 55 miles near the Kings River and averages about 35 miles.

The study area, the southern half of the San Joaquin Valley, includes about 5,000 square miles of the valley floor.

The warm climate, rich soil, and extensive irrigation make the San Joaquin Valley the largest single agricultural area in the State and one of the most productive agricultural areas in the country. Water from wells is the sole irrigation-water supply for about half the irrigated land within the valley and is a supplemental supply for another quarter of the irrigated area. Ground water also supplies nearly all the municipal, industrial, and domestic needs for the area.

Widespread pumping of ground water in the San Joaquin Valley began about 1900, and since 1940 pumpage has increased at an accelerated rate. In response to the heavy withdrawal of ground water, water levels have declined rapidly beneath extensive areas of the valley. Water levels will continue to decline as long as ground-water pumpage exceeds the natural and artificial recharge to the ground-water reservoir.

## CLIMATE

The climate in the southern part of the San Joaquin Valley is characterized by hot summers and mild winters. Precipitation occurs mostly during the winter months, and the quantity of precipitation in the area is small. The cooling of moisture-laden air as it moves eastward from the Pacific Ocean across the Coast Ranges results in condensation of water vapor and precipitation in the mountains; consequently, airmasses that cross the valley floor from west to east have lost much of their moisture, and rainfall is a scanty 5–10 inches a year. Precipitation increases as storms ascend the west slope of the Sierra Nevada and exceeds 60 inches in the higher parts of the range. In the winter months, snow may be heavy above the 4,000-foot level. In the valley, midday temperatures during the summer commonly exceed 100°F, and extremes as high as 120°F are on record.

## DRAINAGE

The Kings, Kaweah, Tule, and Kern Rivers (pl. 4), the only perennial streams entering the area, drain the western slopes of the Sierra Nevada. The streams that drain the Coast Ranges, Tehachapi, and San Emigdio Mountains are intermittent and flow only during the short rainy season. On the valley floor, the northern distributaries of the Kings River discharge into the San Joaquin River, the principal drainage outlet for the northern part of the San Joaquin Valley (pl. 4). The Kaweah and Tule

Rivers and the southern distributaries of the Kings River flow onto Tulare Lake bed. The Kern River flows onto Kern and Buena Vista Lake beds.

The southern part of the San Joaquin Valley is a region of interior drainage (Davis and Green, 1962, p. 89). Under present day conditions there is no surface discharge of water toward the ocean, but prior to regulation some water occasionally discharged northward through Fresno Slough.

At present, Tulare, Buena Vista, Kern, and Goose Lake beds are dry because of diversion of water from tributary streams for irrigation. At the time settlers first entered the area, these lakes contained water, and the surrounding marshes and connecting sloughs were covered with rank vegetation. The outlet for Buena Vista Lake is at an altitude of 295 feet above sea level. When the water reached this height, overflow occurred through Buena Vista Slough into Tulare Lake. Tulare Lake overflowed into the San Joaquin River when the lake surface reached about 210 feet above sea level. Overflow from Tulare Lake has not occurred since 1878.

## PURPOSE AND SCOPE

The purpose of this investigation is (1) to supplement earlier general and specific problem studies in the San Joaquin Valley by interpreting and presenting data on the geology of aquicludes and aquifers in the southern part of the valley; and (2) to describe briefly the occurrence of ground water as related to the aquicludes and aquifers and potential sites for artificial recharge.

The scope of the investigation is to delineate the major aquicludes and associated aquifers in the subsurface in sufficient detail to define and describe their thickness, lithology, and stratigraphic relations.

The investigation was made by the U.S. Geological Survey as a part of the program of ground-water studies in cooperation with the California Department of Water Resources. The report was prepared under the successive supervision of Fred Kunkel, district geologist for ground-water investigations in California, and Willard W. Dean, chief of the Sacramento subdistrict of the Water Resources Division.

## PREVIOUS STUDIES

The search for oil spurred early systematic geologic investigations by Watts (1894) and Anderson (1912) in the southern part of the San Joaquin Valley. Since that time, most geologic work has been confined to consolidated oil-bearing rocks of Cretaceous and Tertiary age. Consequently, many publications on the geology of numerous oil fields are available, most of which have been prepared by the California Division of Mines and Geology or the California Division of Oil and Gas. Unconsolidated deposits of late Tertiary and Quaternary age, the subject of this report, overlie the oil-bearing rocks.

Unconsolidated deposits of late Tertiary and Quaternary age have been mapped on the south and west sides of the valley at several locations where they truncate the underlying oil-bearing rocks. These deposits in the Coalinga district were named the Tulare Formation by F. M. Anderson (1905), and the name was extended to similar deposits in the Diablo Range by Anderson and Pack (1915). The Tulare Formation was mapped in the foothills of the Techachapi and the San Emigdio Mountains at the south end of the valley by Pack (1920) and by Hoots (1930). Detailed studies of the Tulare Formation have been made by Woodring, Roundy, and Farnsworth (1932) and Woodring, Stewart, and Richards (1940) in the Elk and Kettleman Hills. Fresh-water-bearing deposits of late Tertiary and Quaternary age that occur in the vicinity of the Kern River were named the Kern River Beds by Anderson (1905) and were termed the Kern River Series by Diepenbrock (1933). Other important detailed geologic descriptions of surface and subsurface lacustrine and alluvial deposits of Pliocene and Quaternary age include papers by Barbat and Galloway (1934), Frink and Kues (1954), and Klausing and Lohman (1964). Geomorphic studies of alluvial fans in western Fresno County have been made by Bull (1964a, b).

Several ground-water reconnaissance reports, prepared by Federal and State agencies, are available for the San Joaquin Valley. The earliest valley-wide reconnaissance report, prepared by Mendenhall, Dole, and Stabler (1916), was made when ground-water development was in its infancy. The report outlined the state of ground-water development, ground-water use, and quality of the water. Later, Harding (1927) made a study of ground-water conditions in the southern part of the valley and outlined areas of insufficient supply.

Davis, Green, Olmsted, and Brown (1959) made a study of ground-water conditions and storage capacity in the San Joaquin Valley. Their report outlined the principal geologic and hydrologic features that control the movement of ground water. They estimated that the valley has a storage capacity of 93 million acre-feet available for cyclic storage of water in the interval between 10 and 200 feet in depth below land surface. Later, Davis, Lofgren, and Mack (1964, p. 119) concluded most of the 93 million acre-feet of ground-water storage capacity is usable, but more basic information on rates of infiltration, geologic controls, and ground-water movement is needed before firm estimates of usable storage capacity can be made. Other geologic and hydrologic reports of areas within the valley have been made by Davis and Poland (1957), Wood and Davis (1959), Hilton, McClelland, Klausing, and Kunkel (1963), and Wood and Dale (1964). The California Department of Water Resources has made numerous investigations of various aspects of geology and hydrology in the San Joaquin Valley.

## WELL-NUMBERING SYSTEM

Well sites in the San Joaquin Valley and the corresponding lithologic data and well logs are assigned numbers according to the location of the site in the rectangular system for the subdivision of public lands. For example, in the number 19S/22E–19A1, assigned to a well south of Hanford, the part of the number preceding the slash indicates the township (T. 19 S.) and the number between the slash and hyphen indicates the range (R. 22 E.) Mount Diablo base line and meridian; the number between the hyphen and letter indicates the section (sec. 19); and the letter after the section number indicates the 40-acre subdivision of the section, as shown in the accompanying diagram.

Within each 40-acre tract the wells are numbered serially, as indicated by the final digit of the well number (fig. 2). If the final digit is missing, the site was plotted in the office from an adequate

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

FIGURE 2.—Well-numbering system.

location without field verification or completion of a well schedule. A Z following the section number indicates that the location of a well within a section has not been verified in the field, but information supplied with the log indicates the location probably is accurate.

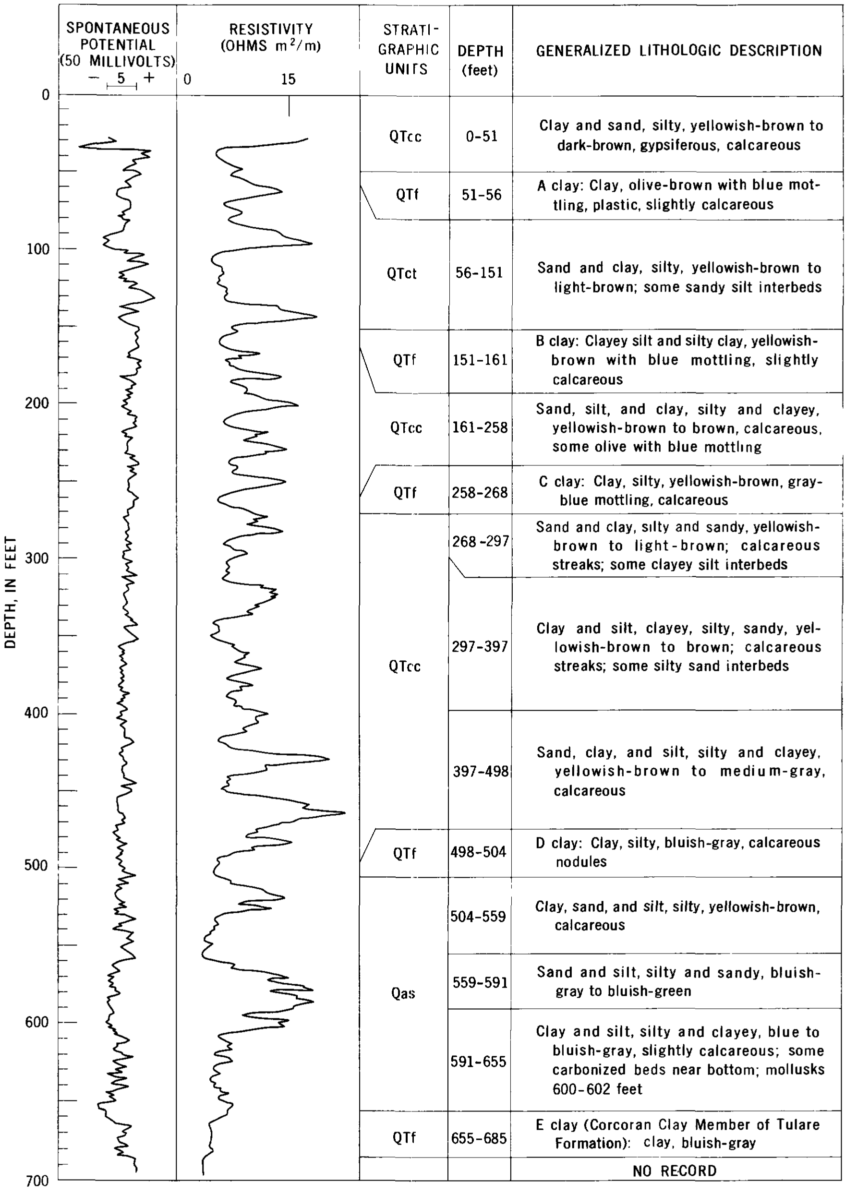
## METHOD OF STUDY AND NATURE OF THE DATA

Fieldwork and office work for this report were begun in January 1964 and completed in June 1965. Because other agencies and the U.S. Geological Survey have collected a vast amount of well log and other data, most of the information in this report was assembled from existing files. However, in areas where data were scanty, several hundred additional logs were collected, and wells were located in the field to supplement the available information.

The U.S. Bureau of Reclamation, Geological Survey, and California Department of Water Resources have cored and made detailed lithologic logs of about 210 holes in the fresh-water-bearing deposits in the southern part of the San Joaquin Valley. For about half the core holes the electrical resistivities of the units were logged. Figures 3 and 4 show the electric logs and lithology of selected core holes. In addition, the Geological Survey has about 4,000 electric logs of water wells and logs of several hundred auger and reverse-rotary holes on file; these logs were obtained from well owners, drillers, ground-water consultants, and logging companies with appropriate clearance from owners.

The techniques used for this study are similar to those used in general geologic mapping: beds are separated into informal units, and lateral and vertical changes in lithology and texture are described. Mappable units were identified in logs of core holes, correlated with electric logs of the same or adjacent wells, and then correlated with units in more distant wells. The stratigraphic relationships of the deposits are illustrated in geologic sections (pls. 1–3, see pl. 4 for location of cross sections).

Electric logs and lithologic logs from core holes were used exclusively in the geologic sections because lithologic logs obtained from drillers generally are not satisfactory for correlation purposes. However, drillers logs, not shown on the cross sections, did provide useful information about the general character and color of the deposits, and the drillers logs influenced the interpretations shown on structure-contour maps and geologic sections in this report.



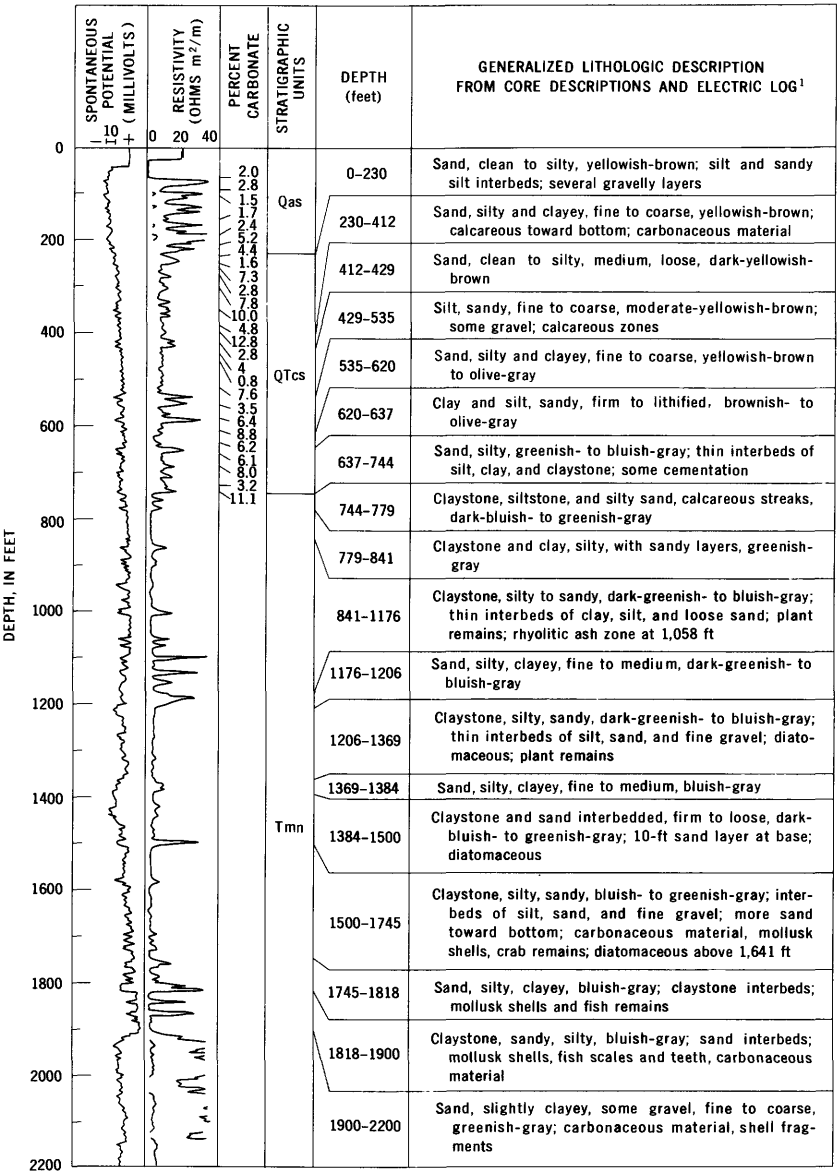
| STRATIGRAPHIC UNITS | DEPTH (feet) | GENERALIZED LITHOLOGIC DESCRIPTION |
|---|---|---|
| QTcc | 0-51 | Clay and sand, silty, yellowish-brown to dark-brown, gypsiferous, calcareous |
| QTf | 51-56 | A clay: Clay, olive-brown with blue mottling, plastic, slightly calcareous |
| QTct | 56-151 | Sand and clay, silty, yellowish-brown to light-brown; some sandy silt interbeds |
| QTf | 151-161 | B clay: Clayey silt and silty clay, yellowish-brown with blue mottling, slightly calcareous |
| QTcc | 161-258 | Sand, silt, and clay, silty and clayey, yellowish-brown to brown, calcareous, some olive with blue mottling |
| QTf | 258-268 | C clay: Clay, silty, yellowish-brown, gray-blue mottling, calcareous |
| QTcc | 268-297 | Sand and clay, silty and sandy, yellowish-brown to light-brown; calcareous streaks; some clayey silt interbeds |
|  | 297-397 | Clay and silt, clayey, silty, sandy, yellowish-brown to brown; calcareous streaks; some silty sand interbeds |
|  | 397-498 | Sand, clay, and silt, silty and clayey, yellowish-brown to medium-gray, calcareous |
| QTf | 498-504 | D clay: Clay, silty, bluish-gray, calcareous nodules |
| Qas | 504-559 | Clay, sand, and silt, silty, yellowish-brown, calcareous |
|  | 559-591 | Sand and silt, silty and sandy, bluish-gray to bluish-green |
|  | 591-655 | Clay and silt, silty and clayey, blue to bluish-gray, slightly calcareous; some carbonized beds near bottom; mollusks 600-602 feet |
| QTf | 655-685 | E clay (Corcoran Clay Member of Tulare Formation): clay, bluish-gray |
|  |  | NO RECORD |

(U.S. Bureau of Reclamation core hole)

FIGURE 3.—Logs of core hole 20S/19E-31P. For explanation of symbols used for stratigraphic units, see plate 1.

## ACKNOWLEDGMENTS

The collection of data and successful completion of the investigation for this report were made possible by the cooperation of



| DEPTH (feet) | GENERALIZED LITHOLOGIC DESCRIPTION FROM CORE DESCRIPTIONS AND ELECTRIC LOG[1] |
|---|---|
| 0–230 | Sand, clean to silty, yellowish-brown; silt and sandy silt interbeds; several gravelly layers |
| 230–412 | Sand, silty and clayey, fine to coarse, yellowish-brown; calcareous toward bottom; carbonaceous material |
| 412–429 | Sand, clean to silty, medium, loose, dark-yellowish-brown |
| 429–535 | Silt, sandy, fine to coarse, moderate-yellowish-brown; some gravel; calcareous zones |
| 535–620 | Sand, silty and clayey, fine to coarse, yellowish-brown to olive-gray |
| 620–637 | Clay and silt, sandy, firm to lithified, brownish- to olive-gray |
| 637–744 | Sand, silty, greenish- to bluish-gray; thin interbeds of silt, clay, and claystone; some cementation |
| 744–779 | Claystone, siltstone, and silty sand, calcareous streaks, dark-bluish- to greenish-gray |
| 779–841 | Claystone and clay, silty, with sandy layers, greenish-gray |
| 841–1176 | Claystone, silty to sandy, dark-greenish- to bluish-gray; thin interbeds of clay, silt, and loose sand; plant remains; rhyolitic ash zone at 1,058 ft |
| 1176–1206 | Sand, silty, clayey, fine to medium, dark-greenish- to bluish-gray |
| 1206–1369 | Claystone, silty, sandy, dark-greenish- to bluish-gray; thin interbeds of silt, sand, and fine gravel; diatomaceous; plant remains |
| 1369–1384 | Sand, silty, clayey, fine to medium, bluish-gray |
| 1384–1500 | Claystone and sand interbedded, firm to loose, dark-bluish- to greenish-gray; 10-ft sand layer at base; diatomaceous |
| 1500–1745 | Claystone, silty, sandy, bluish- to greenish-gray; interbeds of silt, sand, and fine gravel; more sand toward bottom; carbonaceous material, mollusk shells, crab remains; diatomaceous above 1,641 ft |
| 1745–1818 | Sand, silty, clayey, bluish-gray; claystone interbeds; mollusk shells and fish remains |
| 1818–1900 | Claystone, sandy, silty, bluish-gray; sand interbeds; mollusk shells, fish scales and teeth, carbonaceous material |
| 1900–2200 | Sand, slightly clayey, some gravel, fine to coarse, greenish-gray; carbonaceous material, shell fragments |

[1] The many beds in the depth interval 744–1,900 feet described as claystone from field examination of cores are shown by particle-size analyses to be chiefly siltstone

FIGURE 4.—Logs of core hole 24S/26E–36A2. (After Klausing and Lohman, 1964.) For explanation of symbols used for stratigraphic units, see plate 1.

public agencies, private companies, and individuals. Well logs were furnished by the U.S. Bureau of Reclamation, California Department of Water Resources, ground-water consultants, well drillers, and private-land companies. Copies of electric logs were obtained from commercial blueprint firms or were made available by the Schlumberger Well Surveying Corp., the Zublin Well Logging Corp., and the California Division of Oil and Gas, with the permission of well owners. A. I. Johnson, of the U.S. Geological Survey, Denver, Colo., supervised the determination of percentage carbonate for the samples from U.S. Geological Survey test well 24S/26E–36A2.

## CONSOLIDATED ROCKS

### BASEMENT COMPLEX

The basement complex forms much of the southern Sierra Nevada, Tehachapi, and San Emigdio Mountains and is composed of a mass of plutonic and metamorphic rocks commonly referred to as the Sierra Nevada batholith of pre-Tertiary age. The surface of the basement slopes about 3–5° southwestward from the foothills to beneath the valley floor (Smith, 1964). The basement complex is buried beneath Tulare Lake bed by more than 14,000 feet of rocks of Cretaceous, Tertiary, and Quaternary age and beneath Buena Vista Lake bed by more than 20,000 feet of rocks of Cretaceous, Tertiary, and Quaternary age.

The rocks of the basement complex are of little importance as a source of ground water because they are largely impermeable and generally lie beneath most water wells, except locally along the eastern margin of the valley. Wells have been drilled into the basement complex in areas where it is found at 300 feet or less beneath land surface. Yields to wells open only to the basement complex generally are small. Consequently, the development of agriculture in areas tapped by these wells is dependent to a large extent on surface-water supplies.

### MARINE ROCKS OF PRE-TERTIARY AGE

Marine rocks of Jurassic and Cretaceous age form a minor part of the Coast Ranges and underlie the western part of the study area at great depth beneath the valley floor. These rocks generally are mapped on the surface as the Franciscan, Panoche, and Moreno Formations. Because of their great depth of burial, they are not penetrated by water wells, and they are not shown in the geologic sections.

## MARINE AND NONMARINE SEDIMENTARY ROCKS OF TERTIARY AGE

Marine and nonmarine sedimentary rocks of Tertiary age underlie unconsolidated deposits which form the floor of the San Joaquin Valley. They overlie rocks of Cretaceous age in the Diablo and Temblor Ranges and beneath the central part of the valley. They lie upon the basement complex along the eastern margin of the valley adjacent to the Sierra Nevada (Hoots and others, 1954, p. 115). The rocks of Tertiary age consist largely of consolidated to semiconsolidated fossiliferous sandstone, siltstone, and shale which thicken from east to west and from north to south (Park and Weddle, 1959); the maximum thickness of about 29,000 feet is near the southwest corner of the valley (Hoots, 1930, p. 243). The structure of the Tertiary section is highly asymmetrical (Hoots and others, 1954, p. 116). The Tertiary rocks beneath the western and southern flanks which form a major part of the Coast Ranges and beneath the foothills of the Tehachapi and the San Emigdio Mountains are steeply tilted, overturned, and intricately broken by thrust faults. The comparatively gentle westerly dip of the eastern flank approximately parallels the downdip western part of the Sierra Nevada fault block.

Petroleum geologists have divided the marine and nonmarine rocks of Tertiary age into numerous formations and members. Although these rocks generally contain saline water, unsuitable for most uses, they are locally a source of water for irrigation along the eastern and western margins of the valley where the water is of suitable chemical quality. Of these rocks, the marine Santa Margarita Formation as used by Diepenbrock (1933), of late Miocene age, and overlying marine and nonmarine sedimentary rocks of Pliocene age are most commonly penetrated by water wells.

### SANTA MARGARITA FORMATION AS USED BY DIEPENBROCK (1933)

Along the east side of the San Joaquin Valley, the upturned and locally outcropping Santa Margarita Formation as used by Diepenbrock (1933), of late Miocene age, roughly parallels the trough of the valley from Fresno to Wheeler Ridge. At the south end of the valley where the formation crops out and dips steeply, it was mapped and studied in detail by Hoots (1930). The formation, which ranges in thickness from 100 to 400 feet, is an excellent stratigraphic marker and consists of well-sorted gray sandstone, gravel, and shale. The beds, probably highly permeable, are penetrated by water wells near Richgrove (Hilton and others, 1963, p. 107–109) and near the foothills of the Sierra Nevada southeast of Bakersfield.

### MARINE AND NONMARINE SEDIMENTARY ROCKS OF PLIOCENE AGE

Marine and nonmarine sedimentary rocks (Hoots and others, 1954, fig. 10) that range from early Pliocene to late Pliocene in age overlie the Santa Margarita Formation and underlie the unconsolidated deposits (pls. 1–3). The beds, which consist mainly of silt, clay, and fine sand, are about 2,000 feet thick near Poso Creek. In the Kettleman Hills where the unit is about 7,000 feet thick, Woodring, Stewart, and Richards (1940) divided it into the Jacalitos, Etchegoin, and San Joaquin Formations. At the south end of the valley, Hoots (1930) divided this unit into the Jacalitos, Etchegoin, and Chanac Formations. Klausing and Lohman (1964) recognized upper Pliocene and Pliocene(?) marine strata on the east side of the valley near Richgrove. The strata considered Pliocene(?) by Klausing and Lohman (1964, p. D14) contain *Macoma* sp. and *Cryptomya* sp. and are possibly equivalent to the Macoma Shale (Etchegoin marine finger) of Hoots, Bear, and Kleinpell (1954, p. 123), which reportedly lies unconformably on the Santa Margarita Formation; Edwards (1943, p. 573) tabulated casts of these two fossils in the "Etchegoin claystone member" of Pliocene age.

The upper *Mya* zone, a widely recognized fossil horizon occurring in the uppermost beds of the San Joaquin Formation (Woodring and others, 1940, p. 28–29), is used to establish the top of the consolidated rocks where control is present. The contact is shown in cross section at those places where the fossil was reported in oil and gas-test wells by the California Division of Oil and Gas (1964). The change in degree of consolidation probably is gradational across the boundary between the consolidated rocks and unconsolidated deposits.

The marine and nonmarine rocks of Pliocene age are penetrated by water wells along the west side of the valley north of Tulare Lake bed and from near the Kern River to near the Tule River along the east side of the valley.

## UNCONSOLIDATED DEPOSITS

Most of the ground water pumped in the southern part of the San Joaquin Valley occurs in the unconsolidated deposits ranging from late Pliocene to Holocene in age. These deposits consist of gravel, sand, silt, and clay; they blanket the underlying consolidated rocks. The unconsolidated deposits thicken toward the valley trough from a featheredge at the valley margins. The base is about 3,300 feet below sea level beneath Tulare Lake bed (pl. 1) and is more than 3,400 feet below sea level (not shown) beneath Buena Vista Lake bed.

The unconsolidated deposits are equivalent to strata which, in earlier reports, have been divided on the surface into formal and informal geologic units. They are equivalent to the Tulare Formation and younger formations of Hoots (1930) and Woodring, Stewart, and Richards (1940). The unconsolidated deposits probably are equivalent to the unconsolidated deposits of Hilton, McClelland, Klausing, and Kunkel (1963) and are equivalent to the continental deposits from the Sierra Nevada of Klausing and Lohman (1964). The upper part of the Kern River Series of Diepenbrock (1933), the Kern River Formation of local usage, probably is equivalent to the unconsolidated deposits of this report. Wood and Dale (1964), using soil maps and geologic maps of other authors, divided the continental deposits in the Edison-Maricopa area into the Tulare Formation, continental deposits undifferentiated, older alluvial-fan deposits, tilted alluvial-fan deposits, and younger alluvial and flood-basin deposits.

### GENERAL CHARACTER

The lithology and water-bearing character of the unconsolidated deposits is dependent upon several controlling factors: (1) environment of deposition, (2) type of rock in the source area, and (3) competence of the streams that transported the sediment.

According to Davis, Green, Olmsted, and Brown (1959, p. 58–59) and Meade (1967, p. C7), environment of deposition controls the degree of oxidation of sediments and, hence, the color of the materials. Oxidized deposits generally represent subaerial deposition, and reduced deposits generally represent subaqueous deposition. The colors used herein mostly are from drillers logs and were not altered to conform with standard color charts. Oxidized deposits are weathered, and contain soil profiles; the deposits are red, yellow, and brown. Reduced deposits are blue, green, or gray and commonly are calcareous. The stratigraphic relationships and contained fossils show that, in general, reduced beds consisting of silt and fine to coarse sand were laid down mainly on flood plains and deltas. Reduced beds composed of fine sand, silt, and clay were laid down for the most part in flood basins, lakes, and marshes. The reduced deposits have a generally higher organic content than the oxidized deposits.

Unconsolidated deposits in the southern part of the San Joaquin Valley were derived from the Sierra Nevada, Coast Ranges, Tehachapi, and San Emigdio Mountains. Sedimentary deposits derived from the igneous and metamorphic rocks that compose the Sierra Nevada were deposited mostly by the major east side streams. They are arkosic and micaceous and are oxidized in the upper parts of alluvial fans and reduced in the lower parts of the fans. Sedimentary deposits derived from gypsiferous marine shale, sandstone, and volcanic rocks that compose the Coast Ranges were deposited mostly by ephemeral streams of intermediate to small size as water-laid sands and mudflows (Bull, 1964b). They are mainly oxidized and generally finer grained than comparable sedimentary deposits derived from the Sierra Nevada. Sedimentary deposits derived from the two sides of the valley are distinguishable on the basis of minerals and lithic fragments. Sedimentary deposits derived from the metamorphic and igneous rocks that make up the higher parts of the Tehachapi and the San Emigdio Mountains and from the marine shale and sandstone that form the lower parts were deposited by small streams at the south end of the valley. These deposits are mainly oxidized and are not as coarse as the sedimentary deposits derived from the Sierra Nevada.

Quaternary climatic change and uplift of the surrounding mountains have altered the competence and capacity of the streams. The coarsest deposits of a given stream generally are laid down where the gradient flattens near the valley margin. Most sedimentary deposits show a fairly consistent decrease in average grain size downstream from their source.

In this report, unconsolidated deposits are divided into informal units principally on the basis of their source, texture, and environment of deposition. Thus, the extensive beds of mostly silt and clay were mapped as flood-basin, lacustrine, and marsh deposits. The alluvial deposits on the east and south sides of the valley were divided into two units: continental deposits and alluvium. The alluvial deposits derived from the Coast Ranges on the west were mapped as continental and alluvial deposits.

Deposits derived from the Coast Ranges and from the Sierra Nevada, where they are not separated by flood-basin deposits, do not always interfinger beneath the present trough of the valley. Instead, these deposits interfinger at certain horizons beneath the western part of the valley (pls. 1, 2).

## CONTINENTAL DEPOSITS

Continental deposits are arkosic beds derived from the Sierra Nevada, Tehachapi, and San Emigdio Mountains. The unit includes the lower part of the continental deposits from the Sierra Nevada of Klausing and Lohman (1964, p. D15) and many of the strata at the south end of the valley mapped as the Tulare Formation by Hoots (1930, pls. 31, 43). Because the basal beds characteristically consist of sand containing *Amnicola* sp. and *Fluminicola* sp., also common to the basal beds of the Tulare Formation (Woodring and others, 1940, p. 18, 22–23, 85), and because the unit overlies rocks probably equivalent to the late Pliocene San Joaquin Formation (Klausing and Lohman, 1964, p. D14–D17), the continental deposits are considered to be late Pliocene and Pleistocene(?) in age and partly equivalent in age to much of the Tulare Formation in the Kettleman Hills. The age of the Tulare Formation was considered by Woodring (Woodring and others, 1940, p. 103–104) to be late Pliocene and Pleistocene(?) on the basis of a large fauna of mollusks. More recent faunal and potassium-argon dating (p. 22–23) has proven uncontrovertibly that the upper part of the Tulare Formation, which includes the Corcoran Clay Member, is of Pleistocene age.

### CONTINENTAL DEPOSITS FROM THE SIERRA NEVADA

Continental deposits derived from the Sierra Nevada are indicated on plates 1, 2, and 3. On the plates, a reduced-oxidized contact is shown to transgress these deposits. This contact is based on color changes indicated in available core and drillers logs. Where logs were not available, the contact was not indicated.

The reduced deposits consist mainly of moderately permeable fine to medium sand, silt, and clay that are blue, green, or gray, micaceous, and calcareous. They contain little or no gravel and were deposited probably in a deltaic or flood-plain environment. Samples from U.S. Geological Survey test well 24S/26E–36A2 (fig. 4) ranged in percentage carbonate from 3.2 to 11.1 and averaged 6.9. (See Johnson and others, 1968, table 7, p. A59.) The percentage carbonate includes all material dissolved out of a sample by a cold, dilute solution of hydrochloric acid (termed "acid solubility" by Johnson and others, 1968, p. A37).

The oxidized deposits consist mainly of poorly permeable moderately yellowish-brown calcareous silt and fine sand. Coarse sand and gravel are rare, but where present commonly contain much silt and clay. Where identified, these deposits range in thickness from 0 to about 800 feet (pls. 1, 2). They contain abundant calcareous nodules and stringers; samples from U.S. Geological Survey test well 24S/26E–36A2 ranged in percentage carbonate from 0.8 to 12.8 and averaged 5.7 percent (Johnson and others, 1968, table 7, p. A59).

### CONTINENTAL DEPOSITS FROM THE TEHACHAPI AND THE SAN EMIGDIO MOUNTAINS

Continental deposits at Wheeler Ridge (pl. 3) overlie fine-grained marine and nonmarine beds mapped as the Etchegoin and Chanac Formations by Hoots (1930); they are not shown on plate 3. The deposits underlie alluvium. Most logs indicate that the beds consist of poorly to moderately permeable yellowish-brown sand and silt eroded from the granitic rocks exposed in the higher parts of the mountains and from the marine and volcanic rocks of Tertiary age exposed in the foothills.

### FLOOD-BASIN, LACUSTRINE, AND MARSH DEPOSITS

The flood-basin, lacustrine, and marsh deposits consist of nearly impermeable blue-green or gray gypsiferous fine sand, silt, and clay. These deposits extend to a depth of about 3,300 feet beneath parts of Tulare Lake bed (pl. 1). In other parts of the valley trough, the flood-basin, lacustrine, and marsh deposits branch into tongues which interfinger with alluvium. Because of the contained fossils, high organic content, and stratigraphic relationship to adjacent deposits, the clay tongues are considered to be of a lacustrine or paludal origin. Where the clay tongues are interbedded with coarse deposits, they are traceable on electric logs, but where they are interbedded with fine deposits, their identification generally is speculative without detailed lithologic or paleontologic data. Six uppermost clay tongues are designated in descending order by the letter symbols A through F and are shown in cross sections (pls. 1–3). Five of the clay tongues and intervening geologic units are described in the log of core hole 20S/19E–31P (fig. 3). Plate 4 is a map showing the structural features and extent of the E clay, which includes the Corcoran Clay Member of the Tulare Formation; plates 5 and 6 are maps showing the structure and extent of the C and A clays, respectively. Three clays, labeled B, D, and F, are of limited extent and are difficult to correlate consistently on electric logs. Contour maps were not drawn on these clays because of their small extent, inadequate number of control points, and limited hydrologic significance.

Extensive lacustrine clay deposits at the base of the unconsolidated deposits are equivalent to lake sediments of the Tulare Formation reported in the Kettleman Hills by Arnold and Anderson (1910, p. 143–151), Barbat and Galloway (1934, p. 491), and Woodring, Stewart, and Richards (1940, p. 13–14). Because the clay deposits contain *Amnicola* and overlie the upper *Mya* zone, the basal lacustrine beds largely are equivalent to the A zone of Barbat and Galloway (1934). Consequently, the flood-basin, lacustrine, and marsh deposits range in age from late Pliocene to Holocene.

Basal lacustrine beds of the Tulare Formation in the Kettleman Hills (Woodring and others, 1940, p. 103–104) are reported to contain the largest fossil fauna of fresh-water mollusks known on the Pacific coast, as well as a highly diverse flora of diatoms (Lohman, 1938, p. 88). Of the 31 forms of mollusks recognized, only four are identified as living forms.

## E CLAY

The E clay, an extensive, confining stratum of silty clay, clayey silt, and sand, silt, and clay, was correlated on the basis of its distinctive resistivity and similar stratigraphic positioning in electric logs (fig. 3). In the study area, this clay, which was deposited in a lake occupying the San Joaquin Valley trough, underlies about 3,500 square miles of bottom land and the western part of the valley. It extends northward from Kern Lake bed to beyond the area shown on plate 4. The E clay is found about 250 feet below land surface in the vicinity of U.S. Highway 99, near Goshen and Pixley, and, locally, is more than 800 feet below land surface beneath Tulare Lake bed. The clay is commonly called the blue clay by water-well drillers. As mapped in this report, the clay includes and extends beyond previously described boundaries of the Corcoran Clay Member of the Tulare Formation (the diatomaceous clay of Davis and others, 1959, pl. 14).

The stratum north of Buena Vista Slough was originally named the Corcoran Clay by Frink and Kues (1954, p. 2358), who show the type section on electric and core logs of a well near the town of Mendota, Calif. In the progress report of the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley (1958, p. 117–119), Poland, Davis, Lofgren, and others formally designated the deposit as the Corcoran Clay Member of the Tulare Formation. The southward extension of the clay into a second basin of interior drainage, the Buena Vista Lake bed (pl. 4), is based on a few electric logs in the vicinity of Buena Vista Slough.

The Corcoran Clay Member of the Tulare Formation has not been previously identified south of Buttonwillow Ridge (Davis and others, 1959, p. 81 and pl. 14). However, a blue silty, sandy clay, which is rarely more than 75 feet thick, was correlated from the vicinity of Buttonwillow to Buena Vista and Kern Lake beds (pls. 2–4). Although diatoms have not been reported within the clay southward from Buttonwillow Ridge, volcanic ash was reported below it at a depth of 718 feet in core hole 31S/25E–27F1 (pl. 2). On the basis that the ash was deposited during the same episode as the ash found beneath the E clay to the north, the blue clay south of Buttonwillow Ridge is considered by the author to be a southward extension of the E clay of this report.

Frink and Kues (1954) concluded, on the basis of indirect evidence, that the deposit was Pleistocene in age. According to Davis, Green, Olmsted, and Brown (1959, p. 77–78), K. E. Lohman, on the basis of fossil diatom assemblages from core holes in the clay, correlated the Corcoran with part of the Tulare Formation and considered the diatomaceous clay to be of probable late Pliocene age. Lohman (written commun., May 10, 1968) has revised his opinion because of more recent data and now considers the Corcoran solely Pleistocene in age.

Vertebrate fossils from two sites show that the Corcoran is of middle or late Pleistocene age. Teeth of a caballine *Equus* (Irvingtonian or Rancholabrean age) found in an excavation of the Madera Canal were cited as stratigraphically beneath the Corcoran by Frink and Kues (1954, p. 2367). In 1964, Charles Hall (1965, p. 144–145), of the U.S. Bureau of Reclamation, discovered vertebrate remains in the Corcoran exposed by the San Luis Canal excavation, about 15 miles northwest of Mendota. The fauna, according to Dr. John Mawby of University of California, Berkeley (written commun., 1967, to J. F. Poland, U.S. Geological Survey), is either of middle Pleistocene (Irvingtonian) age or of late Pleistocene (Rancholabrean) age.

On the basis of paleontological evidence (also discussed in the section "Alluvium") and stratigraphic relationships (pls. 1–3), the E clay of this report is considered to be of Pleistocene age.

The E clay is warped into a gentle asymmetric northwesterly trending syncline, whose steeper flank is on the west side (pl. 4). Superimposed on the larger structure are smaller northwest-trending anticlines and synclines. North of Tulare Lake bed, the axis of the major syncline lies west of the present valley trough. Between Buena Vista and Tulare Lake beds, the axis and trough approximately coincide. South of Buena Vista Lake bed, the axis of the major syncline lies south of the present valley trough.

Near the northern end of Buttonwillow Ridge, the E clay generally is a dark-greenish-gray silty dense plastic diatomaceous stratum. In the northern part of the study area, the beds above the Corcoran are highly pumiceous (Frink and Kues, 1954, fig. 6 and p. 2358); within the E clay, a 0.5-foot bed of pumicite was cored at seven tests holes. Also, in several test holes at sites throughout the area, thin beds of ash were reported beneath the E clay. Marginally, the E clay bifurcates into an upper and a lower stratum which contains thin beds of moderately yellowish-brown silt and fine sand. The lower stratum probably represents the early transgression of Corcoran Lake (Frink and Kues, 1954, p. 2363–2365).

### C CLAY

The C clay (pl. 5) is a fine-grained lacustrine or paludal deposit occurring at a depth of about 100 feet near Buttonwillow Ridge, 50 feet beneath Semitropic Ridge (pl. 3), and 220 to more than 300 feet beneath Tulare Lake bed and parts of Fresno Slough (pls. 1, 3). Structure contours indicate that the deposit has been extensively warped and folded.

The logs of two core holes, one of which is shown in figure 2, show that the C clay is a yellowish-brown to grayish-blue silty calcareous clay about 10 feet thick. This clay, also identified on other electric logs, rarely is more than 50 feet thick. The C clay is considered to be of Pleistocene age.

### A CLAY

The A clay is a fine-grained lacustrine or paludal deposit composed mainly of plastic silty sandy gypsiferous highly organic clay that is blue, olive brown, or dark greenish gray. A log is shown in figure 3. In some areas, the clay is interbedded with a few lenses or stringers of fine to medium sand. The deposit generally is less than 60 feet thick and occurs at a depth of 10–60 feet beneath Buena Vista, Kern, and Tulare Lake beds and parts of Fresno Slough (pls. 1–3, 6).

The deposit was mapped on the basis of electric logs as a single lens of fine-grained sediment, but logs of core and auger holes indicate that in some areas it consists of several thin clay layers separated by thin beds of sand. The upper stratum was observed in a pit in section 9, T. 25 S., R. 23 E., about 10 feet below land surface. North of Buttonwillow Ridge (pl. 6), structure contours were drawn on the base of the lowest stratum of the A clay. Beneath Buena Vista and Kern Lake beds, it was necessary to draw structure contours on the base of the upper stratum because lithologic data were lacking at the lower stratum.

Croft (1968) reported that a radiocarbon date (W–1506) of 26,780 ± 600 years was obtained from wood found in a core sample about 3 feet beneath the A clay at a depth of 39 feet in well 25S/21E–21D. The date suggests a correlation with the Stansbury stage of Lake Bonneville as dated by Eardley, Gvosdetsky, and Marsell (1957, p. 1141) and is comparable to several radiocarbon dates at Searles Lake (fig. 1) that were obtained from material occurring near the base of the parting mud (Smith, 1962, p. 66). A radiocarbon date (W–1505) of 9,040 ± 300 years was obtained from wood within the upper stratum of the A clay in 32S/26E–10N, at a depth of 38 feet. The age of the A clay is therefore considered to be Pleistocene and Holocene(?). Radiocarbon determinations were by Meyer Rubin, Radiocarbon Laboratory, U.S. Geological Survey (in Ives and others, 1967, p. 514–515).

## CONTINENTAL AND ALLUVIAL DEPOSITS FROM THE COAST RANGES

Deposits eroded from the Coast Ranges, which interfinger with reduced continental deposits and with alluvium from the Sierra Nevada (pls. 1, 2), are shown as continental and alluvial deposits. Deposits occurring on the upper parts of Panoche, Cantua, and Los Gatos Creek fans consist of moderately permeable yellowish-brown sand, silt, and gravel.

Deposits of fans occurring between the fans noted above consist mainly of poorly permeable yellowish-brown calcareous sand, silt, and clay. In some areas, clayey deposits have not been wetted since burial and are susceptible to compaction due to wetting (near-surface subsidence). Deposits of subsiding fans have a clay content of about 15–30 percent, but deposits of nonsubsiding fans of the same size have a clay content of about 5–15 percent (Bull, 1964b). Mudflow deposits are more common in subsiding fans, and water-laid sediments are more common in nonsubsiding fans.

Irrigation has caused minor compaction due to wetting in one small area on the Panoche Creek fan; near-surface subsidence has not been noticed on the fans of Cantua and Los Gatos Creeks. In general, these three fans are considered to be nonsubsiding.

### ALLUVIUM

Alluvium is composed of coarse arkosic beds derived from the Sierra Nevada, Tehachapi, and San Emigdio Mountains. These beds overlie the continental deposits along the east and south sides of the valley (pl. 3), interfinger in parts of the valley trough with the flood-basin, lacustrine, and marsh deposits, and interfinger on the west side of the valley with the continental and alluvial deposits (pls. 1, 2). The unit ranges in depth from the land surface to 230 feet in test hole 24S/26E-36A2 (fig. 4) and from the land surface to 1,400 feet beneath Tulare Lake bed (pl. 1, *B–B′*). Logs indicate that the alluvium generally is coarser than the underlying continental deposits. This textural change at the top of the continental deposits is easily recognized in many areas (pl. 3) on electric logs; however, in some areas the contact with the continental deposits is arbitrary (pls. 1, 2, 3).

Mollusks obtained from a depth of 600–602 feet in core hole 20S/19E-31P (fig. 3 and pl. 1, *B–B′*), about 50 feet above the E clay and within the older alluvium, were examined by Taylor (1966) of the U.S. Geological Survey. The following forms, of Pleistocene age, were identified:

Fresh-water clam:
    *Sphaerium kettlemanense* Arnold
Fresh-water snails:
    *Valvata utahensis* Call
    *Lithoglyphus seminalis* (Hinds)
    *Tryonia*?

According to Taylor (1966, p. 48),

> This assemblage is different from those known previously from stratigraphically lower parts of the Tulare Formation. *Sphaerium kettlemanense* is known from the basal part of the formation, but none of the others have been found in the Tulare previously. *Lithoglyphus seminalis* lives in the Sacramento River, but has not been known as a fossil. *Valvata utahensis* is known as a Pleistocene fossil from western Nevada, southeastern California, and the northern borders of the Great Basin, but it has not been found previously west of the Sierra-Cascade Range.

The alluvium is considered to be of Quaternary age because of the paleontological evidence and the stratigraphic relationship to the E clay. The E clay, which contains fossils of middle or late

Pleistocene age and which is at least 600,000 years old, is found in about the middle of the alluvium as defined in this report (pls. 1–3). Assuming the same rate of deposition for the alluvium below the E clay as for that above the E clay, the alluvium represents about 1 million years of deposition.

Janda (1966, p. 221–229) stated that there is an apparent conformable relationship between a pumice bed in a rhyolithic ash deposit near Friant and the Corcoran Clay Member. He stated further (Janda, 1966, p. 245–246) that potassium-argon dating by G. B. Dalrymple of sanidine phenocrysts from pumice pebbles in the pumice bed near Friant gave an age of 600,000 ± 20,000 years and that this age probably corresponds closely with the age of alluvial deposition of ash overlying the Corcoran.

## ALLUVIUM FROM THE SIERRA NEVADA

Alluvium from the Sierra Nevada is shown on plates 1, 2, and 3, and a reduced-oxidized contact is shown to transgress these sedimentary deposits. Oxidized deposits occur mostly on the upper part of fans, and reduced deposits on the lower part.

The oxidized deposits of the alluvium deposited by the Kings, Kaweah, Tule, and Kern Rivers mainly consist of yellowish-brown gravel, fine to very coarse sand, and silt. These beds generally are highly permeable. Oxidized deposits, in the vicinity of Poso Creek (pls. 1, 3), were derived in part from the basement complex of the Sierra Nevada and in part from the Tertiary marine and nonmarine shale and sandstone that form the foothills between the Tule and the Kern Rivers. These sedimentary deposits are poorly to moderately permeable and consist mainly of yellowish-brown sand, silt, and clay. Gravel is reported in some logs near the mouth of Poso Creek.

Logs indicate that coarse- and fine-grained oxidized deposits of the alluvium generally are not as calcareous as the underlying continental deposits. Stringers and nodules of calcium carbonate were reported only rarely in cored material. In samples from well 24S/26E–36A2 (fig. 4), the percentage of carbonate ranged from 1.5 to 5.2 and averaged 2.6 (Johnson and others, 1968, table 7, p. A59).

The reduced deposits of the alluvium consist of moderately permeable bluish-green fine to coarse sand, silt, and clay. Gravel is rare and the sediments are sporadically cemented with calcium carbonate. The reduced deposits interfinger with flood-basin, lacustrine, and marsh deposits beneath Tulare Lake bed and with alluvium of Tertiary and Quaternary age from the Coast Ranges, west of the present valley trough.

### ALLUVIUM FROM THE TEHACHAPI AND THE SAN EMIGDIO MOUNTAINS

Alluvium has been derived from granitic, marine, and volcanic rocks that form the Tehachapi and the San Emigdio Mountains. These deposits generally are oxidized and, on the upper parts of the larger fans adjacent to the mountains (pl. 3), consist of moderately to highly permeable yellowish-brown gravel, sand, and silt. On the lower parts of the fans and beneath the valley trough, these deposits consist of poorly to moderately permeable yellowish-brown sand and silt. In general, these deposits are coarser than underlying deposits; but in some localities, the contact shown is arbitrary.

## HYDROLOGY

Unconsolidated deposits of late Tertiary and Quaternary age contain most of the usable ground water in the southern part of the San Joaquin Valley. Brackish to saline water occurs in a few isolated beds within the unconsolidated deposits, but most of it occurs within the marine and nonmarine rocks of Tertiary age that underlie the unconsolidated deposits. Where the upper part of the marine and nonmarine rocks of Tertiary age contain fresh water, they are part of the fresh ground-water reservoir.

The principal aquifers, which are also the most permeable geologic units along the east side of the valley, are the reduced continental deposits and the oxidized and reduced deposits of the alluvium. At the south end of the valley, the principal aquifers are the continental deposits and the coarse oxidized deposits of the alluvium. The principal producing aquifers on the west side of the valley are the coarse oxidized continental and alluvial deposits from the Coast Ranges and the reduced continental deposits and the alluvium from the Sierra Nevada.

The flood-basin, lacustrine, and marsh deposits are aquicludes that do not transmit water fast enough to furnish an appreciable supply for a well. The lacustrine clay tongues are virtually impermeable horizons that separate the alluvial sequence into separate aquifers.

### OCCURRENCE OF GROUND WATER

Ground water occurs under unconfined (water table), semiconfined, or confined (artesian) conditions within the ground-water reservoir in the San Joaquin Valley (Davis and others, 1959, Hilton and others, 1963, and Davis and Poland, 1957). The water table is the upper surface of the zone of saturation. Water-table conditions exist where an aquifer consists of relatively permeable deposits and water is free to move downward to the zone of saturation from land surface. Semiconfined conditions (Davis and others, 1959, p. 87) exist in water bodies that react to stresses of short duration, such as fluctuations in pressure due to pumping, in much the same manner as confined conditions exist in water bodies; however, in semiconfined water bodies the head adjusts to equilibrium with the water table over long periods of time. Confined or artesian conditions exist where water in an aquifer is confined under hydrostatic pressure by relatively impermeable beds and will rise in a well to a level above the base of the confining bed.

Detailed descriptions and water-level contour maps showing the position of the water table and the piezometric surface of the confined, semiconfined, and unconfined aquifers are available in reports by Davis, Green, Olmsted, and Brown (1959), Wood and Dale (1964), Hilton, McClelland, Klausing, and Kunkel (1963), and by many other authors whose works are listed in the selected references.

Although the E clay is the principal confining bed in the valley (Davis and other, 1959, p. 87–90; Davis and Poland, 1957, p. 426), water-level data indicate that the A clay also is an effective confining bed throughout most of its extent. Unpublished water-level maps by the U.S. Soil Conservation Service (written commun., 1957), Westlands Water District (written commun., 1965), well and auger-hole data supplied by John Glavinovich (written commun., 1964), and water-level records by Gordon and Croft (1964) and by Hilton, Klausing, and McClelland (1960) indicate that a shallow water body occurs in the strata above the A clay in irrigated areas. The water level in the shallow strata generally is 3–25 feet below land surface. Water levels in wells perforated immediately beneath the A clay, during the period 1960–65, were 50–100 feet below land surface (Gordon and Croft, 1964, and Hilton and others, 1960 and 1963, fig. 25).

## ARTIFICIAL RECHARGE

A ground-water reservoir can be most effectively utilized if it can be emptied during periods of heavy demand and refilled when demand is less, during periods of surplus water supply. Water spreading in stream channels, canals, spreading basins, or a combination of channels and spreading basins is the chief form of artificial recharge in the San Joaquin Valley (Davis and others, 1964, p. 34). Artificial recharge will be more successful if sites are located in areas underlain by coarse permeable deposits.

The most permeable strata along the eastern and southern margins of the valley are the coarse oxidized deposits of the alluvium. The coarse oxidized deposits of the continental and alluvial deposits are the most permeable strata along the western margin of the valley. These sedimentary deposits contain beds that probably are sufficiently permeable for artificial recharge. Sites for spreading basins, in the southern part of the San Joaquin Valley, should be located by test drilling in areas underlain by these deposits. Artificial recharge is impractical in areas underlain by the fine oxidized continental and alluvial deposits and by the fine oxidized continental deposits, because the beds are poorly permeable. Strata that perch water are reported to occur extensively within the fine oxidized deposits of the continental and alluvial deposits in the vicinity of Cantua Creek (Bianchi and others, 1962, p. 171–178). Similar strata probably occur elsewhere in these deposits and may cause serious drainage problems in the future when irrigation becomes more intense.

Coarse beds of sand and gravel, underlain by the confining A, C, or E clays, are suitable for artificial recharge. Recharge will be effective down to the top of the first confining clay. The deposits beneath the lacustrine clays can be recharged only through wells.

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