Geology of the Compacting Deposits in the Los Banos-Kettleman City Subsidence Area, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 497-E

Geology of the Compacting Deposits in the Los Banos-Kettleman City Subsidence Area, California

By R. E. MILLER, J. H. GREEN, *and* G. H. DAVIS

MECHANICS OF AQUIFER SYSTEMS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 497-E

Geology of the deposits undergoing compaction due to head decline, including source, type, physical character, and mode of deposition, and the hydrologic framework so developed

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1971

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-card No. 70-610408

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

GEOLOGY OF THE COMPACTING DEPOSITS IN THE LOS BANOS-KETTLEMAN CITY SUBSIDENCE AREA, CALIFORNIA

By R. E. Miller, J. H. Green, and G. H. Davis

ABSTRACT

The Los Banos–Kettleman City area includes 1,500 square miles on the central west side of the San Joaquin Valley, Calif., chiefly in western Fresno County. It is an agricultural area, irrigated chiefly by ground water. Intensive pumping has lowered the artesian head several hundred feet and has caused the water-bearing deposits to compact. By 1959 the resulting regional subsidence of the land surface exceeded 4 feet in most of the area and locally attained 20 feet. Superimposed on this regional subsidence was as much as 10–15 feet of localized subsidence due to hydrocompaction of moisture-deficient near-surface deposits, which affected at least 80 square miles. This is the largest known area of intensive land subsidence due to withdrawal of ground water. Therefore, the geology of the compacting deposits, including source, type, physical character, and thickness, is of primary interest in appraising the response of the sediments to change in effective stress.

The fresh-water-bearing deposits of late Pliocene to Holocene age forming the ground-water reservoir in the Los Banos–Kettleman City area have been derived from both the Diablo Range to the west and the Sierra Nevada to the east.[1] Rocks exposed in the tributary drainage area in the Diablo Range, which range in age from Jurassic to Pleistocene, shown on a generalized geologic map, are chiefly sandstone and mudstone. Unconsolidated to semiconsolidated sediments of continental, and, locally, of marine origin, which crop out along a relatively continuous strip 1–6 miles wide bordering the western flank of the subsiding area, were mapped for this report. They include the Jacalitos, Etchegoin, and San Joaquin Formations of Pliocene age and the Tulare Formation of Pliocene and Pleistocene age.

The principal aquifers occur within the alluvial and lacustrine deposits of the Tulare Formation, which underlies all of the Los Banos–Kettleman City area and ranges in subsurface thickness from a few hundred to more than 3,000 feet. The underlying formations of Pliocene age contain brackish or saline water, except in the central southwestern part of the area where fresh water occurs in the San Joaquin and Etchegoin Formations.

In a series of subsurface maps and sections based on electric logs and core records, the Tulare Formation and overlying younger deposits are subdivided into alluvial-fan, flood-plain, deltaic, and lacustrine deposits and are identified as to source area—Sierra Nevada or Diablo Range. The one persistent mappable subsurface stratigraphic unit is the Corcoran Clay Member of the Tulare Formation, a diatomaceous lacustrine clay 0–120 feet thick that underlies most of the project area and is the principal confining bed.

Deposits derived from the Sierra Nevada extend far west of the modern axis of the San Joaquin Valley. The axis of the valley shifted laterally in Tulare time, in response to tectonic uplift in the mountains, warping in the valley, and climatic changes, which determined the relative proportion of sediments being contributed from the east and west. In pre-Corcoran time, Sierra flood-plain deposits extended a maximum of 13–17 miles west of the modern topographic axis; immediately after deposition of the Corcoran—about 600,000 years ago—Sierra micaceous sands extended as much as 13 miles west. Subsequently, the axis gradually moved east to its modern position.

In general, the deposits from the Sierra Nevada, which are mostly flood-plain deposits, are coarser, better sorted, and more permeable than those from the Diablo Range, which are mostly alluvial-fan deposits. The depositional history and the character of the deposits are primary factors in determining areal variation in permeability and compaction characteristics of the water-bearing sediments in the Los Banos–Kettleman City area.

The continental fresh-water-bearing deposits can be subdivided into two principal hydrologic units. The upper unit, termed the "upper water-bearing zone," extends from the land surface to the top of the Corcoran Clay Member at a depth ranging from 20 to 900 feet below the land surface. The lower unit is referred to as the "lower water-bearing zone." It is 600 to more than 2,000 feet thick and extends from the base of the Corcoran Clay Member down to the deposits containing the main saline water body.

The chemical character of the ground water changes markedly with depth. The major changes with depth are a marked decrease in dissolved solids and an increase in the percent of sodium among the cations.

INTRODUCTION

The Los Banos–Kettleman City area of California, as referred to in this report, is that part of the west side of the San Joaquin Valley extending from Los Banos in Merced County, through western Fresno County, to Kettleman City in Kings County. As shown in figure 1, it is bounded on the west by the foothills of the Diablo

[1] Principal source of deposits, where identified, is indicated as Diablo (derived from the Diablo Range) or Sierra (derived from the Sierra Nevada).

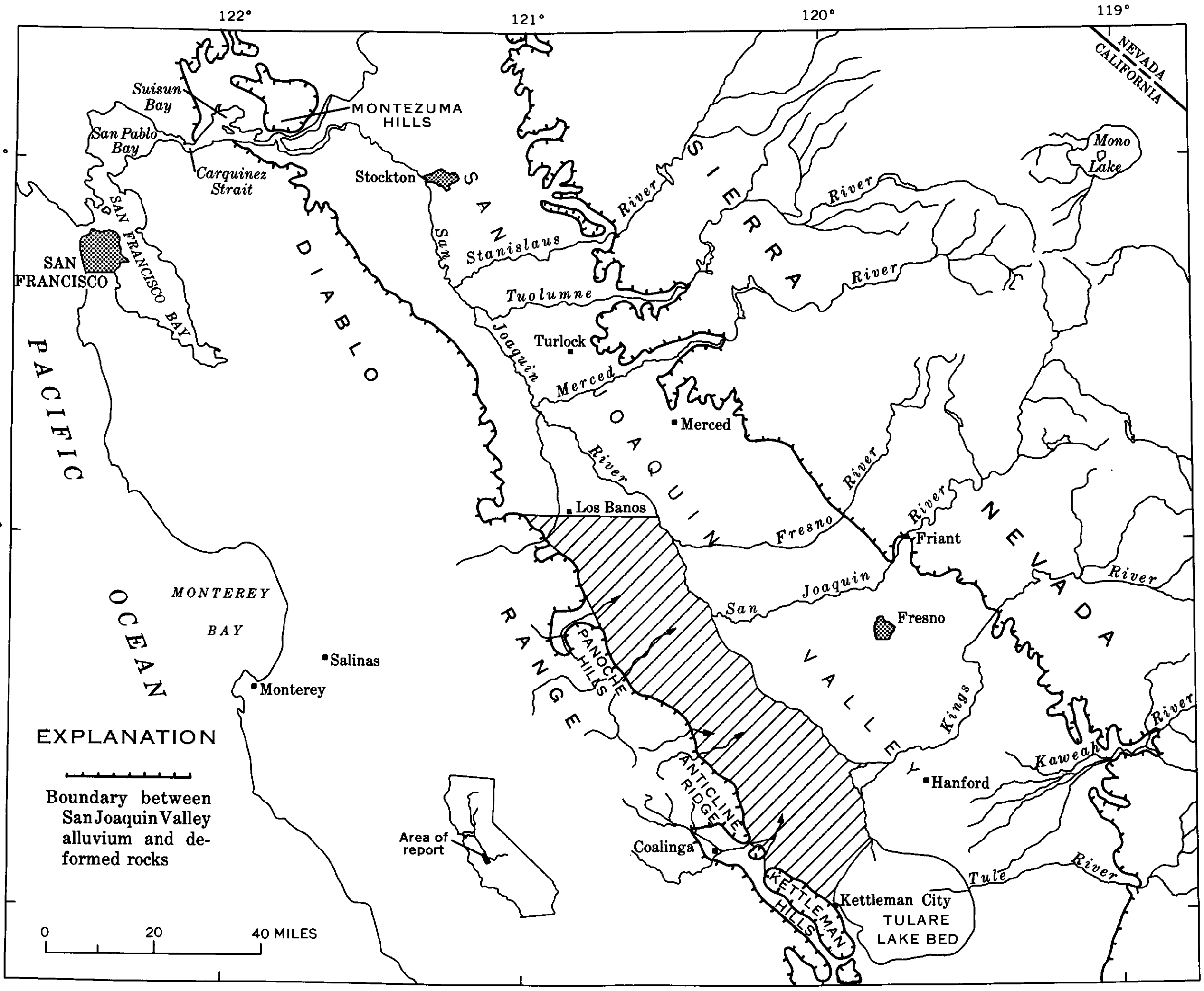


FIGURE 1.—Index map of central California. Los Banos–Kettleman City area shown by diagonal ruling.

Range, and on the east, by the trough of the San Joaquin Valley.

When the first Spanish soldiers entered the valley in 1772, they found it populated with Indians and wild game. Since that time the changes imposed by man on the landscape have been primarily due to agriculture. The land has been tilled nearly to the edge of the foothills and irrigated with water chiefly pumped from deep wells but, in part, imported in canals; the principal crops grown in the Los Banos–Kettleman City area are grain, cotton, and alfalfa. Sheep graze in the Coast Ranges west of the valley.

The climate is arid and the summers are very hot. This climatic condition combined with high mineral content of the ground water has discouraged any large-scale urban or industrial development in the area. Less than a dozen very small towns occupy this 1,500-square-mile area where the annual rainfall is from 6 to 8 inches.

Large declines in artesian head in confined aquifers, due to the intensive pumping of ground water for irrigation, had caused more than 2 feet of subsidence of the land surface throughout 1,200 square miles of the Los Banos–Kettleman City area as of 1959. Maximum subsidence of 20 feet had occurred west of Mendota; near Huron in the southern part of the area, maximum subsidence totaled 16 feet in 1959 (fig. 2). Between 1955 and 1959 the rate of land-surface subsidence ranged from 0.2 foot to 1.5 feet per year. Near-surface subsidence has resulted from hydrocompaction of moisture-deficient deposits above the water table in 82 square miles along the western border of the valley (Lofgren, 1960; Bull, 1964). This hydrocampaction, which is locally (fig. 2) superimposed on the more widespread compaction due to decline of head, has resulted in startling surface slumpage and very extensive damage to structures. Land subsidence in this area has been, and probably will continue for some years to be, a serious problem in the design and maintenance of highways, oil pipelines,

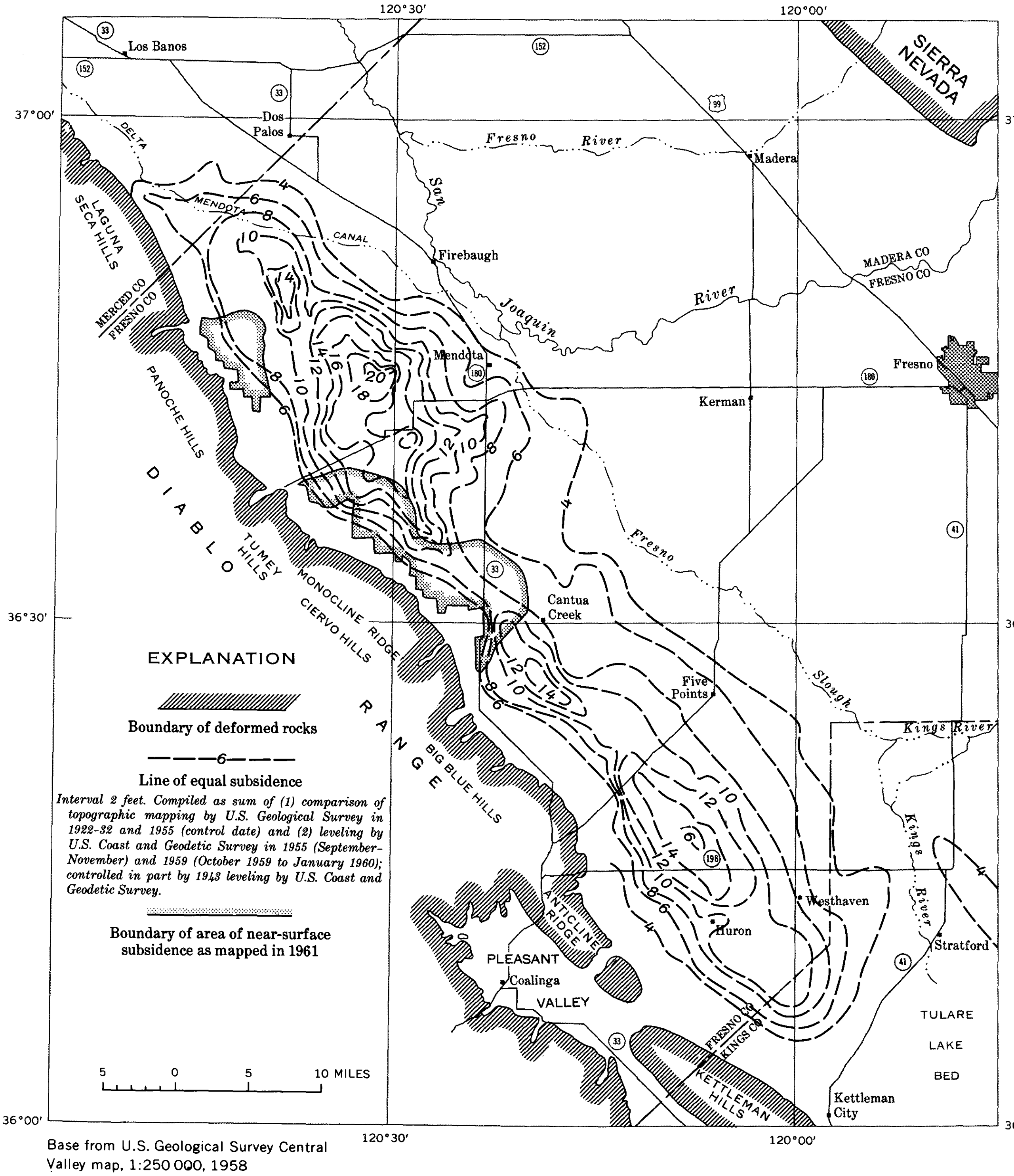


FIGURE 2.—Land subsidence, 1922–32 to 1959.

powerlines, irrigation canals and ditches, and other large structures. However, increased understanding of the subsidence phenomenon has made it possible to cope with many of the subsidence problems.

PREVIOUS INVESTIGATIONS

Geologists first turned their attention to the Los Banos–Kettleman City area in the 1890's when the first oil wells were drilled in the vicinity of Coalinga. The earliest systematic geologic investigation was that of W. L. Watts (1894), who reported on the oil fields along the border of the San Joaquin Valley for the California State Mining Bureau. Since that time, many reports on the geology of the oil fields in, and adjacent to, the Los Banos–Kettleman City area have been written. Most of the work, however, has been concerned chiefly with the oil-bearing formations of Cretaceous and Tertiary age. The earliest published detailed geologic descriptions of subsurface Pliocene and Quaternary deposits are in papers on the Kettleman Hills oil field by Goudkoff (1934), Barbat and Galloway (1934) and Woodring, Stewart, and Richards (1940).

The first detailed geologic studies in the area were by Arnold and Anderson (1910), who described and mapped the geology of the hills around Coalinga and a part of the Kettleman Hills. Anderson and Pack (1915) extended reconnaissance geologic mapping of the western border of the San Joaquin Valley from the Coalinga area northward to Suisun Bay. Woodring, Stewart, and Richards (1940) enlarged upon the earlier work of Arnold and Anderson in their comprehensive report on the geology and paleontology of the Kettleman Hills. Their report contributed greatly to dating of the formations exposed there.

Work by later authors has been mostly detailed studies of small areas. These studies include a report on the Moreno Formation at its type section on Moreno Gulch by Payne (1951), a report on the geology of the Ortigalita Peak quadrangle by Briggs (1953), and a report on the geology of Tumey and Panoche Hills by Schoellhamer and Kinney (1953). The areas covered by these reports are shown in the index to geologic mapping (pl. 2).

The rapid growth of irrigation on the central west side of the San Joaquin Valley during and after World War II greatly increased the rate of ground-water withdrawal from the late Cenozoic water-bearing deposits. This increase in withdrawal caused a rapid decline in water levels, and an investigation of possible overdraft was made by the U.S. Geological Survey in cooperation with the California Department of Water Resources (Davis and Poland, 1957). In the fieldwork for this investigation, which began in 1950, about 700 drillers' logs and electric logs were collected; these data formed the basis for a general description of the water-bearing deposits throughout most of the area covered in this report.

During 1951 and 1952, the U.S. Bureau of Reclamation drilled 64 core holes in the San Joaquin Valley as part of their ground-water and canal studies. Twelve of these core holes are in the Los Banos-Kettleman City area. A paper by Frink and Kues (1954) described some of the late Tertiary and Quaternary stratigraphy of the San Joaquin Valley as interpreted from the core-hole studies. Their paper was the first to describe the wide extent and hydrologic importance of the Corcoran Clay Member of the Tulare Formation.

PURPOSE OF INVESTIGATION AND SCOPE OF REPORT

Previous geologic investigations along the west border of the San Joaquin Valley were concerned primarily with petroleum development and were directed mainly at the stratigraphy and structure of marine deposits of Pliocene age and older. Hydrologic investigations, although they dealt with the compacting deposits, were directed mainly at evaluating the water resources of the area.

By 1954, pronounced subsidence of the land surface in most of the Los Banos-Kettleman City area and in two other extensive areas in the valley resulted in the formation of an Inter-Agency Committee on Land Subsidence in the San Joaquin Valley for the purpose of planning and coordinating the study of this phenomenon. The committee recommended (1955) a comprehensive investigation of the extent, magnitude, causes, and possible remedies for the subsidence.

As one result of the Inter-Agency planning, the U.S. Geological Survey undertook intensive studies of subsidence due to water-level decline in the San Joaquin Valley. These studies are being made in cooperation with the California Department of Water Resources.

Poland and Davis (1956) summarized the available information on subsidence in the Los Banos-Kettleman City area as of the start of the investigation. Ireland (1962) prepared an inventory and description of wells, and Bull (1961, 1964) has described extent, causes, and mechanics of near-surface subsidence in the Los Banos-Kettleman City area.

Areas of active and substantial land subsidence afford an unusual opportunity to study the compaction of sediments in response to increase in applied stress that can be measured. In 1956, therefore, the Survey also began a companion federally financed research investigation; it is directed toward determining the principles controlling the deformation (compaction or expansion) of aquifer systems resulting from change in effective stress (grain-to-grain load), caused by change in internal fluid pressure. This research study on the mechanics of aquifer systems is under the direction of J. F. Poland.

This report is one product of the Federal research program. It describes the geology of the deposits that are undergoing compaction in the Los Banos-Kettleman City area and includes discussions of stratigraphy, lithology, source, environment of deposition, structure, and geologic history. The report also describes briefly the hydrologic framework of the compacting deposits and the chemical quality of the ground waters.

Geologic mapping of the water-bearing deposits exposed along the western border of the valley is shown on plate 1. The description of the subsurface geology is supported by electric-log sections and by maps showing extent, configuration, and thickness of various important geologic units in the water-bearing section.

The data presented herein furnish the basis for study of the relationship between the physical character and depositional environment of the different types of the continental sediments and their relative compaction in response to the increased effective stress caused by the decline in artesian head.

Other reports in this series describe the physical and hydrologic properties of the water-bearing deposits (Johnson and others, 1968), their particle sizes and clay minerals (Meade, 1967), and the factors that influence change in pore volume and compaction under increasing effective overburden load (Meade, 1968). Several short papers describing methods of study and selected findings have been published while the investigation was in progress (Lofgren, 1961; Meade, 1961a, b; Miller, 1961; Poland, 1960, 1961; Poland and Evenson, 1966).

The analysis and interpretation of subsurface geology was done by R. E. Miller from data available prior to 1963. The surface geologic mapping was done in 1957 by J. H. Green, assisted by W. A. Cochran. A manuscript describing the subsurface geology, hydrology, and geochemistry of the ground waters was written by R. E. Miller; a companion manuscript written by J. H. Green described the stratigraphy of the exposed rocks. These two manuscripts subsequently were revised and combined by G. H. Davis in this report.

The geologic map (pl. 1) included in this report shows the outcrop areas of the unconsolidated and semiconsolidated formations of Pliocene and Pleistocene age and the outlines of the moderately to poorly permeable alluvial soils that border the foothills. The Etchegoin and Jacalitos Formations are differentiated, and the Tulare Formation is distinguished from the terrace deposits. Geologic sections measured at eight locations are presented in graphic form to illustrate the lithologic character of the late Tertiary and Quaternary deposits as exposed at the land surface (figs. 5–7).

In the areas mapped in detail by earlier workers, their geologic mapping was adopted in most part with little or no modification. This was done for mapping in the Kettleman Hills (Woodring and others, 1940), the mapping in the Tumey and Panoche Hills by Schoellhamer and Kinney (1953), and the mapping in the Ortigalita Peak quadrangle (Briggs, 1953). The principal modification, discussed under the Tulare Formation, involved the reassignment of Briggs' Oro Loma Formation between Little Panoche and Ortigalita Creeks to the Tulare Formation on the basis of evidence developed during 1961–64.

The reconnaissance mapping was done by J. H. Green and W. A. Cochran in July–November 1957. Aerial photographs aided immensely in this work. The usual procedure for mapping was to determine formation boundaries by inspection in the field and then to extend them on the photographs. Many repetitions of this process, with additional detailed field inspections and measurements at selected locations, allowed mapping of a large area in the relatively short period of fieldwork.

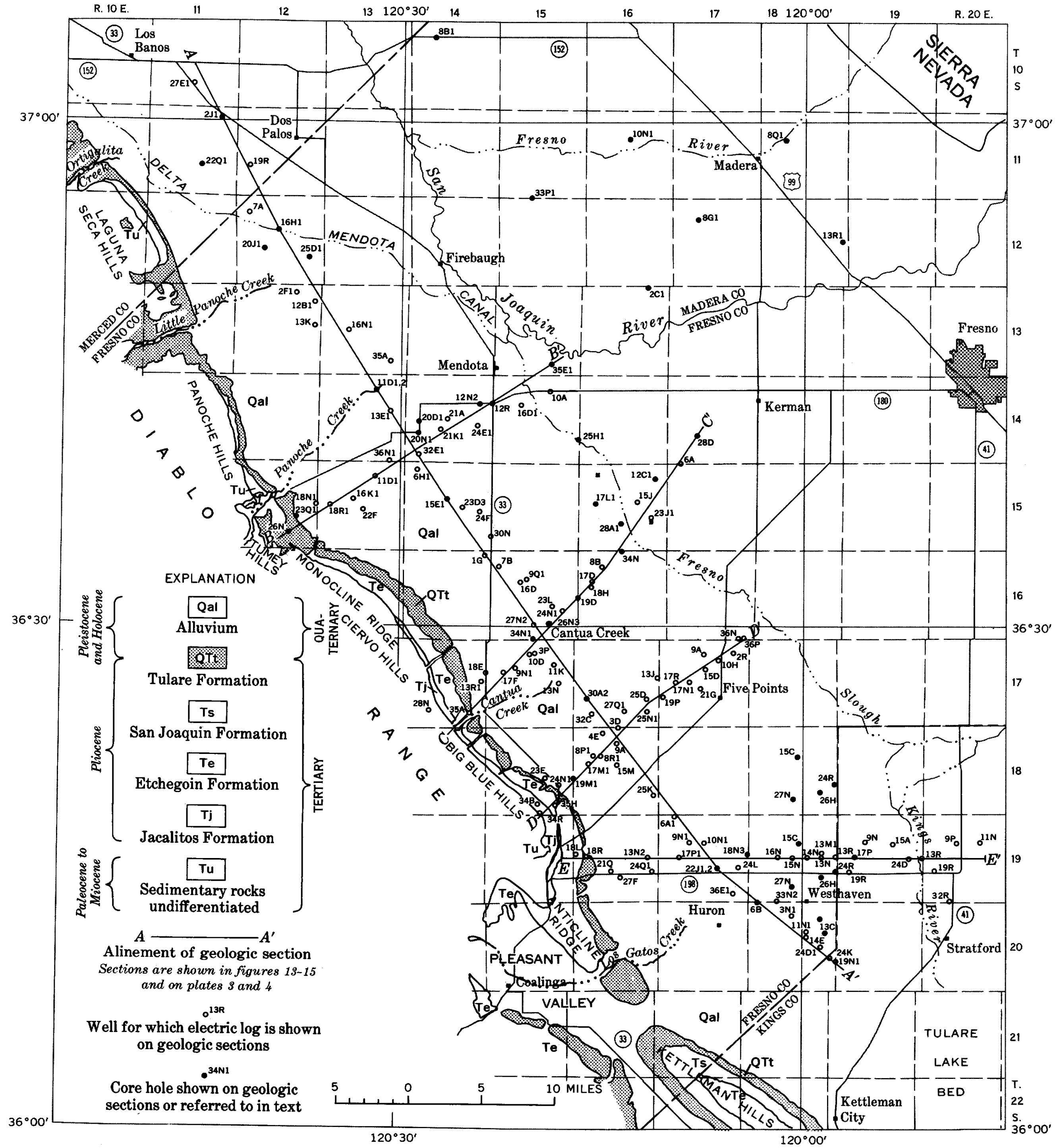
The interpretation of the subsurface geology was based largely on interpretation of electric logs of water wells in conjunction with stratigraphic information from exploratory core holes.

As part of the Inter-Agency Committee's activity during 1957 and 1958, four core holes were drilled in the Los Banos-Kettleman City area. Composite logs of these holes are presented on plate 5.

About 500 electric logs and several hundred drillers' logs of water wells collected to June 1961, and more than 400 single-point electric logs of shallow exploration holes drilled in the San Joaquin Valley by the Geochemical Surveys of Dallas, Tex., were utilized in the present study. Lithologic and stratigraphic data from 31 core holes in or near the Los Banos-Kettleman City area (table 1) were used in preparing this report. Stratigraphic interpretations of the subsurface geology are shown by a series of four transverse and one longitudinal sections (fig. 3).

ELECTRIC-LOG INTERPRETATION

Electric logs of boreholes in alluvial sediments seek to measure and record two quantities. The first is the variations, in the borehole, of natural electrical currents that flow between clay beds and more permeable beds wherever such beds are in contact. The mud column in the borehole and the adjacent sediments constitute an electrical resistance, and flow of current through this



Base from U.S. Geological Survey Central Valley map, 1:250 000, 1958

Geology chiefly by J. H. Green, 1957

FIGURE 3.—Location of geologic sections and core holes.

TABLE 1.—*Core holes in or near the Los Banos–Kettleman City area*

[Locations of core holes shown in figure 3]

Core hole	Year drilled	Depth (feet)	Drilled by—
12/12–16H1	1957	1, 005	Inter-Agency Committee on Land Subsidence in the San Joaquin Valley.
14/13–11D1	1957	1, 500	Do.
16/15–34N1	1958	2, 000	Do.
19/17–22J1, 2	1957	2, 203	Do.
10/14–8B1	1952	1, 002	U.S. Bureau of Reclamation.
11/11–2J1	1952	600	Do.
11/11–22Q1	1952	598	Do.
11/15–33P1	1952	850	Do.
11/16–10N1	1952	500	Do.
11/18–8Q1	1952	810	Do.
12/12–20J1	1952	430	Do.
12/12–25D1	1952	420	Do.
12/17–8G1	1952	500	Do.
12/18–13R1	1952	700	Do.
13/15–35E1	1952	735	Do.
13/16–2C1	1952	750	U.S. Bureau of Reclamation.
14/15–25H1	1952	705	Do.
15/12–23Q1	1952	850	Do.
15/14–15E1	1952	800	Do.
15/16–12C1	1952	733	Do.
15/16–17L1	1952	800	Do.
15/16–28A1	1952	800	Do.
17/16–30A2	1952	1, 500	Do.
20/18–13C	1936	3, 501	Seaboard Oil Corp. of Delaware.
19/18–15C	1929	1, 022	Shell Oil Co.
19/18–24R	1929	2, 559	Do.
19/18–26H	1929	3, 071	Do.
19/18–27N	1929	2, 242	Do.
19/19–17P	1929	3, 835	Do.
20/18–6B	1929	3, 607	Do.
20/18–11A	1929	1, 881	Do.

NOTE.—In determining the source areas of the deposits, the authors are indebted to Ira E. Klein, of the U.S. Bureau of Reclamation, for his petrographic analysis of many of the core samples.

resistance causes a potential change equal to the product of the magnitudes of the resistance and the current. The driving potential that causes the currents to circulate is called a spontaneous or self potential. The record of variations of this potential in millivolts is the "S. P. curve" of the electric log.

The second quantity that the electric log seeks to measure is the electrical resistivity of the strata penetrated by the borehole, generally expressed in ohm-meters (ohm-m²/m). This measurement is commonly done by what is known as the three-electrode method, in which one current electrode is placed at the surface, and the other current electrode and two potential electrodes variously spaced on a mandrel or "sonde" are lowered into the borehole. The distance between the potential electrodes is called the pickup span, which is generally small compared with the distance between the borehole current electrode and the midpoint between the potential electrodes which is commonly called the electrode spacing of the arrangement. The greater the electrode spacing, the deeper the penetration of the current into the beds forming the walls of the borehole. Resistivity curves on electric logs are generally made using two or more different electrode spacings. The purpose of this method, in part, is to make possible a determination of the depth of the invasion of the drilling-mud filtrate into the beds adjacent to the borehole. This can only be done in permeable formations, however, and in addition, the mud resistivity, borehole diameter, and bed thickness must be known. In the more heterogeneous alluvial sediments, only the relative amount of drilling-mud-filtrate invasion can be determined. This is done by noting the differences in resistivity recorded for the same stratum by resistivity curves made with different electrode spacings. If the drilling mud has a lower restivity than the pore water in the formation, then the resistivity recorded by the shorter electrode spacing is lower than that recorded by the longer spacing and the radius of the drilling-mud-filtrate invasion is greater. If the drilling-mud filtrate has a higher resistivity than the pore water, the reverse relationship occurs. The depth of the mud-filtrate invasion is sometimes an indicator of the relative permeability of the bed invaded, because, in beds composed of similar sediments, the greater the permeability, the greater the amount of mud-filtrate penetration. This criterion can only be used as a rough indicator, however, and is not always dependable because other factors are involved, such as variations in hole diameter, thickness of the bed in relation to the electrode spacings, and the difference in head between the drilling mud and the formation water.

The type of sediments forming alluvial strata is reflected by their spontaneous potential and resistivity as shown in figure 4. Clays generally give a maximum deflection to the right on the spontaneous-potential curve and have a low resistivity on the resistivity curve. Fresh-water sands and gravels give a deflection to the left on the spontaneous-potential curve and have a high resistivity on the resistivity curve. The greater the amount of clay and silt present in a sand, the lower the resistivity. If a bed contains brackish water, it generally gives a large deflection to the left on the spontaneous-potential curve and has a low resistivity. The type of alluvial sediments present in the bed then has to be approximately by the relative amount of drilling-mud invasion, assuming that greater invasion would occur in sands than in clays. More detailed information on electric-log interpretation can be found in many texts on the subject.

The electric logs included on geologic sections in this report show only two curves. These two are the spontaneous-potential curve on the left and the short spacing ("short normal") resistivity curve on the right. Because of the small scale of the sections, it was not practicable to show the longer spacing ("long nor-

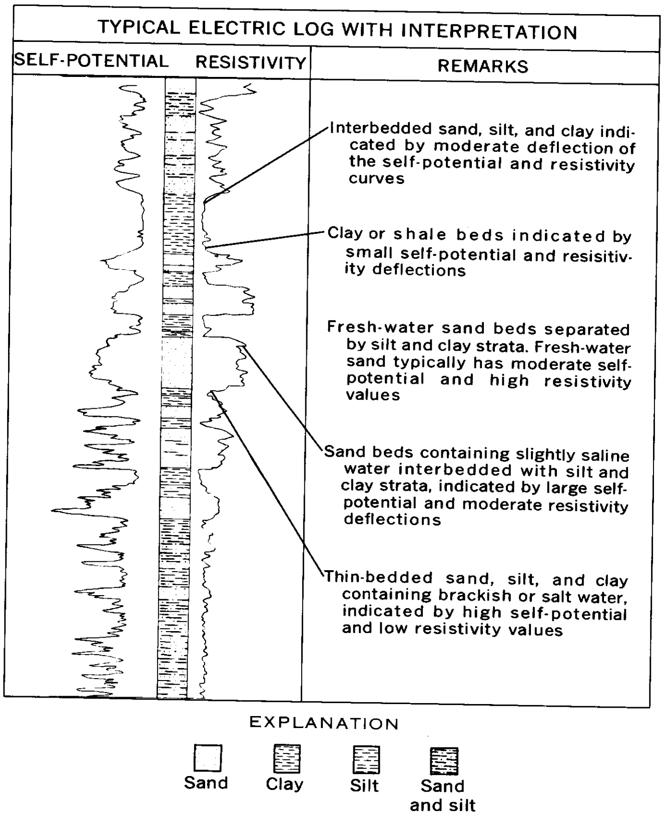


FIGURE 4.—Typical electric log with interpretation. From Davis and Poland (1957, pl. 30).

mal") resistivity curve on the geologic sections; but this second resistivity curve also was used in study and interpretation of the electric logs.

ACKNOWLEDGMENTS

The writers are grateful for the whole-hearted cooperation and material aid received from other public agencies participating in the Inter-Agency investigation, from private firms, and from individuals in the San Joaquin Valley. Special thanks are due to Ira E. Klein, geologist, Bureau of Reclamation, whose petrographic studies of many of the core sample furnished part of the basis for interpretations of the source of the deposits; to Geochemical Surveys Inc., of Dallas, Tex., who supplied electric logs of some 400 exploratory holes drilled by them; to the California Division of Highways for supplying excellent low-altitude aerial photographs of the western border of the valley, which were invaluable in the geologic mapping; to Griffin Inc., for permission to drill core holes on their property; and to the Pacific Gas & Electric Co., for supplying information on well yields and pumpage.

WELL-NUMBERING SYSTEM

The well-numbering system used in this report is the one used by the Geological Survey in California and by the California Department of Water Resources. It shows the locations of wells according to the rectangular system for the subdivision of public land. For example, in the number 14/15–18E1, which was assigned to a well 2½ miles south of Mendota, the part of the number preceding the slash indicates the township (T. 14 S.); the number following the slash, the range (R. 15 E.); the digits following the hyphen, the section (sec. 18); and the letter following the section number, the 40-acre subdivision of the section as shown in the accompanying diagram.

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 number. Thus, well 14/15–18E2 is the second well to be listed in the SW¼ of the NW¼ of sec. 18. As all of the Los Banos–Kettleman City area is south and east of the Mount Diablo base and meridian, the foregoing abbreviation of the township and range is sufficient. Exploration test holes and oil wells have not been assigned final digits.

GEOLOGY

GEOLOGIC HISTORY AND STRUCTURE

The San Joaquin Valley is a great structural downways between the tilted block of the Sierra Nevada on the east and the complexly folded and faulted Coast Ranges on the west. The geologic history and development of the valley is intimately related to events in the bordering mountains; hence, geologic studies in the mountains are most helpful in unraveling the geology of the valley.

The Sierra Nevada rises from an altitude of 500 feet along the east border of the San Joaquin Valley to more than 14,000 feet in a distance of about 60 miles. The range may be visualized as a much-dissected tilted plateau, uplifted along its eastern flank and depressed along its western flank, where it is overlain by sedimentary deposits of the San Joaquin Valley.

The crystalline complex of the Sierra Nevada consists of metamorphosed shale, sandstone, limestone, and chert, intruded by plutonic rocks that range in composition from peridotite to granite. The bulk of the rocks of the range, however, are of granitic composition. Sparsely scattered fossils found in the metasediments indicate marine deposition during the Paleozoic Era and in the Triassic and Jurassic Periods. Potassium-argon dating of the intrusive rocks (Curtis and others, 1958; Kistler and others, 1965) suggests three intrusive episodes: Early Jurassic, Late Jurassic, and Late Cretaceous time.

Beneath the San Joaquin Valley, crystalline basement rocks similar to those exposed in the Sierra Nevada are overlain by a wedge of sediments, partly of marine origin, that thickens westward. The full thickness of these rocks has not been penetrated by drilling, but geophysical and other indirect evidence suggests that the Sierra Nevada block extends westward to the flanks of the Coast Ranges (Davis and others, 1959, p. 41). The oldest beds known from drilling in the Los Banos–Kettleman City area are of Late Cretaceous age. Marine sediments of Early Cretaceous age, however, are exposed in the Diablo Range to the west and may extend a short distance beneath the San Joaquin Valley along its western border.

The Diablo Range (the most easterly of the Coast Ranges) forms the western border of the San Joaquin Valley. In a general sense, the structure of this range is a broad anticline whose eastern monoclinal limb dips beneath the valley. The exposed core of the range is formed by complexly folded and contorted sedimentary and igneous rocks of the Franciscan Formation. Less deformed sedimentary strata exposed along the western border of the valley and folded during the uplift of the Coast Ranges range in age from Late Cretaceous to Quaternary.

Although broadly anticlinal, the Diablo Range is characterized by lesser folds that trend obliquely to the range and pass beneath the valley. In general, the structural complexity along the west flank of the Los Banos–Kettleman City area increases southward. For example, the Kettleman Hills is the surface expression of one of these oblique-trending anticlinal folds.

During the Cretaceous and throughout early Tertiary time, the Los Banos–Kettleman City area was the site of marine deposition. From Miocene time onward, deposition was mainly nonmarine in the northern part of the area, while marine deposition continued in the southern part until late in Pliocene time. The youngest marine deposits, which are extensively exposed along the southwestern border of the area, are sedimentary rocks of the Etchegoin and San Joaquin Formations, of middle and late Pliocene age, respectively. The Pliocene marine deposits grade northward into nonmarine deposits. At the north edge of the area, the youngest exposed marine deposits are in the San Pablo Formation of Miocene age.

GEOLOGY OF THE TRIBUTARY DRAINAGE AREA, DIABLO RANGE

Beneath the Los Banos–Kettleman City area, predominantly well-sorted sandy sediments from the Sierra Nevada interfinger with predominantly poorly sorted silty and clayey sediments from the Coast Range. Continental deposits of Pliocene and Pleistocene age, and, to a lesser extent, Pliocene marine sediments, together with overlying Holocene alluvium, constitute the ground-water reservoir of the Los Banos–Kettleman City area.

The geology of the tributary drainage area in the Diablo Range to the west is directly pertinent to this investigation for several reasons. First, this tributary area is the source of more than half of the deposits that constitute the ground-water reservoir. Second, the geologic history of the tributary mountain area is an aid in deciphering that of the valley deposits. Third, the fine-grained deposits of the ground-water reservoir, which are derived chiefly from the Diablo Range source area, are the ones most subject to compaction. For these several reasons, the source areas in the Diablo Range are described in some detail on following pages.

Plate 2 presents a highly generalized picture of the geologic units that underlie the drainage basins of the west border of the San Joaquin Valley between latitude 36°N. and 37°N.—virtually the west border of the Los Banos–Kettleman City area. The geologic units have been combined into six broad categories as shown in table 2.

The formational units listed are those given in the principal sources of the mapping as shown in the index to plate 2—namely, Arnold and Anderson, 1910; Anderson and Pack, 1915; Woodring and others, 1940; Schoellhamer and Kinney, 1953; Briggs, 1953; and the California Division of Mines, 1958 (Santa Cruz sheet).

The general description of the geology of the drainage area tributary to the Los Banos-Kettleman City area is based on the same sources as plate 2. Specific references have largely been omitted for the sake of simplicity. Formational names and ages used in the discussion are in accord with the currently accepted nomenclature of the U.S. Geological Survey.

JURASSIC AND CRETACEOUS ROCKS

In can readily be seen from plate 2 that rocks of the oldest generalized unit, those of Jurassic and Cretaceous age, are common in the tributary drainage basins in the northern part of the area. Rocks of this unit are not common in the southern part of the area where marine rocks of Cretaceous and Tertiary age predominate in the drainage basins. The areas occupied by the different geologic units within 13 of the largest drain-

TABLE 2.—*Generalized geologic units of the drainage area tributary to the Los Banos–Kettleman City area*

Generalized geologic unit	Symbol on pl. 2	Formations and age
Alluvium	Qal	Alluvium (Pleistocene and Holocene).
Undifferentiated continental deposits.	QTu	Alluvium (Pleistocene and Holocene), terrace deposits (Pleistocene), and Tulare Formation (Pliocene and Pleistocene).
Continental and marine sedimentary deposits of late Tertiary and Quaternary age.	QT	Terrace deposits (Pleistocene); Tulare Formation (Pliocene and Pleistocene); San Joaquin, Etchegoin, and Jacalitos Formations (Pliocene).
Marine sedimentary and volcanic rocks of early Tertiary age.	Tu	San Pablo, Temblor, Santa Margarita, and Vaqueros Formations (Miocene); Monterey Shale (Miocene); Quien Sabe Volcanics of Taliaferro (1949) (Miocene?); Kreyenhagen Formation (Eocene and Oligocene?); Domengine Sandstone, Yokut Sandstone of White, (1940), Avenal Sandstone, and Tesla Formation (Eocene); Lodo Formation (Paleocene and Eocene); Laguna Seca Formation of Payne (1951) (Paleocene); and Martinez Formation (Paleocene).
Marine sedimentary rocks of Cretaceous age.	Ku	Moreno Formation (Upper Cretaceous and Paleocene?); Panoche Formation (Upper Cretaceous); Wisenor Formation of Briggs (1953) (Lower Cretaceous).
Marine sedimentary and volcanic rocks of Jurassic and Cretaceous age and associated ultramafic instrusive rocks.	KJu	Franciscan Formation and associated ultramafic intrusive rocks (Jurassic and Cretaceous).

age basins are given in table 3 (modified from Davis, 1961, table 1, p. B7). Because most of the materials eroded from these basins have been deposited on alluvial fans, there has been little mixing of erosional debris from drainage basins underlain by differing lithologies.

FRANCISCAN FORMATION

The Franciscan Formation, which forms the core of the Diablo Range, is most extensively exposed in the northern part of the area shown on plate 2, particularly in the drainage areas between Los Banos and Little Panoche Creeks. It underlies 26–81 percent of these four drainage areas (table 3). Its maximum thickness is unknown as neither the top nor base of the formation has been recognized, but Briggs (1953, p. 11) estimates that at least 20,000 feet of the Franciscan is exposed near Ortigalita Peak.

The Franciscan of this area consists predominantly of thin-bedded and massive graywacke sandstone, dark slaty shale, and siltstone. Other common rock types include bedded chert and mafic volcanic rocks (sometimes lumped under the general term "greenstone"). Less common rock types include limestone, glaucophane schist, and actinolite schist.

ULTRAMAFIC INTRUSIVE ROCKS

Ultramafic rocks intrusive into the Franciscan have been noted in many places. Most of these are narrow bodies of small extent, although one such body underlies more than 35 square miles in T. 18 S., Rs. 12 and 13 E. The ultramafic rocks are commonly termed serpentine, because they have been almost completely altered to minerals of the serpentine group. In addition, hornblende-quartz gabbro has been reported in the northern part of the area by Briggs (1953, p. 17).

CRETACEOUS SEDIMENTARY ROCKS

LOWER CRETACEOUS SEDIMENTARY ROCKS

Lower Cretaceous sedimentary rocks unconformably underlie Upper Cretaceous strata north of Little Panoche Valley in secs. 8 and 17, T. 13 S., R. 10 E. (Briggs, 1953, pl. 1). At least 1,800 feet of dark shale and thin hard carbonaceous sandstone extends for 2 miles between the basal conglomerate of the Panoche Formation and rocks of the Franciscan Formation, with which they are in fault contact on the west. These Lower Cretaceous strata have been named the Wisenor Formation by Briggs (1953, p. 20).

UPPER CRETACEOUS SEDIMENTARY ROCKS

The thickest and most extensively exposed stratigraphic unit in the areas tributary to the Los Banos-Kettleman City area is the Panoche Formation of Late Cretaceous age. This unit forms a nearly continuous belt roughly 6 miles or more wide that extends virtually uninterrupted nearly the entire length of the area. The thickness ranges from about 8,000 feet north of Coalinga to 30,000 feet north of Little Panoche Valley where the base and top of the unit are both exposed (Briggs, 1953, p. 24). Except where it overlies Lower Cretaceous rocks, the Panoche is in fault contact with the Franciscan Formation along its western contact.

In the southern part of the area the Panoche consists predominantly of massive sandstone, flaggy sandstone, coarse conglomerate, siltstone, and mudstone. North of Panoche Creek, the Panoche is generally finer,

TABLE 3.—*Areas*[1] *of generalized geologic units within stream basins*

[Modified from Davis, 1961, p. B7]

Drainage basin	Drainage area (square miles)	Area, in percent, occupied by indicated geologic unit: Franciscan Formation	Ultramafic intrusive rocks	Marine sedimentary rocks of Cretaceous age	Marine sedimentary rocks of Tertiary age	Continental deposits of Tertiary and Quaternary age
Los Banos	132	81	0	16	3	0
Salt (Merced County)	26	26	0	55	0	19
Ortigalita	60	43	0	33	0	24
Little Panoche	103	41	0	25	0	34
Panoche	298	17	0	26	42	15
Cantua	48	0	13	52	35	0
Salt (Fresno County)	25	0	0	68	32	0
Domengine	11	0	0	59	41	0
Los Gatos	127	0	6	84	10	0
Warthan	110	3	0	34	59	4
Jacalitos	60	34	0	5	61	0
Zapato	47	5	0	40	50	5
Canoas	20	0	0	19	65	16

[1] Areas and percentages based on them are approximate; determined by planimeter from "Geologic map of California" (Jenkins, 1938; Kundert, 1955).

and, although massive fine concretionary sandstone forms an important part of the unit, dark mudstone with thin beds of fine sandstone predominates.

Overlying the Panoche with little, if any, unconformity, is the Moreno Formation, which includes the youngest Cretaceous rocks and probably beds of Paleocene age. The Moreno ranges in thickness from 1,000 to about 2,500 feet.

The Moreno is characterized by purplish or maroon organic mudstone. Much of the mudstone is diatomaceous and is white where weathered. Massive concretionary sandstone identical to that of the Panoche Formation locally makes up a substantial part of the Moreno, but the most important constituent after the organic deposits is mudstone.

SIGNIFICANCE OF MESOZOIC ROCKS

Underlying more than half of the drainage basins tributary to the western slope of the San Joaquin Valley in the Los Banos–Kettleman City area, and the steepest parts of those drainage basins, the rocks of Mesozoic age are the predominant source of sediment of the westside streams. These rocks are more than 50,000 feet thick in places and consist predominantly of clastic sediments—chiefly feldspathic sandstone and mudstone, although mafic and ultramafic igneous rocks are prominent in the Franciscan sequence and organic sediments are important in the uppermost Cretaceous deposits.

The type of material eroded from the various source rocks influences the lithology, mode and rate of deposition, and compactibility of the materials deposited in the San Joaquin Valley. For example, Meade (1967) concluded in his studies of the sediments from the Little Panoche Creek basin that mixed-layer montmorillonite-illite and illite seem to be derived largely from rocks of the Franciscan Formation (p. C22, C73). In contrast, he found that the clay minerals derived from the marine sedimentary rocks of Cretaceous and Tertiary age are predominantly montmorillonite. Such differences in clay mineralogy directly affect the compactability of the sediments that are subject to increased effective stress resulting from artesian-head decline.

The different types of rocks also have a profound influence on the chemical character of the stream waters of the area, as shown by Davis (1961, p. B20–B21). The ultramafic rocks supply abundant magnesium, and the mudstones and shales account for large sulfate concentrations in the waters.

LOWER TERTIARY SEDIMENTARY ROCKS

The marine sedimentary rocks of early Tertiary age, as the term is used in this report (pl. 2; table 2), include all the rocks of Paleocene, Eocene, Oligocene, and Miocene age. In the northern part of the area especially, some sedimentary deposits laid down in brackish water and some continental deposits are included in this unit. As compared to the Mesozoic rocks, the post-Oligocene rocks are characterized by rapid changes in lithology over short distances and by a greater proportion of organic deposits. As shown on plate 2, the lower Tertiary deposits form a narrow, discontinuous ribbon of outcrops flanking the San Joaquin Valley north of Panoche Creek. They are thicker and more extensively exposed south of Panoche Creek, especially along the flanks of the Vallecitos syncline south of Panoche Valley, and in the drainage basins of Warthan and Jacalitos Creeks southwest of Coalinga.

The large exposure of lower Tertiary rocks shown in the northwest corner of the area consists of the Quien Sabe Volcanics of Taliaferro (Leith, 1949). These volcanic rocks consist of about 4,000 feet of andesite and basalt flows, and sediments, including agglomerate, conglomerate, and tuffaceous sandstone, intruded by rhyolite and andesite. The age of the volcanic rocks has not been determined, but, on the basis of evidence from other areas in the Coast Ranges. Leith concluded that the Quien Sabe Volcanics was of Miocene age.

The marine sedimentary rocks of early Tertiary age are similar in many respects to the Cretaceous sedimentary rocks. Arkosic sandstone, commonly containing as much as 50 percent feldspar, and sandy or silty shale, commonly micaceous, make up most of the lower Tertiary section. In parts of the area, however, organic siliceous shale of the Kreyenhagen Formation makes up fully half of the lower Tertiary section.

PALEOCENE AND EOCENE MARINE SEDIMENTARY ROCKS

Between the organic siliceous Moreno Formation (Upper Cretaceous and Paleocene?) and the organic siliceous Kreyenhagen Formation (Eocene and Oligocene?) are clastic marine sedimentary rocks of Paleocene and Eocene age. In most of the area a sequence of dark clay shale with fine sandy beds rests conformably on the Moreno. This unit, the Lodo Formation, is exposed from Panoche Creek south to the Coalinga anticline. Locally, especially in the upper basins of Cantua Creek and Arroyo Hondo, the Lodo contains a massive concretionary sandstone member. The Lodo ranges in thickness from about 1,000 feet north of Coalinga to as much as 5,000 feet in the upper basin of Arroyo Hondo. North of the Fresno–Merced County line similar dark clay shale about 1,200 feet thick exposed along the west border of the San Joaquin Valley has been called the Laguna Seca Formation by Payne (1951).

Overlying the shale of the Lodo Formation and resting directly on Cretaceous rocks in the Panoche Hills is a light-yellow to white quartzose sandstone unit 50–750 feet thick. The sandstone is interbedded with highly colored shale, carbonaceous clay, clay shale, and pebble beds. This distinctive lithology, which generally is interpreted as indicating tropical weathering in Eocene time, is known variously as the Tejon Formation, Domengine Sandstone, Yokut Sandstone of White (1940), and the Telsa Formation.

Southwest of Coalinga the Kreyenhagen Formation is underlain by an Eocene sandstone (the Avenal Sandstone) about 500 feet thick that rests directly on Upper Cretaceous rocks.

Overlying the clastic sedimentary rocks of Eocene age throughout the area is a highly organic siliceous marine shale, the Kreyenhagen Formation, locally of Eocene and Oligocene(?) age. In addition to the organic shale, the Kreyenhagen also contains sandstone near the base and is cut by many sandstone dikes. The Kreyenhagen is as much as 2,000 feet thick north of Cantua Creek but thins to about 700 feet in Merced County. The Kreyenhagen is extensively exposed in the basins of Arroyo Ciervo and Arroyo Hondo, and fragments of the distinctive shale are ubiquitous on the Holocene alluvial fans of these streams in the San Joaquin Valley.

The Kreyenhagen is particularly important as a marker, especially in the northern part of the area and beneath the valley, where it not only is of distinctive lithology but also is the youngest extensive marine deposit. The overlying Miocene deposits, although marine in part, are in part subaerial and are therefore difficult to trace on the surface and in the subsurface.

The marine Kreyenhagen Formation where it underlies the fresh-water-bearing deposits on geologic sections *A–A′* and *B–B′* (pls. 3, 4) is about 700–800 feet thick. At the nearest outcrop north of Panoche Hills (Briggs, 1953, p. 41–44), the Kreyenhagen is 700 feet thick, the basal part consisting primarily of a brown sandy shale and white laminated sandstone, overlain by more than 600 feet of white-weathering diatomite and radiolarite. Seven miles northeast of this outcrop, on longitudinal geologic section *A–A′* (pl. 3), the top of the Kreyenhagen Formation is at a depth of 2,800–3,200 feet. Opposite the Panoche Hills the dip of the formation increases southward; beneath Tulare Lake bed, 45 miles to the south, electric logs of deep oil exploration holes show its top to be at a depth below 11,000 feet. The Kreyenhagen Formation is unconformably overlain by Miocene marine and nonmarine strata, except in surface exposures in the Panoche Creek area (Schoellhamer and Kinney, 1953) where it is overlapped by the Tulare Formation (Pliocene and Pleistocene).

MIOCENE DEPOSITS

The Miocene deposits along the west border of the Los Banos–Kettleman City area are marked by great changes in thickness and lithology along their strike.

In the southern part of the area—south of Coalinga and at Kettleman Hills—the Miocene is represented by thick marine shales and sandstones. North of Coalinga and extending to Panoche Creek the section is predominantly marine sandstone with interbedded diatomaceous shale. North of the Fresno-Merced County line the Miocene is represented by a thin sequence of tuffaceous, partly nonmarine sandstone, gravel, and clay.

Wells in the Kettleman Hills penetrate some 4,000 feet of Miocene strata consisting of 500 feet of the Reef Ridge Shale, a soft silty shale with some interbedded volcanic sandstone; 1,500 feet of the McLure Shale Member of the Monterey Shale, a brown porcelaneous organic mudstone; and 2,000 feet of the Temblor Formation, predominantly dirty sandstones and interbedded shales.

Only 20 miles northwest along strike from Kettleman Hills, the Miocene section exposed at the north end of Anticline Ridge consists of about 1,200 feet of predominantly sandstone. The upper 550 feet, the Santa Margarita Formation, is a fine-grained, locally pebbly, brown sandstone with some calcareous reef-forming beds. The lower 650 feet is the Temblor Formation, chiefly soft gray to blue sandstone interbedded with diatomaceous siltstone and shale. Between Anticline Ridge and Cantua Creek the upper part of the Temblor consists of the Big Blue Serpentinous Member, a shale characterized by a high content of serpentine flakes which give it a distinctive blue color. Between Panoche Creek and the Fresno-Merced County line, the Miocene beds are overlapped by younger deposits. North of the county line the Miocene section consists of the San Pablo Formation, which rests unconformably on the Kreyenhagen Formation. The San Pablo varies in thickness from less than 100 to 400 feet and consists of volcanic gravel, sand, and clay. It is characterized by irregularly colored red, yellow, and green tuffaceous deposits. Locally, marine fossils are found in the San Pablo, but much of it is of fresh water or subaerial deposition.

The subsurface geologic information available was insufficient to differentiate the Miocene formations that have been mapped in the foothills along the western boundary of the Los Banos–Kettleman City area on the electric logs of the geologic sections. They are shown, therefore, as an undifferentiated unit overlying the Kreyenhagen Formation.

In the southern part of the area, where the undifferentiated Miocene deposits underlie the fresh-water-bearing deposits, the section is primarily marine. There, it is 3,000–4,000 feet thick, and its top is at a depth of 6,000–7,000 feet. In the northern part of the area, the subsurface Miocene section is primarily of continental deposition, 700–800 feet thick, and its top is at a depth of 1,900–2,000 feet.

UPPER TERTIARY AND QUATERNARY DEPOSITS UNDIFFERENTIATED

In the drainage basins tributary to the Los Banos–Kettleman City area are many isolated bodies of continental deposits of late Tertiary and Quaternary age. Rocks of this age flanking the San Joaquin Valley have been mapped (pl. 1) as part of this investigation, but time and funds did not permit study of presumably equivalent deposits farther back in the Coast Ranges. Accordingly, these deposits, which include terrace deposits capping the older rocks as well as valley fill in the Vallecitos, Panoche Valley, and lesser valleys, have been treated on plate 2 as undifferentiated continental deposits of Pliocene to Holocene age.

STRATIGRAPHY OF THE WATER-BEARING DEPOSITS

The fresh-water-bearing deposits forming the ground-water reservoir in the Los Banos–Kettleman City area are restricted to late Pliocene and younger formations. The principal aquifers occur within the alluvial and lacustrine deposits of the Tulare Formation of Pliocene and Pleistocene age. The underlying formations of Pliocene age contain brackish or saline water, except in the central southwestern part of the area where fresh-water-bearing strata occur in the San Joaquin Formation and in the upper part of the Etchegoin Formation. No fresh water is known to occur in the Jacalitos Formation or underlying strata.

Surface and subsurface geologic studies made as part of this investigation were focused on the fresh-water-bearing deposits because compaction of these deposits due to withdrawal of ground water was presumed to be the major cause of the land subsidence.

Unconsolidated to semiconsolidated deposits of Pliocene and Pleistocene age which crop out along a relatively continuous strip 1–6 miles wide bordering the western flank of the project area were mapped for this report. They include the Jacalitos, Etchegoin, San Joaquin, and Tulare Formations, and terrace deposits. These strata are chiefly continental but, locally, of marine origin. The surface extent of each of these formations is shown on plate 1; they are shown jointly as one unit, "Continental and marine sedimentary deposits," on the generalized geologic map (pl. 2).

In general, the older of these Pliocene and Pleistocene formations are more consolidated than the younger units. Silt, sand, and sandy silt strata comprise the major part of the exposed section; true clay is rare. Sandstone, gravel, and conglomerate are relatively common, and their presence is usually marked by strong topographic relief. Good exposures are uncommon, owing to the relatively unconsolidated character of the deposits. Slumpage, weathering, and soil formation also contribute to the difficulty of finding fresh exposures. Generally, deep stream cuts, roadcuts, and back slopes of hills provide the best outcrops.

Lithologic characteristics change parallel to the strike of the beds as well as normal to it. This feature, coupled with the lack of good exposures, makes long-distance correlations impractical. Extensive use of aerial photographs, in part, helped to alleviate this problem.

In the following descriptions of the surface geology, the Jacalitos, Etchegoin, San Joaquin, and Tulare Formations are described from south to north. Measured geologic sections are presented in the text in the same order.

In order to show the character, source and environment of deposition, and the relationship of the strata forming the aquifer systems in the Los Banos-Kettleman City area, five geologic sections based on drill-log, core-hole, and electric-log data are presented on plates 3 and 4. The location of these sections is shown in figure 3. The land-surface elevation datum used on all the cross sections in this report is taken from the 1922–32 series of U.S. Geological Survey topographic maps. It was not considered practical to compensate for elevation changes caused by compaction and to adjust the land-surface datum on any of the geologic sections or on the structure map because of the subsidence. The land-surface datums of the individual core logs and electric logs used in this report are from the period 1929–1961; so the approximate maximum error that could have been introduced by land-surface subsidence can be determined from the map shown in figure 2.

Generalized composite logs of four core holes, drilled as part of the program of the Inter-Agency Committee on Land Subsidence, are presented on plate 5.

JACALITOS FORMATION (PLIOCENE)

The Jacalitos Formation was named by Arnold and Anderson (1908) for its characteristic exposures near Jacalitos Creek. According to Arnold (1909, p. 23),

> The formation may be roughly distinguished as that portion of the series between the shale of the Santa Margarita(?) below and the major beds of blue sand that characterize the lower part of the formation above it (the Etchegoin) throughout the district. The Jacalitos, however, includes a great thickness of blue sand beds at its summit in the southeastern part of the Kreyenhagen Hills.

EXTENT

The Jacalitos is the oldest formation mapped for this report. It crops out discontinuously from the southern end of the San Joaquin Valley to a point about 4 miles north of Arroyo Hondo. Plate 1 shows the extent of the formation as mapped in this investigation—from Anticline Ridge north about 23 miles to 1 mile north of Arroyo Ciervo. The average width of surface exposure of the Jacalitos in this area is less than 1 mile. In general, the outcrop width decreases from about a mile near the junction of State Highway 33 and the Coalinga-Fresno Road to less than a quarter of a mile at Arroyo Ciervo, north of which it is overlapped by younger deposits of the Etchegoin Formation.

The predominantly fine-grained sedimentary rock comprising the Jacalitos Formation greatly influence its topographic development. Strike valleys, formed between more resistant strata above and below, characterize the major part of the outcrop area near Oilfields and near Arroyo Hondo. Elsewhere, the more consolidated sandy rocks of the Jacalitos resist erosion equally as well as the younger deposits above, but not nearly so well as the older rocks below. Therefore, the surface outcrops of the Jacalitos generally are considerably lower than those of the older rocks to the west.

LITHOLOGY

The Jacalitos Formation consists mainly of banded red, green, and gray silt and sandy silt beds and only minor amounts of sandstone and gravel. When seen from the West, particularly in the late afternoon or evening sun, the color banding of the silt is very noticeable and in places very outstanding.

Measured sections of the Jacalitos Formation are shown in figure 5. A section spanning the full outcrop of the Jacalitos (fig. 5*A*, section *a* to *a′*) was measured 3.5 miles south of Salt Creek.

From near the town of Oilfields north to Salt Creek the upper part of the formation contains a blue sandstone similar to those found in the overlying Etchegoin Formation. Logically, this sandstone might be included with lithologically similar materials above. Arnold and Anderson (1910, p. 114), however, defined the base of the Etchegoin Formation as the *Glycymeris* fossil zone, which in this area lies above the lowest blue sandstone. That definition was followed for this investigation. Below the sandstone, and continuing to the base of the Jacalitos Formation, is an alternating series of red and gray silt interbedded with sandstone and gravel. The basal unit of the formation in this area generally is a deep red silt, but, locally, a fossiliferous sandy gravel marks the base. Fossils found in the Jacalitos generally are waterworn and broken, indicative of reworking by streams. Opalized wood fragments are common, including remnants of large logs or tree trunks.

Between Salt and Cantua Creeks, the top of the Jacalitos is taken as the top of the bed just beneath the lowest blue sandstone. In a section measured 0.3 mile south of Cantua Creek (fig. 5*B*, section *b‴* to *b⁗*), the top is an olive sand. The blue sandstone found in the Jacalitos farther south does not extend into this area, nor does the *Glycymeris* zone. The red silt found at the base to the south grades northward into drab gray and tan silt. With the gradational color change, the basal member becomes more sandy in the vicinity of Salt Creek. At Cantua Creek, the basal member is taken as the first gray silt overlying fossiliferous Miocene gravel and sandstone.

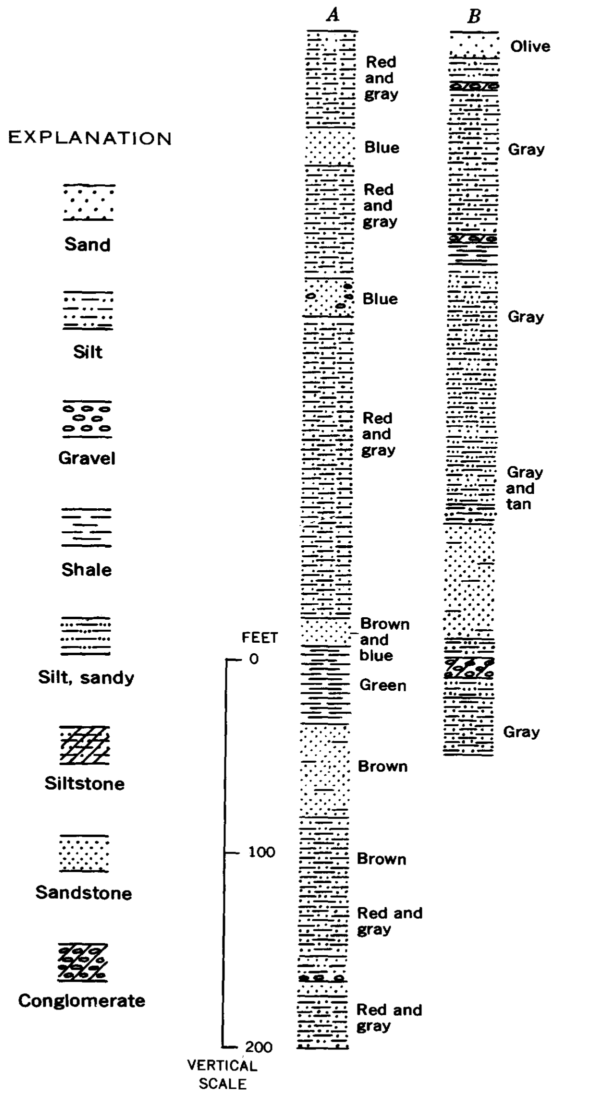


FIGURE 5.—Sections of strata in the Jacalitos Formation.

A. Section *a–a'*, strata exposed near Martinez Creek, sec. 20, T. 18 S., R. 15 E.

B. Section *b'''–b''''*, strata exposed near Cantua Creek, sec. 2, T, 18 S., R. 14 E.

North of Cantua Creek, the Jacalitos consists principally of dull-green, gray, and tan slightly sandy silt. The color banding, so conspicuous farther south, is subdued here, owing to lesser amounts of contrasting red silt in the section. Gravel and sandstone are present in small amounts. The base of the formation is marked by a slightly gravelly gray to tan sand or sandstone. Opalized wood fragments were observed but not in amounts comparable to the area farther south. About 3 miles north of Arroyo Hondo, the coarse gravelly sand at the base of the Jacalitos fills root or worm holes that extend into the underlying Miocene strata.

THICKNESS, MODE OF ORIGIN, AND STRATIGRAPHIC RELATIONS

The exposed section of the Jacalitos Formation thins progressively from a stratigraphic thickness of more than 1,000 feet, near the intersection of State Highway 33 and the Coalinga-Fresno Road, to nothing about 4 miles north of Arroyo Hondo where it is overlapped by the Etchegoin Formation.

Massive, thick sections of silt suggest the possible marine origin of most of the Jacalitos Formation. Minor amounts of crossbedded sandstone indicate that at least part of the formation is of deltaic origin. The presence of a number of bones and teeth of unidentified terrestrial animals, found in NW¼NW¼ sec. 13, T. 19 S., R. 15 E., indicates continental deposition at that locality.

Angular unconformities are not apparent between the Jacalitos Formation and either the overlying or underlying formations in this area. Aerial photographs, however, show that each unit in turn overlaps the next older formation, indicating that disconformities probably exist between them. Other evidence of a disconformable contact at the base of the Jacalitos Formation is the presence of fossil wood in the basal conglomerates.

The Jacalitos Formation is generally considered to be of Pliocene age. Woodring and others (1940, p. 103) state,

> The assignment of the Jacalitos, Etchegoin, and San Joaquin Formations to the Pliocene is now generally accepted. The marine faunas of these formations have a Pliocene aspect in terms of the succession of Tertiary faunas on the Pacific Coast. The vertebrate evidence now known is not opposed to this assignment.

SUBSURFACE EXTENT

In the subsurface of the Los Banos-Kettleman City area approximately south of a line extending from Arroyo Hondo to the town of Cantua Creek, electric logs indicate that possibly as much as 500 feet of continental deposits of the Jacalitos Formation overlies the Miocene section. In the subsurface at Kettleman Hills, Goudkoff (1934, p. 440) differentiated the Jacalitos into seven zones on the bases of faunal and lithologic evidence and noted a distinct break in deposition at the base.

The relation of the subsurface Jacalitos to the surface section is illustrated on plate 4. On geologic section *C–C'* the Jacalitos, which is 375 feet thick where it crops out, is shown dipping 18° toward the valley. On section *D–D'*, parallel to *C–C'* and about 8 miles southeast, the Jacalitos dips 33° and is about 1,800 feet thick. Electric logs of oil exploration holes indicate that in the San Joaquin Valley proper to the east, the top of the Jacalitos Formation is at a maximum depth of slightly more than 4,000 feet.

ETCHEGOIN FORMATION (PLIOCENE)

The Etchegoin Formation was named by F. M. Anderson (1905, p. 178) for its exposure near the old Etchegoin Ranch in NW¼ sec. 1, T. 19 S., R. 15 E. Arnold and R. E. Anderson (1910, p. 114) defined the Etchegoin Formation as

> the succession of beds of sand, gravel, and clay, in part indurated, occurring in the oilfield northeast of Coalinga above the base of the hill-forming sandstone beds referred to for convenience as the *Glycymeris* zone, and in the Kettleman Hills below the fresh-water beds described as the base of the Tulare Formation.

They did not attempt to define the top of the formation in the hills north of Coalinga owing to the "indefiniteness of the line between the Etchegoin and the Tulare there." In the Kettleman Hills, Woodring and others (1940, p. 28) placed the Etchegoin below the San Joaquin Formation, whose base was drawn at the base of the Cascajo Conglomerate Member. South of State Highway 198 on Anticline Ridge the contact between the Tulare and Etchegoin is indefinite, but to the north, the contact is relatively easy to delineate with the use of aerial photographs. On photographs, features such as topographic expression, color (contrasts of dark and light), and overlap of one formation on the other helped to delimit the two formations.

EXTENT

The Etchegoin Formation is exposed discontinuously in the foothills from the southern end of the San Joaquin Valley to a point about 2 miles north of Panoche Creek. Where mapped for this investigation, its outcrop forms a band that averages slightly more than 1 mile in width. The basal part of the formation is not exposed in the Kettleman Hills or on the southern part of Anticline Ridge, where erosion has failed to cut through to the base. North of the Coalinga-Fresno Road, the uppermost part is not exposed because of overlap by the Tulare Formation.

LITHOLOGY

In the North Dome of Kettleman Hills, the exposed Etchegoin strata consist chiefly of brown silty sand and sandy silt with lenses of blue sandstone. About 6 miles north of Coalinga, the Etchegoin, the base of which is marked by the *Glycymeris* fossil zone, consists of beds of compact coarse and fine bluish-gray silty sandstone alternating with zones of pebbly sand, fine gray sand, silt, and clay. The clay increases upward in the section (Arnold and Anderson, 1910, p. 117).

Measured sections of strata in the Etchegoin Formation at six places between Anticline Ridge and Tumey Gulch are shown in figure 6 (*A–F*). Two of these sections (fig. 6*A*, *B*), both of which span the full exposed thickness of the Etchegoin Formation, illustrate its lithologic character between Anticline Ridge and the Coalinga-Fresno Road. Here, the Etchegoin is predominantly gray, brown, and red silt and sandy silt, with thinner, but massive, beds of brown and blue sandstone.

Between the Coalinga-Fresno Road and Cantua Creek, the Etchegoin Formation is characterized by beds of massive blue sandstone and banded sandy silt. Near Cantua Creek, the blue sandstone grades into brown sandstone interbedded with light-brown, tan, and gray silt (fig. 6*C*); blue sandstone is not found north of Cantua Creek in the Etchegoin Formation.

From the Coalinga area northward to about 3 miles north of the Coalinga-Fresno Road, the base of the Etchegoin is marked by the *Glycymeris* zone; this zone can be traced as far north as NW¼ sec. 35, T. 18 S., R. 15 E. North of there to Salt Creek, the base is taken as the base of the blue sandstone that lies directly over the *Glycymeris* zone farther south. Between Salt and Cantua Creeks, the base is taken as the bottom of the lowest persistent blue sandstone.

Just south of Cantua Creek, the Etchegoin can be divided into three lithologic units. A section measured 0.3 mile southeast of Cantua Creek (fig. 6*C*) illustrates the threefold lithologic subdivision in that area. The upper unit is mostly yellow to light-tan silt with thin stringers of gravel. Below this lies a middle unit of brown and blue sandstone and gray to reddish-gray silt, with blue sandstone at the top and base. The lower unit consists predominantly of gray silt with red and tan banding.

Between Cantua Creek and Arroyo Hondo, the section consists chiefly of sandy silt with relatively thin lenses of sandstone, gravel, and silty sand. The silt beds display prominent color banding of red, tan, brown, and gray. The sandstone and gravel are usually gray or grayish brown. Definite evidence of overlap of the Etchegoin by the Tulare Formation is present north of Cantua Creek; therefore, the base of the Tulare was used as the contact between the two formations.

The Etchegoin characteristically contains an extensive basal gravel and sandstone between Cantua Creek and Arroyo Hondo. Just north of Cantua Creek this basal bed consists of interbedded gravel and gravelly sandstone about 20 feet thick containing cobbles as much as 6 inches in diameter. This bed thickens northward and, in the vicinity of Arroyo Hondo, is about 80 feet thick. A section measured across the full outcrop of the Etchegoin 0.1 mile southeast of Arroyo Hondo (fig.

6*D*) shows this basal gravel which there includes two interbeds of sandy silt. In many places the basal gravel contains a large amount of secondary gypsum in the form of crack and cavity fillings.

The lithologic composition of gravel throughout the Etchegoin Formation is fairly constant. Fragments consist mostly of fine-grained igneous and metamorphic rocks, white quartz, chert, and jasper. Less common constituents are fragments of older resistant sandstone and shale, fossils reworked from Miocene strata, and concretions from Cretaceous sandstone.

From Arroyo Hondo northwest about 6 miles to a point in the hills opposite Panoche Junction, the Etchegoin becomes more gravelly and sandy. The upper part is predominantly banded silt but contains much more sand and sandstone than farther south. The basal gravel thickens, and, in sec. 14, makes up about a quarter of the formation thickness, as indicated in section *F′–F″* (fig. 6*E*).

Between Panoche Junction and Tumey Gulch, the Tulare Formation progressively overlaps and conceals the upper Etchegoin strata. Silt and sandy silt still persist as the major constituents of the Etchegoin, but the proportion of sandy material is greater than farther south. The basal part of the Etchegoin grades from gravel near Panoche Junction to sandy silt near Tumey Gulch. (See fig. 6*F*.) Secondary gypsum is very common in this lower part and also is some of the upper coarse-grained beds. Also, many of the coarse-grained beds contain fossilized wood fragments. Red and gray colors still predominate. Some of the silt beds in the lower part of the Etchegoin display very bright and contrasting color bands. Color differences of red and gray sediments are attributed by many geologists to variation in conditions prevailing at the time of deposition—that is, red is inferred to indicate oxidizing conditions at the time of deposition, and gray, reducing conditions. However, some of the silts in the Etchegoin seem to be developing their red color at present. Specimens of the red silt taken from below the surface have a mottled gray and red pattern, possibly indicating active oxidation of the gray material at, or very near, the surface.

Near Panoche Creek, the Etchegoin Formation is exposed only in a very narrow discontinuous strip; all but the lowest part is overlapped by the Tulare. The northernmost exposure is about 2 miles north of Panoche Creek. There, the base of the formation consists of pebble and cobble conglomerate with a reddish-brown dirty sandy matrix. Cobbles of glaucophane schist as large as 6 inches in diameter are common in the conglomerate. This basal conglomerate grades upward into a pebble conglomerate of the same general compisiton. Overlying this conglomerate is a yellow-brown friable arkosic sandstone, a sequence of greenish-gray clayey siltstone and sandstone, and a crossbedded arkosic sandstone, the highest exposed bed.

THICKNESS, MODE OF ORIGIN, AND STRATIGRAPHIC RELATIONS

The exposed thickness of the Etchegoin is not constant because of the unconformable contact at the base and progressive overlap of the Tulare Formation at the top. Measured sections at six localities (fig. 6) indicate that the exposed Etchegoin thins from south to north. At State Highway 198 the thickness exceeds 2,000 feet, but near Tumey Gulch, 30 miles northwest, it is less than 500 feet, and near Panoche Creek, it is only a few tens of feet.

The Etchegoin Formation is partly marine and partly fluviatile and lacustrine in origin. Marine fossils are absent throughout much of the formation north of Anticline Ridge but are abundant in the Kettleman Hills (Woodring and others, 1940, p. 55). North of Anticline Ridge, many of the sandstone and gravel beds contain fossilized bones of terrestrial animals and are doubtless of continental origin. Rock constituents of the clastic sediments indicate that the source of the Etchegoin was the older rocks of the Diablo Range farther west.

Angular discordance between the Etchegoin and Jacalitos Formations is not discernible in the field, and the formations appear conformable in individual outcrops. However, the regional overlap of the younger upon the older shows that an unconformity does exist between the two. The Tulare Formation appears to be conformable upon the Etchegoin in the southern part of the area. North of Cantua Creek, however, aerial photographs show overlap of some of the upper Etchegoin beds by the Tulare. At Tumey Gulch, there is a measurable unconformity between the two units.

Woodring and others (1940, p. 103) assigned the Etchegoin Formation to the Pliocene on the basis of marine invertebrate and nonmarine vertebrate fossils.

SUBSURFACE EXTENT

The Etchegoin Formation underlies the fresh-water-bearing deposits of the San Joaquin and Tulare Formations throughout most of the Los Banos-Kettleman City area. In the west-central part of the Los Banos-Kettleman City area, the upper part of the Etchegoin Formation is fresh-water bearing (pl. 4). Several wells near the foothills and a few very deep wells (3,000–3,800 ft) in the valley proper south and southwest of the town of Cantua Creek tap the thin sand layers in the upper part of the Etchegoin. However, its depth of more than 3,000 feet beneath most of the valley prevents it from being considered as an important source of water for irrigation wells.

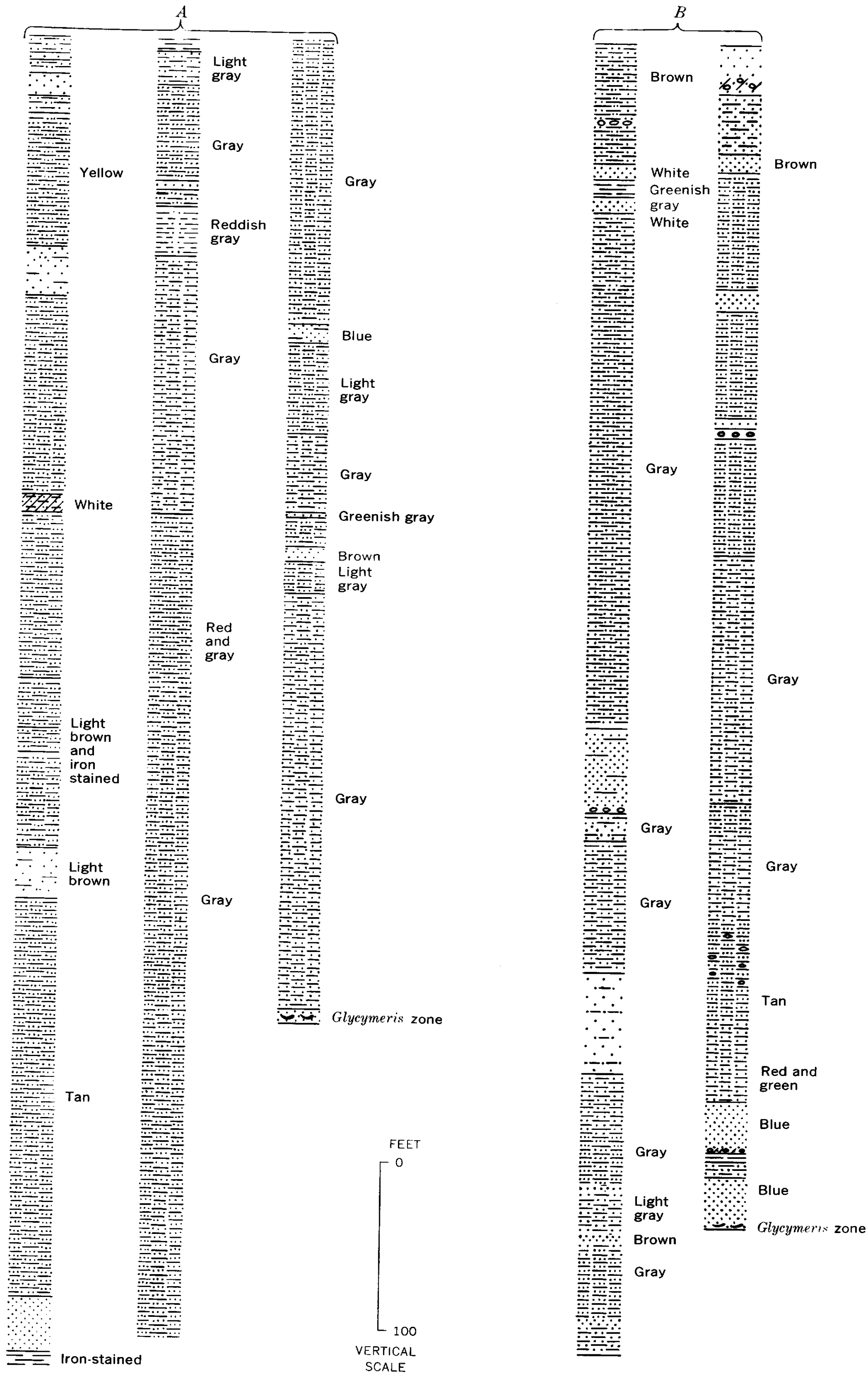
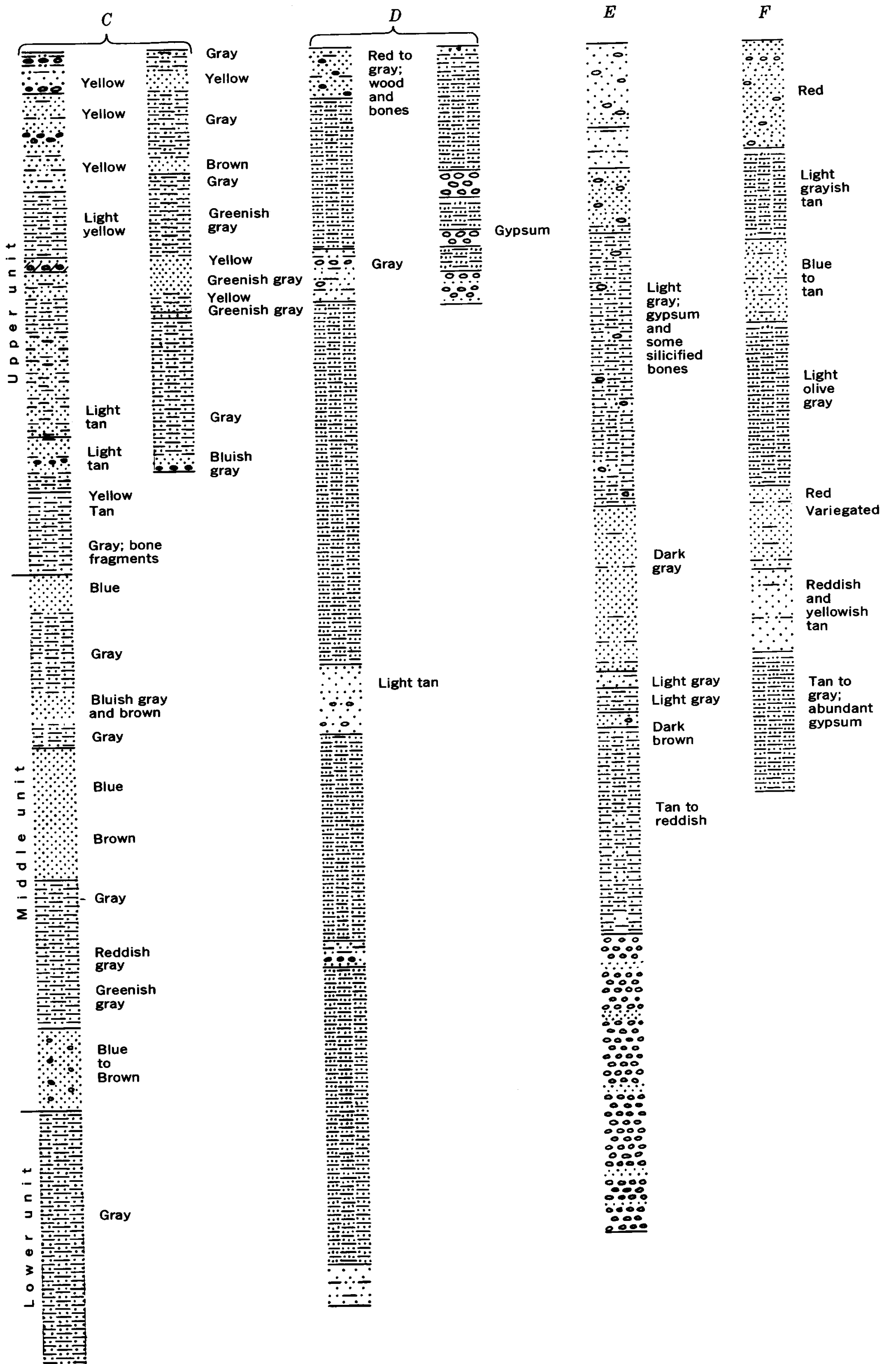


FIGURE 6.—Sections of strata in the Etchegoin Formation.

A. Section *c–c*,. strata exposed along State Highway 198, sec. 30, T. 19 S., R. 16 E. and secs, 25 and 26, T. 19 S., R. 15 E.
B. Section *d–d'*, strata exposed along Coalinga-Fresna Road, sec. 7, T. 19 S., R. 16 E. and sec. 12, T. 19 S., R. 15 E.
C. Section *b''–b'''*, strata exposed near Cantua Creek, sec. 35, T. 17 S., R. 14 E. and sec. 2, T. 18 S., R. 14 E.



D. Section *e′–e″* strata exposed near Arroyo Hondo, secs. 9 and 10, T. 17 S., R. 14 E.
E. Section *f′–f″*, strata exposed near Panoche Junction, secs. 14 and 23, T. 16 S., R. 13 E.
F. Section *g′–g″*, strata exposed near Tumey Gulch, SW¼NE¼, sec. 1, T. 16 S., R. 12 E.

The Etchegoin is differentiated near the western end of three of the transverse geologic sections (pl. 4). However, it is not differentiated beneath most of the valley proper because of lack of subsurface stratigraphic information. On the basis of electric logs alone, the Etchegoin cannot be reliably distinguished from the underlying and overlying deposits, which in much of the area are lithologically similar to the Etchegoin.

SAN JOAQUIN FORMATION (PLIOCENE)

EXTENT

The San Joaquin Formation, which is extensively exposed at Kettleman Hills and underlies the southern part of the Los Banos-Kettleman City area, contains the uppermost marine strata in the San Joaquin Valley. F. M. Anderson (1905) first described the "San Joaquin clays" from the Kettleman Hills, but he did not designate a type locality. Barbat and Galloway (1934) presented the first definitive paper on the "San Joaquin Clay," including the first designation of a type section and a type locality for the formation. Woodring and others (1940, p. 27) changed the name to San Joaquin Formation and suggested a section along Arroyo Hondo in Kettleman Hills as a standard section. In this report, the San Joaquin is distinguished only in the Kettleman Hills, as mapped by Woodring and others (1940), and in the subsurface. On Anticline Ridge, the upper part of what is mapped as Etchegoin on plate 1 may be equivalent to the San Joaquin Formation of the Kettleman Hills. There is, however, no readily distinguishable lithologic basis for separation. A detailed study to try to resolve this problem was not within the scope of this field mapping.

LITHOLOGY

The most apparent lithologic feature of the San Joaquin Formation as exposed on Kettleman Hills is the predominance of fine-grained materials—silty sandstone, silt, and clay. On weathered surfaces the unit appears to consist mostly of clay, but fresh exposures show that silt and silty sandstone make up much of the formation. Many beds show pronounced lithologic changes along the strike. However, the basal stratum of the formation, the Cascajo Conglomerate Member, was mapped by Woodring and others (1940) over a large part of the Kettleman Hills.

The San Joaquin Formation is of mixed continental and marine deposition. Much of the fine material appears to be nonmarine, and the remains of fresh-water shells and land plants have been found in some of them. Interbedded sandstones and conglomerates contain marine fossils. Thus, the San Joaquin Formation was probably deposited during a time of fluctuating sea level.

THICKNESS AND STRATIGRAPHIC RELATIONS

The San Joaquin Formation is 1,200–1,800 feet thick where it is exposed on the flanks of Kettleman Hills (Woodring and others, 1940, p. 28). In the Guijarral Hills, where it is concealed beneath the Tulare Formation, the San Joaquin Formation consists of sand, clay, and conglomerate and is 1,700 feet thick (Hunter, 1951, p. 15). Kaplow (1942, p. 22) concluded that, on Anticline Ridge along State Highway 198, exposures of clay with sand streaks, 1,570 feet thick should be assigned to the San Joaquin.

No angular unconformities or major disconformities are recognized at either the base or the top of the San Joaquin in the Kettleman Hills. This fact suggests that the Etchegoin, San Joaquin, and Tulare Formations of the Kettleman Hills were laid down during a time of relatively continuous deposition. However, north of Cantua Creek where distinct unconformities mark the contacts between the Jacalitos, Etchegoin, and Tulare Formations, folding and erosion evidently interrupted the depositional sequence. Thus, it seems that deformation in the Kettleman Hills began somewhat later than that in the foothills north of Cantua Creek.

Woodring and others (1940, p. 103) assigned the San Joaquin Formation to the upper part of the Pliocene on the basis of vertebrate and marine invertebrate fossils.

SUBSURFACE EXTENT

In the Los Banos–Kettleman City area, the uppermost stratum in which the pelecypod *Mya* is recognized, has generally been taken as the top of the San Joaquin Formation. This so-called upper *Mya* zone was cored in several exploratory holes drilled in the vicinity of Westhaven in 1929 by the Shell Oil Co.[2] By correlating this lithologic horizon on electric logs, the San Joaquin Formation has been differentiated from the overlying Tulare Formation in the southern part of geologic section *A–A′* (pl. 3). The 500–700 feet of fresh-water-bearing sand and interbedded clay underlying the Tulare Formation and indicated as littoral or estuarine deposits on the southern part of geologic section *A–A′* are considered to be a shoreline phase of the San Joaquin Formation. Many deep water wells in the southwestern part of the Los Banos–Kettleman City area are perforated in these strata, which are highly permeable, and are presently an excellent source of water. (See pl. 4, sections *D–D′*, *E–E′*.) Here, the deposits tentatively assigned to the San Joaquin Formation are much coarser and more permeable than those on Kettleman Hills.

[2] Shell Oil Co., 1929, "Results of Core Drilling on the Boston Land Co. Property," unpublished report.

TULARE FORMATION (PLIOCENE AND PLEISTOCENE)

The alluvial deposits forming the Tulare Formation were first described by W. L. Watts (1894, p. 55, 67) and later assigned the name Tulare Formation by F. M. Anderson (1905, p. 181–182). No type locality was designated for the Tulare Formation by Anderson, but the Kettleman Hills have been regarded generally as the type region, and Woodring has proposed the east side of northern North Dome on La Ceja as the type locality (Woodring and others, 1940, p. 13). Woodring placed the base of the Tulare just above the youngest widespread marine deposit constituting the upper *Mya* zone of the San Joaquin Formation. The Tulare conformably overlies the San Joaquin Formation in the Kettleman Hills, but, where exposed elsewhere in the Diablo Range, it rests unconformably on Pliocene and older formations. The top of the Tulare Formation by definition is the boundary between the uppermost deformed or tilted strata and the overlying alluvium, which can be mapped with fair accuracy along most of the outcrop of the Tulare as shown on plate 1.

SURFACE EXTENT

The Tulare Formation extends almost continuously from the southeast to the northwest edge of the area shown on plate 1. Its outcrop averages less than 1 mile in width and at only a few places exceeds 1 mile. Notable exceptions are in the Guijarral Hills, between Tumey Gulch and Panoche Creek, along Little Panoche Creek, and in the vicinity of Ortigalita Creek where broad outcrops result from gentle dips in the Tulare. In addition to the narrow strip that borders the foothills, the Tulare also caps some isolated hills north of Anticline Ridge, but most of the individual exposures are too small to show on plate 1. At one time the Tulare may have formed a broad blanket across most of the present foothill area.

In the North Dome of Kettleman Hills, the Tulare consists principally of sand, much of which is silty, pebbly, and crossbedded; it contains some gravel, apparently laid down as stream deposits. The lower part contains some thin-bedded fine sediments that are interpreted as lake deposits. In the Kreyenhagen, Jacalitos, and Guijarral Hills, the exposed Tulare is predominantly coarse gravel.

Lag gravels which probably are remnants of high depositional terraces, are found scattered over hilltops underlain by the Etchegoin and Jacalitos Formations from near Domengine Creek north to Arroyo Ciervo. Individual exposures are not large enough to map and at some places consist only of a few cobbles or boulders. Lithologically, the rock constituents are about the same as those in gravels of the Tulare Formation and older Pliocene shown on plate 1. Boulders, however, are as much as 3 feet in diameter.

The occurrence of these cobble and boulder gravels suggests that they once were laterally extensive and later were largely removed by erosion. Their distribution and stratigraphic position are similar to that of the Tulare Formation in the Panoche Hills, suggesting a possible correlation with the Tulare; however, a definite correlation is not practicable.

On Anticline Ridge, the contact between the Tulare and underlying deposits here included in the Etchegoin Formation is difficult to locate on the ground, and the contact shown on plate 1 was delineated on aerial photographs on the basis of soil and vegetation differences. North of this area, the base of the Tulare is generally recognizable on both the ground and aerial photographs.

At most places, the uppermost exposed part of the Tulare may be differentiated easily from the overlying alluvium by angular discordance. Where the discordance is small, the relatively more consolidated Tulare generally is more resistant to erosion and can be distinguished from the alluvium by its more pronounced topographic expression.

LITHOLOGY

From Anticline Ridge to Cantua Creek the Tulare Formation consists of beds of poorly sorted sand, gravel, and silt with a few interbedded lenses of well-indurated sandstone and siltstone. The basal zone, where fine grained, generally is somewhat limy. In much of this area the basal zone consists of coarse gravel or gravel and sandstone. The coarse basal sediments commonly contain many secondary gypsum veins.

Conspicuous dip slopes, generally formed on the more resistant lower members of the Tulare, are found in several places between Domengine and Cantua Creeks. Deposits supporting these slopes locally contain sandstone concretions, as large as 2 feet in diameter, reworked from Cretaceous rocks to the west.

Measured sections of strata in the Tulare Formation at seven places between Cantua and Little Panoche Creeks are shown in figure 7 (*A–G*). Section *b–b′* (fig. 7*A*) illustrates the lithologic character of the Tulare Formation as exposed on the south flank of Cantua Creek valley.

Between Cantua Creek and Arroyo Hondo the base of the Tulare is marked by a layer of locally concretionary well-indurated light-grayish-brown sandstone about 15–20 feet thick. At several places north of Cantua Creek, the basal sandstone is overlain by a bed of hard reddish-tan marl. This lower marl is not found at Arroyo Hondo but is common near the base of the

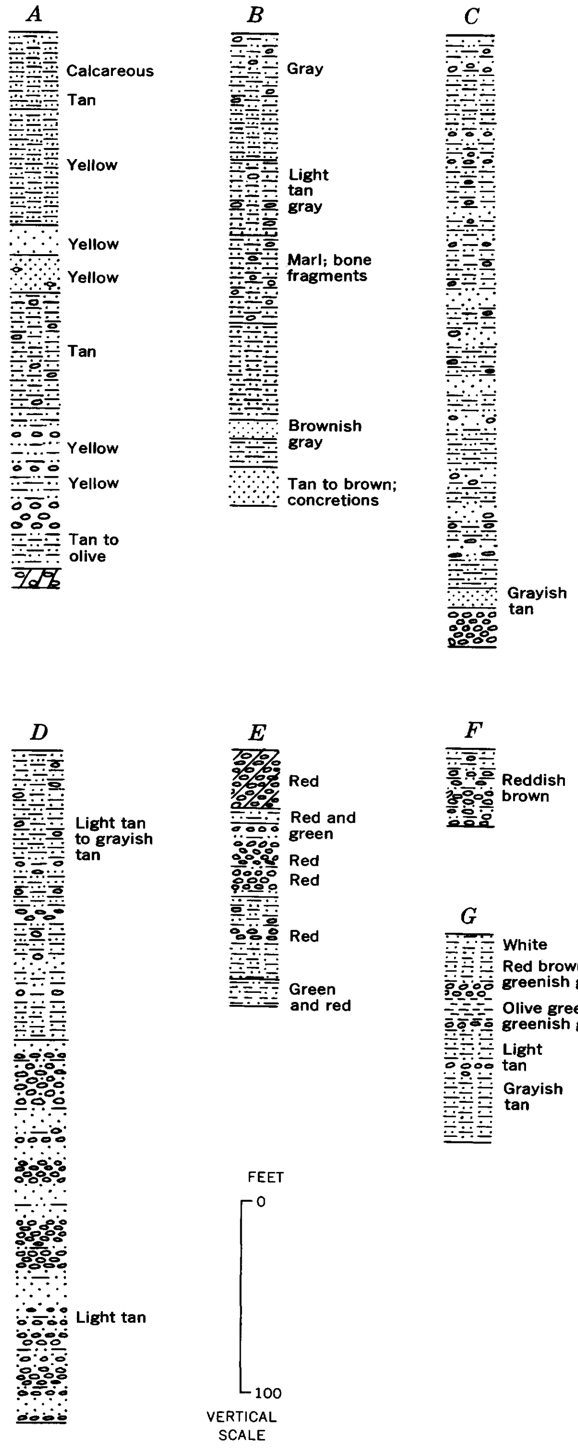


FIGURE 7.—Sections of strata in the Tulare Formation.

A. Section *b–b′*, strata exposed near Cantua Creek, secs. 35 and 36, T. 17 S., R. 14 E.
B. Section *e–e′*, strata exposed near Arroyo Hondo, secs. 3 and 10, T. 17 S., R. 14 E.
C. Section *f–f′*, strata exposed near Panoche Junction, secs. 12–14, T. 16 S., R. 13 E.
D. Section *g–g′*, strata exposed near Tumey Gulch, sec. 31, T. 15 S., R. 13 E., sec. 6, T. 16 S., R. 13 E., and sec. 1, T. 16 S, R 12 E.
E. Section *h–h′*, strata in upper part of Tulare Formation exposed near Little Panoche Creek, SE¼NW¼, sec. 21, T. 13 S., R. 11 E.
F. Section *h″–h‴*, strata in middle part of Tulare Formation exposed near Little Panoche Creek, NE¼SW¼, sec. 20, T. 13 S., R. 11 E.
G. Section *h⁗–h′′′′′*, strata in lower part of Tulare Formation exposed near Little Panoche Creek, NE¼NW¼, sec. 31, T. 13 S., R. 11 E.

Tulare farther north. The remainder of the formation is predominantly sandy silt containing thin stringers of gravel and sandstone.

Section *e–e′* (fig. 7*B*) shows the lithology of the Tulare Formation exposed along the south side of Arroyo Hondo.

Between Arroyo Hondo and Panoche Junction the basal part of the Tulare Formation becomes gravelly (fig. 7*C*) and commonly contains cobbles as large as 6 inches in diameter. The gravel constituents are about the same as those of gravels in the Etchegoin—igneous and metamorphic rocks, quartzite, chert, white quartz, siliceous shale, and large oyster shells reworked from the Miocene strata. Abundant secondary gypsum fills the interstitial openings in the gravel. Above the base the formation consists of poorly consolidated interbedded sandy and gravelly silt, as shown by section *f–f′* (fig. 7*C*) of the Tulare Formation near Panoche Junction. In part, this silt is moderately to highly calcareous.

Between Panoche Junction and Tumey Gulch the coarse basal bed of the Tulare Formation thickens and grades into a light-tan silty gravel and sand (fig. 7*D*). Gravel constituents are the same as described above, but they also include olivine-basalt and sandstone fragments. Strata in the upper part of the section, particularly the uppermost exposed layer, appear to contain a large amount of gypsite. It is uncertain whether the gypsite is within the Tulare Formation or is an evaporite deposited on the slightly eroded Tulare surface, and therefore it is not included in the measured section shown in figure 7*D*.

In the Tumey and Panoche Hills, the Tulare Formation consists of clayey and siltly sandstone and siltstone interbedded with pebble conglomerate and unconsolidated sand. The conglomerate beds are lenticular and grade laterally into sandstone. The gravel fragments are mostly of igneous and volcanic rocks, shale chips, and glaucophane schist; in addition, the basal conglomerate contains fragments of limy brown sandstone.

The basal gravel grades northward into finer material until, at Little Panoche Creek, the basal zone is about 90 percent marl or marly silt with thin gravel stringers. The gravels are predominantly igneous and metamorphic rock fragments, but, locally, they contain sandstone concretions as large as 3 feet in diameter reworked from Cretaceous rocks. Gypsite is common, but as farther south, its exact age and its position in the section are somewhat in doubt. At most places, however, the gypsite appears to be either in the uppermost exposed Tulare or to be an evaporite deposited on a slightly eroded Tulare surface. The columnar sections of figure 7*E–G* show the lithologic character of strata in the upper, middle, and lower parts, respectively, of the Tulare Formation near Little Panoche Creek.

In his report on the Ortigalita Peak quadrangle, Briggs (1953, p. 46) assigned the name Oro Loma Formation to a narrow unit of continental deposits exposed along the front of the Laguna Seca Hills, extending northwest for about 6 miles nearly to Ortigalita Creek and dipping at angles as much as 40° under the alluvium. He concluded that these beds were lithologically and structurally distinct from, and older than, relatively flat-lying deposits to the south near Little Panoche Creek, which he mapped as Tulare Formation.

In 1961 the Bureau of Reclamation drilled several core holes in connection with foundation studies for a pumping plant for the San Luis project about 3 miles south of Ortigalita Creek and about a quarter of a mile from the foothills. A diatomaceous silty clay 30–40 feet thick penetrated in these test holes has been identified as the Corcoran Clay Member of the Tulare Formation, on the basis of the presence of diatoms, lithologic similarity, and the known subsurface occurrence of the Corcoran Clay Member to the east (I. E. Klein, U.S. Bur. Reclamation, written commun., May 1962). The core holes also were the basis for extension of the Corcoran to the outcrop of a gray silty clay in the foothills dipping 30°–50° toward the valley (Carpenter, 1965), which had been mapped by Briggs (1953, p. 47) as the uppermost unit of his Oro Loma Formation. Where exposed, the gray silty clay is underlain conformably by several hundred feet of reddish-gray gravel, silty sand, and silt, stratigraphically above the San Pablo Formation. The gray silty clay (Corcoran Clay Member) and the underlying gravelly deposits are therefore shown in the Tulare Formation on plate 1.

The steeply dipping Tulare along the front of the Laguna Seca Hills appears to be unconformable with gently dipping beds to the south near Little Panoche Creek and to the north near Ortigalita Creek, which were mapped by Briggs as Tulare Formation and have been so mapped on plate 1. Working out the detailed field relations was not practicable within the scope of this study, but, evidently, beds of different ages separated by an unconformity are included in the Tulare Formation from Little Panoche Creek to Ortigalita Creek as mapped on plate 1.

THICKNESS AND STRATIGRAPHIC RELATIONS

The exposed Tulare Formation ranges widely in thickness. On the west side of North Dome in the Kettleman Hills, the maximum exposed thickness is about 2,600 feet. North of Coalinga, the thickness in measured sections (fig. 7) does not exceed 350 feet and in most places is less than 300 feet.

The exposed Tulare consists mainly of alluvium deposited on the post-Etchegoin erosion surface. However, calcareous beds and clay strata of considerable lateral extent indicate that locally it is of lacustrine origin. The processes of deposition probably were similar to those that currently are forming alluvial-fan, flood-plain, and lake-bed deposits on the west side and in the trough of the San Joaquin Valley.

In the southern part of the area, the Tulare appears to rest conformably on the San Joaquin and Etchegoin Formations. North of Cantua Creek, aerial photographs show definite evidence of overlap of the Tulare on the Etchegoin, although this relationship is not obvious on the ground. Numerous strata of the Etchegoin, indistinguishable on the ground but traceable on aerial photographs, are progressively overlapped to the northward by the Tulare. From the vicinity of Tumey Gulch northward, angular discordance between the Etchegoin and Tulare Formations is apparent in the field and indicates pronounced pre-Tulare deformation. As already noted in the discussion of the Tulare in the Laguna Seca Hills, some deformation evidently occurred there during Tulare time. Furthermore, the steep dip of the Tulare beds along the front of these hills demonstrates pronounced post-Tulare deformation. South of the Tumey Gulch area, all exposed sections of the Tulare are tilted, suggesting post-Tulare folding in that area also.

The age of the Tulare Formation has been a subject of disagreement among geologists for many years and it is still in dispute. The dispute involves also the position of the Pliocene-Pleistocene boundary in the Coast Ranges and the geomorphic development of the present topography of the Sierra Nevada. Discussion of these problems is beyond the scope of this report; however, direct evidence on the age of the Tulare is pertinent.

Direct evidence on the age of the Tulare in and near the study area includes a fresh-water molluscan fauna in the basal part of the Tulare exposed at Kettleman Hills, which has also been cored at several points in the San Joaquin Valley; diatom floras from the basal part of the Tulare Formation exposed at Kettleman Hills and from the Corcoran Clay Member of the Tulare Formation cored at many places in the valley; potassium-argon dating of a rhyolitic ash bed exposed near Friant which has been correlated with volcanic ash just overlying the Corcoran Clay Member; and fossil mammal bones excavated from the Corcoran Clay Member in the San Luis project canal section of the California Aqueduct in 1964.

According to Woodring and others (1940, p. 104), the lower part of the Tulare Formation in Kettleman Hills contains the largest fossil fauna of fresh-water mollusks known on the Pacific coast. On the basis of study of this fossil assemblage (p. 22–26), Woodring concluded (p. 104) that "assignment to the upper Pliocene is consistent with the character of the fauna."

Dwight Taylor (oral commun., 1963), who has studied the fresh-water mollusks from the Tulare, concluded that—

> the fresh-water mollusks indicate that the basal Tulare in the Kettleman Hills is equivalent to the lower part of the Santa Clara Formation of the Santa Clara Valley and to some part of the Tehama Formation of the Sacramento Valley. On the basis of present knowledge, it is convenient to assign this sequence to the Pliocene.

In the upper part of the Tulare, near Little Panoche Creek, he concluded that fossils suggest a Pleistocene age (written commun., January 1962).

K. E. Lohman (1938) assigned the basal Tulare to the Pliocene on the basis of diatom studies. Diatom floras studied by Lohman from the Corcoran Clay Member (report on referred fossils, February 1954) resemble the assemblage from the basal Tulare much more than they do numerous Pleistocene collections from the Western States (oral commun., 1963). From this, Lohman concluded that at the youngest the Corcoran is probably no later than early Pleistocene.

A volcanic ash exposed near Friant in eastern Fresno County and correlated with volcanic ash just overlying the Corcoran Clay Member was dated at 600,000± 20,000 years by G. B. Dalrymple (in Janda, 1965). The potassium-argon date demonstrated that the upper part of the Tulare Formation is of Pleistocene age.

In 1964, fossil mammal bones were recovered by Bureau of Reclamation geologists from the Corcoran Clay Member during excavation of the San Luis project canal section of the California Aqueduct (Carpenter, 1965, p. 143). These bones were found about 5 miles southeast of the Dos Amigos pumping plant, in NW¼, sec. 28, T. 12 S., R. 11 E., at a depth of 25–30 feet below the land surface (R. E. Trefzger, oral commun., August 1967). The assemblage, which included remains of mammoths, camels, and *Equus*, has been examined by Dr. J. E. Mawby; he reported (written commun., July 1967, to J. F. Poland) that the mammoths identify the age of the Corcoran Clay Member as Irvingtonian or younger.

According to the Holmes (1965) time scale, the Pleistocene Epoch began 2–3 million years ago. If volcanic ash beds just overlying the Corcoran Clay Member are about 600,000 years old, and the Corcoran is of Irvingtonian (middle Pleistocene) age, then all of the Tulare above the Corcoran Clay Member, the Corcoran, and at least part of the Tulare beneath the Corcoran is of Pleistocene age. As shown on geologic section *A–A′* (pl. 3), the part of the Tulare Formation underlying the Corcoran Clay Member attains a thickness of 2,500 feet near Tulare Lake bed (south end of section *A–A′*). A substantial part of this 2,500 feet of pre-Corcoran Tulare doubtless is of early Pleistocene age, but data are not available to define the position of the Pliocene-Pleistocene boundary in these strata.

SUBSURFACE CHARACTER

In the subsurface, sediments derived from the Diablo Range interfinger with, and grade into, sediments derived from the Sierra Nevada. The eastern source arkosic sediments may be equivalent to part of the Kern River Formation of Diepenbrock (1933), which is exposed in the foothills adjacent to the southeastern part of the San Joaquin Valley. However, no attempt was made to assign an eastern boundary to the Tulare Formation on the geologic sections.

The Tulare Formation consists of deposits laid down in a fresh-water environment, and it underlies all of the Los Banos–Kettleman City area. As discussed above, it crops out nearly continuously along the eastern slope of the Diablo Range where it is poorly to moderately consolidated.

The top of the Tulare Formation in the subsurface in the Los Banos–Kettleman City area is not definable because the boundary between the uppermost tilted strata and the overlying alluvium in the outcrop area is a feature that cannot be recognized in wells in the San Joaquin Valley. In fact, beneath most of the Los Banos–Kettleman City area, the deposits between the Corcoran Clay Member and the land surface presumably are conformable and thus the criterion used at the outcrop does not even exist beneath most of the valley area. Furthermore, these deposits, which are as much as 900 feet thick, are almost entirely of alluvial-fan and flood-plain origin. Although the topographic axis migrated eastward during post-Corcoran time, as shown by the gradual eastern extension of Diablo Range source materials, there is no marked change in physical character or other criterion that can be related to the top of the uppermost tilted beds that define the top of the Tulare in the foothills. For purposes of defining thicknesses in this report, the depth to the top of the Tulare Formation is arbitrarily assumed to increase eastward from a featheredge at the foothills to about 200 feet below the land surface beneath the present valley axis. Obviously, a top so arbitrarily defined in no sense represents a time line.

The subsurface thickness of the Tulare Formation ranges from more than 3,000 feet in the southern part of the Los Banos–Kettleman City area to less than 800 feet locally in the northern part of the area. Thus, the subsurface thickness is much greater than the thickness in the outcrop area to the west.

The Los Banos–Kettleman City area has been predominantly a region of rapid and nearly continuous deposition during late Tertiary and Quaternary time. Consequently, the fresh-water-bearing sediments underlying the valley floor have undergone little weathering and reworking. Analysis of core samples indicates that very little discernible alteration has taken place in the clay minerals since their deposition (Meade, 1967, p. C6). Accordingly, oxidized sediments can generally be assumed to be representative of subaerial deposition and reduced deposits indicative of subaqueous deposition.

In its subsurface extent, the Tulare Formation has been subdivided on the basis of drill-log and electric-log correlations and petrographic analysis of core samples, into deposits representing four different types of continental deposition. These include alluvial-fan, flood-plain, deltaic, and lacustrine deposits, as shown in the geologic sections (pls. 3, 4) and the core-hole logs (pl. 5). Criteria that were used to identify the types of deposits have been summarized by Meade (1967, table 2). The distribution and poorly sorted character of the highly oxidized deposits underlying the alluvial slopes near the west border of the valley suggest that such deposits accumulated under subaerial conditions similar to those prevailing on the present-day alluvial fans, and therefore they are designated alluvial-fan deposits. Similarly, the lenticular and interfingering reduced fine- to coarse-grained fluvial deposits in the trough of the valley are designated as flood-plain deposits, implying that they were deposited on the ancient river flood plain. This general term, "flood-plain deposit," embraces channel, overbank, natural levee, back-swamp, and point-bar deposits, most of which cannot be differentiated in the subsurface. The lacustrine deposits, where fossil evidence is lacking, are differentiated from the flood-plain deposits by their high clay content, indicative of a still-water environment, the highly reduced nature of the sediments, and their homogeneity and stratigraphic continuity as indicated by electric logs and drill logs. A few extensive, but thin, beds of well-sorted sand, associated with the fine-grained lacustrine silty clay beds, also have been identified as of lacustrine origin.

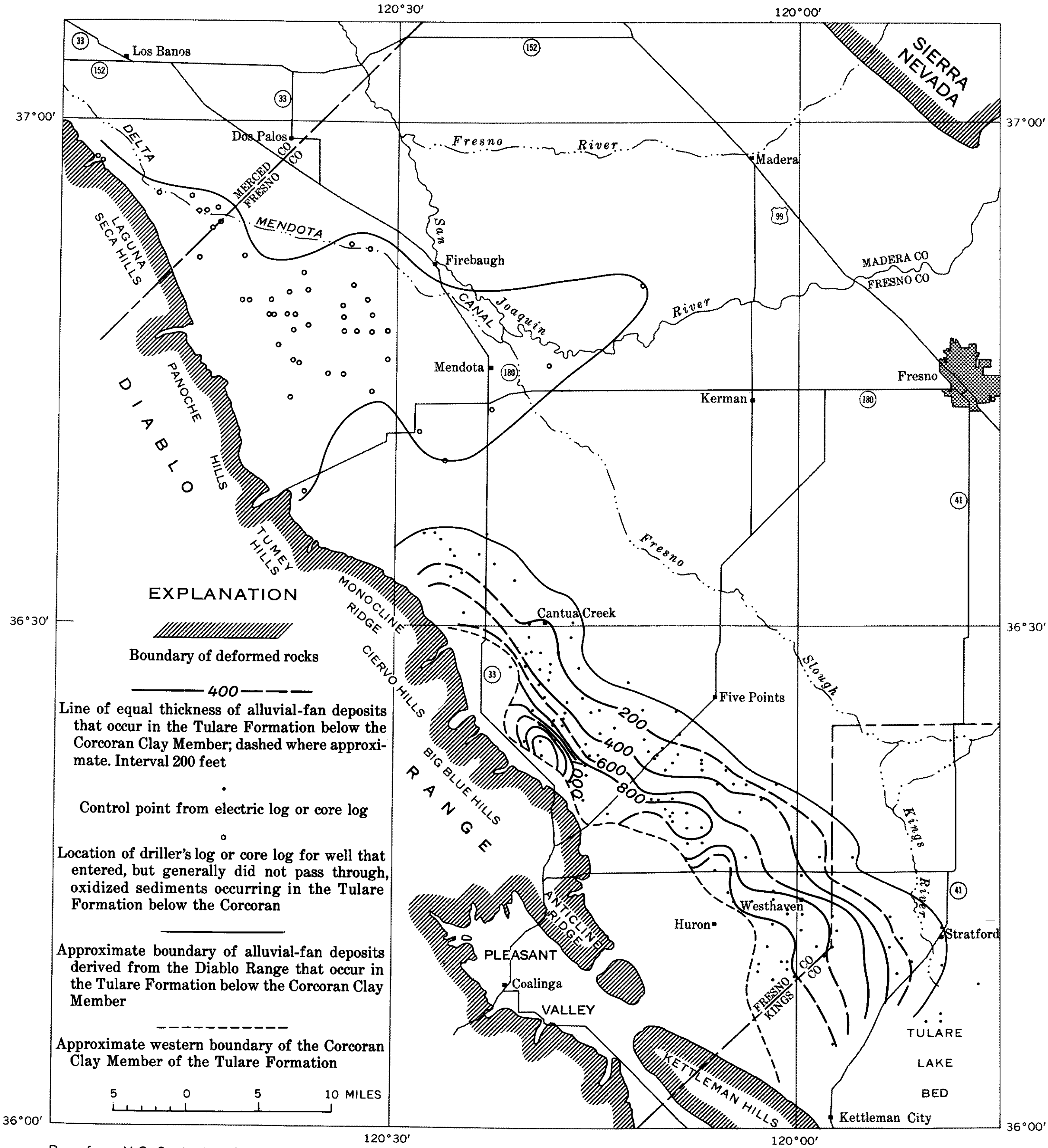
ALLUVIAL-FAN DEPOSITS

The alluvial-fan deposits of the Tulare Formation in the Los Banos–Kettleman City area are derived chiefly from source areas in the Diablo Range. (For source criteria, see Meade, 1967, p. C5.) They consist mainly of poorly sorted silt, clay, and fine to medium sand. The alluvial-fan deposits of Panoche and Los Gatos Creeks are the coarsest; they contain a few layers of medium to coarse sand, with some gravel. Although most of the material presumably was laid down by intermittent streams, boulder deposits suggest mudflow origin for parts of the deposits. The alluvial-fan deposits adjacent to the Diablo Range foothills can easily be recognized in well cuttings or cores by their yellowish-brown to brown color. They are calcareous and gypsiferous and locally contain small calcareous concretions, fragments of serpentine, glaucophane schist, siliceous shale, chert, and jasper derived from older rocks to the west.

The bulk of the alluvial-fan deposits from the Diablo Range probably was laid down in post-Corcoran time. Prior to the deposition of the lacustrine Corcoran Clay Member, the ancestral Los Gatos Creek fan extended 18–22 miles east from the present western edge of the valley. (See fig. 8; pl. 4, geologic section E–E'.) After the deposition of the Corcoran Clay Member, the Los Gatos fan again expanded 18–22 miles eastward from the western edge of the valley (fig. 9). However, the post-Corcoran alluvial-fan deposits that extend northeastward from the western border of the valley in the central part of the Los Banos–Kettleman City area are generally more extensive than the older pre-Corcoran alluvial-fan deposits.

The Panoche Creek fan in the northern part of the Los Banos-Kettleman City area is one of the largest modern alluvial fans on the west side of the San Joaquin Valley, extending 18 miles across the valley floor from the western edge of the valley. However, prior to the deposition of the Corcoran Clay Member, an alluvial fan of western source extended several miles east of the present axis of the valley. The top of a layer as much as 50 feet thick consisting of oxidized deposits derived from the Diablo Range was cored below the Corcoran Clay Member at depths below land surface of 687 and 591 feet, respectively, in Bureau of Reclamation core holes 13/15–35E1 (pl. 4) and 13/16–2C1. A well-developed soil profile has been recognized at the top of the western source materials.

Water wells in the area from near Mendota to the edge of the Panoche Hills commonly bottom in western source oxidized deposits. The uppermost layer of these deposits probably is a soil horizon because it is commonly described in drillers' logs as being red or pink. The location of wells in this area that bottom in such oxidized deposits are plotted in figure 8. These deposits are interpreted as having been laid down on an alluvial fan that extended from the Panoche Hills east across the present valley trough in pre-Corcoran time.



Base from U.S. Geological Survey Central Valley map, 1:250 000, 1958

FIGURE 8.—Thickness of alluvial-fan deposits derived from the Diablo Range in the Tulare Formation below the Corcoran Clay Member.

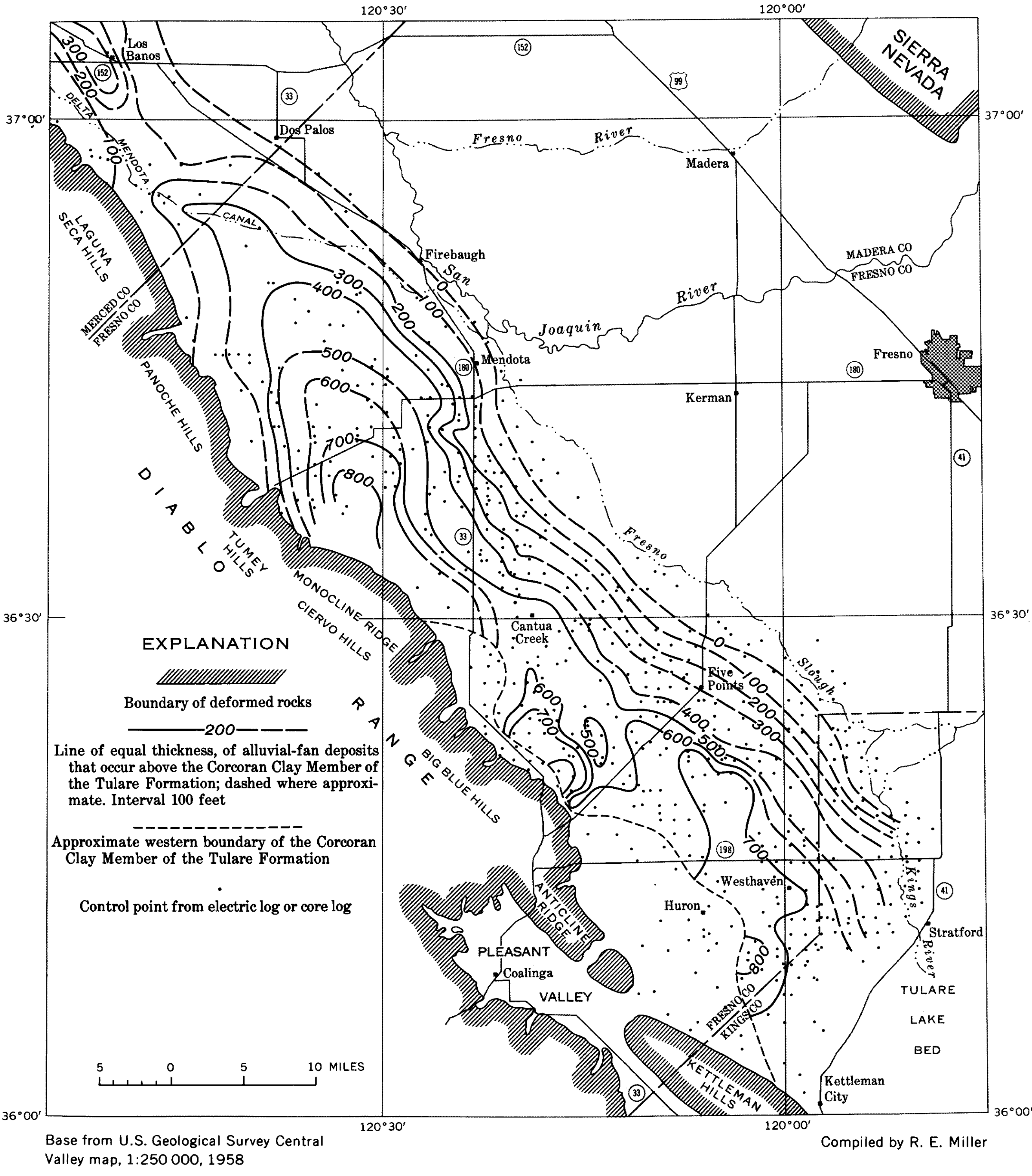


FIGURE 9.—Thickness of alluvial-fan deposits derived from the Diablo Range above the Corcoran Clay Member of the Tulare Formation.

The alluvial-fan deposits underlying the western slope between Cantua Creek and Anticline Ridge generally are finer grained and less permeable than similar deposits to the northwest or southeast. The alluvial-fan deposits derived from the Diablo Range are of relatively low permeability and, for this reason, where such deposits form the bulk of the Tulare Formation, irrigation wells in parts of the area are drilled as deep as 2,500–3,800 feet to tap more permeable aquifers in the underlying San Joaquin and Etchegoin Formations. (See pl. 4, geologic sections *C–C′*, *D–D′*.)

Alluvial-fan deposits derived from the Sierra Nevada that extend subsurface into the northern part of the Los Banos–Kettleman City area (pl. 4, geologic section *B–B′*) are composed chiefly of fine to medium-grained micaceous granitic sand and varying amounts of silt and clay. The color of these deposits ranges from gray to brown. Where the clay content is low, alluvial-fan deposits derived from the Sierra Nevada are moderately permeable and yield adequate water to irrigation wells.

FLOOD-PLAIN DEPOSITS

The term "flood-plain deposit" is used in the present report in a broad sense to include all reduced fluvial deposits laid down in the valley trough area.

The flood-plain deposits derived from the Sierra Nevada as described from core samples generally consist of gray micaceous or arkosic sand with interbedded micaceous sandy silt and clay layers ranging in color from olive brown to greenish blue. The sands generally are subangular to subrounded and have a moderate to high permeability. As shown by the geologic sections, these deposits are extensive below the Corcoran Clay Member in the area west of Fresno Slough. The thickness and areal extent of micaceous sands derived from the Sierra Nevada that overlie the Corcoran Clay Member are shown in figure 10. This unit, which consists primarily of flood-plain deposits, includes just above the Corcoran a zone up to 200 feet thick containing varying amounts, up to 89 percent by weight, of rhyolitic volcanic glass and pumice fragments (pl. 3, geologic section *A–A′*; pl. 4, *B–B′*, *C–C′*). The approximate western boundary of these volcanic deposits is shown in figure 10.

The micaceous sands, which form the bulk of the flood-plain deposits from the Sierra Nevada, are highly permeable and yield water freely. In fact, from Tranquillity to the Kings River and for several miles west, most of the irrigation wells tap the micaceous sand above the Corcoran Clay Member. In parts of the Fresno Slough area, however, the water in the flood-plain deposits both above and below the Corcoran has such a high mineral content that it is not satisfactory for domestic or irrigation use. (See pl. 4, geologic sections *B–B′*, *C–C′*.)

The flood-plain deposits derived chiefly from the Diablo Range generally have low to moderate permeabilities. They generally are greenish gray to greenish black and are characterized by an abundance of andesitic and basaltic detritus. Locally, they contain moderate amounts of serpentine, chert, and other rock fragments derived from older rocks in the Diablo Range. They are also slightly to moderately micaceous, in contrast to the generally nonmicaceous character of the alluvial-fan deposits derived from the Diablo Range. Most of the western-source flood-plain deposits are found in the northern half of the Los Banos-Kettleman City area.

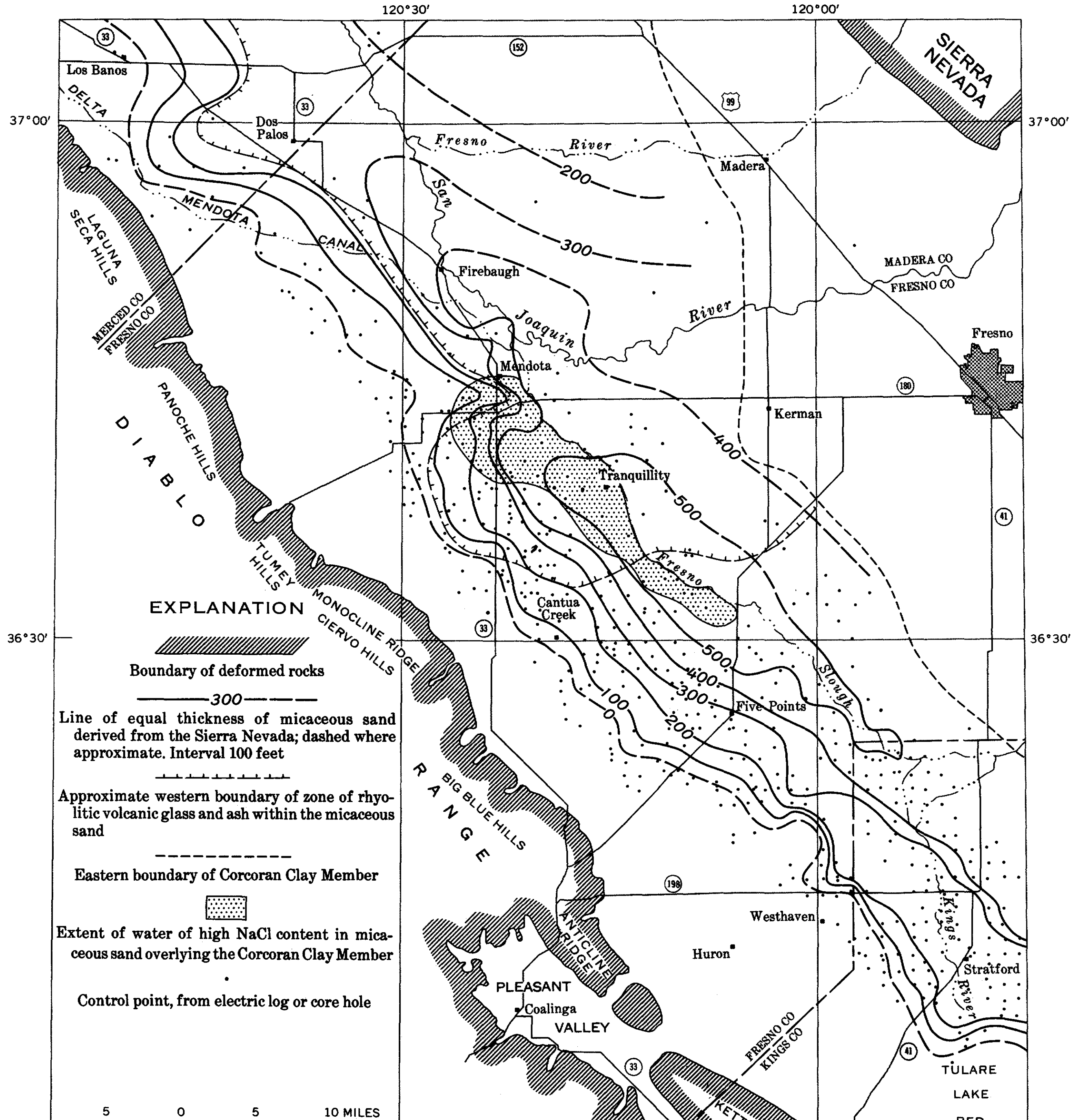
Modern near-surface deposits laid down in flood basins by overflow of the San Joaquin and Kings Rivers in the level central floor of the valley consist largely of impervious clay and clay adobe with a texture that ranges from medium to heavy (Davis and others, 1959, p. 27, pl. 29, basin soils). In contrast, the flood-plain deposits of the Tulare Formation are coarser and contain little clay, indicating that the depositional environment was different from the present regime. The comparative coarseness of flood-plain sediments in the Tulare suggests that streams that deposited them were more competent than the modern streams of the same areas. The relatively low clay content of the flood-plain deposits indicates excellent sorting.

DELTAIC DEPOSITS

Thick beds of medium to coarse well-sorted sand in the Tulare Formation in the southern part of the Los Banos–Kettleman City area are interpreted as deltaic deposits of extensive lakes. These deposits consist primarily of bluish- or greenish-gray angular and subangular medium- to coarse-grained arkosic sand with a high biotite mica content. Crossbedding and depositional dips of 10°–40° and numerous carbonaceous layers are reported in core descriptions of these deposits. Deltaic deposits are differentiated on geologic sections *A–A′* and *E–E′* (pls. 3, 4). At the east end of geologic section *E–E′*, sandy deposits beneath the Corcoran Clay Member, presumably of deltaic origin, are 2,000 feet thick. (See well 19/20–32R.) Where tapped by wells, these thick sands yield abundant water.

LACUSTRINE DEPOSITS

The basal deposits of the Tulare Formation in the southern and central parts of the Los Banos–Kettleman City area and nearly all the deposits underlying the modern Tulare Lake bed consist of clay, silt, and sand



Base from U.S. Geological Survey Central Valley map, 1:250 000, 1958

FIGURE 10.—Thickness of micaceous sand overlying the Corcoran Clay Member of the Tulare Formation.

commonly containing lacustrine fossils. These deposits are more homogeneous than the flood-plain deposits and generally are fine grained, except where intermixed with deltaic sands derived from the Sierra Nevada. The lacustrine sediments usually are strongly reduced, which accounts for their greenish or bluish color, and carbonaceous clay and peat layers are common. Thin oxidized layers found in parts of this sequence are generally yellowish brown to reddish orange.

As shown on geologic sections *A–A′* and *E–E′* (pls. 3, 4), at least three extensive lake expansions since the retreat of the late Pliocene sea are recorded in the subsurface deposits in the southern part of the Los Banos–Kettleman City area. The initial lake in the basin is represented by the basal Tulare sediments, which consist of 400–500 feet of sandy lacustrine and deltaic deposits. Core holes drilled by the Shell Oil Co.[3] in the vicinity of Westhaven indicate that these deposits contain abundant fossils of *Amnicola* and other freshwater lacustrine fauna. Analyses of water from this interval and electric logs indicate that the water in these lacustrine deposits is now very brackish.

On the west flank of North Dome where the Tulare Formation is well exposed, Woodring and others (1940, p. 22) noted small oysters and mussels in a sandstone 1,636 feet above the base of the formation and upward to the top of the measured section through a thickness of 322 feet of sandstone and conglomerate. About 1,300 feet of apparently nonfossiliferous poorly bedded and crossbedded yellowish to brownish-gray sandstone containing conglomerate lenses and a few interbedded silt layers separate this fossiliferous zone from the uppermost *Amnicola* zone in the lower part of the Tulare Formation. The fossiliferous zone described by Woodring in the uppermost exposed Tulare Formation on North Dome represents a second major lake phase. A lacustrine deposit is found at a similar position in the subsurface northeast of North Dome. It is shown at the south end of geologic section *A–A′* (pl. 3) 1,200–1,600 feet above the base of the Tulare Formation. This deposit is about 100 feet thick, and in core holes 20/18–11A and 19/18–24R (pl. 4) where samples of it were recovered from depths of 1,151–1,160 feet and 1,039–1,050 feet, respectively, ostracodes, *Amnicola*, and fish remains were reported.

The third and largest lake is represented by the diatomaceous Corcoran Clay Member of the Tulare Formation, which at core hole 20/18–6B is separated from deposits of the second lake phase by 800 feet of western-source alluvium.

Additional lacustrine deposits of lesser extent and thickness have been mapped by Croft (1968) between the Corcoran and land surface in the vicinity of Tulare Lake. A lacustrine clay about 30 feet thick, 250 feet above the Corcoran, and 250 feet below the land surface, is shown at the eastern end of section *E–E′* (pl. 4). This unit has been designated the C clay by Croft.

[3] Shell Oil Co., 1929, "Results of Core Drilling on the Boston Land Co. Property," unpublished report.

CORCORAN CLAY MEMBER

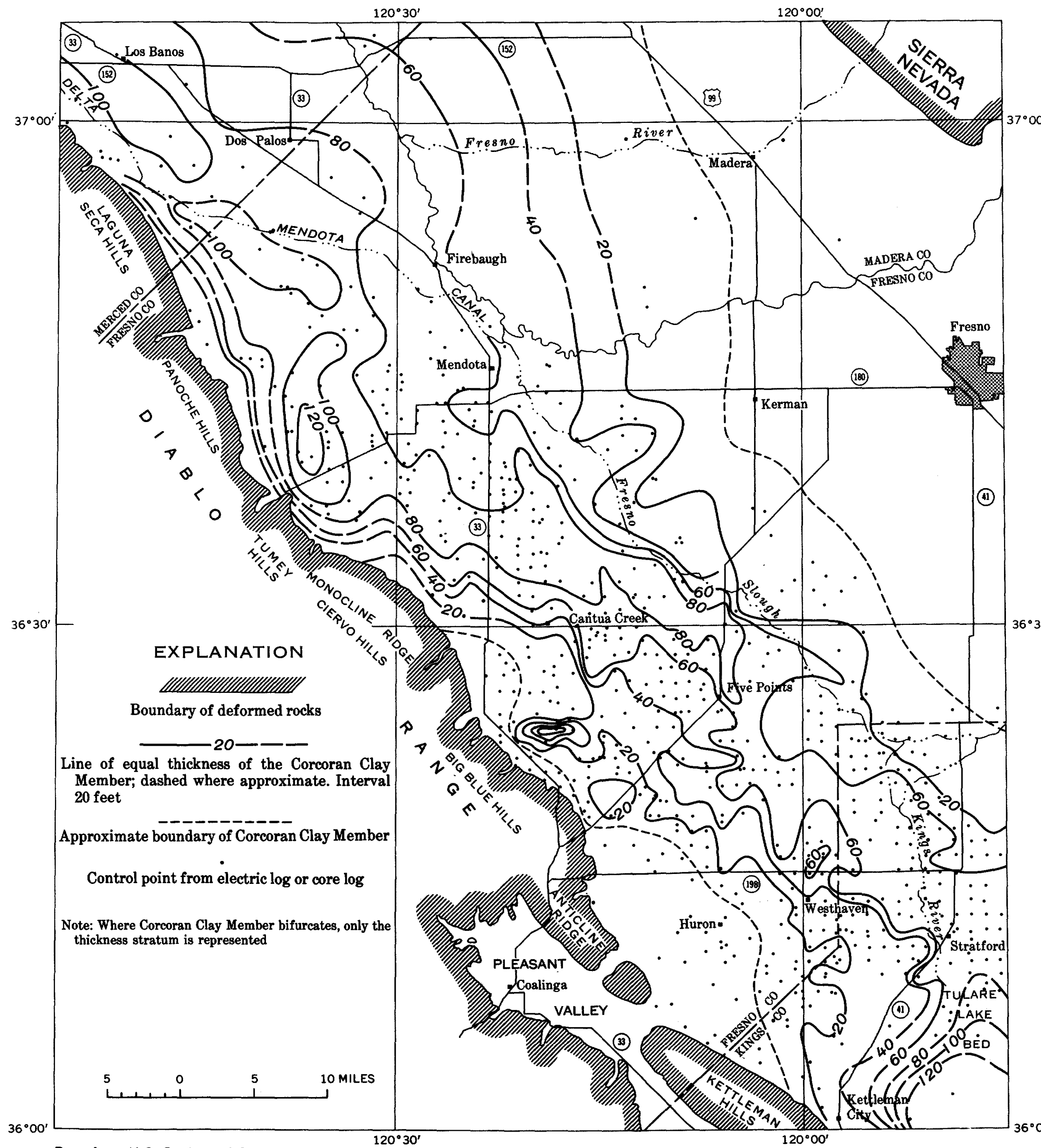
A widespread diatomaceous clay stratum, first named as a separate formation by Frink and Kues (1954, p. 2357–2370), was redefined as the Corcoran Clay Member of the Tulare Formation by Davis (in Inter-Agency Committee, 1968, p. 120). The Corcoran Clay Member extends beneath the entire Los Banos–Kettleman City area, except in a narrow zone adjacent to the hills in the southern part of the area where, as shown in figure 11 and geologic section *E–E′* (pl. 4), it grades into the surrounding deposits.

The Corcoran Clay Member is the principal confining layer for the artesian system throughout a large part of the San Joaquin Valley. The Corcoran is of very low permeability (Davis and others, 1964, p. 88), and in 1960 the difference in head in aquifers above and below the Corcoran locally was as much as 200 feet.

The Corcoran Clay Member was deposited in a freshwater lake 10–40 miles wide and more than 200 miles long (Davis and others, 1959, p. 77; pl. 14). The longitudinal axis of the lake in which the clay was deposited was about 5–10 miles west of the present topographic axis of the valley. The maximum known thickness of the Corcoran Clay Member in the Los Banos–Kettleman City area is 120 feet, at a place 5 miles northeast of the mouth of Panoche Creek, and beneath Tulare Lake bed. At both places, thickness is based on electric-log interpretation. As shown in figure 11, the thickness exceeds 100 feet in several localities. Along the west edge of the valley adjacent to Monocline Ridge and the Ciervo Hills, the Corcoran is less than 20 feet thick. Its exact western extent is difficult to delineate because, as it thins, it bifurcates and its sand and silt content gradually increase until it cannot be distinguished in electric logs from littoral sands that occur along its western edge. The Corcoran is generally reduced and is greenish blue, except locally along the western border of the Los Banos–Kettleman City area where it has been uplifted and has been partially oxidized to brown or red.

Adjacent to the Panoche and Tumey Hills, the Corcoran is 30–80 feet thick. At core hole 15/12–23Q1 (pl. 4), on the east flank of the Tumey Hills, 35 feet, the lower 10 feet of which is diatomaceous, has been assigned to the Corcoran Clay Member.

From Tumey Hills northward in the Los Banos–Kettleman City area, the western edge of the Corcoran Clay Member has been uplifted (fig. 12). Fine dark silty



Base from U.S. Geological Survey Central Valley map, 1:250 000, 1958

FIGURE 11.—Thickness of the Corcoran Clay Member of the Tulare Formation.

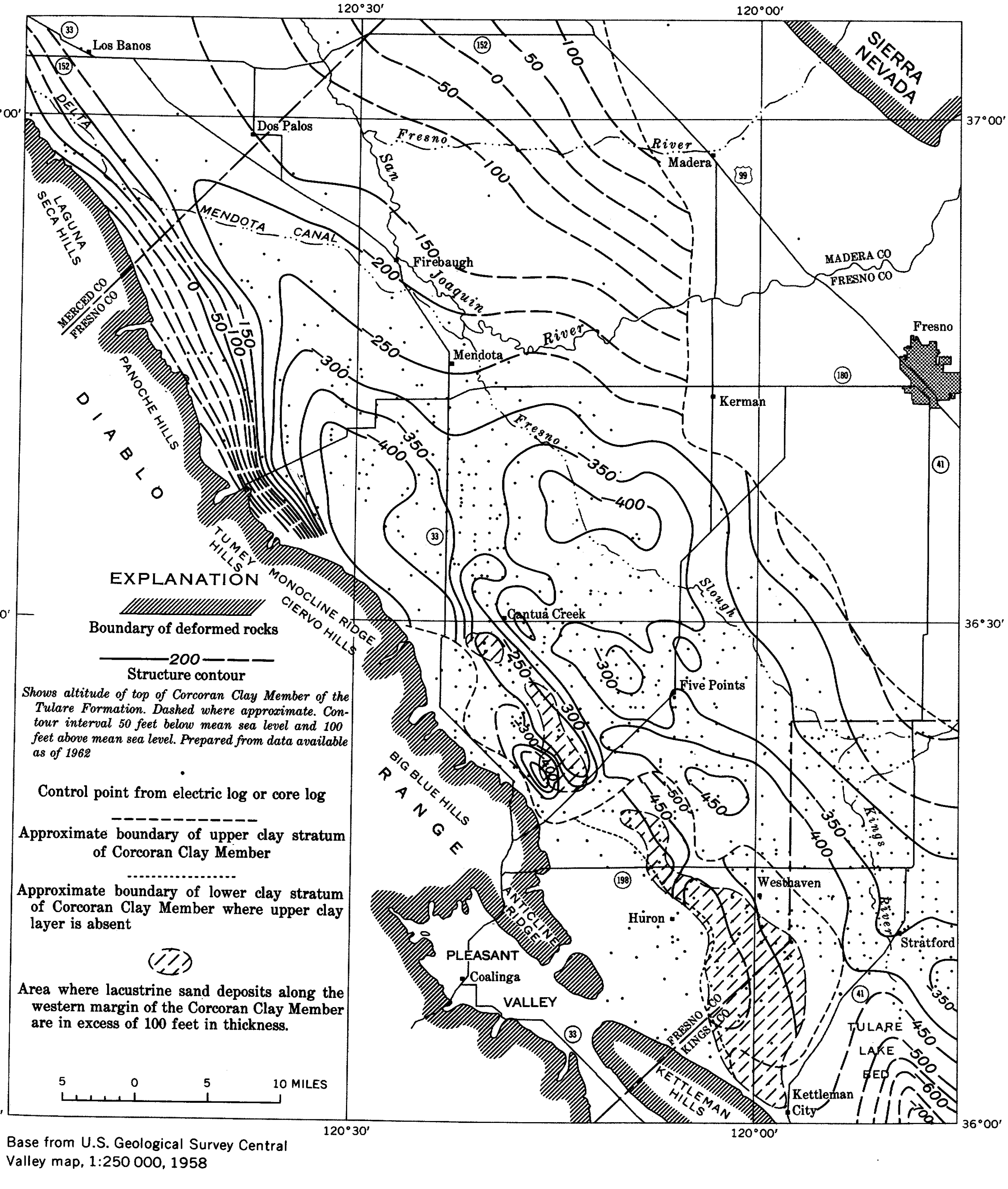


FIGURE 12.—Structure of the Corcoran Clay Member of the Tulare Formation.

material exposed at an altitude of 500 feet in a roadcut at the north end of the Panoche Hills where Little Panoche Creek enters the San Joaquin Valley may represent the Corcoran. The material consists of two grayish-green silt strata; the upper, about 1 foot thick, and the lower, 4 feet thick. The upper stratum is overlain by about 90 feet of ill-sorted red alluvial detritus ranging from silt to cobble conglomerate. Separating the two reduced silt strata is 6–8 feet of sand and gravel. The material underlying the lower silt is poorly exposed, but it appears to consist of intermixed sand and gravel. The silt strata are exposed intermittently for more than a quarter of a mile in the roadcut and indicate a slight anticlinal upwarp. The silt appears to be nondiatomaceous and contains many subrounded pebbles and sand grains indicating a probable nearshore lake environment. Where the Corcoran Clay Member is known in the subsurface 2½ miles east of this outcrop, it is 25 feet thick. At that point, the Corcoran is 320 feet lower in altitude than the exposure described, but is rising about 110 feet per mile toward the west at a gradually increasing rate. Lithologic similarity, stratigraphic position, and the fact that in this part of the San Joaquin Valley the Corcoran is the uppermost reduced deposit, strongly suggest correlation of the lacustrine silt exposed at the mouth of Little Panoche Creek with the Corcoran.

A few miles to the northwest, the outcrop of the Concoran Clay Member along the east edge of the Laguna Seca Hills has been described (p. E23).

TERRACE DEPOSITS (PLEISTOCENE)

Stream-terrace deposits, obviously older than the present flood plains, are found along nearly all the streams, but only along the north sides of Cantua and Panoche Creeks are they sufficiently extensive to be shown on plate 1. The deposits are similar to some of the coarser materials in the underlying Pliocene and Pleistocene formations. They consist principally of gravel containnig boulders to about 2 feet in diameter in a matrix of sand and silt. Thickness commonly ranges between 2 and 20 feet.

The terrace deposit mapped along Cantua Creek evidently was laid down by the creek when its erosional and load-carrying capabilities were much greater than at present. The deposit appears to be flat lying, or nearly so, and thus is unconformable on, and younger than, the Tulare. As the terrace deposits are younger than the Tulare but older than the alluvial deposits now laid down in the stream channel, they are presumed to be of Pleistocene age.

ALLUVIUM (PLEISTOCENE AND HOLOCENE)

For practical purposes, the entire post-Tulare section in the San Joaquin Valley is grouped in this report into a single unit—alluvium—which includes stream-laid and still-water deposits ranging in age from Pleistocene to Holocene. As the Tulare Formation is defined (p. E21) as the uppermost deformed or tilted strata, the valley alluvium can readily be distinguished from the Tulare along most of the west border of the area. Beneath the San Joaquin Valley, however, this distinction is virtually meaningless because the Tulare and the overlying alluvium are conformable.

The thickness of the post-Tulare alluvium is not known because the top of the Tulare Formation cannot be identified in the valley. An indicated on page E23, for purposes of defining thickness in this report the depth to the top of the Tulare Formation is arbitrarily assumed to increase eastward from a featheredge at the foothills to about 200 feet below the land surface beneath the present valley axis. Under this arbitrary assumption, the thickness of the post-Tulare alluvium ranges from 0 to about 200 feet.

The lithology of the alluvium is similar to that of the underlying deposits of the Tulare; it consists of sand, silt, clay, and minor gravel laid down as alluvial fans and on flood plains. Poorly sorted alluvial-fan deposits from the Diablo Range generally predominate, except in the eastern part of the area, which is underlain chiefly by well-sorted micaceous sands derived from the Sierra Nevada, and by fine-grained basin deposits near the surface.

SOILS

The alluvium at the land surface near the west border of the valley has been subdivided on plate 1 mainly on the basis of soil-profile development. Soil surveys of the U.S. Department of Agriculture (Harradine and others, 1952, 1956) were used to delineate the soil types. The valley soils in the area of plate 1 that are characterized by profile development include the Panhill, Lost Hills, and Ortigalita soil series. In the area mapped, only the Panoche soil series is characterized by a lack of profile development.

Other factors being equal, the degree of profile development could be taken as a measure of relative age of the soils. However, the characteristics of the soil at a given place depend also on such variable factors as (1) the lithology of the source material, (2) the environment in which the soil was deposited and the climate since deposition, (3) plant and animal life in the soil, and (4) relief and drainage. These variables in the area mapped are very complex. As a result, the two classes of soil-profile development indicated by plate 1 are at best poor indicators of younger and older surfaces.

The division of the surface alluvium into the two classes is useful as a rough measure of relative permeability to influent seepage. The Panoche soils are permeable to moderately permeable; the others (Panhill series and older) are in general only moderately to poorly permeable.

HYDROLOGIC UNITS IN THE GROUND-WATER RESERVOIR

The geologic maps and sections in this report show that the subsurface geology of the fresh-water-bearing deposits is highly complex when the deposits are differentiated with respect to source, environment of deposition, and, in part, lithologic character. Fortunately, the hydrologic units are not so complex in their gross features relating to occurrence and movement of ground water. As pointed out by Davis and Poland (1957, p. 421), a generalized threefold subdivision of the fresh-water-bearing deposits can be made as follows: An upper unit extending from the land surface to the top of the relatively impervious Corcoran Clay Member (diatomaceous clay) at a depth ranging from 10 to 900 feet below the land surface; the Corcoran Clay Member, ranging in thickness from a featheredge to 120 feet, which separates waters of substantially different chemical quality; and a lower unit 100 to more than 2,000 feet thick that extends down to the deposits containing the main saline water body. The saturated part of the uper unit they referred to as the upper water-bearing zone, and the lower unit, as the lower water-bearing zone.

As shown by the electric logs on the geologic sections and by core-hole logs, the fresh-water-bearing deposits in the Los Banos-Kettleman City area are heterogeneous, as would be expected from their environments of deposition, and they display rapid variation in texture and permeability, especially in the vertical direction. Beds or lenses of sand are separated by strata of silt and clay of low permeability.

If an aquifer is defined as a permeable deposit that will yield water to wells, the entire lower zone can be considered an aquifer in a broad sense. On the other hand, the permeable sand units can be considered as aquifers, separated hydraulically in varying degree by the finer grained less permeable interbeds of silt and clay. Silt and clay, especially the latter, are much more compressible than sand under load, such as that applied when artesian head declines. Therefore, it is important in study of subsidence problems and the compaction of deposits under increased effective stress to differentiate between a water-bearing unit that is composed entirely of coarse material, such as clean sand and gravel, and one that contains many fine-grained interbeds of silt and clay. For purposes of differentiation in the studies of compaction and subsidence, a water-bearing unit characterized by approximate hydraulic continuity but that contains many fine-grained interbeds is termed an aquifer system. Thus, under this definition, the lower water-bearing zone is a confined aquifer system.

A simplified picture of the hydrologic units that constitute the ground-water reservoir is presented in four generalized sections to show the principal geologic controls and the two hydrologic units—the semiconfined aquifer system of the upper zone and the confined aquifer system of the lower zone. These sections (figs. 13, 14) coincide with the detailed geologic sections of plates 3 and 4, and are identified by the same letters.

The depth of wells tapping the ground-water reservoir generally decreases from west to east and ranges from as much as 3,800 feet in the southwestern part of the area along the west border of the valley to less than 200 feet near Fresno Slough. In the western and central parts of the area, most wells tap both the upper and lower water-bearing zones, although many tap only the lower zone. The deepest wells are in the western part of the area south of Panoche Creek, because the average permeability of the aquifer systems is low. In order to obtain the locally required 1,000–2,000 gallons per minute for irrigation, wells must tap a thicker saturated section and are drilled through thick alluvial-fan deposits of generally low permeability to reach more permeable underlying flood-plain and deltaic deposits. In the eastern part of the area from Tranquillity south to the Kings River, in the reach where the thickness of the highly permeable Sierra micaceous sand above the Corcoran exceeds 300 feet and the water is of good quality (fig. 10), most wells tap only the upper zone. Here, the average depth of wells is 400–600 feet.

The yield factor [4] (Poland, 1959, p. 32), which is an approximate measure of the average permeability of the water-bearing material tapped by a well, is shown in figure 15 to be highest for shallow wells which tap only the flood-plain deposits (Sierra micaceous sand) in the upper water-bearing zone (section *C–C′*). The wells with the lowest yield factor are generally those which tap mainly alluvial-fan deposits.

[4] Yield factor $=\frac{\text{Specific capacity (gallons per minute per foot of drawdown} \times 100)}{\text{Perforated casing interval, in feet}}$.

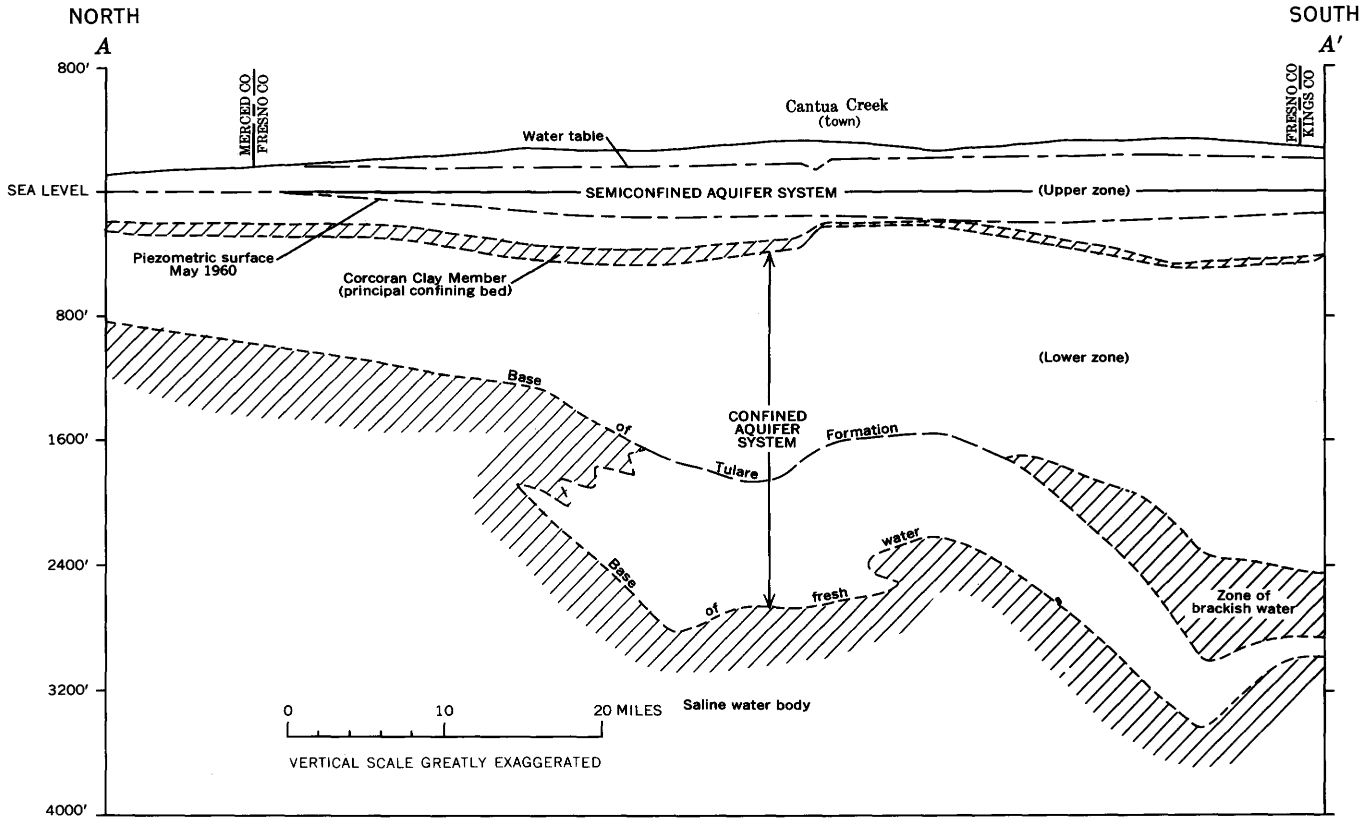


FIGURE 13.—Generalized section *A–A′*, showing hydrologic units. See figure 3 for location of section.

UPPER WATER-BEARING ZONE

The upper water-bearing zone has a water table, and, locally, the water is unconfined. In general, however, the ground water in this zone is semiconfined to confined. Under conditions of pumping draft, head differentials of 100–200 feet or more have developed between the water table and the water levels in wells tapping the base of this zone just above the Corcoran Clay Member. Hence, confinement is known to be substantial in some parts of the area, and, in general, it increases with depth; but in places where the deposits are more coarse grained and have greater vertical permeability, differences in head are not great. This upper zone thus contains a number of semiconfined aquifers, with the degree of confinement varying from place to place. Considered as a unit, this upper zone is termed a semiconfined aquifer system in this report.

Most of the more than 1,000 active irrigation wells that furnish the bulk of the irrigation supply in the Los Banos–Kettleman City area are perforated in the lower part of the upper zone as well as in the lower zone. However, in most of the area, the low permeability of the alluvial-fan deposits, and, locally in the eastern part, the poor water quality in the more permeable Sierra flood-plain deposits precludes the upper zone as a sole source of irrigation water. In an area about 5 miles wide along Fresno Slough, however, from Tranquillity southeast to the Kings River, wells tapping the upper zone yield water of adequate quantity and good quality for irrigation. The temperature of the water from these wells ranges from 65° to 75°F (fig. 15). Most of this supply is from permeable micaceous sand 200–500 feet thick that overlies the Corcoran Clay Member.

LOWER WATER-BEARING ZONE

The lower water-bearing zone is effectively confined by the Corcoran Clay Member (figs. 11, 12), except locally in the southwestern part of the Los Banos–Kettleman City area where the Corcoran Clay Member is absent, and confinement is poor or lacking. This lower zone is the principal source of ground water for irrigation in the Los Banos–Kettleman City area, and Davis and Poland (1957, p. 432) estimated that it supplies 75–80 percent of the pumpage. Much of the water presently (1966) being produced from the lower zone is pore water that is being squeezed out of the fine-grained clayey sediments (aquitards) by compaction of the aquifer system due to decline in artesian head.

The temperature of the water produced from wells tapping only the lower water-bearing zone ranges from about 80° to 90°F, except where water is drawn from the permeable deposits below the Tulare Formation. In

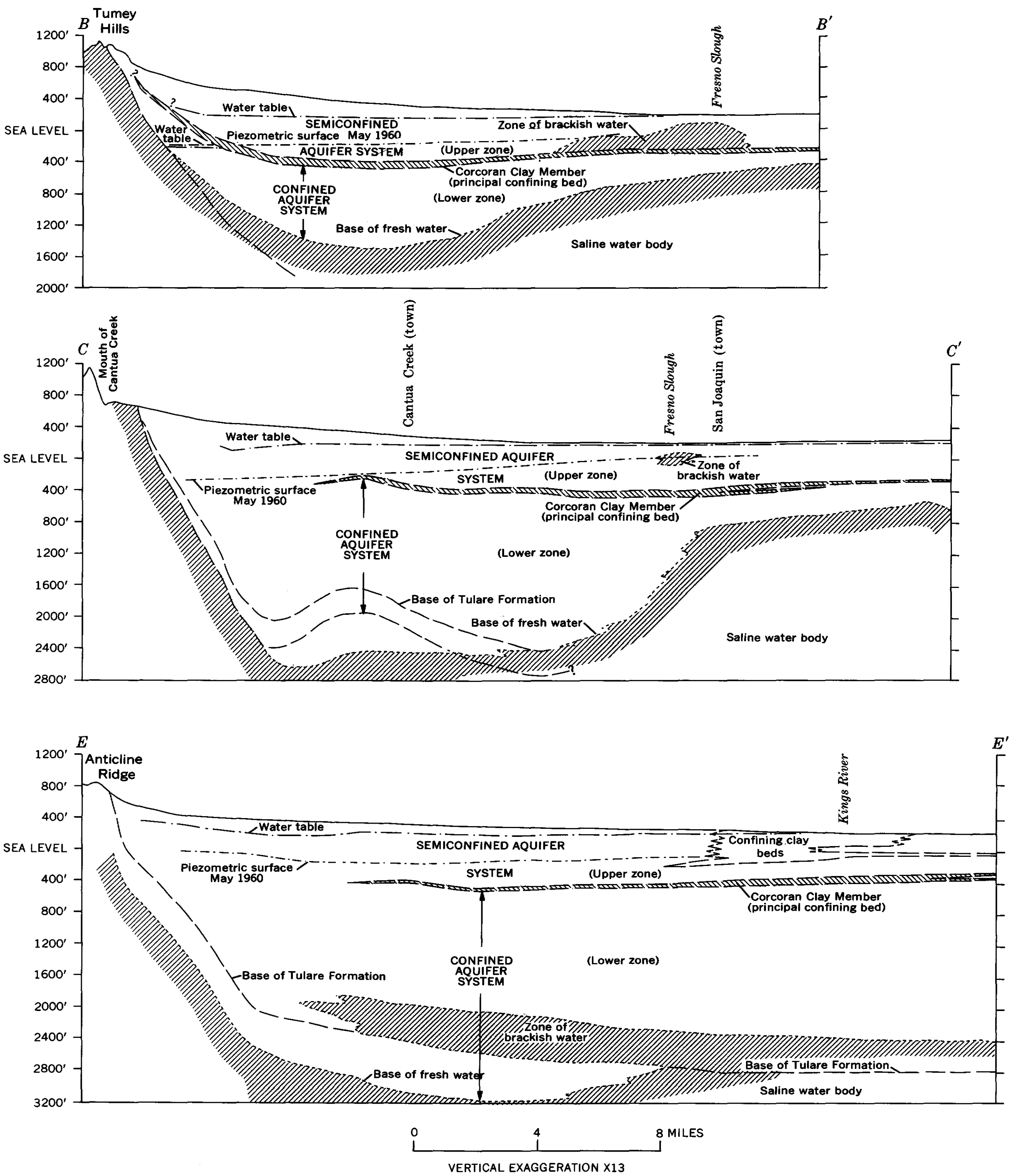


Figure 14.—Generalized sections *B–B′*, *C–C′*, and *E–E′*, showing hydrologic units. See figure 3 for location of sections.

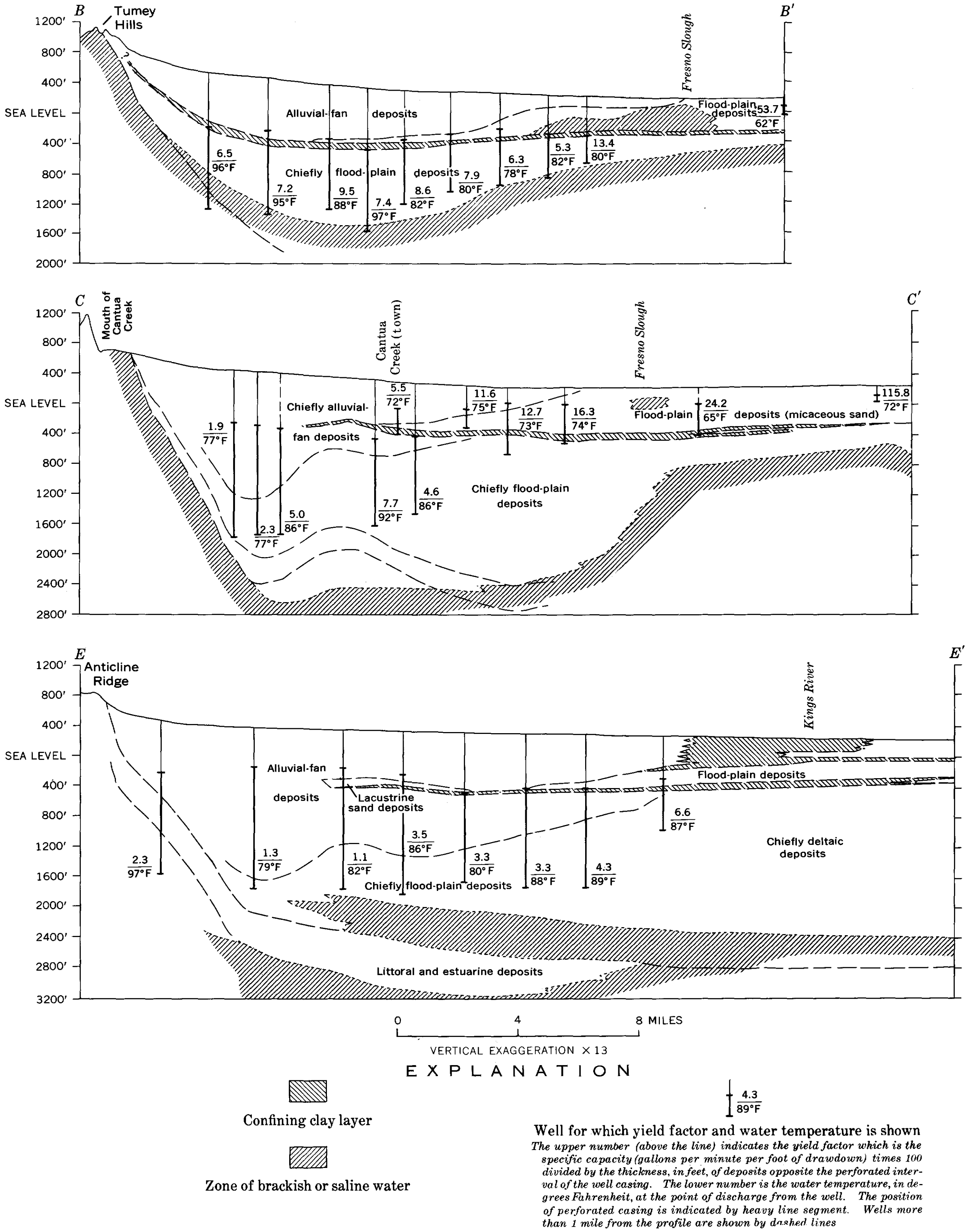


FIGURE 15.—Generalized sections *B–B'*, *C–C'*, and *E–E'* showing yield factors of wells in relation to the depositional environment. See figure 3 for location of sections.

such wells, the water temperature generally exceeds 90°F (fig. 15, section *E–E′*) and is as high as 114°F. West of the edge of the confining clay bed (Corcoran Clay Member) the temperature of the water produced from wells which do not completely penetrate the Tulare Formation is generally in the high seventies (fig. 15, sections *C–C′*, *E–E′*). This fact suggests that recharge to the lower water-bearing zone by surface and shallow ground waters is rapid enough to alter the geothermal gradient locally.

Although the geologic sections accompanying this report indicate a complexity of geologic elements in this lower zone with respect to source and type of deposits, hydrologic evidence of various types and consideration of the relatively uniform chemical quality of the ground water in this lower zone lead to the conclusion that, in general, the zone has reasonably good hydraulic continuity laterally and vertically. At Westhaven, for example, paired observation wells perforated at the top and near the base of the lower zone, respectively, have not shown more than 30 feet difference in artesian head during an 8-year period (1958–65), although the seasonal fluctuation of head in both wells due to nearby pumping has been as much as 80 feet. From 1962 to 1965, the head in both wells was equal within a few feet for about three-quarters of each year. On the other hand, at the northern end of the area near Oro Loma, head differences of 75 feet have been observed in paired observation wells tapping two separate aquifers in the lower zone. Water-level data indicate that in the southern and central parts of the Los Banos–Kettleman City area at least north to Panoche Creek, hydraulic continuity throughout the zone is reasonably good; but from Little Panoche Creek north, confining interbeds are sufficiently thick, extensive, and impermeable to cause substantial differences in artesian head locally.

CHEMICAL CHARACTER OF THE GROUND WATER

The chemical character of the ground water in the Los Banos–Kettleman City area changes notably with depth. The two major and most consistent changes with depth are (1) a marked decrease in dissolved solids and (2) an increase in the percent of sodium among the cations. The increase in percent sodium among the a geochemical feature influencing the compaction of the sediments under increasing effective stress. The clayey sediments are primarily montmorillonite (Meade, 1967, p. C18). Experimental studies, summarized by Meade (1964, fig. 4), have demonstrated that montmorillonitic clays are more compressible than illitic or kaolinitic clays. They have also demonstrated that, at effective stresses up to at least 150 psi (pounds per square inch), montmorillonite saturated with sodium has a larger void ratio and is more compressible than montmorillonite saturated with calcium or mangesium (Meade, 1964, fig. 11). Meade's (1963) study of montmorillonite-rich sediments in the San Joaquin Valley suggests that the influence of different exchangeable cations may be significant for effective stresses as great as 750 psi. The percent of absorbed sodium compared to other cations increases with depth in the montmorillonitic sediments of the project area (Meade, 1967, fig. 15). For these reasons the chemical character of the ground waters in the Los Banos–Kettleman City area is reviewed briefly in this report.

Many of the irrigation wells in the western two-thirds of the Los Banos-Kettleman City area are perforated opposite both the upper and lower water-bearing zones. There are marked differences in quality between the waters of the two zones; accordingly, the chemical quality of water from different wells differs considerably, depending chiefly upon the position of the perforated interval in the stratigraphic section and the relative permeability of the zones at that place. The chemical character of the water of the upper and lower water-bearing zones in this part of the San Joaquin Valley has been described in some detail by Davis and Poland (1957, p. 448–462), and the character of the surface streams was discussed by Davis (1961). Much of the following discussion is based on these earlier reports. The chemical analyses furnishing the basis for the discussion of ground waters were made on water samples from 774 wells collected in August 1951. About all the well pumps had been operated continuously for a week to a month or more prior to sampling; therefore, the chemical character of the discharge at the time of sampling was, for most wells, representative for the intervals tapped. The sum of determined constituents utilized in defining concentration includes all principal cations and anions, but it does not include nitrate and silica. Therefore, the value cited is 20–150 mg/l (million gallons per liter) less than total dissolved solids.

WATERS OF THE UPPER WATER-BEARING ZONE

Ground waters of the upper water-bearing zone generally contain high concentrations of calcium, magnesium, and sulfate. Pronounced changes in the chemical characteristics of these waters occur laterally along the eastern and western margins of the area, and gradational changes occur vertically with increasing depth. The ground waters of the upper zone, however, can be divided into two types:

1. The ground waters occurring in the uppermost 200–300 feet below the land surface are predominantly calcium and magnesium sulfate waters with total determined constituents averaging about 3,000

mg/l and a percent sodium of about 35. Except for local variations caused by differences in quality of the surface streams that provide recharge along the western margin of the area, the chemical character of the ground waters tapped by most shallow wells is relatively constant. An abrupt change, however, occurs along the eastern border of the area, where the water from the west side, characterized by high concentration of sulfate, merges into the calcium and sodium bicarbonate ground water of low dissolved solids typical of shallow water of the east side of the San Joaquin Valley.

2. The chemical character of the waters contained in the deposits from 200 to 300 feet below land surface down to the top of the Corcoran Clay Member is marked by considerable lateral variance. As compared to the overlying shallower waters, these waters have lower total determined constituents—on the order of 1,500 mg/l, and higher percent sodium—about 55.

West of the Fresno Slough the ground water of the upper zone in the micaceous sand just overlying the Corcoran Clay Member (excluding the area of brackish water shown in fig. 10) has average total determined constituents of about 850 mg/l, and the percent sodium is about 60. This micaceous sand stratum represents deposition by streams originating in the Sierra Nevada, and east of Fresno Slough it is presently receiving recharge water that is probably little different from that in which it was deposited. Water that runs off the relatively insoluble silicate rocks of the basement complex of the Sierra Nevada is predominantly calcium bicarbonate water generally containing less than 100 mg/l of dissolved solids.

In the Fresno Slough area along the axis of the San Joaquin Valley from Mendota southeast about 22 miles, flood-plain and lacustrine deposits that form most of the post-Corcoran section contain brackish water (fig. 10). Presumably, this mineralized water resulted from evaporation at land surface in a swampy environment. In this area, ground waters containing high sulfate and chloride concentrations are found in the basal and middle parts of the upper water-bearing zone (see fig. 15, generalized sections *B–B′*, *C–C′*). The total determined constituents in this ground water of poor quality average about 5,000 mg/l, and the percent sodium averages about 55. The ratio of sulfate to chloride is on the order of 2 to 1.

STREAM WATERS

The chemical character of the ground water in the upper water-bearing zone along the western margin of the Los Banos-Kettleman City area reflects the chemical character of the tributary streams. In general, the stream waters contain high concentrations of sulfate and sodium with dissolved solids ranging from less than 1,000 mg/l to as much as 9,000 mg/l (Davis, 1961, p. B16). Davis explained the wide variation in the chemical character of the surface water as due mainly to fluctuations in rainfall and local differences in the lithology of the rocks underlying the drainage basins.

Examples from the five largest streams of the area, Los Banos, Little Panoche, Panoche, Los Gatos, and Warthǎn Creeks (Davis, 1961, table 2) illustrate the extreme variability of the chemical composition and character. In Los Banos Creek, the dissolved-solids content ranged from 128 mg/l at a flow of 450 cfs (cubic feet per second) to 583 mg/l at a flow of 0.7 cfs. An intermediate cation composition characterized the water at both extremes; the anion composition, however, changed from predominantly bicarbonate at high flow to bicarbonate chloride at low flow. In Little Panoche Creek, the dissolved-solids content ranged from 422 mg/l at a flow of 30 cfs to 3,820 mg/l at 0.8 cfs. At the highest stage, the water was characterized by an intermediate cation distribution, and bicarbonate and chloride, among the anions. At all other stages the stream was a sodium chloride water.

In Panoche Creek, the dissolved-solids content ranged from 1,310 mg/l at a flow of 200 cfs to 5,250 mg/l at 1 cfs. At all stages, it was predominantly sulfate water of intermediate cation composition. In Los Gatos Creek, the dissolved-solids content ranged from 273 mg/l at a flow of 375 cfs to 1,530 mg/l at 0.7 cfs. The water changed from a magnesium bicarbonate water at high stage to a sodum bicarbonate sulfate water at low stage. In Warthan Creek, the dissolved-solids content ranged from 350 mg/l at a flow of 400 cfs to 3,280 mg/l at 0.5 cfs. The water changed in chemical character from sodium sulfate bicarbonate type at high flow to sodium magnesium sulfate at low flow.

As most of the ground-water recharge from west-side streams is contributed at high stage, the chemical character of the ground waters commonly more closely resembles that of the high flows than the low flows.

WATERS OF THE LOWER WATER-BEARING ZONE

Ground waters of the lower water-bearing zone (confined aquifer system) under native conditions were effectively separated from those of the upper water-bearing zone throughout most of the Los Banos-Kettleman City area by the Corcoran Clay Member of the Tulare Formation. Because about three-quarters of the water pumped from the project area has been taken from the lower zone, the head in that zone has been drawn down 150–500 feet, historically. The head in the lower part of the upper zone also has been drawn down substantially. Locally in the southern third of the area, the head in the basal aquifers of the upper zone has been drawn down as much as 30 feet below the head in the lower zone, but in the northern two-thirds of the area, the head in the upper zone is still 50–200 feet higher than that in the lower zone. Therefore, in most of the project area, most wells tapping the lower water-bearing zone admit water from the upper water-bearing zone either through perforations or casing leaks above the Corcoran or by movement from the upper zone outside the casing through gravel envelopes. For wells perforated only in the lower zone, however, downward movement of water from the upper zone is small, and this water is withdrawn after a few hours of continuous pump operation.

The data accompanying the chemical analyses of well waters collected in August 1951 (Davis and Poland, 1957, tables 2, 3) indicate that of 774 wells in the Los Banos-Kettleman City area sampled for chemical analysis, perforated interval was known for 447. Stratigraphic control largely developed since 1957 indicates that the casings of 108 of these wells (24 percent) were perforated only in the lower zone, or in its stratigraphic equivalent in the areas where the Corcoran Clay Member is absent. Based chiefly on the analyses from the 108 wells, the areal variation in chemical character of the ground water in the lower zone as of 1951 is summarized as follows (W. B. Bull, U.S. Geol. Survey, written commun., March 1968):

> The sum of determined constituents in the lower zone ranged from about 600 to 2,500 mg/l. The concentration was lowest, 600–800 mg/l, in a strip about 8 miles wide just west of Fresno Slough extending from 7 miles south of Mendota to the Kings River. To the west, the concentration ranged from 800 to 1,200 mg/l, except in two lobes of high concentration within 6–8 miles of the foothills—on Los Gatos Creek fan and opposite the Big Blue Hills south of Cantua Creek, where concentration is as much as 2,100 mg/l. In the 255-mile reach from the vicinity of Mendota to the Fresno–Merced County line, the concentration ranged from 1,000 mg/l near Firebaugh to 2,300 mg/l 4 miles east of the Panoche Hills and near the apex of Panoche Creek fan.
>
> The percent sodium ranged from 55 to 90 mg/l and averaged about 75 within the extent of the lower zone overlain by the Corcoran. The lower zone water is primarily a sodium sulfate water, with a notably higher bicarbonate content than the overlying upper zone waters.

Locally along the western margin of the area where the Corcoran Clay Member is absent, the chemical character of the ground water discharged by deep wells approaches that of the waters in the upper water-bearing zone. This fact suggests that there may be some recharge of the lower zone by surface and shallow ground waters with high concentration of dissolved solids passing directly downward through the alluvial-fan deposits, especially in the vicinity of the Los Gatos Creek alluvial fan (pl. 4, geologic section *E–E′*). The dissolved-solids content in the water from deep wells in this area ranges from 1,000 mg/l to as much as 2,100 mg/l, and the percent sodium is 50 or less.

In the southern and southeastern parts of the Los Banos–Kettleman City area, analyses of ground waters taken from wells near Westhaven 2,000–2,200 feet deep, show that, at a depth of 1,800–2,000 feet below the land surface, the chemical character of the water changes from sodium sulfate water above to sodium chloride water below. This deeper water, although definitely poorer for irrigation than the overlying water, is still usable for a blend and is considered a basal water in the lower water-bearing zone. The deeper wells in the vicinity of Westhaven produce a mixture of the normal lower zone sulfate water and the deep chloride water that averages about 900 mg/l in dissolved solids and 90 percent sodium. Carbon dioxide and hydrogen sulfide have also been reported from these deep wells, which partially penetrate the deltaic and lacustrine deposits in the lower part of the Tulare Formation.

Electric logs suggest that the water from the sands in the confined aquifer system that underlie the Tulare Formation in generalized sections *A–A′*, *C–C′*, and *E–E′* (figs. 13, 14) has a relatively low sodium chloride content. Any marine water originally present in these estuarine or littoral sand deposits must have been flushed out.

SALINE WATER BODY

A saline water body underlies the fresh ground-water reservoir throughout the Los Banos–Kettleman City area. Along the eastern margin of the area, northwest from about the town of San Joaquin, this saline water body is high in sodium chloride, and its top occurs at depths of 800–1,500 feet below the land surface. (See fig. 14 generalized section *B–B′*.) At one place 5 miles west of Mendota, the chloride content of this water has been computed to be about 7,700 mg/l (Davis and Poland, 1957, p. 462). The position of the top of this highly concentrated chloride water is only approximately known, because few wells tap it. The upper surface of the saline water body dips westward, and in some places this dip is very steep. (See figure 14, section *C–C′*, beneath Fresno Slough.) Wells drilled along the western margin of the valley to depths of as much as 3,000 feet do not reach the saline water. Electric-log correlations on geologic sections *C–C′* and *D–D′* (pl. 4) suggest that this saline water body may have crossed stratigraphic boundaries, implying an upward and westward migration since the last marine deposition in Miocene and Pliocene time.

During 1905–7 when Mendenhall and others (1916, pl. 1) made the first ground-water investigations in the

Los Banos–Kettleman City area, the general movement of the fresh ground water in the confined aquifer system was northeasterly from the Diablo Range foothills to the vicinity of Fresno Slough, and flowing artesian wells were common in the valley trough area. The large withdrawal of water from the aquifer system below the Corcoran Clay Member gradually reversed the hydraulic gradient, and by 1960 it was 20–25 feet per mile southwestward to within a few miles of the Diablo Range foothills.

In the central part of the Los Banos-Kettleman City area the altitude of the top of the saline water body east of Fresno Slough is at least 1,000 feet higher than it is a few miles west of the slough (fig. 14, section *C–C′*). It would seem likely that, in response to the reversed hydraulic gradient, the shallow saline water east of Fresno Slough would move westward and displace fresh water. However, water samples taken from scattered wells west of the saline water front in this area during the 10 years 1953–62 and at equivalent depths have shown no significant chemical changes. This is not surprising, however, because ground water moves very slowly through even the coarsest and most permeable deposits in this area under the hydraulic gradient developed. For example, the coefficient of permeability of the coarsest deposits in the confined aquifer system probably is on the order of 500–1,000 gallons per day per square foot. At a constant hydraulic gradient of 20 feet per mile, about 9–18 years would be required for water to move 1 mile. Thus, westward movement of the relatively shallow upper part of this saline water body into the Los Banos–Kettleman City area in the vicinity of the town of San Joaquin (section *C–C′*) probably has not exceeded 1–3 miles, even in the coarsest deposits.

The saline water body above the base of the Tulare Formation in the southeastern part of the Los Banos–Kettleman City area (fig. 14, generalized section *E–E′*) contains fresh-water fossils, and its present salinity is thought to be a secondary feature. Chloride analyses of core samples from core hole 19/19–17P show a range of chloride concentration in this zone of 2–60 grains per 1,000 cc of core sample.[5] Porosities in this zone are thought to average about 40 percent. This would indicate that the approximate chloride concentration of the water ranges from 320 mg/l to 9,700 mg/l. Core samples in the main saline water body below the base of the Tulare Formation to a depth of 3,735 feet below land surface show chloride concentrations that range from 2 to 106 grains per 1,000 cc of core sample. Assuming a 40 percent porosity for these samples also, the chloride content of this water would range from about 320 mg/l to 17,000 mg/l; the maximum would be comparable to modern sea water.

[5] Shell Oil Co., 1929, "Results of Core Drilling on the Boston Land Co. Property," unpublished report.

REFERENCES CITED

Anderson, F. M., 1905, A stratigraphic study in the Mount Diablo Range of California: California Acad. Sci. Proc., 3d ser., v. 2, p. 155–248.

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. Geol. Survey Bull. 603, 220 p.

Arnold, Ralph, 1909, Paleontology of the Coalinga district, Fresno and Kings Counties, California: U.S. Geol. Survey Bull. 396, 173 p., 30 pls.

Arnold, Ralph, and Anderson, R. E., 1908, Preliminary report on the Coalinga oil district, Fresno and Kings Counties, California: U.S. Geol. Survey Bull. 357, 142 p., 2 pls.

——— 1910, Geology and oil resources of the Coalinga district, California: U.S. geol. Survey Bull. 398, 354 p.

Axelrod, D. I., 1962, Post-Pliocene uplift of the Sierra Nevada, California: Geol. Soc. America Bull., v. 73, p. 183–198.

Axelrod, D. I., and Ting, W. S., 1960, Late Pliocene floras east of the Sierra Nevada, California: California Univ. Geol. Sci. Pub., v. 39, no. 1, p. 1–118.

——— 1961, Early Pleistocene floras from the Chagoopa surface, southern Sierra Nevada, California: California Univ. Geol. Sci. Pub., v. 39, no. 2, p. 119–194.

Barbat, W. F., and Galloway, John, 1934, San Joaquin Clay, California: Am. Assoc. Petroleum Geologists Bull., v. 18, No. 4, p. 478–499.

Bull, W. B., 1961, Causes and mechanics of near-surface subsidence in western Fresno County, California, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–B, p. B182–B189.

——— 1964, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geol. Survey Prof. Paper 437–A, 71 p.

Briggs, L. I., 1953, Geology of the Ortigalita Peak quadrangle, California: California Div. Mines Bull. 167, 61 p.

California Division of Mines, 1958, Geologic map of California, Santa Cruz sheet.

Carpenter, D. W., 1965, Pleistocene deformation in the vicinity of the Mile 18 pumping plant, *in* Northern Great Basin and California: Internat. Assoc. Quaternary Research Cong., 7th, USA, 1965, Guidebook for Field Conf. 1, p. 142–145.

Cole, R. C., and others, 1952, Soil survey of the Los Banos area, California: U.S. Dept. Agriculture, ser. 1939, no. 12, 119 p., soil map, 1:31,680.

Croft, M. G., 1968, Geology and radiocarbon ages of late Pleistocene Lacustrine clay deposits, southern part of San Joaquin Valley, California, *in* Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600–B, p. B151–B156.

Curtis, G. H., Evernden, J. F., and Lipson, J., 1958, Age determination of some granitic rocks in California by the Potassium-argon method: California Div. Mines Spec. Rept. 54, 16 p.

Davis, G. H., 1961, Geologic control of mineral composition of stream waters of the eastern slope of the southern Coast Ranges, California: U.S. Geol. Survey Water-Supply Paper 1535–B, 30 p.

Davis, G. H., Green, J. H., Olmstead, F. H., and Brown, D. W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, Calif.: U.S. Geol. Survey Water-Supply Paper 1468, 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, Calif.: U.S. Geol. 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. Geol. Survey Water-Supply Paper 1360–G, 180 p.

Diepenbrock, Alex, 1933, Mount Poso oilfield: Summary of operations, California Oil Fields, v. 19, no. 2, p. 12–29.

Frink, J. W., and Kues, H. A., 1954, Corcoran clay—A Pleistocene lacustrine deposit in San Joaquin Valley, California: Am. Assoc. Petroleum Geologists Bull., v. 38, no. 11, p. 2357–2371.

Goudkoff, P. P., 1934, Subsurface stratigraphy at Kettleman Hills oilfield, California: Am. Assoc. Petroleum Geologists Bull., v. 18, no. 4, p. 435–475.

Harradine, F. F., and others, 1952, Soil survey of the Coalinga area, California: U.S. Dept. Agriculture, ser. 1944, no. 1, 91 p., soil map, 1:63,360.

——— 1956, Soil survey of the Mendota area, California: U.S. Dept. Agriculture, ser. 1940, no. 18, 96 p., soil map, 1:63,360.

Holmes, Arthur, 1965, Principles of physical geology [2d ed.]: New York, Ronald Press, p. 360.

Hunter, G. W., 1951, Guijarral Hills oil field: Summary of operations, California Oil Fields, v. 37, no. 1, p. 13–19.

Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1955, Proposed program for investigating land subsidence in the San Joaquin Valley, California: Sacramento, Calif., 59 p., 9 pls.

——— 1958, Progress report on land-subsidence investigations in the San Joaquin Valley, California, through 1957: Sacramento, Calif., open-file report, 160 p., 45 figs. (prepared chiefly by U.S. Geol. Survey).

Ireland, R. L., 1963, Description of wells in the Los Banos-Kettleman City area, Merced, Fresno, and Kings Counties, Calif.: U.S. Geol. Survey open-file report, 519 p.

Janda, R. J., 1965, Quaternary alluvium near Friant, California, *in* Northern Great Basin and California: Internat. Assoc. Quaternary Research Cong., 7th, USA, 1965, Guidebook for Field Conf. 1, p. 128–133.

Jenkins, O. P., 1938, Geologic map of California: California Dept. Nat. Resources, Div. Mines.

Johnson, A. I., Moston, R. P., and Morris, D. A., 1968, Physical and hydrologic properties of water-bearing deposits in subsiding areas in central California: U.S. Geol. Survey Prof. Paper 497–A, 71 p.

Kaplow, E. J., 1942, East Coalinga extension oil field: Summary of operations, California Oil Fields, v. 28, no. 1, p. 15–29.

Kundert, C. J., 1955, Geologic map of California: California Dept. Nat. Resources, Div. Mines.

Kistler, R. W., Bateman, P. C., and Brannock, W. W., 1965, Isotopic ages of minerals from granitic rocks of the central Sierra Nevada and Inyo Mountains, California: Geol. Soc. America Bull., v. 76, p. 155–164.

Leith, C. J., 1949, Geology of the Quien Sabe quadrangle, California: Calif. Div. Mines Bull. 147, 59 p.

Lofgren, B. E., 1960, Near-surface land subsidence in western San Joaquin Valley, California: Jour. Geophys. Research, v. 65, p. 1053–1062.

——— 1961, Measurement of compaction of aquifer systems in areas of land subsidence, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–B, p. B49–B52.

Lohman, K. E., 1938, Pliocene diatoms from the Kettleman Hills, Calif.: U.S. Geol. Survey Prof. Paper 189–C, p. 81–102.

Matthes, F. E., 1930, Geologic history of the Yosemite Valley: U.S. Geol. Survey Prof. Paper 160, 137 p.

Meade, R. H., 1961a, X-ray diffractometer method for measuring preferred orientation in clays, *in Short* papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–B, p. B273–B276.

——— 1961b, Compaction of montmorillonite-rich sediments in western Fresno County, Calif., *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–D, p. D89–D91.

——— 1963, Factors influencing the pore volume of fine-grained sediments under low-to-moderate overburden loads: Sedimentology, v. 2, p. 235–242.

——— 1964, Removal of water and rearrangement of particles during the compaction of clayey sediments—Review: U.S. Geol. Survey Prof. Paper 497–B, 23 p.

——— 1967, Petrology of sediments underlying areas of land subsidence in central California: U.S. Geol. Survey Prof. Paper 497–C, 83 p.

——— 1968, Compaction of sediments underlying areas of land subsidence in central California: U.S. Geol. Survey Prof. Paper 497–D, 39 p.

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

Miller, R. E., 1961, Compaction of an aquifer system computed from consolidation tests and decline in artesian head, *in* Short Papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–B, p. B54–B58.

Payne, M. B., 1951, Type Moreno Formation and overlying Eocene strata on the west side of the San Joaquin Valley, Fresno and Merced Counties, California: California Div. Mines Spec. Rept. 9, 29 p., 5 pls., 11 figs.

Poland, J. F., 1959, Hydrology of the Long Beach-Santa Ana area, California, with special reference to the watertightness of the Newport-Inglewood structural zone: U.S. Geol. Survey Water-Supply Paper 1471, p. 32.

——— 1960, Land subsidence in the San Joaquin Valley, Calif., and its effect on estimates of ground-water resources: Internat. Assoc. Scientific Hydrologists, Comm. Subterranean Waters, Pub. 52, p. 324–335.

——— 1961, The coefficient of storage in a region of major subsidence caused by compaction of an aquifer ssytem, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–B, p. B52–B54.

Poland, J. F., and Davis, G. H., 1956, Subsidence of the land surface in the Tulare-Wasco (Delano) and Los Banos-Kettleman City area, San Joaquin Valley, California: Am. Geophys. Union Trans., v. 37, no. 3, p. 287–296.

Poland, J. F., and Evenson, R. E., 1966, Hydrogeology and land subsidence, Great Central Valley, Calif., *in* Bailey, E. H., ed., Geology of northern California: California Div. Mines and Geology, Bull. 190, p. 239–247.

Schoellhamer, J. E., and Kinney, D. M., 1953, Geology of a part of Tumey and Panoche Hills, Fresno County, California: U.S. Geol. Survey Oil and Gas Inv. Map OM 128.

Taliaferro, N. L., 1949, Geologic map of the Hollister quadrangle, California: California Dept. Nat. Res., Div. Mines Bull. 143, pl. 1.

Wahrhaftig, Clyde, and Birman, J. H., 1965. The Quaternary of the Pacific Mountain system in California, *in* Wright, H. E., Jr., and Frey, D. G., eds., The Quaternary of the United States, A Review Volume for the 7th Congress of the Internat. Assoc. for Quaternary Research: Princeton, N.J., Princeton Univ. Press, p. 299–340.

Watts, W. L., 1894, The gas and petroleum yielding formations of the central valley of California: California State Mining Bureau, Bull. 3, 100 p.

White, R. T., 1940, Eocene Yokut sandstone north of Coalinga, California: Am. Assoc. Petroleum Geologists Bull., v. 24, no. 10, p. 1722–1751.

Woodring, W. P., 1952, Pliocene-Pleistocene boundary in California Coast Ranges: Am. Jour. Sci., v. 250, no. 6, p. 401–410.

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

INDEX

[Italic page numbers indicate major references]

U. S. GOVERNMENT PRINTING OFFICE : 1971 O - 411-341