Land Subsidence Due to Ground-Water Withdrawal in the Los Banos-Kettleman City Area, California
Part 1. Changes in The Hydrologic Environment Conducive to Subsidence

GEOLOGICAL SURVEY PROFESSIONAL PAPER 437-E

Prepared in cooperation with the
California Department of Water Resources

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By WILLIAM B. BULL and RAYMOND E. MILLER

STUDIES OF LAND SUBSIDENCE

GEOLOGICAL SURVEY PROFESSIONAL PAPER 437-E

Prepared in cooperation with the California Department of Water Resources

A description of the ground-water reservoir and the great stress imposed on the aquifer system by man's mining of ground water

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STUDIES OF LAND SUBSIDENCE

LAND SUBSIDENCE DUE TO GROUND-WATER WITHDRAWAL IN THE LOS BANOS-KETTLEMAN CITY AREA, CALIFORNIA

PART 1. CHANGES IN THE HYDROLOGIC ENVIRONMENT CONDUCIVE TO SUBSIDENCE

By WILLIAM B. BULL and RAYMOND E. MILLER

ABSTRACT

About 500 to 2,000 feet of unconsolidated flood-plain, alluvial-fan, lacustrine, deltaic, and marine deposits are compacting at accelerated rates because of man's changes in the hydrologic environment in the west-central San Joaquin Valley. Ground-water pumping has increased the stresses tending to compact the deposits by as much as 50 percent.

Three basic hydrologic units comprise the ground-water reservoir between Los Banos and Kettleman City. An upper-zone aquifer system, 100–900 feet thick, extends from the land surface to the top of the second unit. It is a lacustrine confining clay. The upper zone consists mainly of poorly permeable alluvial-fan deposits derived from the Diablo Range that contain semiconfined water of poor quality. Little water is pumped from the fan deposits; however, water of good quality is pumped from an extensive wedge of arkosic, micaceous sands. These sands are flood-plain deposits derived from the Sierra Nevada that extend 4–10 miles west of the valley trough along the full reach of the area.

The lacustrine aquiclude, the Corcoran Clay Member of the Tulare Formation, extends beneath the entire study area except for the southwestern part adjacent to the Diablo Range.

The third hydrologic unit, the confined aquifer system of the lower zone, supplies about three-fourths of the ground water pumped and is the zone in which 50–95 percent of the compaction causing the subsidence occurs. The lower zone consists mainly of flood-plain deposits in the northern part, alluvial-fan deposits in the southern part, and diverse continental to marine deposits in the central part of the area.

The thickness of the fresh-water bearing deposits and the perforated interval of the deposits below the Corcoran rarely are the same. Some wells that have sufficient yields bottom 1,000 feet above the base of the fresh water. In other areas, 3,000-foot wells obtain a sufficient yield only by withdrawing part of their water from deep brackish-water-bearing marine deposits.

The sodium-sulfate water of the lower zone indicates that the connate water has been flushed out of the marine and Sierra sands. Maximum concentrations of dissolved solids in the well water occur opposite the mouths of the two major streams and in the area of pumping from the marine sand.

Initially the lower-zone potentiometric surface sloped gently from the bordering mountains to the valley trough where it was more than 20 feet above the land surface.

Agricultural development has resulted in more than a million acre-feet of water being pumped from the ground-water reservoir each year since 1951; has lowered the potentiometric surface as much as 600 feet; has reversed an eastward gradient in the study area of 2–5 feet per mile to a westward gradient of 30 feet per mile; and has caused water levels to decline below the base of the Corcoran adjacent to the Diablo Range.

The steep westward gradient of the lower-zone potentiometric surface has increased the recharge to the area. Pumpage stopped increasing in the early 1950's when most of the land had been developed. By the early 1960's, a rough balance between the amount of water being pumped from the lower zone and the amounts of water derived from compaction, recharge, and storage was obtained for most of the area. The potentiometric surface did not steepen further, and artesian-head decline ceased or decreased to rates of less than 5 feet per year in most of the area.

Applied stresses on the lower zone have been greatly increased by the large historic decline of artesian head but have not been affected appreciably by water-table changes. Water-table rises of as much as 100 feet and declines of as much as 350 feet locally have caused large changes in applied stress on the upper-zone deposits. Water-table rise or decline causes little net change in applied stress on the lower zone because concurrent seepage stress changes more than offset the effects of buoyancy change and the effects of change in the stress condition of part of the contained water that occur when the degree of saturation is changed.

Change to a water-table condition below the Corcoran decreases the future rate of increase in applied stress from 1.0–0.8 foot of water per additional foot of lower-zone water-level decline.

INTRODUCTION

By increasing the stress tending to compact the unconsolidated deposits by as much as 50 percent, man has created what is believed to be the world's largest area of intense land subsidence in the west-central part of the San Joaquin Valley. Withdrawal of ground water for agriculture has caused more than 2,000 square miles to subside more than 1 foot. As of 1966, the area that had subsided more than 10 feet was 70 miles long and extended 500 square miles. Maximum subsidence was 26 feet.

Water-level changes in the aquifer systems have increased the applied stresses on the deposits and have caused compaction of the aquifer systems. Detailed knowledge of the interrelations of water-level change, change in thickness of the aquifer system, and the concurrent changes in the altitude of the land surface is necessary for a more complete understanding of the mechanics of aquifer systems, compaction of sediments, and for the development of adequate criteria for the prediction of future land subsidence.

The hydrologic environment and the changes man has made in it to cause land subsidence—which are the main topics of this paper—will be presented for one of four major areas of intense land subsidence caused by ground-water withdrawal in California. The general location of the Los Banos–Kettleman City subsidence area, and its geographic relation to the three other subsidence areas is shown in figure 1.

The topographic and cultural features of the Los Banos–Kettleman City area and part of the area to the northeast of the study area of this paper are shown in figure 2. All the place names used in this paper also are shown in figure 2.

The boundaries of the Los Banos–Kettleman City study area and the lines of sections and profiles referred to in this paper are shown in figure 3. The boundary of deformed rocks at the edge of the Diablo Range foothills is the southwestern boundary of the study area, although small parts of the area of deformed rocks subsided 1–2 feet during the 1943–66 period. The southeastern boundary of the area is State Highway 41 on the northwest side of Tulare Lake bed between Kettleman City and Stratford. Small amounts of subsidence have occurred farther to the east between the Los Banos–Kettleman City and Tulare-Wasco subsidence areas (fig. 1). The northern boundary of the study area is State Highway 152 which passes through the town of Los Banos. The northeastern boundary, as originally defined (Inter-Agency Comm., 1958), for most aspects of this paper is the San Joaquin River, Fresno Slough, and the Kings River.

However, as much as 8 feet of subsidence has occurred east of the trough of the valley. Therefore, in discussions of the amount and extent of subsidence, the 1-foot subsidence line shown in figure 4 provides a better definition of the eastern boundary of the system being affected by appreciable compaction. Geologic and hydrologic aspects east of the valley trough will be discussed also.

The effects of land subsidence have become increasingly costly in the study area, which is traversed by several canals of large capacity and low gradient. One canal, the San Luis Canal, is part of the California Aqueduct, which is the major canal for transporting water from areas of abundant water in northern California to areas needing water in the San Joaquin Valley and southern California. The amounts, rates, and distribution of subsidence pose serious problems in the construction and maintenance of the canals and their extensive distribution systems. Subsidence also poses problems for local water-distribution, sewage disposal, and drainage systems. A major drain just west of the present trough of the valley will be built to remove drainage water of poor quality and to assist in maintaining a salt balance. Another major expense resulting from subsidence is the damage that occurs to well casings as the sediments adjacent to the wells compact to cause compressional casing failures.

INTER-AGENCY COMMITTEE ON LAND SUBSIDENCE

As a result of the problems posed by subsidence, the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley was formed in 1954 with J. F. Poland of the U.S. Geological Survey as its chairman. The purpose of the committee was to plan and coordinate a program that would provide information about the extent, magnitude, rates, and causes of the various types of land subsidence in the San Joaquin Valley (Inter-Agency Committee, 1958, p. 21). Other objectives of the program were to estimate future subsidence under assumed conditions and to suggest ways of alleviating subsidence. Representatives from the Geological Survey, U.S. Bureau of Reclamation, U.S. Coast and Geodetic Survey, (now National Geodetic Survey of the National Ocean Survey), U.S. Army Corps of Engineers. Soil Conservation Service, the California Department of Water Resources, California Division of Highways, University of California at Davis, and Stanford University composed this committee.

A proposed program of investigation was prepared by the Inter-Agency Committee (1955), and in 1958 a progress report on land-subsidence investigations in the San Joaquin Valley was published.

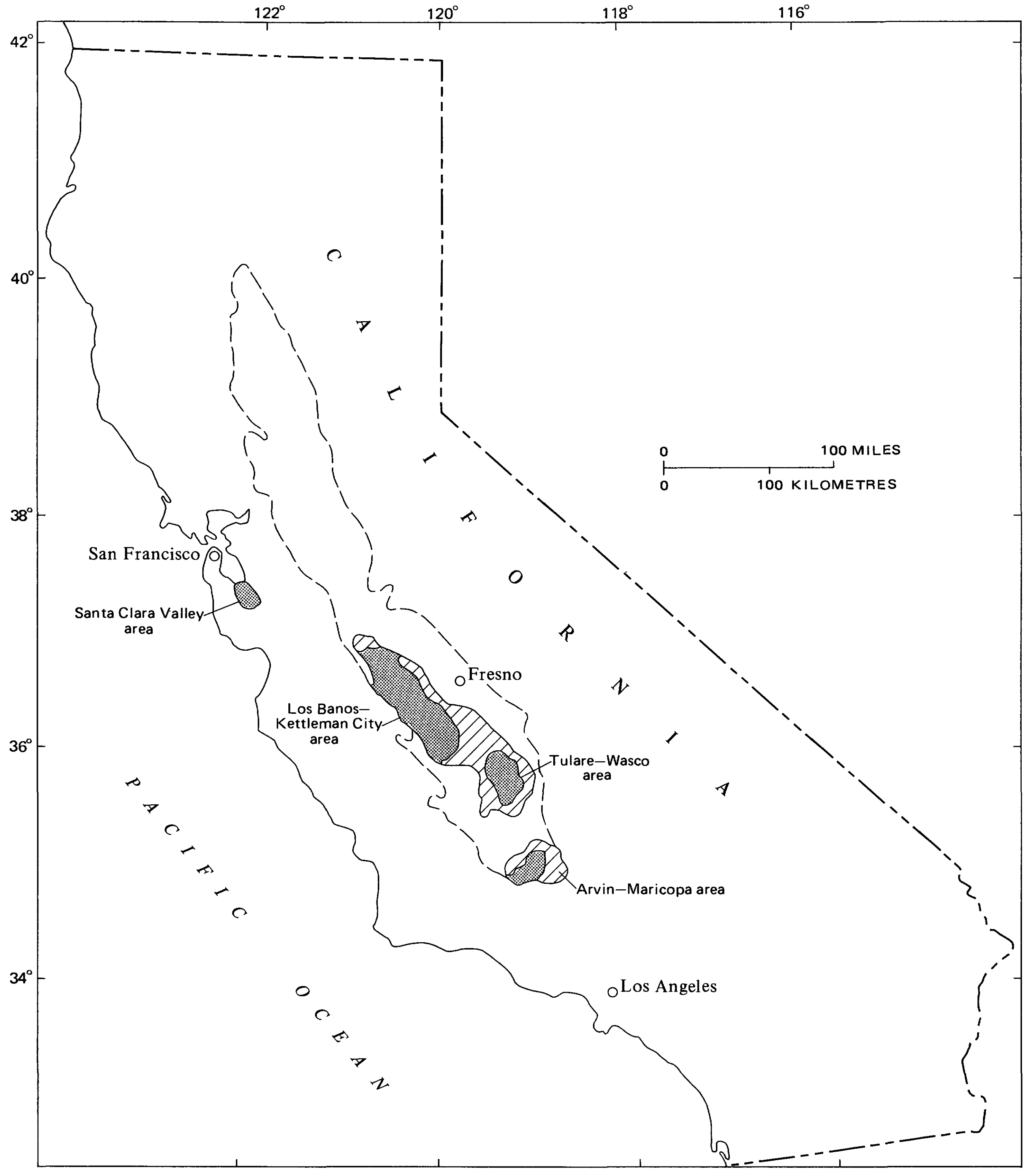
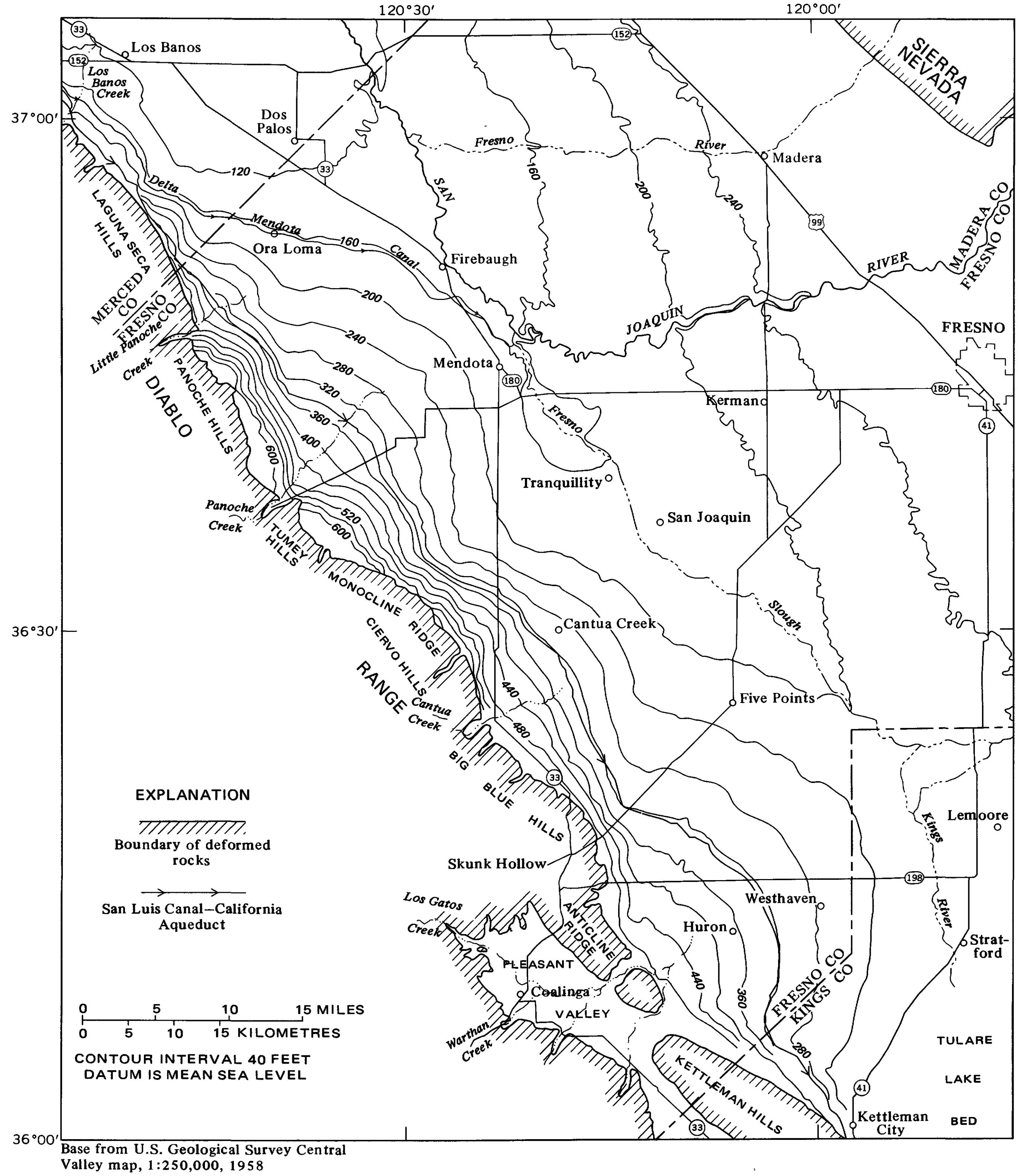
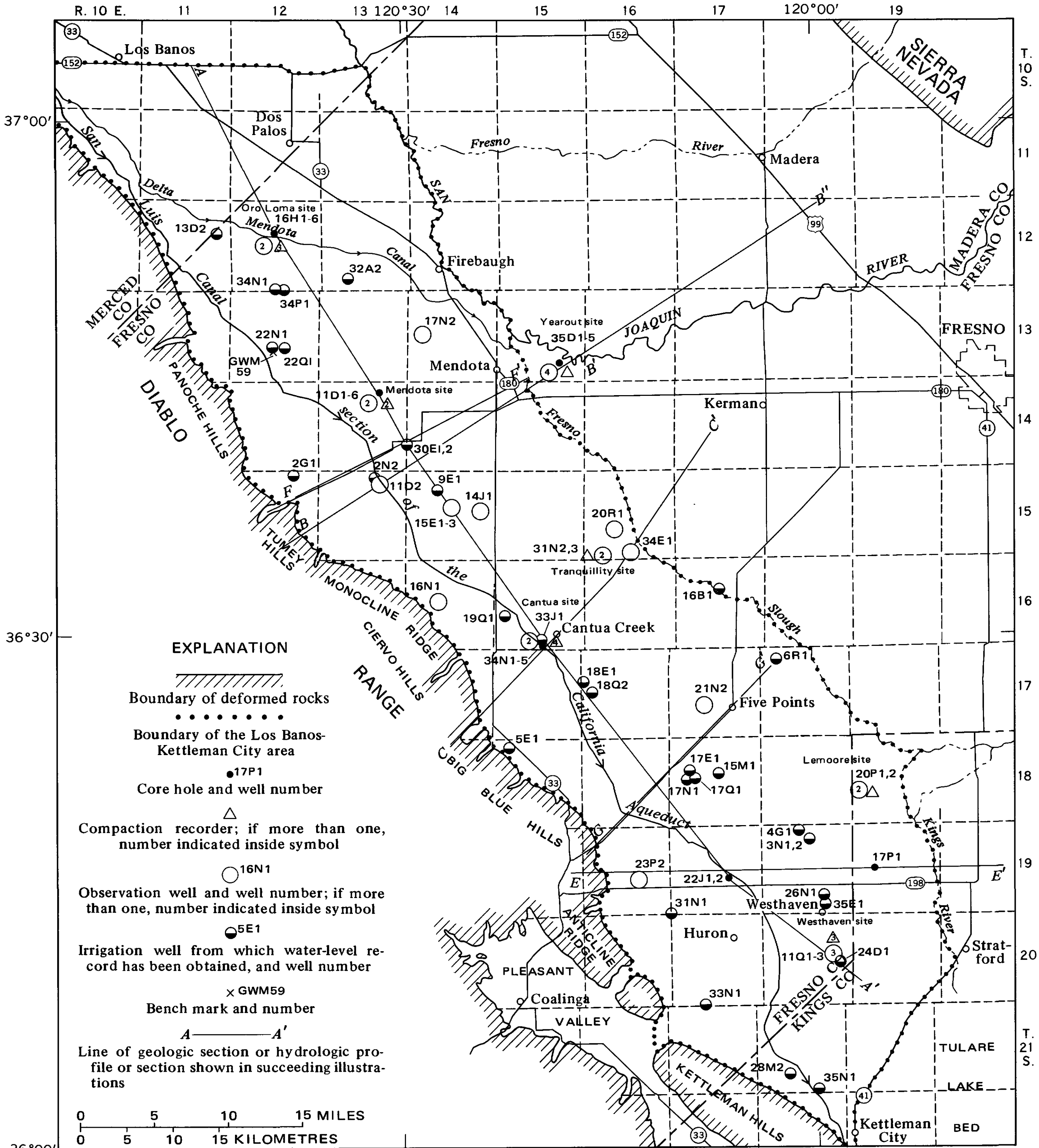


FIGURE 1.—Principal areas of land subsidence in California due to ground-water withdrawal. Outline of Central Valley dashed; areas of major subsidence shaded black; areas of lesser subsidence hachured.



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

FIGURE 2.—Topographic features of the Los Banos–Kettleman City area.



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

FIGURE 3.—The boundaries, bench marks, observation wells, compaction recorders, core holes, and lines of sections referred to in this report.

COOPERATIVE AND FEDERAL SUBSIDENCE PROGRAMS

One result of the inter-agency cooperation was the initiation in 1956 of an intensive study of land subsidence in the San Joaquin Valley, by the Geological Survey, in financial cooperation with the California Department of Water Resources. The objectives of the cooperative subsidence program, of which this report is one result, were to define the rate, magnitude, and extent of subsidence through a vertical-control measurement program; to determine the various causes of subsidence, and the depth intervals in which the compaction was occurring; to furnish criteria for the prediction of future subsidence; and to determine whether any part of the subsidence is reversible, and, if so, to what extent.

In 1956, the Geological Survey also began a federally financed investigation of the mechanics of aquifer systems: the fieldwork was concentrated chiefly in the San Joaquin and Santa Clara Valleys in California. It was recognized that those areas of active subsidence due to water-level change offered an unexcelled opportunity to study compaction of sediments in response to increase in effective stress. Objectives of the Federal program were to determine the principles controlling the change in aquifer-system thickness resulting from change in grain-to-grain load, and to appraise the meaning and utility of the storage coefficient in compactible aquifer systems. Within the Los Banos–Kettleman City area, both the change in stresses causing compaction of the saturated deposits and the change in thickness of the deposits can be measured at many sites.

SCOPE OF FIELD AND LABORATORY WORK

Many of the results of the cooperative and federally funded investigations are of mutual benefit, as is evident from the following brief description of types of facts gathered to assess compaction of saturated deposits due to changes in water levels.

Field Program

A vital supporting program for the subsidence investigations has been the periodic surveying of a network of bench marks by the Coast and Geodetic Survey to determine changes in altitude. Starting in 1955 and continuing until 1959, the network was surveyed every 2 years, and since 1959 the bench marks have been surveyed every 3 years.

A method (see section on "Compaction") was developed for the measurement of compaction within specified depth intervals. Both unused irrigation wells and specially drilled wells were used for this purpose.

The well-numbering system identifies wells according to their location in the township and range grid used for subdivision of public land. For example, well 14/13–11D6 designates the sixth well assigned a number in the NW¼ of the NW¼ of section 11, Township 14 South, Range 13 East. The letters that are used to indicate the 40-acre subdivision of the section are as follows.

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

Because all the wells within the study area are south and east of the Mount Diablo base and meridian, the foregoing abbreviation of the township and range is sufficient.

A well canvass was made in the study area west of the San Joaquin River and Fresno Slough. The descriptions of the 3,600 wells that were canvassed have been tabulated by Ireland (1963).

Periodic water-level measurements have been made at the times of the winter or spring recovery highs to determine the position of the potentiometric surface of the principal confined aquifer system in the study area. Water levels were measured each year during the 1950's and bench-mark surveys during the winters in the 1960's.

A problem peculiar to land-subsidence areas is that the altitude of the reference point changes with time for all water-level, electric log, core hole, and other data. Errors in data, such as altitudes of geologic or hydrologic horizons, could be partially corrected by establishing for each data site a history of reference-point altitude change. However, this procedure is not practical and would introduce additional problems. One problem would be how to prorate the depth to geologic horizons at different depths in a system in which the unit compaction varies with depth. Subsidence corrections would also lead to misinterpretation of data. For example, if the depth to the water table at a subsiding site did not change over a long time period, a hydrograph of the altitude of the water table, if corrected for subsidence during the period of record, would show an apparent decline in the water table and could be interpreted erroneously as a decrease in storage.

One possible procedure is to make an altitude adjustment for the measuring points of wells at the time of each releveling. However, this method results in displacement of the plot of water-level altitude at each time of adjustment.

The approach of the Geological Survey has been to use the land-surface altitudes established on topographic maps made in the 1920's as the reference altitudes for all measuring points. This approach introduces a gradually increasing error in all maps, sections, and hydrographs dependent on altitude that is equal to the amount of subsidence since the 1920's. The error is of little concern in areas of less than 10 feet of subsidence when one considers the general order of accuracy of altitude of a rapidly changing potentiometric surface or the altitude of the top of the confining clay. The problem can be circumvented; for example, indicate the change in the position of the water table by using change in depth instead of change in altitude.

Observation wells are measured by the Geological Survey throughout the study area to obtain information about the changes in the water table and the potentiometric levels in the confined aquifer systems above and below the principal confining bed. Some of the observation wells are unused irrigation wells, but many are wells that have been drilled by the Survey and other agencies to obtain a specific type of water-level information. At least one observation well is situated at each compaction-recorder site. The wells that are referred to in this paper are shown in figure 3.

Another major source of water-level information has been the records of the Pacific Gas and Electric Co. These records have provided long-term histories of water-level declines based on both static and pumping measurements. Many of the hydrographs used in this paper are based on these records. Measurements usually are made at least once a year. The time of measurement may be anywhere in the seasonal fluctuation range but most commonly is during the summer pumping season. The measurements selected for the hydrographs in this paper are those made at the times of low-water levels—the times of maximum applied stress on the aquifer system. Since 1964, the power-company measurements have been supplemented by measuring selected wells at the time of the summer low-water level in late August.

Regional geologic studies also were made of the Los Banos–Kettleman City area and the adjacent foothill belt to provide an appropriate framework for the studies of compaction and land subsidence. The classification and correlation of the subsurface geologic and hydrologic units tapped by wells and the mapping of the continental deposits exposed in the foothills adjacent to the study area are described in detail in a report by Miller, Green, and Davis (1971). In addition to establishing the areal extent of the various components of the aquifer systems, the regional geologic studies provided valuable basic information about the lithology, source, and mode of deposition of the deposits.

In order to provide additional information about the petrology, and mode and source of deposition of the sediments, four core holes were drilled along the axis of the subsidence trough at the Oro Loma, Mendota, Cantua, and Huron sites by the Inter-Agency Committee. These multiple-purpose holes were also used to obtain electric logs and caliper logs.

Laboratory Program

A laboratory program that was part of the Federally financed investigation was conducted at the Geological Survey's hydrologic laboratory on cored samples to provide information about the physical, hydrologic, and engineering properties of the sediments that are compacting in this and the three other subsidence areas shown in figure 1. Some of the test results most applicable to the studies of land subsidence are particle-size analyses, specific gravity and unit weight, porosity and void ratio, consolidation and rebound, and permeability. The results are reported by Johnson, Moston, and Morris (1968).

The core samples also provided abundant samples for laboratory petrographic examination. The general petrology of the deposits and the details of the clay mineralogy are discussed by Meade (1967). In a major contribution, Meade (1968) relates the variations in overburden load and petrologic factors to the variations in pore volume and fabric of the sediments of several subsidence areas in central California.

PURPOSES OF REPORT

This report is part 1 of a series of three reports concerned with land subsidence due to ground-water withdrawal in the Los Banos–Kettleman City area. It describes the subsurface hydrologic environment in 2,000 square miles of the west-central San Joaquin Valley. Within this scope, the report has two specific purposes. The first is to describe the extent, thickness, and hydraulic character of the deposits comprising the two principal aquifer systems and the confining clay that separates them. The second purpose is to assess the changes caused by man in the hydrologic environment that have been responsible for the increase in applied stress, the compaction of the ground-water reservoir, and the concurrent subsidence.

The bulk of the information presented in this paper concerns events that occurred before April 1966 which was the time of completion of a complete leveling of the bench-mark network by the Coast and Geodetic Survey. Some 1966–68 data are presented and discussed, but only to present facts that cannot be demonstrated with the earlier data.

The authorship of this report is as follows. Mr. Miller prepared most of the section, "Description of the Ground-Water Reservoir." Mr. Bull is responsible for the rest of the paper. Mr. Miller's detailed and careful study of the geologic and hydrologic framework of the study area (Miller and others, 1971) has been very helpful in the preparation of all subsequent reports on the Los Banos–Kettleman City area.

Two other papers on the Los Banos–Kettleman City area were prepared by W. B. Bull as companion reports to this paper. Part 2 (Bull, 1974) "Subsidence and Compaction of Deposits") describes the subsidence due to artesian-head decline, and compaction of the ground-water reservoir; the paper also discusses the geologic factors influencing compaction of the saturated deposits. Part 3 (Bull and Poland, 1974, "Interrelations of Water-Level Change, Change in Aquifer-System Thickness, and Subsidence") uses the data and interpretation in Parts 1 and 2 as a basis for discussing some of the principles of mechanics of aquifer systems.

ACKNOWLEDGMENTS

The cooperation of numerous ranchers, landowners, and companies is acknowledged for supplying essential information to the subsidence project and for giving permission to install and maintain wells and equipment for obtaining water-level and compaction information. Particular assistance was given by the Pacific Gas and Electric Co., Westlands Water District, and Russell Giffen, Inc.

The financial cooperation of the California Department of Water Resources made this study possible, and information provided by the U.S. Bureau of Reclamation from core holes and observation wells contributed significantly to the essential data.

This work could not have been completed without the discussions, interest, and assistance of many people who have been associated with the land-subsidence studies of the Geological Survey since 1956. We appreciate the helpful discussions and review of the manuscript by the Project Chief, J. F. Poland, and our colleagues G. H. Davis, B. E. Lofgren, S. W. Lohman, and F. S. Riley. We enjoyed working together with R. L. Ireland and R. G. Pugh on a variety of jobs in the field and appreciate their extensive help in the collecting and assembling of field data. Particular credit is due Mr. Ireland for his meticulous care and thoughtful foresight in the installation and operation of the equipment for recording compaction and water-level changes during the entire period of record.

DEFINITIONS

The geologic and engineering literature contains a variety of terms that have been used to describe the processes and environmental conditions involved in the mechanics of stressed aquifer systems and of land subsidence due to withdrawal of subsurface fluids. The usage of certain of these terms in reports by the U.S. Geological Survey research staff investigating mechanics of aquifer systems and land subsidence is defined and explained in a glossary published separately (Poland and others, 1972). Several terms that have developed as a result of the Survey's investigations are also defined in that glossary.

The aquifer systems that have compacted sufficiently to produce significant subsidence in California and elsewhere are composed of unconsolidated to semiconsolidated clastic sediments. The definitions given in the published glossary are directed toward these types of sediments; they do not attempt to span the full range of rock types that contain and yield ground water. In defining the components of the compacting stresses, the contribution of membrane effects due to salinity or electrical gradients has been discounted as relatively insignificant in the areas studied.

In this series of research reports, pressures or stresses causing compaction are usually expressed in equivalent "feet of water head" [1 foot of water =0.433 psi (pounds per square inch)].

A committee on redefinition of ground-water terms, composed of members of the Geological Survey, recently issued a report entitled "Definitions of Selected Ground-Water Terms" (Lohman and others, 1972). The reader is referred to that report for definitions of many ground-water terms.

GEOGRAPHIC SETTING

The area included in this paper includes about 2,000 square miles of the west side of the San Joaquin Valley adjacent to the Diablo Range in central California (figs. 2, 3). Most of the discussions will concern sites in the 1,500 square miles west of Fresno Slough, and the San Joaquin River between the towns of Los Banos and Kettleman City. However, the subsidence bowl extends far to the east of the trough of the valley (fig. 4). Between the trough of the valley and the Diablo Range to the southwest is a belt of coalescing alluvial fans 12–22 miles wide. The altitude at the base of this bajada ranges from 150 to 200 feet, from which the alluvial fans rise to altitudes of about 500–900 feet at their apexes. The slopes range from about 5 feet per mile near the base of the larger fans to about 150 feet per mile on the upper slopes of some of the small fans. Local relief generally is less than 5 feet, except where stream channels are incised 10–40 feet.

The Diablo Range to the southwest of the study area consists of several groups of foothills bordering the San Joaquin Valley and the main range, which rises to altitudes of more than 5,000 feet about 10–15 miles from the valley. The core of the anticlinal part of the main range consists of deformed and slightly metamorphosed shale and graywacke of the Franciscan Formation of Jurassic to Late Cretaceous age and of ultrabasic rocks. The east flank of the range consists mainly of 20,000 feet of Cretaceous marine mudstone and sandstone. The foothill belt is underlain by anticlinally and monoclinally folded Cretaceous marine rocks, by easily eroded Tertiary marine rocks, and by Pliocene and Quaternary unconsolidated sediments.

LAND SUBSIDENCE

Changes in bench-mark altitudes in the Los Banos–Kettleman City area during the past five decades have been affected by tectonic movements, pumping of petroleum, and compaction due to wetting of moisture-deficient alluvial-fan deposits, but mainly have been caused by compaction of saturated deposits as a result of water-level change.

The compaction due to wetting causes near-surface subsidence, which is superimposed on the compaction of the saturated deposits. About 130 square miles (fig. 4) have subsided; 3–10 feet of near-surface subsidence is common, and 10–15 feet of compaction due to wetting has occurred locally. Near-surface subsidence results chiefly from the compaction of deposits by an overburden load as the clay bond supporting the voids is weakened by water percolating through the deposits for the first time since burial. The amount of compaction due to wetting is dependent mainly on the overburden load, natural moisture conditions, and the type and amount of clay. Reports about near-surface subsidence within the study area include those by Lofgren (1960), and Bull (1964, 1972). Both the magnitude and extent of the subsidence due to artesian-head decline are larger than for the near-surface subsidence. Figure 4 shows the subsidence in the Los Banos–Kettleman City area between the time of the first topographic mapping in the early 1920's, and the 1966 bench-mark leveling. The subsidence pattern is an elongate oval that is 90 miles long and 24 miles wide. As of 1966, more than 2,000 square miles had subsided more than 1 foot, and the area that had subsided more than 10 feet was 70 miles long and 7 miles wide. A maximum subsidence of about 26 feet had occurred 10 miles southwest of Mendota.

The histories of subsidence rates show that the rate of subsidence increased until about the mid-1950's, but since then the rate of subsidence has decreased, but not so rapidly as the decrease in the rate of artesian-head decline. During the 1959–63 period, 480 square miles was subsiding more than 0.5 foot per year, and 63 square miles was subsiding more than 1.0 foot per year.

An example of the change in land-surface altitude caused by artesian-head decline is shown in figure 5. Subsidence rates in the vicinity of bench mark GWM59 increased between 1940 and 1955 but since 1955 have undergone a continuing decrease in rate. The plot of artesian-head decline reveals a parallel history of accelerating and then decelerating rate of head decline. Since 1960 the summer low-water levels have shown little decline, but subsidence has continued at a moderately rapid rate. Much of the subsidence since 1960 is interpreted as being the result of delayed compaction resulting from continued expulsion of water from fine-grained beds of low permeability years after pore-pressure decline had occurred in the aquifers adjacent to the aquicludes and aquitards (Bull and Poland, 1974).

COMPACTION

Special recorders operating in wells have been measuring most of the decrease in thickness of the aquifer system that has been responsible for the land subsidence. A diagrammatic sketch of one of the compaction recorders is shown in figure 6. At well 19/16–23P2, the recorder is actually measuring casing shortening that results from the compaction of the adjacent deposits. At other sites the anchor weight is set below the bottom of the casing, thereby allowing the compaction to be measured independently of the casing. For the recorder system shown in figure 6, a 300-pound anchor was set on the cement plug with a cable that was passed over sheaves at land surface, counterweighted, and linked to a recorder by a fine wire attached to the cable. The ⅛-inch, 1 × 19 stranded, reverse-lay, uncoated stainless-steel cable resists corrosion, has low stretch and casing-cable friction characteristics, and has little tendency to untwist. Friction has been reduced at the land surface by mounting ball-bearing sheaves in a teeter bar that can pivot about a fulcrum for short distances. The fine wire is passed over the drive sheave of a recorder, which records changes in the position of the cable clamp (fig. 6) relative to the concrete slab at a 1:1 scale. A 24:1 expanded-scale record is obtained by a second recorder (not shown in fig. 6) linked to the first by gears. A float-operated water-level recorder (not shown in fig. 6) is set on the table below the compaction recorders. The tension in the compaction cable is uniform only above the uppermost point of contact between the casing and the cable. In wells that have casing-cable friction, tension is less below the uppermost friction point than above it during compaction and is more during the periods of aquifer-system expansion. Thus, casing-cable contact not only introduces friction into the recorder system, but it also introduces a mechanical lag at those times when the direction of movement of the cable, relative to the casing, is reversed. The mechanics of the compaction-recorder systems and the locations of the compaction recorders and observation wells operated by the Geological Survey in the study area are described in Bull (1974).

The proportion of the subsidence that is being measured has decreased at some compaction-recorder sites. For example, at the Cantua site, the 2,000-foot compaction recorder measured 99 percent of the compaction

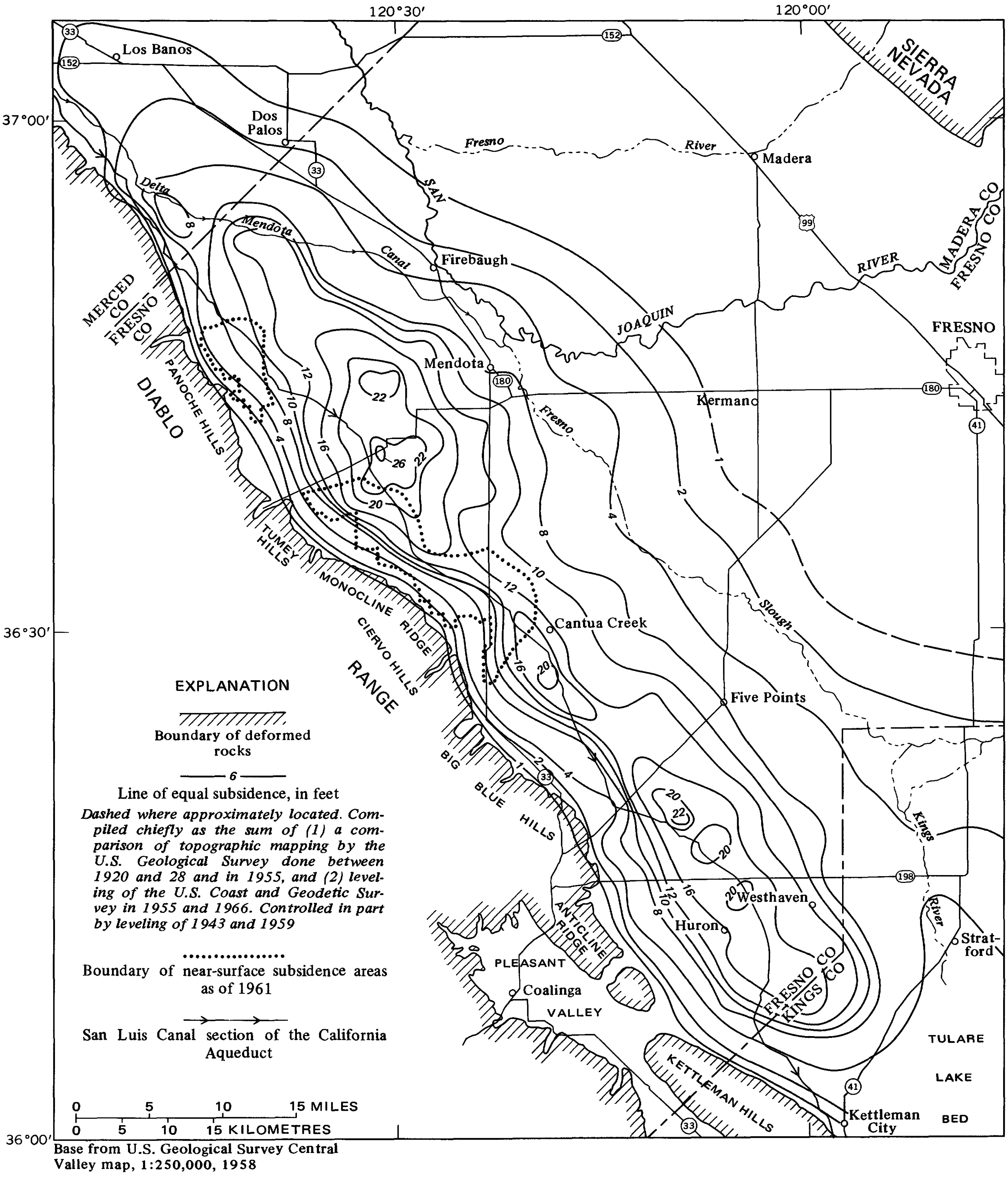


FIGURE 4.—Land subsidence, 1920–28 to 1966.

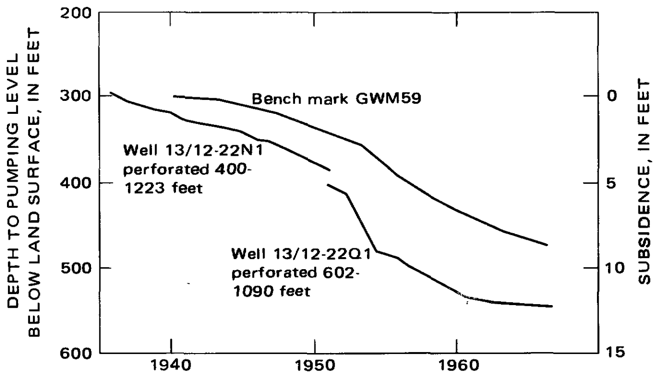


FIGURE 5.—Subsidence and artesian-head decline near bench mark GWM59.

causing subsidence between 1959 and 1963 and 88 percent between 1963 and 1966; it measured 79 percent of the subsidence that occurred between March 1966 and November 1967. The change in the percentage of subsidence measured suggests that pore-pressure decline and compaction are occurring at progressively greater depths below the anchor weight.

The compaction rates are seasonal, they are most rapid during the late winter and the summer when water levels are drawn down.

The use of multiple compaction recorders at a site permits a determination of the unit compaction occurring at specific depth intervals. The annual unit compaction has varied from zero for the 350–500 foot depth interval at the Oro Loma site to 0.00115 foot per foot per year in the 503–703 depth interval at the Cantua site.

Casing-failure studies (W. E. Wilson, written commun., April 1968) indicate that little compaction is occurring in the upper 300 feet of deposits; that maximum unit compaction is occurring between 100 feet above the Corcoran and 400 feet below the Corcoran; and that only moderate amounts of unit compaction occur below a depth of 400 feet below the Corcoran.

Many geologic factors influence the amounts and rates of compaction (see Part 2). The following geologic conditions promote large amounts of rapid compaction: a confined aquifer system that is undergoing large declines in head; a minimum overburden load that has compacted the deposits in the geologic past; many thin beds of montmorillonite clay with absorbed sodium interbedded with permeable, highly micaceous sands that have a large lateral extent. Meade (1968, p. 28) also points out that the presence of diatoms increases the compressibility of the deposits.

STRESSES TENDING TO CAUSE COMPACTION

The stress tending to cause compaction of all deposits is the grain-to-grain load that is transmitted to a given

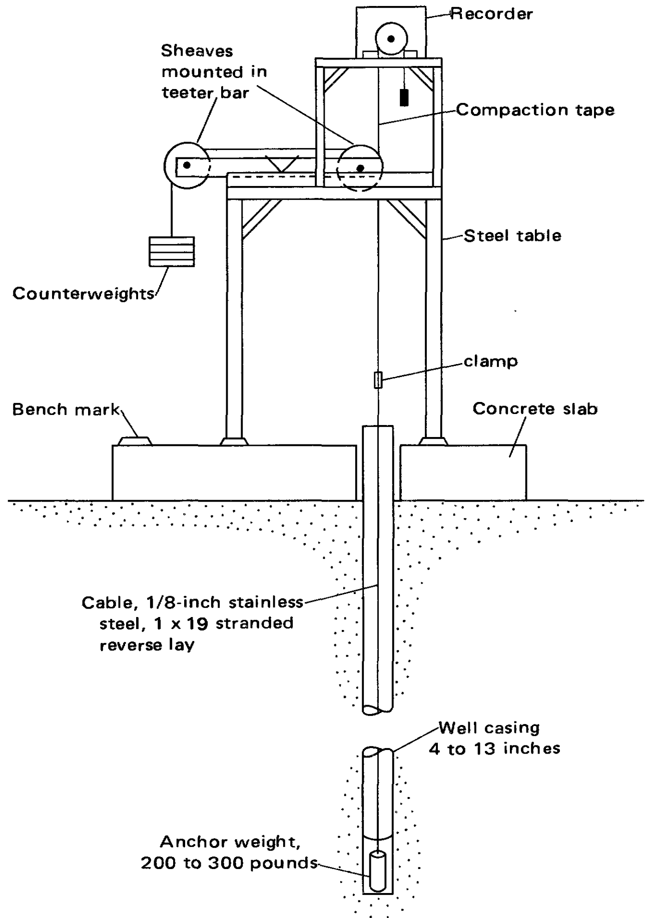


FIGURE 6.—Diagram of compaction-recorder installation.

bed as the result of the sum of all stress-producing factors in the overlying stratigraphic section. In the Los Banos–Kettleman City area and elsewhere, stress changes caused by man's changes of the hydrologic environment are superimposed on the natural stresses tending to compact the deposits. The ratio of manmade to natural applied stress varies considerably with geographic area and depth, but it can be large. For example, the natural applied stress at the 600-foot depth at the Cantua recorder site was increased from about 330 to about 500 psi as the result of about 400 feet of artesian-head decline. About a 52 percent increase in applied stress has occurred as a result of man's change in the hydrologic environment at the 600-foot depth level. However, at the 200-foot depth, no change in applied stress has occurred. The 200-foot depth is about 10 feet below the water table which has not changed position appreciably at the site during the past 60 years.

Water-level changes in both the confined and unconfined parts of the aquifer systems have altered the preexisting distribution of stresses. Changes in applied stress that result from changes in the hydrologic environment are concurrent with the water-level changes. Applied stresses become effective stresses only as rapidly as water can be expelled from a bed of a given lithology.

A stress that does not tend to cause compaction is a neutral or hydrostatic stress. This stress, which is the weight of the interstitial water, is transmitted downward through the water between the grains. The hydrostatic stress is considered neutral because, although it tends to compress each grain, it does not tend to change the grain-to-grain relationships significantly.

The basic theory regarding the stresses produced by water-level change within an aquifer system has been discussed in detail by Lofgren (1968) and by Poland and Davis (1969). The computation of change in applied stress in the Los Banos–Kettleman City area studies is different with respect to item 4 in the following paragraph than the mode of computation used by Lofgren. For a complete discussion of the analysis of stress changes resulting from water-level change within the study area, the reader is referred to Part 3 (Bull and Poland, 1974). The following summary is included here in order to provide the reader with a brief background regarding the four components of change in applied stress and to demonstrate the need for detailed information about changes in water level in subsidence areas.

Changes in water level resulting from pumping of ground water and irrigation have changed the applied stress tending to compress the deposits in several different ways. Change in total stress applied to a confined zone is the algebraic sum of the following stresses:

1. A seepage stress that is equal to the head differential caused by change in artesian head within the confined zone.
2. A seepage stress that is equal to the head differential caused by change in the position of the water table.
3. A stress caused by change in buoyancy of the deposits within the depth interval that is being dewatered, or saturated, as a result of water-table change.
4. A stress caused by part of the pore water being changed from a condition of neutral stress to applied stress, or vice versa, that occurs within the depth interval being affected by water-table change.

The magnitudes of the various stress components on the confined zone, expressed in feet of water (1 foot of water = 0.43 psi), are as follows: an assumed porosity of 0.4, a specific gravity of 2.70, and an average moisture content of the dewatered deposits of 0.2 the volume. Seepage stresses resulting from either artesian-head change or change in water-table position cause 1 foot of change in applied stress per foot of change in head differential. Buoyant changes cause 0.6 foot of change in applied stress per foot of water-table change. Change in the stress condition of part of the pore water causes 0.2 foot of change in applied stress per foot of water-table change. The effects of changes in buoyant support and in the stress condition of the pore water tend to cancel the effect of change in seepage stress caused by water-table change. The net effect of water-table change on the applied stress on the confined zone is an increase of 0.2 foot of water per foot of water-table rise and a decrease of 0.2 foot of water per foot of water-table decline.

DESCRIPTION OF THE GROUND-WATER RESERVOIR

GENERAL FEATURES

The 500 to more than 3,000 feet of poorly to moderately consolidated sediments that form the ground-water reservoir in the Los Banos–Kettleman City area was deposited in the San Joaquin Valley geosynclinal trough since late Pliocene time. As shown in figure 7, these sediments consist primarily of flood-plain, alluvial-fan, and lacustrine deposits. Some deeply buried deltaic sediments occur in the southern part of the area. Most of these deposits are part of the Tulare Formation, which is overlain by additional alluvium and underlain by Pliocene littoral and estuarine deposits of the San Joaquin and Etchegoin Formations. The Pleistocene deposits accumulated rapidly as a result of uplift and erosion in the Diablo Range and uplift and glacial scouring in the Sierra Nevada. The rapid rate of deposition is one reason for the poorly consolidated nature of most of the deposits.

The subsurface geology of the fresh-water-bearing deposits is complex when the deposits are differentiated with respect to source, environment of deposition, and lithology. The subsurface geology is described by Miller, Green, and Davis (1971).

Fortunately, the hydrologic units are not so complex as the geologic units. As pointed out by Davis and Poland (1957, p. 421), a general threefold hydrologic subdivision of the continental 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 of the Tulare Formation at a depth ranging from less than 100 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 pressures and chemical qualities; and a lower unit, 400 to more than 2,000 feet thick that extends down to the main saline water body. The two fresh-water-bearing units are referred to as the upper zone and lower zones, and the lacustrine clay that separates the two zones is commonly referred to as the Corcoran.

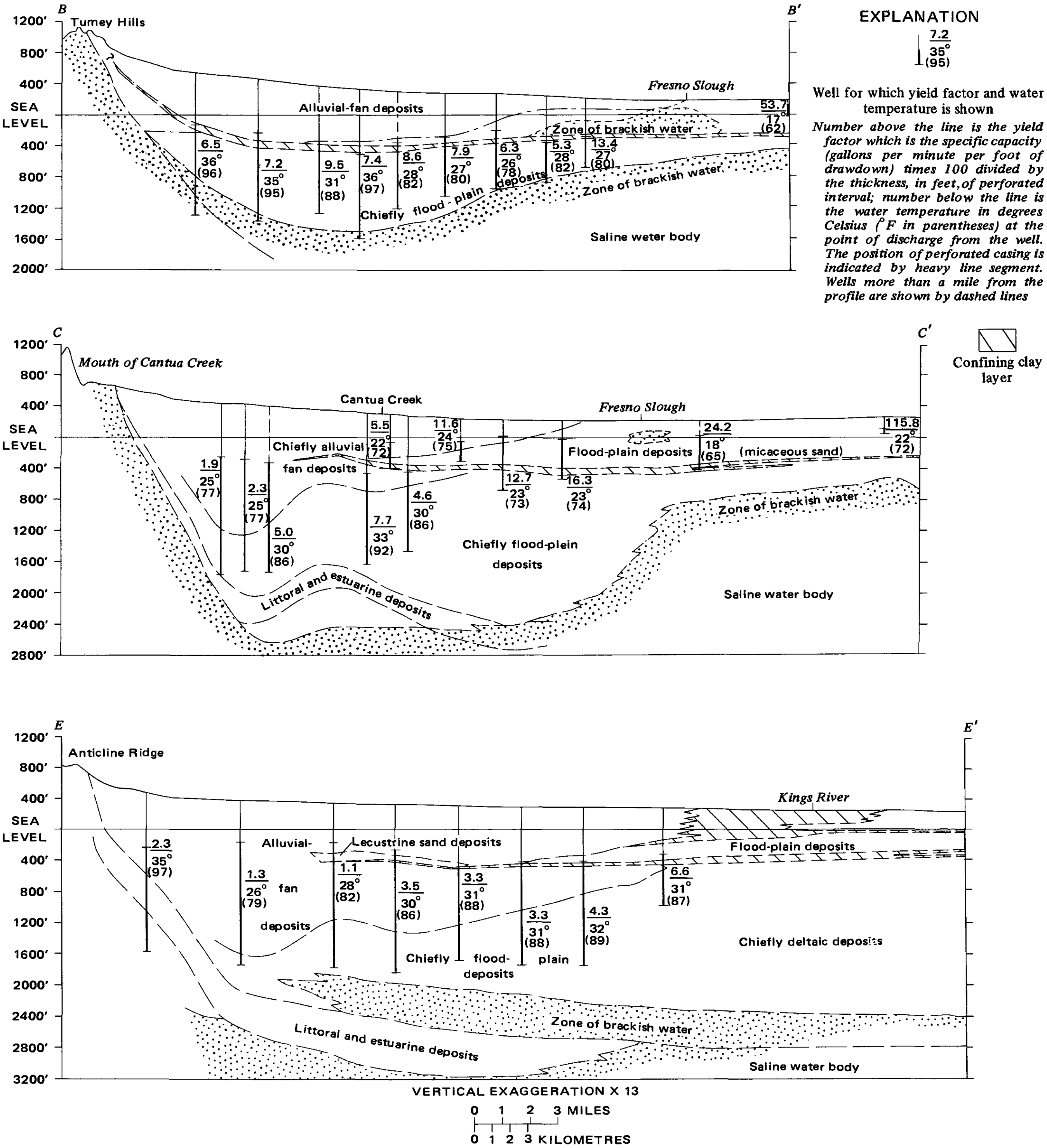


FIGURE 7.—Cross sections showing well-yield factors and depositional environments of the aquifer systems. Lines of sections shown in figure 3. (From Miller and others, 1971, fig. 15.)

The three hydrologic units are shown in figures 8 and 9, and the location of the sections is shown in figure 3. The detailed geologic sections on which these sections are based have been presented by Miller in another report (Miller and others, 1971).

Most of the ground water pumped in the Los Banos–Kettleman City area is withdrawn from the lower zone. An accurate estimate of the proportion of water

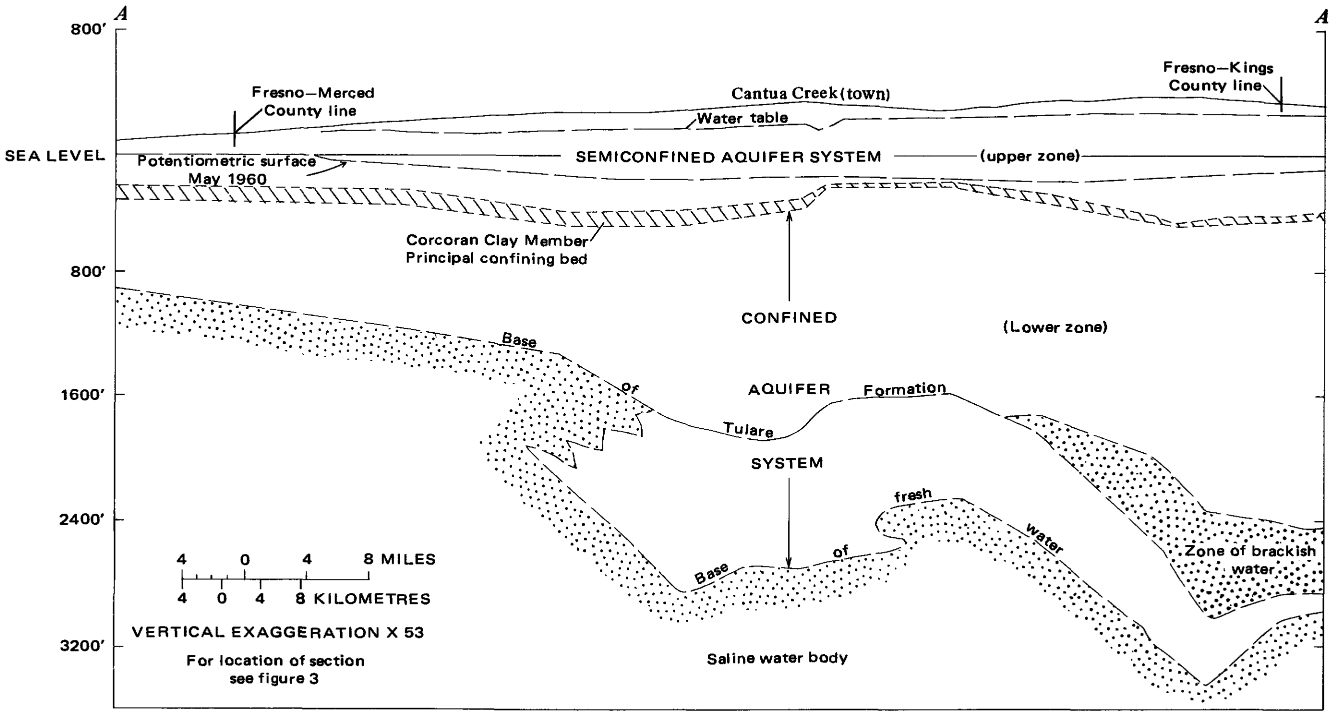


FIGURE 8.—Longitudinal section showing general hydrologic units. (Modified from Miller and others, 1971, fig. 13.)

pumped from the upper zone cannot be made with the data available because many wells tap both zones and because water moves between the zones through well casings and gravel envelopes around the casings. However, study of the spacing and number of wells, perforated intervals, and relative aquifer-system productivities suggests that at least 75 percent and possibly 80 percent of the overall pumpage is from the lower zone.

The general variation in the amount of water pumped from the lower zone or its stratigraphic equivalent is shown in figure 10. The proportion of lower-zone water pumped increases from east to west. The western margin of the 50–75 percent area coincides with the western margin of the highly permeable, upper-zone sands derived from the Sierra Nevada (fig. 11). The amounts of upper-zone water pumped increase to the east of the western margin of these sands because the thickness of the Sierran micaceous sands increases towards the east. Southeast of Mendota, brackish water unfit for agriculture occurs in the upper zone (figs. 7, 9, 10, 11), and virtually all the water pumped within this local area is from the lower zone.

The areas of less than 50 percent pumpage from the lower zone are large, but much of the agricultural water supply for these areas is derived from imported surface waters. Surface-water imports reduce the amount of ground water pumped, thereby reducing the water-table or head decline when compared with areas totally dependent on ground water for agriculture.

UPPER ZONE

The upper zone has a water table, and locally the water is unconfined. In general, however, ground water in this zone is semiconfined to confined. Under conditions of pumping draft, head differentials of 100–400 feet have developed between the water table and the water levels in wells tapping the base of the upper zone immediately above the Corcoran. For example, see figure 28. Hence, confinement is known to be substantial in some parts of the area, but in places where the deposits are coarse grained and have a large vertical permeability, differences in head are not great. In the northern and central parts of the study area the upper zone consists of many semiconfined aquifers and aquitards. In the southeastern part of the area, most of the upper zone is as well confined as the lower zone because of extensive lake clays that occur at various depths. In the southwestern part of the area, lake clays (including the Corcoran) are absent, and where the deposits are sufficiently coarse grained, unconfined condi-

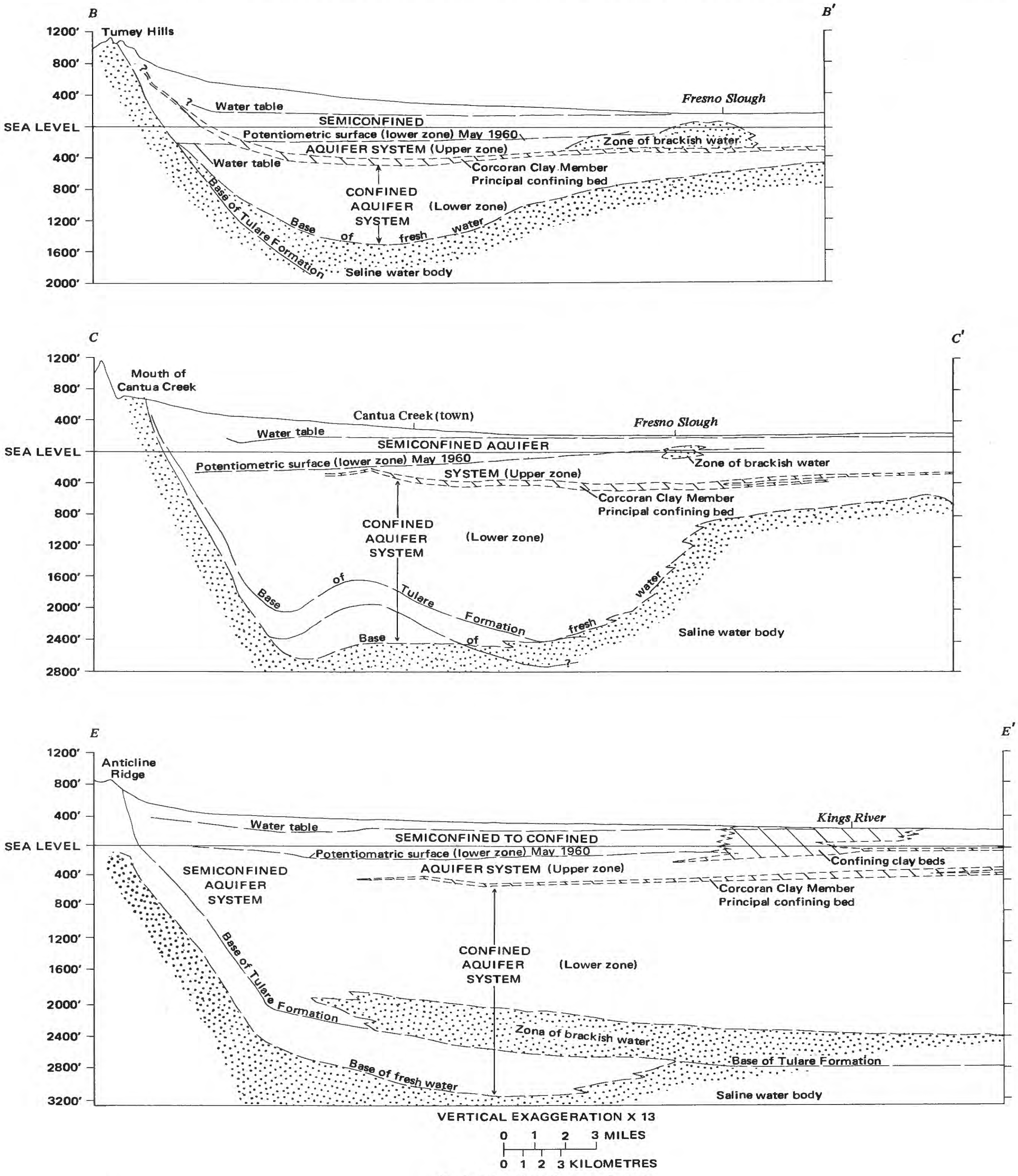


FIGURE 9.—Cross sections showing general hydrologic units. Lines of sections shown in figure 3. (Modified from Miller and others, 1971, fig. 14.)

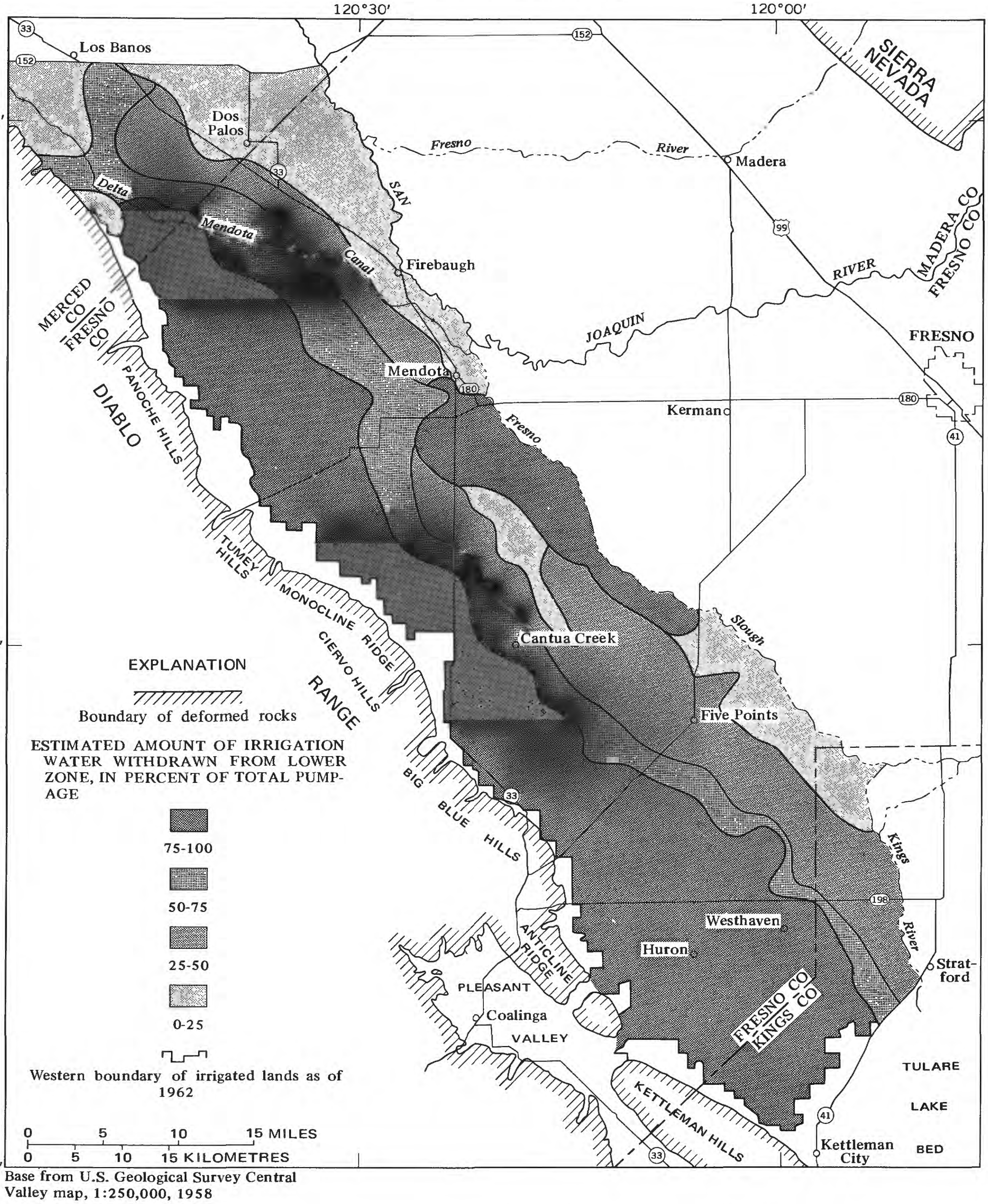


FIGURE 10.—General variation in the amount of water pumped from the lower zone or its stratigraphic equivalent.

tions prevail for the upper deposits. Considered as a unit, the upper zone is termed a semiconfined aquifer system in this report.

PHYSICAL CHARACTER

The upper zone, which includes the upper part of the Tulare Formation and younger alluvium, ranges from about 100 to 900 feet in thickness. The primary upper-zone aquifer is a micaceous sand, which was deposited over 645 square miles of the Los Banos–Kettleman City area (fig. 11) as flood-plain deposits of streams draining the Sierra Nevada. The thickness of the micaceous sand ranges from a featheredge along its western margin to about 580 feet under the present valley trough. In the northern half of the area, volcanic glass and pumice fragments occur in the micaceous sand in the basal part of the aquifer. In the southern part of the area, many of the deep irrigation wells tapping the lower zone are also perforated opposite lacustrine sands associated with the Corcoran Clay Member. Most of these sands are in the upper zone and are from 100 to over 200 feet thick. The lacustrine sands have a low clay content, are well sorted, and are highly permeable.

The alluvial-fan deposits in the upper zone are not productive aquifers except in a small area southwest of Los Banos, in the extreme northern part of the Los Banos–Kettleman City area. The sediments deposited by Los Banos Creek consist primarily of gravel; shallow wells, 100–250 feet deep, provide sufficient water for irrigation. South of the Fresno-Merced County line, the alluvial-fan deposits have a low permeability and consist of clayey sand layers with interbedded poorly sorted silt and clay.

The alluvial-fan deposits are derived from the Diablo Range and are easily recognized in well cuttings or in cores by their yellowish to brownish color. They are calcareous and gypsiferous and locally contain small calcareous concretions, serpentine, glaucophane schist, fragments of siliceous shale, chert, and jasper —lithologies that are typical of Diablo Range source areas.

PRODUCTIVITY

The most permeable aquifers in the Los Banos–Kettleman City area are in the upper zone. These aquifers, however, are of limited extent. A comparison of yield factors[1] (Poland, 1959, p. 32), which are approximate measures for the overall permeabilities of the water-bearing materials tapped by wells, indicates that the gravels forming the Los Banos Creek alluvial-fan deposits are the most permeable. (See table 1.) These deposits are two to five times more permeable than the Sierra micaceous sands which form the primary upper-zone aquifer in the eastern part of the study area. The upper zone alluvial-fan deposits south of the Merced County line which are derived from the Diablo Range, have low permeabilities as indicated by the low productivity of the few wells that tap only these deposits.

TABLE 1.—*Relation of yield factors to types of upper-zone deposits*

Area	Townships represented (Township/Range)	Mean yield factor	Number of wells represented
Wells tapping only upper zone alluvial-fan deposits:			
Los Banos	10S/10E	95	5
South of Fresno-Merced County line	16S/15E; 18S/17E	4	3
Wells tapping only upper zone Sierra micaceous sands:			
West of San Joaquin River	10S/12E; 11S/13E; 12S/14E; 13S/15E	50	4
West of Fresno Slough	15S/15E; 15S/16E; 16S/16E; 16S/17E; 17S/16E; 17S/17E; 17S/18E; 17S/19E; 18S/18E	21	13
East of Fresno Slough	14S/17E; 15S/17E; 16S/18E; 16S/19E	100	15

A fivefold variation in mean yield factors of the upper zone Sierra micaceous sands occurs within the study area. A comparison of mean yield factors indicates that the Sierra micaceous sands are twice as permeable west of the San Joaquin River than west of Fresno Slough. Many shallow wells tapping these deposits west of the San Joaquin River yield about 1,400 gallons per minute. If the Sierra micaceous sands are present and are less than 200 feet thick, most irrigation wells tap both the upper and lower water-bearing zones. In the area west of the Fresno Slough, where sodium chloride water occurs in the upper zone (shown in fig. 11), wells are perforated only opposite the lower zone. Mean yield factors of wells 3–4 miles east of the Fresno Slough indicate that the micaceous sands are five times as permeable as the sands west of the slough.

CHEMICAL CHARACTER OF WATER

Ground waters of the upper zone generally contain high concentrations of calcium and magnesium sulfate. Pronounced changes in the chemical characteristics of these waters occur in adjacent areas along the eastern and western margins of the area, and gradational changes occur with increasing depth (Davis and Poland, 1957, p. 457–458).

The calcium and magnesium sulfate ground waters occurring to a depth of 200–300 feet average about 3,000 mg/l (milligrams per liter) of dissolved solids and have about 35 percent sodium. An abrupt change, however, occurs along the border of the area, where the water from the west side with high sulfate concentrations

[1]Yield factor = $\frac{\text{Specific capacity (gallons per minute per foot of drawdown)} \times 100}{\text{Thickness of deposits, in feet, tapped by perforated interval of well casing}}$

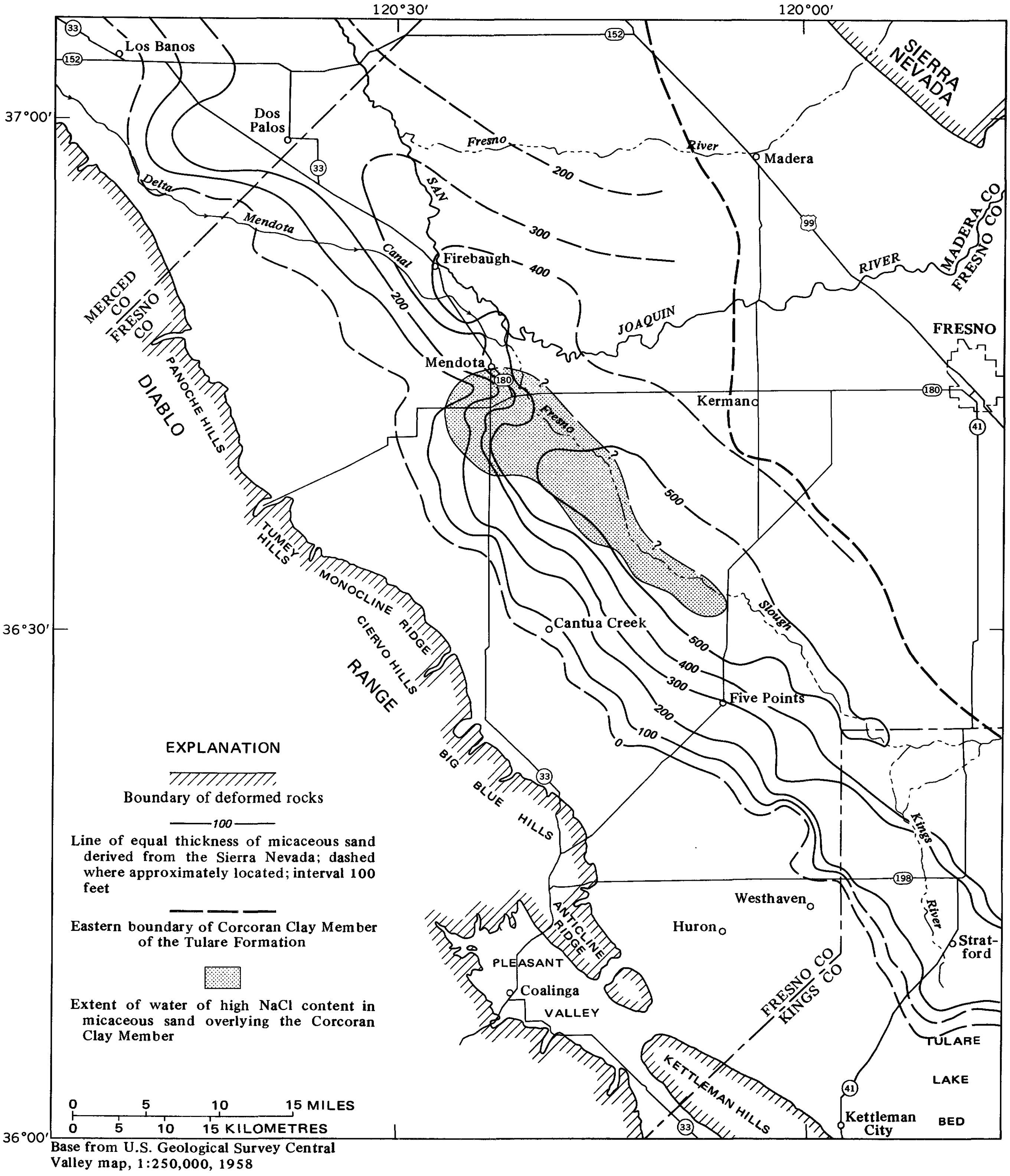


FIGURE 11.—Thickness and extent of the Sierra sand overlying the Corcoran Clay Member of the Tulare Formation. (Modified from Miller and others, 1971, fig. 10.)

merges with the calcium and sodium-bicarbonate ground water of low dissolved solids from the east side of the San Joaquin Valley.

The chemical character of the waters contained in the deposits from a depth of 300 feet to the top of the Corcoran can be distinguished from the overlying waters by their decrease in total dissolved solids to about 1,500 mg/l and an increase in the percent sodium to about 55.

West of the Fresno Slough the water in the micaceous sand immediately overlying the Corcoran Clay Member (with the exception of the brackish water area shown in fig. 11) has a mean total dissolved solids of around 850 mg/l, and the percent sodium is about 60.

CORCORAN CLAY MEMBER OF THE TULARE FORMATION

A widespread diatomaceous clay stratum in the upper part of the Tulare Formation was first described by Frink and Kues (1954, p. 2357–2370) and has been named the Corcoran Clay Member of the Tulare Formation (Inter-Agency Committee, 1958, p. 120). This lacustrine clay extends beneath the entire Los Banos–Kettleman City area (fig. 12) except for a narrow zone adjacent to the hills in the southwestern part of the area where, as is shown in section E–E′ (fig. 7), it feathers out, presumably along a contour of the ancestral Los Gatos Creek fan.

The Corcoran has two lithologies. The upper two-thirds of the Corcoran consists of thin-bedded clayey silt and silty clay. The lower third of the unit commonly is coarser grained, consisting of interbedded sand-silt-clay and clayey silt. The greenish-blue color indicates that the Corcoran is reduced, except in the extreme western part of the study area where it has been uplifted and partially oxidized to brown or red.

The Corcoran Clay Member of the Tulare Formation is the principal confining layer throughout much of the San Joaquin Valley. The vertical permeability of the Corcoran which, based on results of consolidation tests under a simulated natural overburden load, ranges from 4×10^{-5} gpd (gallons per day) per square foot (0.002 feet per year) in the more sandy parts near the top and base to as low as 6×10^{-6} gpd per square foot (0.0003 feet per year) in the less permeable middle section (Johnson and others, 1968, table 9). By 1960, the difference in head in aquifers above and below the Corcoran was as much as 200 feet.

The Corcoran was deposited in a fresh-water lake that was 10–40 miles wide and more than 200 miles long (Davis and others, 1959, p. 77 and pl. 14). Evidence presented by Janda (1965) indicates that the lake existed in Pleistocene time about 600,000 years ago. The longitudinal axis of the lake in which the clay was deposited was approximately 5–10 miles west of the present topographic axis of the valley. The exact western areal extent of the Corcoran is difficult to determine, because as it thins, it bifurcates and its sand and silt content gradually increases until it is not discernible in electric logs from the littoral sands which occur along its west edge.

The thickness of the clay varies considerably. The maximum known thickness of the Corcoran in the study area occurs 5 miles northeast of the mouth of Panoche Creek, where an electric log shows the Corcoran to be 120 feet thick (Miller and others, 1971, fig. 11). Adjacent to Monocline Ridge and Ciervo Hills, the Corcoran is less than 20 feet thick and is more than 900 feet below land surface. In most of the area the Corcoran is 30–60 feet thick.

The map showing the structure of the Corcoran (fig. 13) indicates that there has been gentle postdepositional folding and warping of this lacustrine clay bed. The shift in the structure contours in the Huron-Westhaven area occurs where contours are shown for the lower clay stratum in an area where the upper clay layer is absent.

LOWER ZONE

The lower zone is effectively confined by the Corcoran except in the southwestern part of the Los Banos–Kettleman City area where the Corcoran is absent and confinement is poor or lacking. The lower zone supplies about three-fourths of the ground water for irrigation in the Los Banos–Kettleman City area.

If an aquifer is defined as a permeable deposit that will yield water to wells, the entire lower zone can be considered an aquifer. Permeable sand units can also be considered as aquifers separated hydraulically to varying degrees by the finer grained interbeds of silt and clay. Silt and clay, especially clay, are much more compressible than sand when compressive stresses are increased owing to artesian-head decline. Therefore, it is important in the study of compaction of deposits under increased effective stress to differentiate between a water-bearing unit that is composed entirely of permeable material such as clean sand and one that contains many fine-grained beds of silt and clay. For purposes of differentiation in the studies of compaction and subsidence, a water-bearing unit that has hydraulic continuity but that contains many fine-grained beds is termed an aquifer system. Under this definition, the lower water-bearing zone is a confined aquifer system. The beds of silt and clayey silt that impede ground-

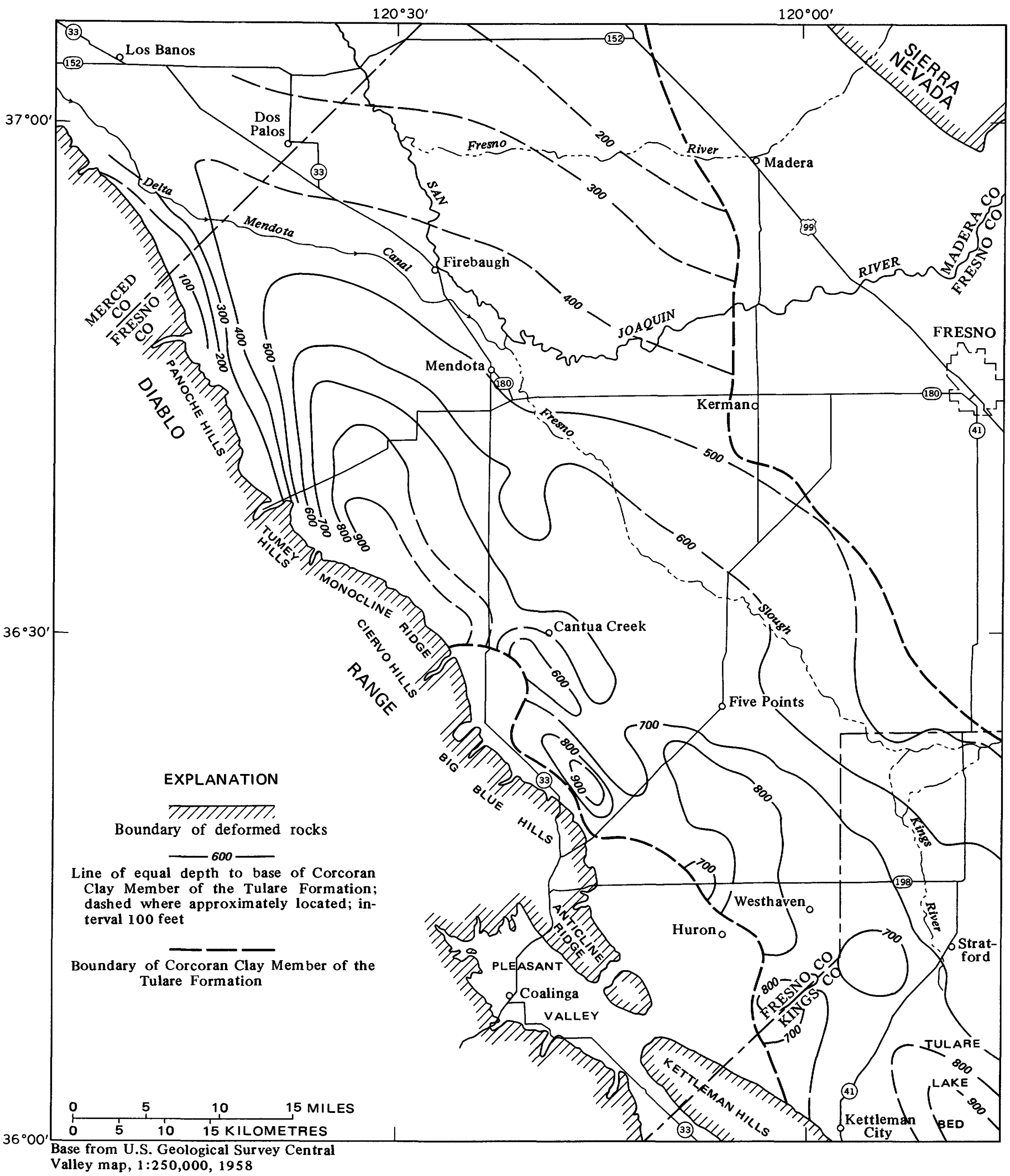


FIGURE 12.—Depth to the base of the Corcoran Clay Member of the Tulare Formation.

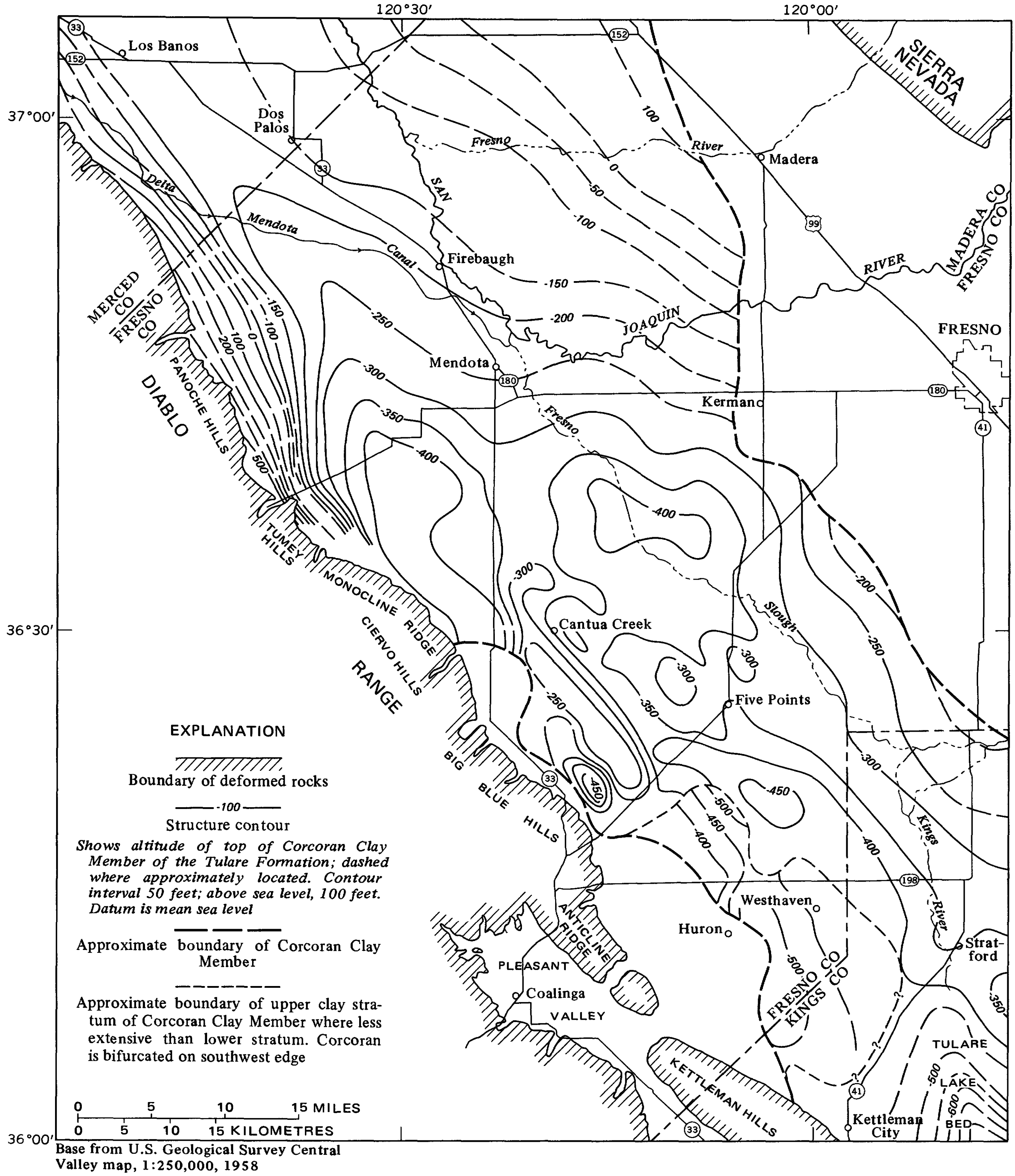


FIGURE 13.—Structure of the Corcoran Clay Member of the Tulare Formation. (From Miller and others, 1971, fig. 12.)

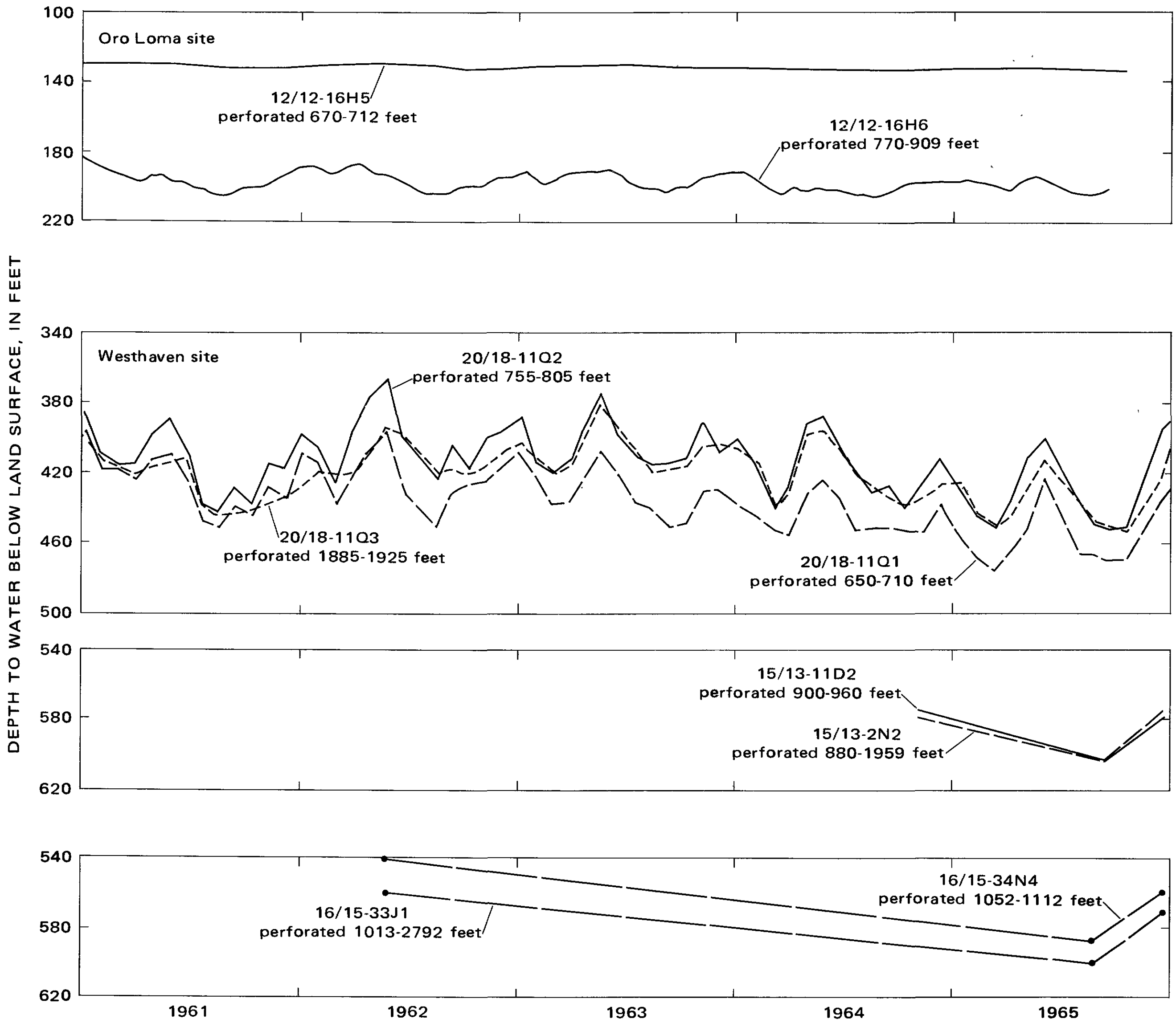


FIGURE 14.—Variation in the hydraulic continuity of the lower zone.

water movement may transmit appreciable water between adjacent aquifers—they are called aquitards.

Throughout most of the area the lower zone has good hydraulic continuity both laterally and vertically. The degree of hydraulic continuity is shown at four sites in figure 14. Lack of hydraulic continuity in the northern part of the area is shown by the marked separation in head and difference in water-level trends in wells 12/12–16H5 and 12/12–16H6 at the Oro Loma site. A second confining clay occurs about 300 feet below the Corcoran in this part of the area, and at the site of these wells it is 38 feet thick. Head differences of 60–75 feet occur between the two lower-zone aquifers, and the greater amount of seasonal fluctuation shown by the record of the deeper well suggests that most of the lower-zone wells in the vicinity are perforated mainly below the lower confining clay. The degree of hydraulic separation shown by the records of these two wells extends about as far south as the southern part of township 13 south.

Hydrographs of two lower-zone wells at the Westhaven site in the southern part of the area show a marked difference in the degree of hydraulic continuity when compared with those at the Oro Loma site. Well 20/18–11Q2 is perforated from 755 to 805 feet, and well 20/18–11Q3 is perforated from 1,885 to 1,925 feet; yet the records show similar water levels and amounts of seasonal fluctuation. The difference in artesian head between the two lower-zone wells has not exceeded 25 feet, although the seasonal fluctuation of head has been as much as 80 feet.

The other two sets of hydrographs in figure 14 are comparisons of water levels in observation wells perforated in an aquifer a short distance below the base of the Corcoran and nonpumping water levels in nearby irrigation wells. The irrigation wells are perforated to depths 1,000–1,700 feet deeper than the observation wells and are within a third of a mile of the observation wells. The small differences in head in each set of hydrographs show that good hydraulic continuity exists throughout the lower zone for these sites in the central and southern part of the study area. The records also indicate that the shallow observation wells have water levels that are representative of nearby deep irrigation wells.

PHYSICAL AND HYDROLOGIC CHARACTER

In most of the study area, the fresh-water-bearing deposits below the Corcoran consist of poorly consolidated alluvial fan, flood-plain, deltaic, and lacustrine deposits of the Tulare Formation. In the southern part of the area, the basal lacustrine deposits of the Tulare are moderately consolidated and contain brackish water.

The productivity of the Tulare is generally inadequate for irrigation purposes in a 3- to 7-mile wide belt along the margin of the valley between the towns of Huron and Cantua Creek. Northwest of the Five Points–Coalinga Road, deep wells extend into the moderately consolidated Pliocene marine littoral and estuarine sands and silty clays of the pre-Tulare San Joaquin and Etchegoin Formations. To the south, the deeper wells tap the upper part of the San Joaquin Formation.

The wells tap those parts of the marine section that have been largely flushed of their connate water. From some wells brackish water of poor quality is pumped from the pre-Tulare Pliocene deposits, but when the poor quality water is mixed with better quality water being drawn through the perforations higher in the well, the quality is improved, and the net result is to increase the yield of the well to an amount that is adequate to irrigate the land in the vicinity. Pore-pressure decline and compaction occur regardless of the quality of the water being removed from unconsolidated or partly consolidated deposits.

The areas where water is being pumped from pre-Tulare formations of Pliocene age are shown in figure 15. Although deposits that are considered to be Pliocene in age are tapped in a large area near the foothills of the Diablo Range, only the area adjacent to the Big Blue Hills and Anticline Ridge is largely dependent on ground-water supplies from the older deposits.

In the northern area where Pliocene deposits are tapped, most of the ground water is pumped from flood-plain deposits in the first few hundred feet below the Corcoran. A few wells are perforated in the upper part of the Kreyenhagen Formation of Eocene and Oligocene age, and many wells tap the deposits immediately above the Kreyenhagen—deposits that have been described by Miller, Green, and Davis (1971) as Pliocene continental deposits. The electric logs suggest considerable variation in lithology and water quality of the Pliocene continental deposits. Differences in the temperature of the well water being pumped are not apparent between wells that in part tap Pliocene continental deposits and those that do not. Since 1960, the new wells have been tapping shallower zones.

As much as 2,000 feet of pre-Tulare Pliocene deposits is tapped by water wells adjacent to the Big Blue Hills. In general, the water being pumped from the pre-Tulare Pliocene deposits in this area is distinctly hotter than the water being pumped by nearby wells that tap only the overlying Tulare Formation. Many of the wells tapping the San Joaquin and Etchegoin Formations have water temperatures of more than 38°C (100°F), and temperatures as high as 45°C (114°F) have been recorded. Adjacent to the northern part of the Big Blue Hills, most of the water being pumped within 5 miles of the foothills probably is coming from the pre-Tulare Pliocene formations. The Tulare is so clayey that some wells are not perforated above a depth of 2,000 feet, and one well was perforated to a depth of 3,800 feet. Well yields generally are less than in areas where wells tap only the Tulare Formation.

The area adjacent to the Big Blue Hills and Anticline Ridge has experienced as much as 500 feet of artesian-head decline, but the amounts of subsidence in those parts of the area where wells derive most of their water from the pre-Tulare Pliocene formations have been minor, presumably because of the partly consolidated nature of the deposits. Only 1 foot of subsidence has occurred in the area of 500 feet of head decline.

The lower zone alluvial-fan deposits are derived from the Diablo Range and have low permeabilities. They are similar in lithology to the upper-zone fan deposits south of the Merced County line. In the southern part of the area, as shown on section *E–E′* (fig. 7), most of the lower zone tapped by wells consists of alluvial-fan deposits, but 20 miles to the northwest (section *C–C′*, fig. 7) fan deposits form less than one-eighth of the lower-zone aquifer system.

The moderately permeable flood-plain and deltaic deposits which form the major part of the lower zone in sections *C–C′* and *E–E′* (fig. 7) were derived from the granitic rocks of the Sierra Nevada. Consequently, they are arkosic in composition and can be recognized in drill cuttings or core samples by their mica content. They are generally grayish green or blue green.

The lower zone in the area of section *B–B′* (fig. 7) is

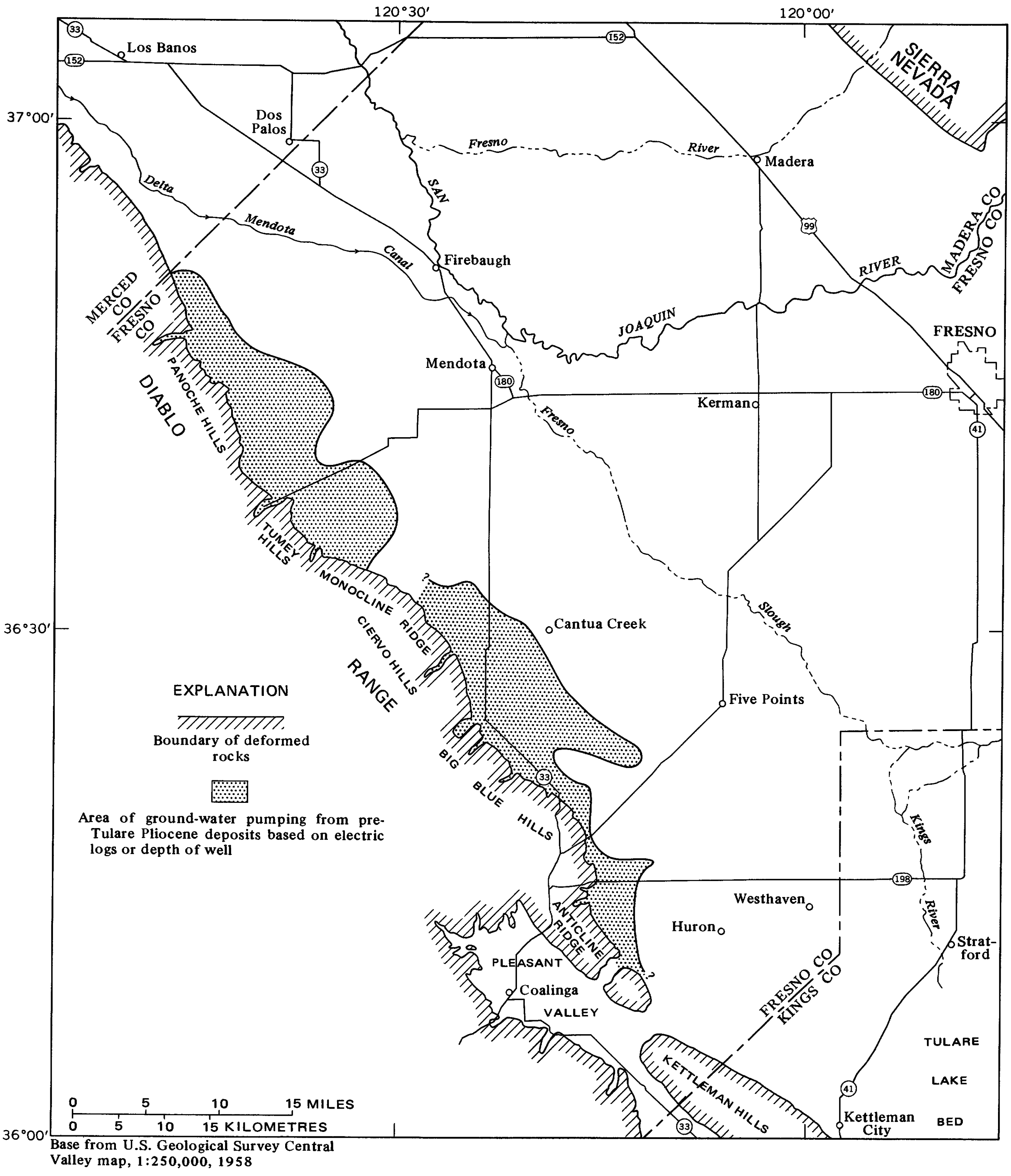


FIGURE 15.—Areas in which part of ground water is pumped from pre-Tulare deposits of Pliocene age.

TABLE 2.—*Relation of yield factors to types of lower-zone deposits*

Area	Townships represented (Township/Range)	Mean yield factor	Number of wells represented
Wells tapping only flood-plain deposits derived from the Diablo Range:			
South of Los Banos Creek to vicinity of Fresno-Merced County line	12S/11E; 12S/12E	24	6
Vicinity of Fresno-Merced County line to Panoche Creek	12S/11E; 12S/12E; 13S/12E; 13S/13E; 14S/12E	9	26
Wells tapping only flood-plain deposits derived from the Sierra Nevada:			
West of Fresno Slough	14S/14E; 14S/15E; 15S/14E; 15S/15E; 17S/16E; 18S/17E	11	9
Wells tapping only deltaic deposits derived from the Sierra Nevada:			
West of Kings River	20S/19E	9	2
Wells tapping intermixed flood-plain deposits derived from the Diablo Range and the Sierra Nevada:			
North of Monocline Ridge	13S/13E; 13S/14E; 14S/13E; 14S/14E; 15S/13E; 15S/14E	6	23
Wells tapping only alluvial-fan deposits derived from the Diablo Range:			
Vicinity of Los Gatos Creek	19S/16E; 19S/18E	3	2
Wells tapping intermixed alluvial-fan deposits derived from the Diablo Range and flood-plain and deltaic deposits derived from the Sierra Nevada:			
Tulare Lake bed to 12 miles northwest of Cantua Creek	16S/14E; 16S/15E; 17S/15E; 17S/16E; 18S/16E; 18S/17E; 19S/17E; 19S/18E; 20S/19E	4	72

composed chiefly of flood-plain deposits derived from the Diablo Range. These deposits which form the bulk of the lower-zone deposits in the northern part of the Los Banos–Kettleman City area have low to moderately high permeabilities. They are greenish gray to greenish black and are characterized by andesitic and basaltic detritus, serpentine, chert, and other rock fragments derived from the Diablo Range. They are slightly to moderately micaceous, in contrast to the generally nonmicaceous character of the alluvial-fan deposits derived from the Diablo Range. This characteristic would suggest that the flood-plain deposits were derived from a different or larger source terrain than the overlying nonmicaceous alluvial-fan deposits.

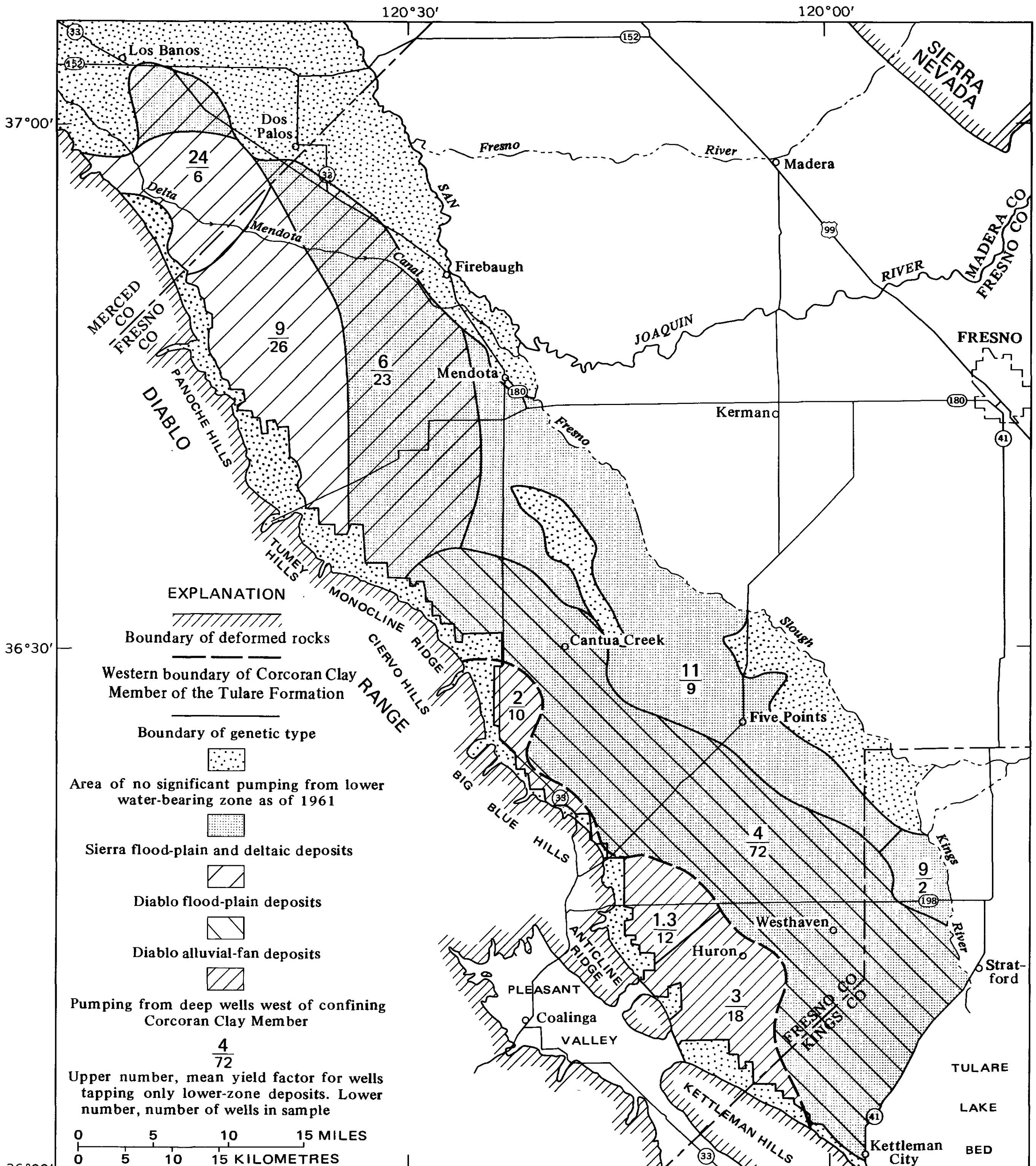
A variety of depositional environments are represented by the deposits in the central part of the study area. Flood-plain and alluvial-fan deposits derived from the Diablo Range interfinger with flood-plain deposits derived from the Sierra Nevada and with lacustrine sands and clayey silts.

PRODUCTIVITY

The deposits forming the lower-zone aquifer system in the Los Banos–Kettleman City area locally are less permeable than the deposits forming the semiconfined aquifer system of the upper zone. However, because of the greater thickness of the lower-zone deposits and the general poorer quality of the water in the upper zone west of the Sierra sands (fig. 11), at least 75–80 percent of the irrigation water pumped in the Los Banos-Kettleman City area is from the lower zone.

The yield factors of the lower water-bearing zone deposits given in table 2 and the areal distribution shown in figure 16 indicate that where wells produce from only one type of lower-zone deposit, the flood-plain deposits derived from the Diablo Range are slightly less permeable than the flood-plain deposits derived from the Sierra Nevada. However, yield factors indicate that where wells produce from lower-zone deposits which consist of Sierra flood-plain deposits interfingered with finer grained Diablo flood-plain deposits, the relative permeability is considerably lower. The general area where this interfingering occurs is in a north-south trending belt 8–9 miles wide which extends 18–25 miles north from Monocline Ridge.

In the western part of the Los Banos–Kettleman City area, between the towns of Cantua Creek and Westhaven, alluvial-fan deposits occur between the Corcoran and the lower-zone Sierra flood-plain deposits. Wells in this area producing from the lower zone and with approximately 20–50 percent of their perforated intervals opposite alluvial-fan deposits have yield factors ranging from less than 1 to a maximum of 9. The average yield factor of lower-zone wells in this area is 4.



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

FIGURE 16.—Yield factors and types of lower-zone deposits.

Only two wells, both located in the Los Gatos Creek area north and east of Huron, are known to tap only lower-zone alluvial-fan deposits. The yield factors of both of these wells is between 2 and 3. A comparison of yield factors suggests that in general the lower-zone flood-plain and deltaic deposits are 3–5 times as permeable as the lower-zone alluvial-fan deposits but only one-half to one-fifth as permeable as the upper-zone flood-plain deposits (Sierra micaceous sands of table 1).

The yield of wells throughout the Los Banos–Kettleman City area does not vary much with the average permeability of the deposits tapped, because the yield needed for irrigation purposes is only from 1,000–2,000 gallons per minute, and yields within this range can be obtained in most of the area. Wells tapping the highly permeable upper-zone Sierra sand near Fresno Slough may be only 150–200 feet deep and yield 1,500 gallons per minute. In the western part of the area where the upper-zone deposits have low permeabilities and the majority of the lower-zone deposits consist of alluvial-fan deposits, wells must be 2,500–3,500 feet deep to obtain 900–1,200 gallons per minute. Thus, where average permeability is low, as indicated by the low yield factor, the discharge capacity needed for irrigation can be obtained either by drilling wells to tap greater thicknesses of the deposits, or by installing pumps to operate with greater drawdowns from static level, or both.

The thickness of the fresh-water-bearing deposits of the lower zone (fig. 17) has been compiled from two maps. One map shows the altitude of the base of the Corcoran (Croft, 1969, pl. 4). The other shows the altitude of the base of fresh water determined from examination of several hundred electric logs, using 3,000 micromhos specific conductance (approximately 2,000mg/l dissolved solids) as the upper limit of fresh water (R. W. Page, 1971). Thus, the thickness map (fig. 17) represents the difference between the two altitudes.

Comparison of figure 17 with the geologic sections showing the base of fresh water (Miller and others, 1971) indicates that the lower-zone thicknesses in figure 17 are, in general, several hundred feet less than in Miller's geologic sections. Thus, the base of fresh water shown by Page in his appraisal of electric logs for water-chemistry purposes is several hundred feet above the base shown by Miller in his studies for geologic correlation purposes because Page used different criteria than Miller.

The thickness of the fresh-water-bearing deposits of the lower zone (fig. 17) varies considerably in the northern, central, and southern parts of the study area. In the northern part of the area, deposits that contain fresh water are 200–600 feet thick, and the maximum thickness occurs about halfway between the San Joaquin River and the Diablo Range.

The thickness of fresh-water-bearing deposits in the central part of the area is highly variable. Near Fresno Slough the deposits are only 600 feet thick, but they thicken westward abruptly, and opposite the Big Blue Hills the thickness exceeds 1,600 feet in an extensive area, and locally is 2,200 feet.

In general, the fresh-water-bearing deposits are the thickest in the southern part of the area, where thicknesses range from 800 to more than 2,000 feet. The thickness increases progressively from Five Points toward Tulare Lake bed.

The thickness of the fresh-water-bearing deposits does not define the thickness of deposits being subjected to large amounts of pore-pressure decline and concurrent compaction. In parts of the area, sufficient yields can be obtained by wells without having to drill to the base of the fresh-water-bearing deposits. In other parts of the area, sufficient yields can be obtained only by pumping part of the water from underlying deposits that contain water of poorer quality than 2,000 mg/l.

The maximum thickness of the perforated interval of the lower zone, and locally of subjacent deposits containing saline water, provides useful information for subsidence-study purposes. Reduction of pore pressure may occur several hundred feet below the lowest perforations in deposits that have hydraulic continuity. This factor is not taken into account in this study because detailed information about hydraulic continuity is not known for the base of the lower zone. Furthermore, the fine-grained lacustrine and deltaic deposits near the base of the lower zone are likely to cause poor hydraulic continuity in that part of the aquifer system in much of the study area. An alternative approach is to use the maximum depth of well perforations to approximate the depths to which pore-pressure decline is occurring. Maximum pore-pressure decline may be occurring higher in the aquifer system where the greatest abundance of well perforations occurs. However the use of the maximum depth of the perforations partly takes into account pore-pressure decline that is occurring below the base of wells that bottom higher in the aquifer system. Maximum depths were not used if only a few deeply perforated wells were present in a township or if the depths appear to be anomalously deep. The maximum thickness of the lower-zone perforated interval is based on the well tabulation compiled by Ireland (1963): this table lists the perforated-interval data for wells

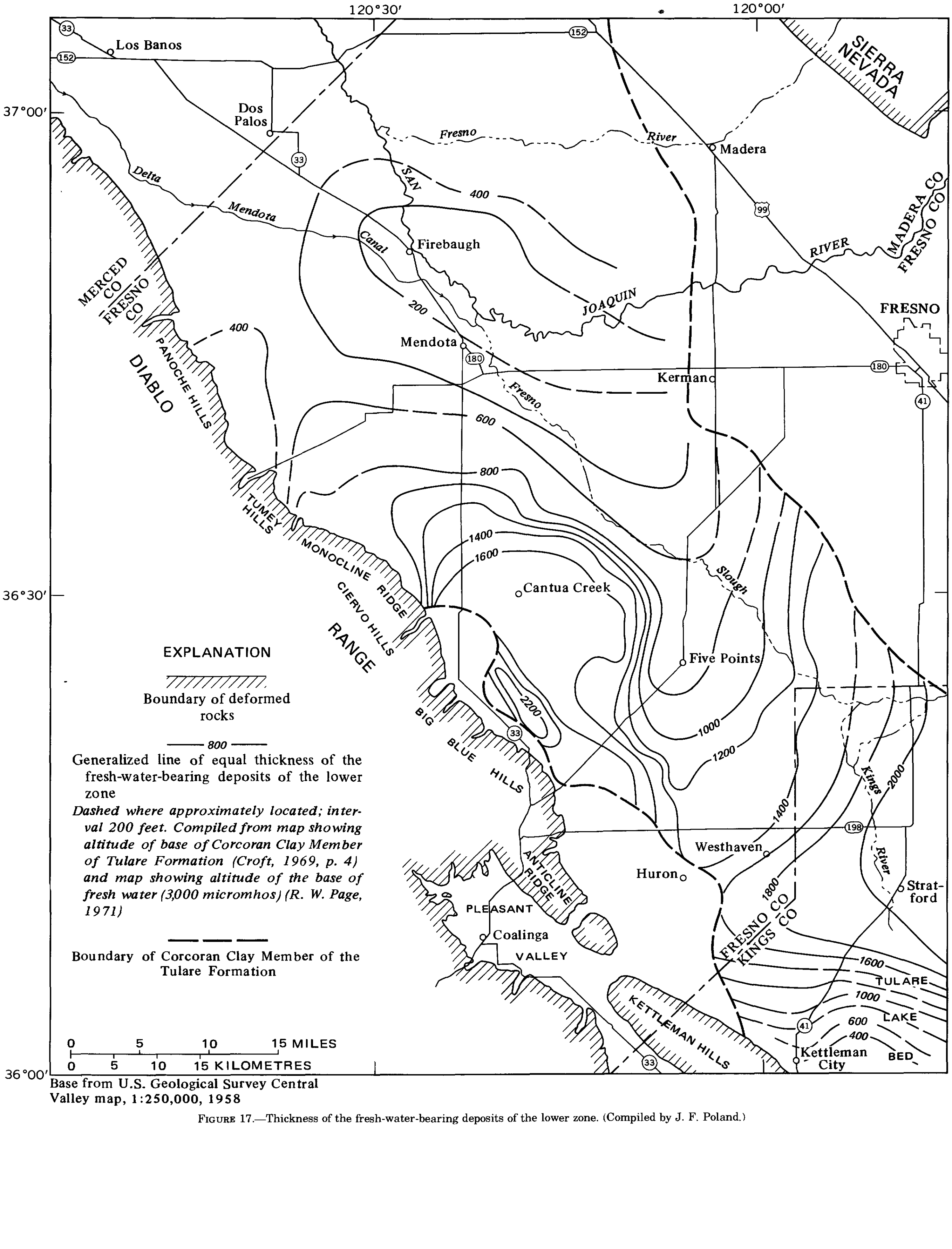


FIGURE 17.—Thickness of the fresh-water-bearing deposits of the lower zone. (Compiled by J. F. Poland.)

drilled before 1962. Since 1960 fewer wells have been tapping the brackish waters that occur below the base of the lower zone.

The maximum thickness of the perforated interval of the lower zone is shown in figure 18. The thickness of lower-zone deposits being tapped ranges from less than 400 feet to more than 2,400 feet. The general pattern is one of overall increasing thickness of perforated interval toward the southwest. Thicknesses of more than 1,800 feet occur in the areas of pumping from the Etchegoin Formation.

Comparison of figures 17 and 18 reveals some interesting differences for the various parts of the study area. In the northern part of the area, the perforated interval exceeds the thickness of the fresh-water-bearing deposits by 200–400 feet near the San Joaquin River. Toward the Diablo Range, however, wells tap progressively more of the underlying sediments containing brackish water; as is shown by the greater disparities between the thickness lines of the two maps. A maximum disparity of 1,000 feet locally is attained east of Panoche Hills.

In the central part of the area, the overall patterns of lines in figures 17 and 18 bear little resemblance. The wells do not extend to the base of the fresh water in the eastern part of the subarea: they do extend as much as 200 feet below the base of the fresh water in the area that is dependent on water yielded from the Pliocene marine sands.

In the southern part of the area, the productivity of the lower zone is sufficiently high that farmers do not need to drill wells to the base of the fresh-water-bearing deposits. South of Five Points, comparison of figures 17 and 18 shows that in nearly all the area the wells do not reach the base of fresh water. East of Westhaven, the thickness of the lower zone exceeds the thickness of perforated interval by as much as 1,000–1,400 feet.

Pore-pressure decline is also occurring below the base of the well perforations in the vicinity of Fresno Slough and Kings River as a result of the large amounts of water being pumped from the deeper aquifers farther west. An example of this type of head decline is shown in figure 24 at the Yearout site (13/15–35D).

CHEMICAL CHARACTER OF WATER

Lower-zone ground waters are effectively separated by the Corcoran Clay Member from upper-zone water throughout most of the study area. The chemical character of the water has been discussed in some detail by Davis and Poland (1957, p. 459–460). Analyses of samples taken in August 1951 from wells with perforations restricted to the lower zone and of samples from older wells in that zone that were not gravel packed provide useful information about the chemistry of the lower-zone water. It is primarily a sodium sulfate water, with noticeably more bicarbonate than in the upper-zone waters. The chloride concentration of the water is generally 100 mg/l or less.

The uniform salinity of the lower-zone water at a given site can be demonstrated by examination of spontaneous potential electric logs. The mud used when drilling a well commonly is mixed with water from a nearby irrigation well, thereby causing a minimum of contrast between the resistivities of the formation fluids and the drilling mud. Under such conditions, the spontaneous potential log will be virtually featureless unless the salinity of the contained waters varies from bed to bed. The featureless spontaneous potential logs of the study area indicate that lower-zone salinities are very uniform or undergo change with depth in a gradual manner.

The chemical character of the water in the lower zone has been influenced by variations in time and place of streamflow from the Coast Ranges, by the initial sources of the deposits and their contained waters, by the presence or absence of the Corcoran as a control for percolation to the lower zone, and by the activities of man. The variations in dissolved solids of lower-zone water shown in figure 19 probably have been little affected by man. The data for the map were taken from values of sums of determined constituents given by Davis and Poland (1957, tables 2 and 3). Some of the data were from wells that are perforated for short distances immediately above the Corcoran, but sums of determined constituents for these wells do not differ appreciably from those for nearby wells perforated only below the Corcoran.

The map showing the chemical character of the water in figure 19 is representative, in general, of the fresh-water-bearing section of the lower zone as shown in figure 17. The map is biased toward mean or minimum sums of determined constituents for two reasons. Anomalously high values could be the result of two causes: (1) The basal part of the perforations of some wells were known to extend below the base of the fresh water; and (2) the presence of poorer quality water in some wells was thought to have been the result of lack of prolonged pumping before sampling in wells that are perforated for a short distance above the Corcoran. In such wells, when the pump is idle, poorer quality upper-zone water may flow down the well and gravel pack and replace the lower-zone water immediately adjacent to the well.

The concentration of dissolved solids in the lower-

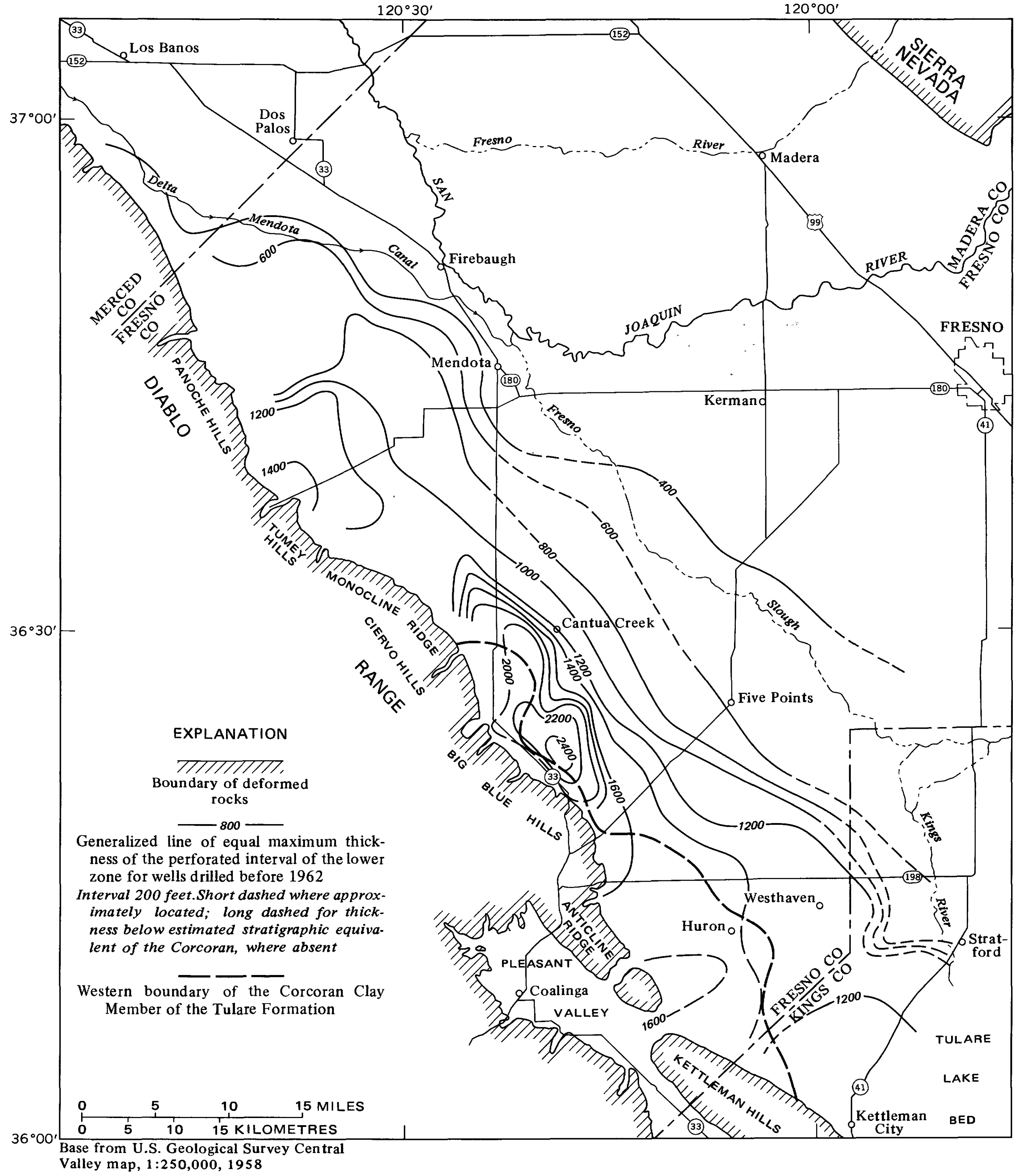


FIGURE 18.—Maximum thickness of the perforated interval of the lower zone.

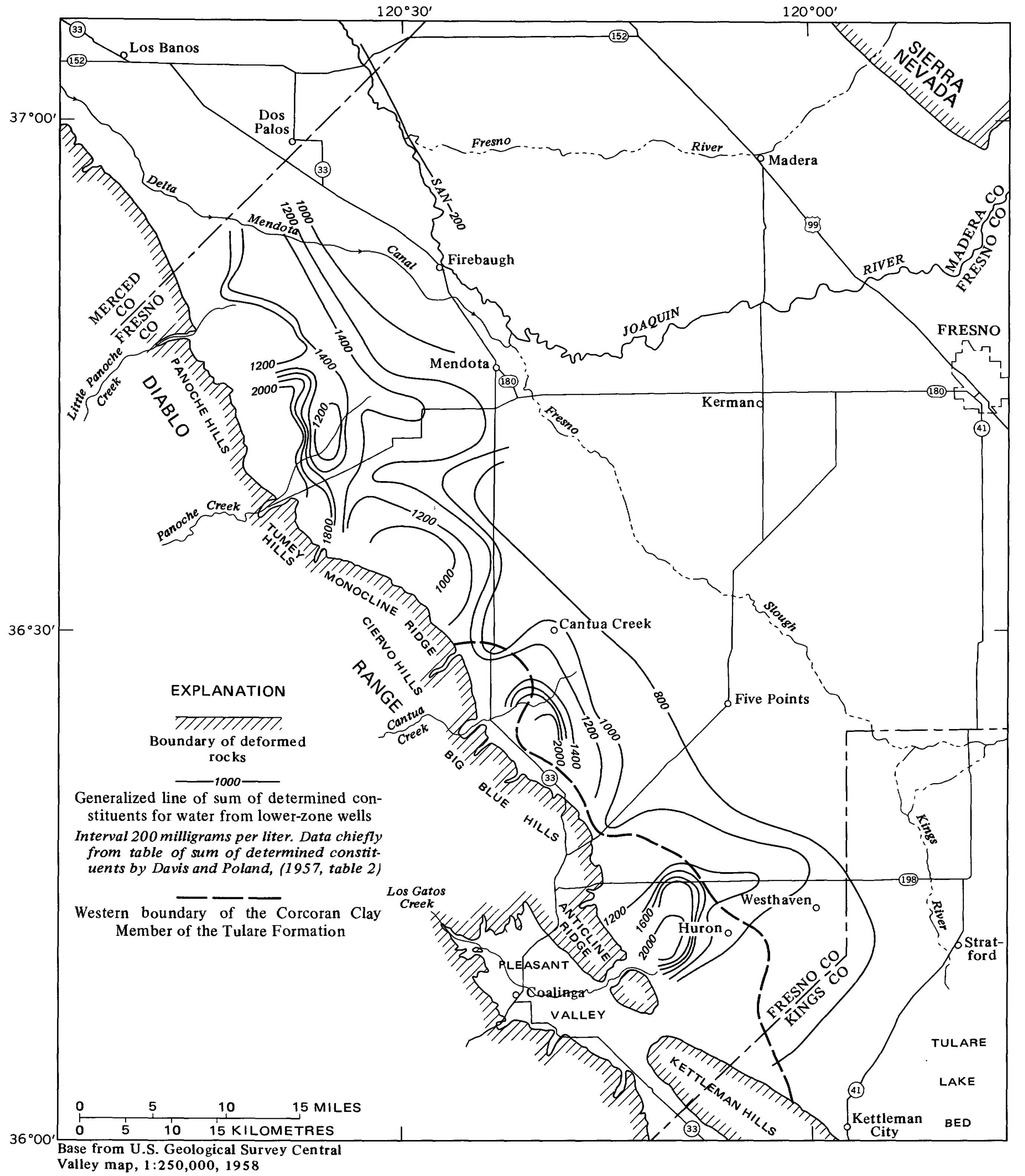


FIGURE 19.—Variation in dissolved solids of the lower-zone water.

zone water increases toward the Coast Ranges. Maximum concentrations occur opposite the mouths of Panoche, Cantua, and Los Gatos Creeks where more than 2,000 mg/l of dissolved solids occur in the water. The absence of the Corcoran west of Huron may have contributed to the high concentration of dissolved solids because of possible recharge of the lower zone by streamflow (Davis and Poland, 1957, p. 459). A concentration of dissolved solids is not present opposite the mouth of Little Panoche Creek, but streamflow from this drainage area did not discharge at this point until after the deposition of the Corcoran lake clay.

The area of high concentration of dissolved solids near the mouth of Cantua Creek is due, in part, to pumping of water from marine deposits below the base of the fresh-water-bearing deposits. Also, the area of high concentration opposite the mouth of Panoche Creek conforms with an area in which perforated intervals in the deeper wells extend below the base of the fresh water.

Areas of low concentration of dissolved solids occur between the mouths of the large streams. The dissolved solids are less than 1,000 mg/l opposite Monocline Ridge, the Ciervo Hills, the southeast end of the Big Blue Hills, and the Kettleman Hills. These areas have received little recharge from streamflow or rainfall since the deposition of the Corcoran.

Electric logs and analyses of well waters suggest that the water from the Pliocene sands that underlie the Tulare Formation has a relatively high dissolved solids content. Water temperatures in excess of the normal temperature gradient with depth in the Tulare and older formations indicate a present lack of circulation of the water in this zone. Recharge of stream water from the Diablo Range into the Pliocene sands is not expected to be rapid because the estuarine deposits have been overlapped by the alluvial silts and clays of the Tulare Formation.

SALINE WATER BODY

A saline water body occurs beneath all the fresh ground-water reservoir in the Los Banos–Kettleman City area. Along the east side of the area, northwest from about the town of San Joaquin, the saline water body occurs at depths of 800–1,500 feet below the land surface. (See generalized sections *B–B'* and *C–C'*, fig. 9.) Five miles west of Mendota the chloride content of this water has been estimated to be about 7,700 mg/l (Davis and Poland, 1957, p. 462). The position of the top of this high chloride water is only approximately known because only a few wells were drilled into the saline water-bearing beds. The upper surface of the saline water body dips steeply westward. (See fig. 9, section *C–C'*, beneath Fresno Slough.) Wells drilled along the western margin of the valley in 18/15–1 and 2 reach the saline water at a depth of 3,150 feet.

The brackish-water body above the base of the Tulare Formation in the southeastern part of the study area (generalized section *E–E'*, fig. 9) contains fresh-water fossils. Its present salinity is thought to be a secondary feature such as Pleistocene lake evaporation (Miller and others, 1971). 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 cubic centimeters of core sample.[2] Porosities in this zone are thought to average about 40 percent.

This would indicate an approximate chloride concentration of the water of 320–9,700 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 have chloride concentrations that range from 2–106 grains per 1,000 cubic centimeters of core sample. If a 40 percent porosity is assumed for these samples, the chloride content of this water ranges from about 320–17,000 mg/l.

NATURAL FLOW SYSTEM

Natural flow conditions in the ground-water reservoir in the central part of the San Joaquin Valley were greatly different before agricultural development of the area. Consideration of the entire hydrologic system, from the Diablo Range to the Sierra Nevada, provides useful information about the natural flow system and the changes of the general flow pattern that have been made by man. Early measurements made by the Geological Survey in 1906 (Mendenhall and others, 1916) form the basis of appraisal of the original conditions.

The extent of the lower-zone confinement and the change in flow conditions for the northern half of the Los Banos–Kettleman City area and the area to the east are shown in figure 20. The great extent of the Corcoran is demonstrated in figure 20*A*. The only sources of potential recharge to the lower zone, under natural conditions, were along the eastern and western boundaries of the confining clay. The amounts of water percolating into stratigraphically lower deposits in the Diablo Range probably have always been small in the northern half of the study area. In the southern part of the study area, the boundary of the Corcoran is east of the mountain front, and the potential for recharge from the Diablo Range is much greater.

[2]Shell Oil Co., 1929, unpublished report, Results of core drilling on the Boston Land Co. property.

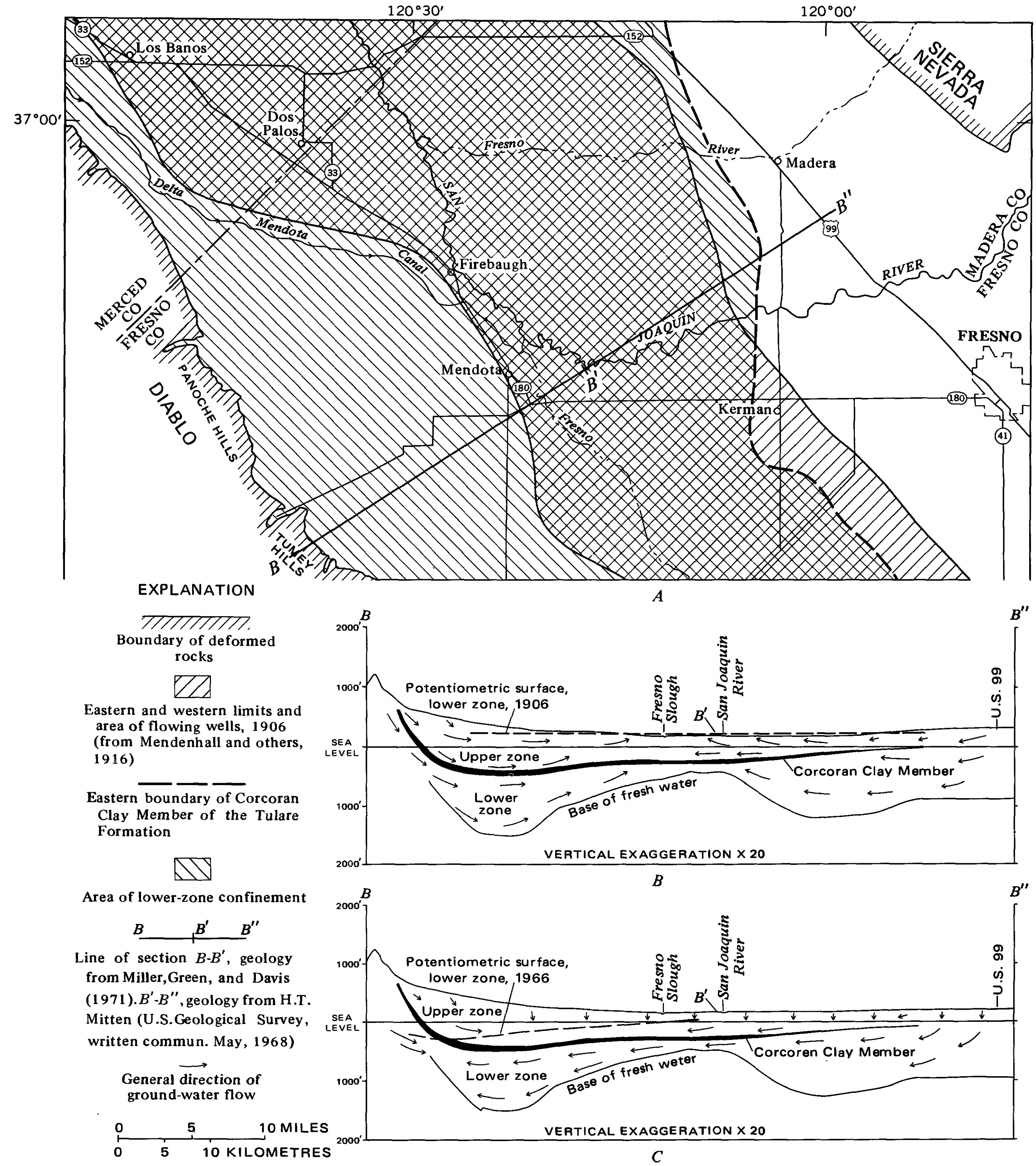


FIGURE 20.—Change in the natural-flow conditions in the central San Joaquin Valley. *A*, Extent of lower-zone confinement. *B*, Flow conditions in 1900. *C*, Flow conditions in 1966.

The largest recharge area for the deposits below the Corcoran is the 10- to 20-mile-wide belt of the San Joaquin Valley west of the Sierra Nevada. Major streams such as the San Joaquin River have supplied large amounts of water to the lower zone. Recharge directly from rainfall before the advent of irrigation probably was insignificant.

Flow conditions in about 1900 are shown in figure 20*B*. Waters of markedly different chemical quality from the two source terrains moved under the Corcoran and migrated to the trough of the valley. General circulation and upward movement through the Corcoran occurred at very slow rates because of the exceedingly low permeability and large thickness of the lacustrine confining clay. As a result, the lower-zone potentiometric surface was more than 20 feet above land surface in the valley trough area. The slope of the potentiometric surface toward the trough of the valley was only 3–4 feet per mile.

The large-scale agricultural development of the west side of the valley resulted in the change in flow shown in figure 20*C*. The potentiometric surface, instead of being above the land surface, was below sea level in most of the area west of Fresno Slough in 1966. Near the Diablo Range, lower-zone water levels were below the Corcoran, and water-table conditions existed. The slope of the potentiometric surface has been reversed to a major degree. Under the initial flow conditions, the potentiometric surface sloped to the east in all the area west of Fresno Slough. By 1966, a belt that was only a few miles wide adjacent to the Diablo Range was still an area of eastern gradient for lower-zone water movement.

Upper-zone conditions were not changed as much as the lower-zone conditions in the northern part of the study area because of the limited pumping of these waters. Recharge to the ground-water reservoir from the surface was occurring—in contrast to the times before agricultural development—as a result of irrigation water percolating below the root zone. Upper-zone changes have been much greater in the central and southern parts of the area where the semiconfined and confined aquifer systems have been pumped heavily.

CHANGES IN THE HYDROLOGIC ENVIRONMENT CAUSED BY MAN

Man has greatly disrupted the natural flow system. Water-level changes have occurred in the different parts of the ground-water reservoir—the water table, the semiconfined aquifer system, and the confined aquifer system. Significant hydrologic changes are responsible for the increased applied stress that has caused land subsidence.

HISTORY OF GROUND-WATER DEVELOPMENT

The early settlers used the Los Banos–Kettleman City area for the grazing of cattle, sheep, and horses. The first canal diversions of surface water in the 1870's, and the first artesian wells put down in the 1880's were primarily for watering of livestock and for irrigation of land for pasture. The land was not irrigated and farmed on a large scale until the First World War.

Although some wells were drilled for stock and domestic water supply as early as 1870 (Mendenhall and others, 1916, table 45), the first known artesian well in the Los Banos–Kettleman City area was drilled in 1886. At the time of the first Geological Survey well canvass in the San Joaquin Valley in 1905–6, 14 flowing artesian wells were reported in the area. In 1905, a well 2 miles west of Tranquillity was described as having a head sufficient to raise a column of water at least 22 feet above land surface. In 1914, artesian flows of more than 1,000 gallons per minute were measured from wells in the trough of the valley. In 1919, the water level in the San Joaquin City well was 19 feet above the land surface. These facts suggest that artesian-head decline was minor in the valley trough between 1905 and 1919.

The use of ground water for irrigation expanded rapidly in the early 1920's, initiating a rapid decline in artesian pressures. The last report of a flowing well in the Los Banos–Kettleman City area was in the winter of 1925–26. By this time 170 wells had tapped the confined aquifer system. In sec. 28, T. 19 S., R. 19 E., where there had been a flowing well in 1905, the static level was at a depth of 50 feet in 1926, indicating a mean head decline of about 3 feet per year.

The first areas to use ground water for diversified agriculture were near Oro Loma, Mendota, Westhaven, and along Fresno Slough. The general areas of early ground-water development are shown in figure 21. In 1915, the area to the west of Oro Loma was subdivided into small tracts which were irrigated with water from 12 wells.

In 1917, the Boston Land Co. began irrigation of 10,000 acres near Westhaven in the southern part of the area, and by 1924, 54 irrigation wells had been drilled on the property. Information about these wells is available in an unpublished report made by H. L. Haehl and Hyde Forbes for the Boston Land Co. in 1926.

In 1926, more than 170 wells had tapped the lower-

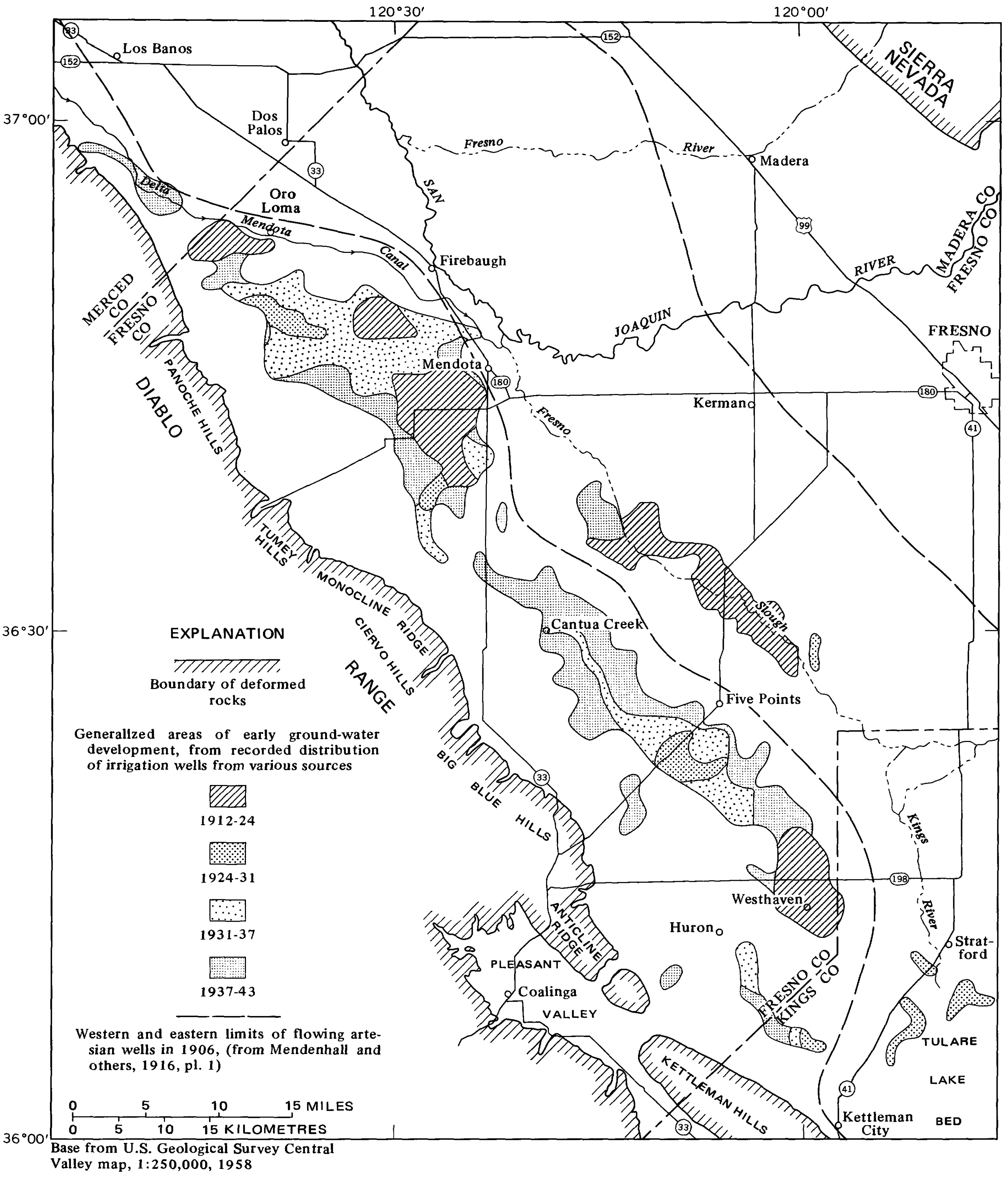


FIGURE 21.—Areas of early ground-water development.

TABLE 3.—*Estimated ground-water pumpage, 1935–66, Los Banos - Kettleman City area*

[Pumpage in thousands of acre-feet; for agricultural year beginning April 1 and ending March 31; data chiefly from Pacific Gas and Electric Co. Northern district is area from Fresno-Merced county line to north line of T. 16 S.; Southern district is area from north line of T. 16 S. to Kettleman City. East boundary is San Joaquin River, Fresno Slough, and Kings River]

Year	Northern district	Southern district	Total	Year	Northern district	Southern district	Total
1935–36	115	20	135	1951–52	245	805	1,050
1936–37	130	30	160	1952–53	340	935	1,275
1937–38	140	75	215	1953–54	350	840	1,190
1938–39	150	110	260	1954–55	315	750	1,065
1939–40	145	130	275	1955–56	405	725	1,130
1940–41	140	130	270	1956–57	430	775	1,205
1941–42	135	145	280	1957–58	385	775	1,160
1942–43	150	170	320	1958–59	405	700	1,105
1943–44	165	175	340	1959–60	375	765	1,140
1944–45	175	175	350	1960–61	370	720	1,090
1945–46	180	190	370	1961–62	345	685	1,030
1946–47	200	255	455	1962–63	375	730	1,105
1947–48	240	355	595	1963–64	360	685	1,045
1948–49	235	410	645	1964–65	330	780	1,110
1949–50	255	590	845	1965–66	310	675	985
1950–51	305	695	1,000				

zone waters in the Los Banos–Kettleman City area. By 1937, about 250 wells were pumping from the lower zone, and by 1942 the number had increased to at least 350. In 1960, there were about 1,100 active irrigation wells, most of which were pumping from the lower zone.

Irrigation with ground water expanded rapidly during the early 1920's, but a low level of commodity prices in the late 1920's and early 1930's discouraged further agricultural expansion. After 1936, a renewed expansion occurred, and pumpage increased rapidly until World War II.

The increase in the irrigated area since about 1940 is shown in figure 22. The growth of the ground-water service areas expanded most rapidly between about 1940 and 1950. Most of this expansion was associated with the high prices paid for crops after World War II. By 1955, most of the available land had been placed under cultivation. Since 1955, the irrigated area has edged closer to the foothills of the Diablo Range, particularly in T. 14 S., R. 12 E., and T. 16 S., R. 14 E.

TRENDS IN TOTAL GROUND-WATER PUMPAGE

The total amount of ground water pumped in the study area increased until the early 1950's. Early in the development of the area, the Boston Land Co. pumped an average of 12,500 acre-feet of water per year between 1917 and 1926 (Haehl and Forbes, 1926, unpub. rept.). In 1924, the total annual pumping draft from the area was about 35,000 acre-feet (Davis and Poland, 1957, p. 431).

The ground-water pumpage in the Los Banos–Kettleman City area (excluding the small area north of the Merced County line) is shown in table 3 and figure 23 for the period 1935–65. Pumpage for a northern and southern district is shown, in addition to the total pumpage, in order to illustrate the rapid growth of pumpage in the southern district from 1945 to 1953. Pumpage in the area north of the Fresno-Merced County line was not included because the available figures for electric-power consumption included power used for many surface-water booster plants.

The data for years 1935–36 through 1961–62 were compiled largely by E. J. Griffith, Pacific Gas and Electric Co., Fresno, and were made available through the cooperation of the San Joaquin Power Division, Pacific Gas and Electric Co. The ground-water withdrawals were computed chiefly from the total power consumption per customer per year; and this amount was divided by an average figure for kilowatt hours per acre-foot for each customer as determined from pump efficiency tests for that customer. Pumpage from 1962–63 through 1965–66 has been compiled from a report by Ogilbee and Rose (1969).

Before 1940, most of the ground water was pumped in the northern district, but the rapid expansion of agriculture in the southern district after 1945 caused the pumpage in that district to surpass pumpage in the northern district, and, since 1948, pumpage in the southern district has been about double that of the northern district (table 3).

The total pumping rate increased until 1952–53 when 1,275,000 acre-feet of water was pumped. Since then the total pumpage has declined gradually to about 1,000,000 acre-feet in 1965–66. The end of the period of accelerated pumping coincided roughly with a sharply reduced rate of agricultural expansion. Although some

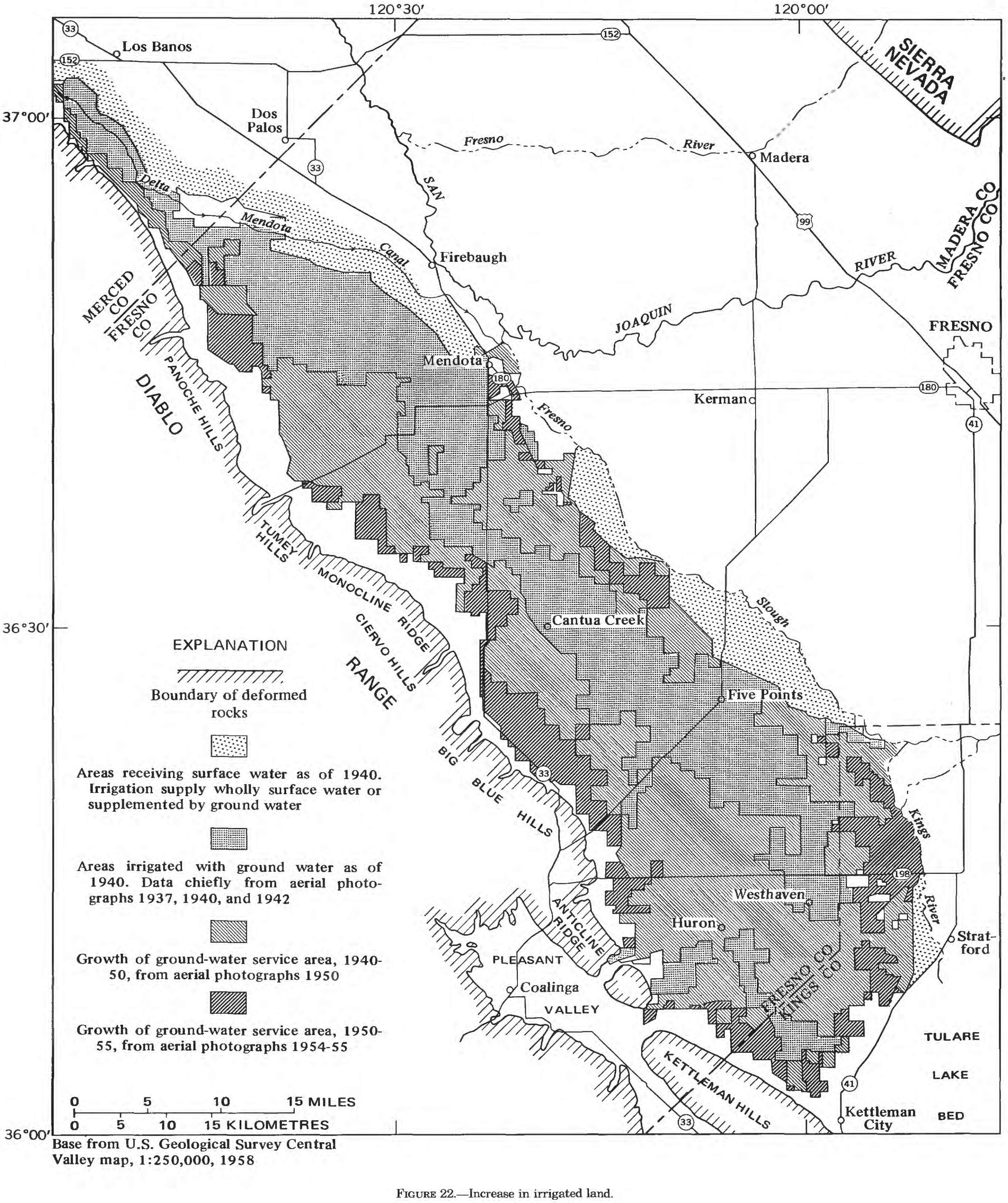


FIGURE 22.—Increase in irrigated land.

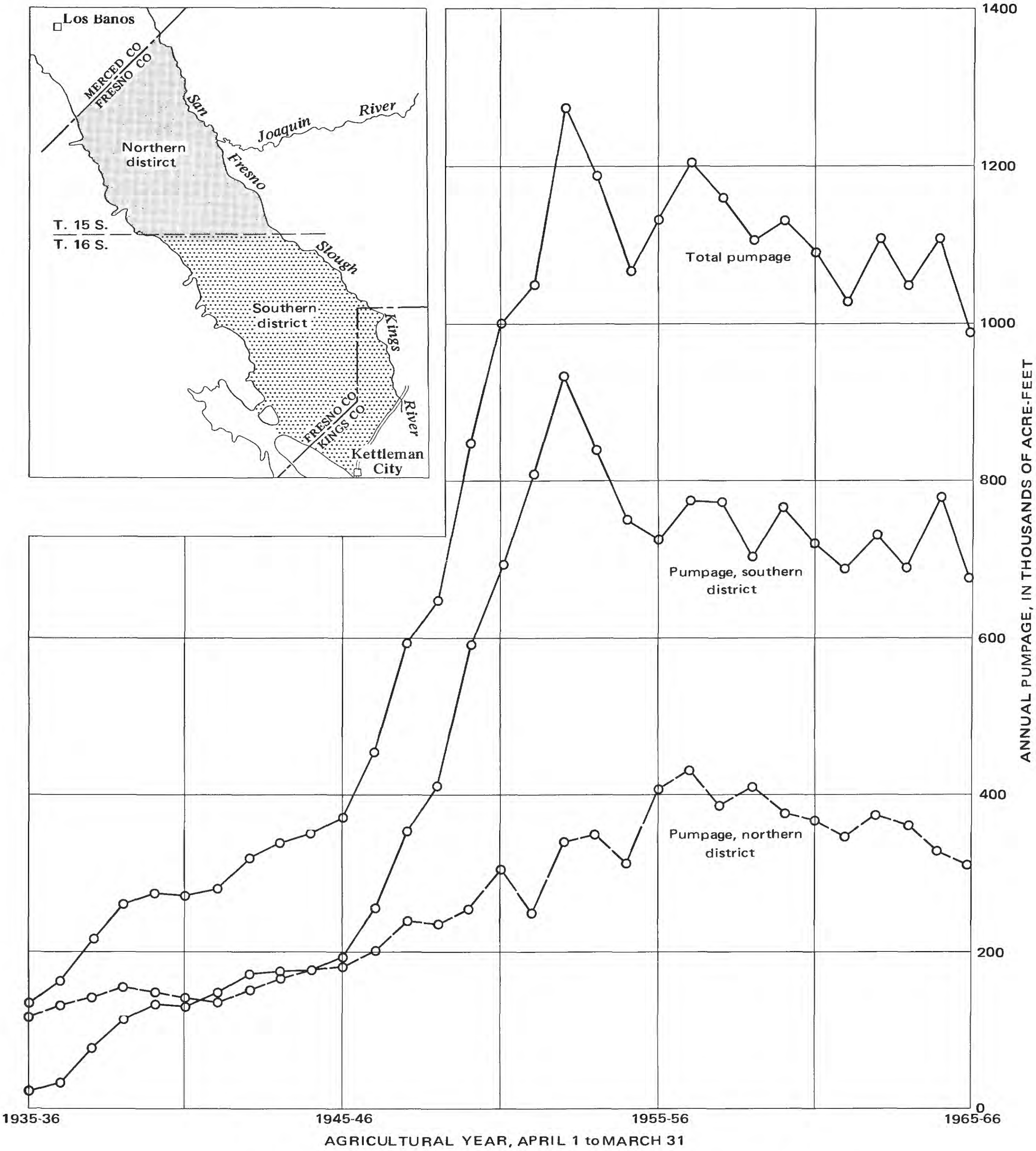


FIGURE 23.—Estimated ground-water pumpage, 1935–66 (area north of Merced County line excluded).

new land has been irrigated for the first time since 1952, the amount of new land is small compared to the overall acreage being irrigated.

The fluctuations in total pumpage since 1952 are largely the result of weather, crop practices, and changes in irrigation procedures. Long hot summers and larger proportions of acreage planted to crops such as alfalfa tend to increase the amounts of water pumped. The trend from furrow to sprinkler irrigation has reduced the amount of water needed to grow a given crop and has required fewer wells because water can be readily transported several miles in pipelines.

The tripling of the overall pumpage since 1945 has resulted in a large overdraft, declining water levels in the zones from which water is being withdrawn, and large amounts of subsidence as water is expelled from unconsolidated sediments to furnish about one-third of the water pumped.

CHANGES IN GROUND-WATER LEVELS

Pumping of ground water and irrigation has changed the water table as well as the water levels in the semiconfined aquifer system above the Corcoran Clay Member and in the confined lower zone. Water-level change varies greatly for the different depth zones of the ground-water reservoir and in the different parts of the area.

The low permeability of the upper-zone deposits, and in some places the inferior quality of the upper-zone water, makes the upper zone generally undesirable as a source of irrigation water. However, in a belt paralleling the trough of the valley from Tranquillity to Stratford, permeable upper zone sands derived from the Sierra Nevada yield good quality water. Many of the wells in this belt are completed only in the upper zone, and they yield ample supplies of irrigation water. Elsewhere in the area many lower-zone wells are perforated opposite sands for a short distance above the Corcoran—a situation that is most common in the southern part of the area.

Water-level trends in three Bureau of Reclamation piezometers east of Mendota at the Yearout site are shown in figure 24 to illustrate water-level trends in the main hydrologic units in the study area. The winter high and the summer low water levels are shown for the period 1951–66. Well 13/15–35D1 reflects the water level of the water table and the upper part of the semiconfined zone. Well 35D2 reflects the water levels in a confined zone above the Corcoran. Well 35D3 reflects lower-zone water-level changes.

Most of the irrigation wells in the vicinity of the Yearout site are perforated only in the upper zone, but a few are perforated in both the upper and lower zones. The result is a 40-foot seasonal fluctuation in the piezometer tapping the upper-zone confined aquifer. The large seasonal fluctuation and the degree of separation between the water levels at well points 100 and 300 feet deep suggest that confinement is good. Water levels in the confined part of the zone did not decline during the early part of the period of record but have declined 8 feet since 1958.

The water level in well 35D1 remained about the same until 1960, but since then it has declined steadily with small seasonal fluctuations. The water-level trend

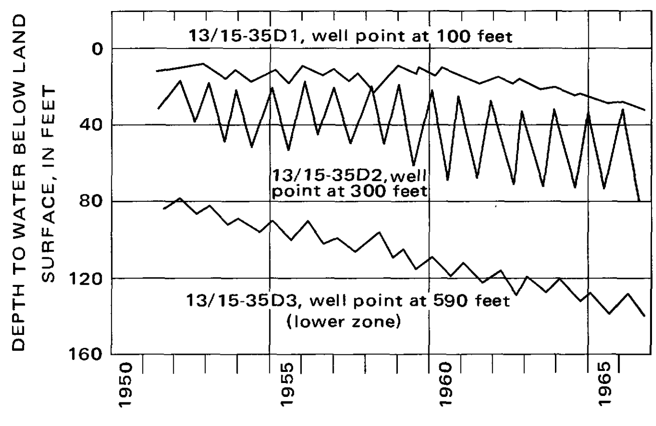


FIGURE 24.—Hydrographs of upper- and lower-zone piezometers at the Yearout site. Data from the U.S. Bureau of Reclamation.

may be representative, but the seasonal fluctuations in well 35D1 are much smaller than in irrigation well 34A1 (325 ft west of 35D1 and perforated at depths of 100–276 ft). Apparently, well 35D1 has limited hydraulic continuity with the adjacent aquifer.

The water levels in the lower-zone well, 35D3, have shown the steadiest and largest decline despite the fact that few wells in the area are perforated in the lower zone. The lack of nearby pumping from the lower zone accounts for the small amounts of seasonal fluctuation of water level. The high winter levels in 1956 and 1958 were coincident with two of the wettest winters since 1870. The 60-foot head decline in 14 years most likely is related to intensive lower-zone pumping farther west. This intensive pumping has produced a steep gradient on the east side of the Los Banos–Kettleman City area which has induced recharge from the east side of the San Joaquin Valley. Hydrographs of wells such as 35D3, from east of Mendota to Stratford, have histories of head decline resulting from the increase in gradient. In most of the project area, the seasonal fluctuation has been larger in the lower than in the upper zone, and water levels have declined more.

THE WATER TABLE

The surface of the unconfined water—the water table—in the Los Banos–Kettleman City area is difficult to define. Very few wells tap only the upper 10–50 feet of the saturated deposits. The lensing, heterogeneous character of the alluvium results in water levels that are not truly indicative of the water table in those wells that tap more than 50–100 feet of saturated alluvium. For example, a 200-foot well may have a gradually rising water level during a 10-year period suggestive of a rising water table that is receiving irrigation water that percolates below the root zone. A nearby 100-foot well may have a more rapidly rising water level, thereby suggesting that it is more indicative of water-table conditions than the 200-foot well.

The minor differences in permeability of adjacent water-yielding beds are such that differences in head can exist between shallow wells during times of heavy pumping. Many of these shallow wells recover to the level of the water table during times of little pumping.

Both semiconfined and perched conditions occur in various degrees. Apparent depths to the water table that are too deep are the result of semiconfinement of part of the beds penetrated by a well. Apparent depths that are too shallow result when the well is tapping a water body that is perched on a lense of fine-grained alluvium. Perched conditions occur where a fine-grained lense allows only part of the water to percolate through it, has unsaturated deposits below it, and saturated deposits above it.

In order to be able to analyze the change in effective stress that causes the subsidence, it is necessary to have knowledge of the changes in the position of the water table as well as the change in conditions in the semiconfined and confined aquifer systems. A rising or falling water table not only can cause expansion or compaction of the unconfined deposits, but also affects the effective stress on the deposits in the confined zone.

The approximate position of the water table was determined by Davis, Green, Olmsted, and Brown (1959, p. 147, 148, pl. 16) on the basis of 1951 measurements and was supplemented by earlier measurements. The approximate position was determined partly by measurements in wells tapping unconfined and semiconfined zones and was supplemented by estimates of the top of the zone of saturation based on electric logs. The depth to water was less than 10 feet in a large area along the trough of the valley from Tranquillity to Los Banos. In general, the depth to water increased from east to west, and near the foothills of the Diablo Range the depth to water was more than 300 feet. These authors concluded that the position of the water table had remained approximately constant, declining slightly in some areas and rising some in others (p.147). A comparison of the altitude of the water table in 1951 (Davis and others, 1959, pl. 15) with the altitude of the water table in 1906 as plotted by Mendenhall (Mendenhall and others, 1916, pl. 1) suggests less than 20 feet of change in the position of the water table in the 46-year period. The water table declined as much as 20 feet in the southern part and rose as much as 20 feet in the northern part of the Los Banos–Kettleman City area.

The Bureau of Reclamation has been obtaining more recent information regarding the water table, as part of projects to bring large amounts of surface water into the area in the Delta-Mendota Canal and the San Luis Canal. The raising of the water table to near the land surface will require that drainage systems be built in order to continue growing crops. The Bureau of Reclamation has drilled or augered more than 100 shallow wells to obtain information about water-levels in the unconfined zone. As a result of these studies, post-1961 water-table information is available for most of the area downslope from the San Luis Canal.

The depth to shallow ground water in 1965 is shown in figure 25. Water levels in most of these wells approximate the water table, but for many wells it is not possible to determine the presence of perched or semiconfined conditions that might affect the water level to a minor degree. Most of the data northeast of the San Luis Canal were obtained from the Bureau of Reclamation. Electric logs of water wells drilled in the mid-1960's were used to determine the depth to the water table in most of the area west of the canal.

The general pattern of the depth to water is much the same as in 1951, with depths of more than 200 feet to water suggested by the map in the western part of the area. West of Huron, the depth to the water table exceeded 500 feet in 1965. The area of depths to water greater than 400 feet at the mouth of Los Gatos Creek coincides with an area of permeable coarse-grained deposits laid down on the ancestral alluvial fan of Los Gatos Creek. Little confinement is present in this area, and the great depth to the water table is the result of water-table declines caused by pumping of wells perforated at depths of more than 1,000 feet. Davis and Poland (1957, p. 429–430) note that the low water temperatures and high sulfate content of the water suggests that recharge from Los Gatos Creek is able to reach the deposits tapped by wells. A similar situation probably exists at the mouth of Cantua Creek.

Water levels were shallow in the eastern half of the area, the depth to water north of Five Points being less than 20 feet, and south of Five Points less than 50 feet. The area in which the depth to water was less than 10 feet was larger than in 1951.

The change in the depth to shallow water between 1951 and 1965 can be obtained in a general way by comparing the 1951 and 1965 maps, as has been done in figure 26. Considerable variation in the trends of shallow water levels are apparent in the different parts of the area. In the northern part of the area, water levels have risen from less than 25 feet to more than 100 feet. A large area in which the water table has risen more than 50 feet extends from the town of Cantua Creek to 15 miles west of Mendota. In 1951 the water table in this area was generally at a depth of about 100–150 feet.

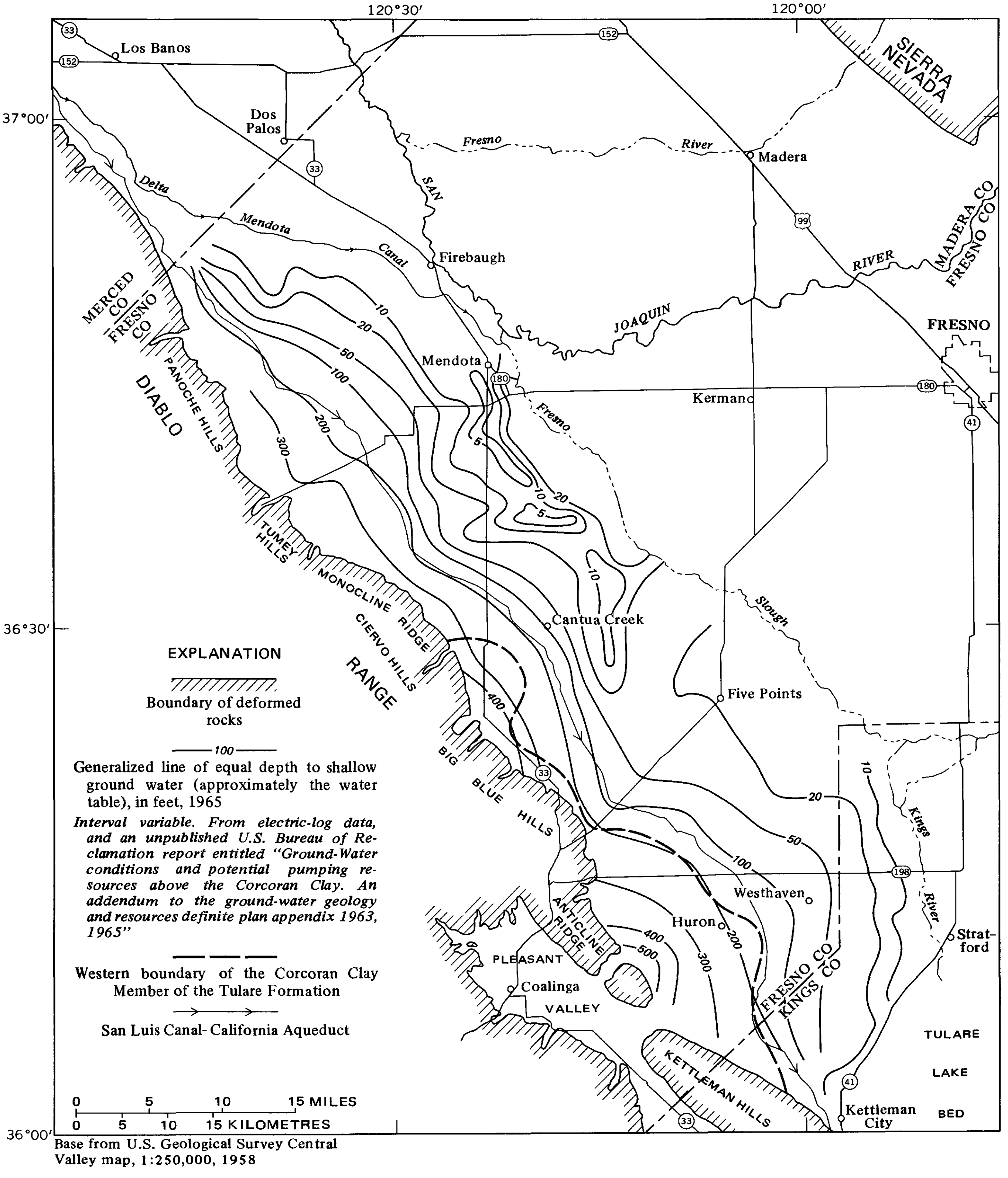
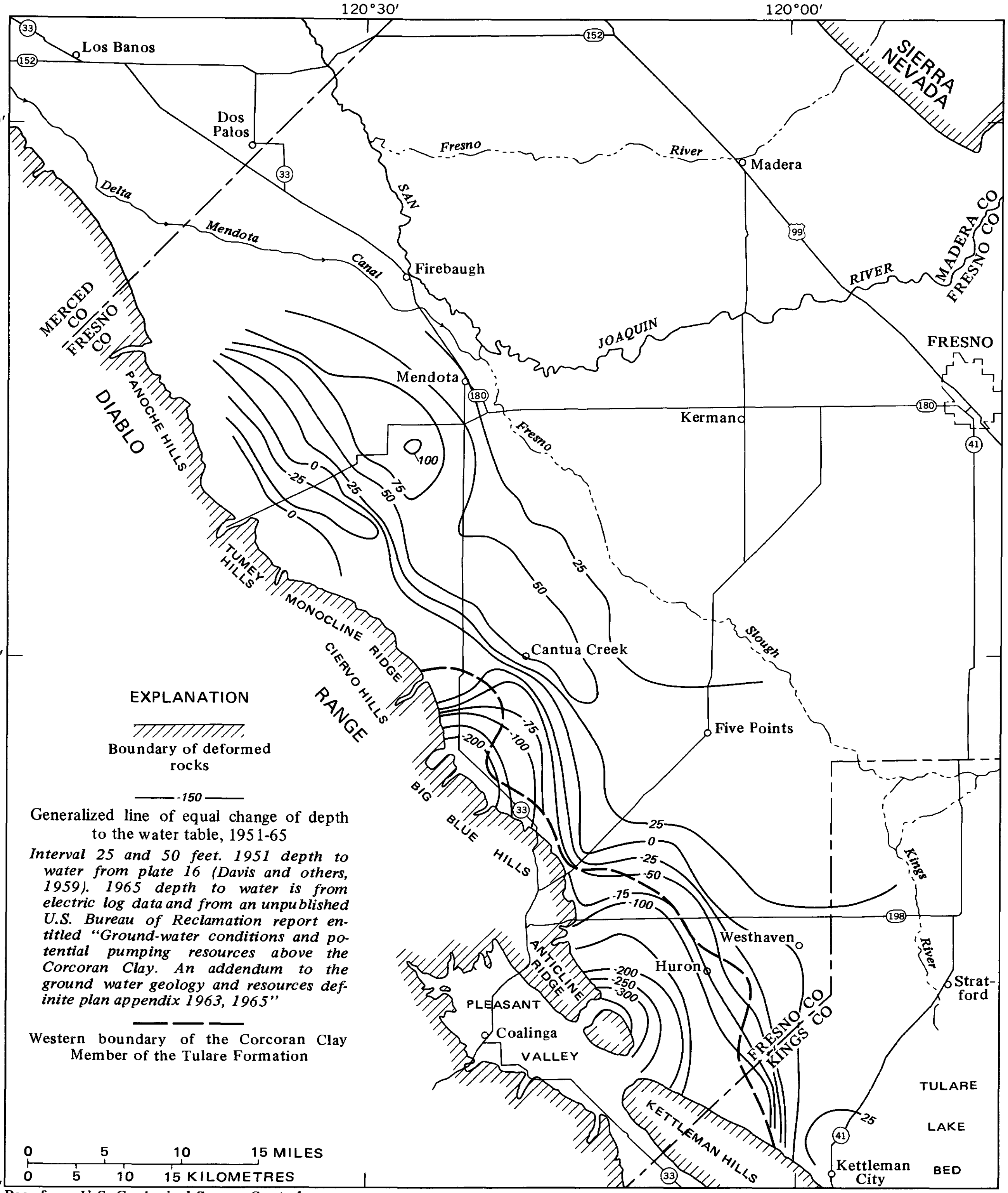


FIGURE 25.—Depth to shallow ground water, 1965.



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

FIGURE 26.—Change in depth to the water table, 1951–65.

Outflow of water accumulating in the upper zone occurs as (1) movement of water toward Fresno Slough and the San Joaquin River, (2) westward movement toward areas of lower ground-water table that are present because of lesser amounts of water being received from irrigation or because the water table has been lowered by pumping; and (3) downward flow through the Corcoran in gravel packs around well casings and through broken well casings.

Water-level rises have been much less along the trough of the valley where many wells are perforated in the upper zone. The water table has risen less than 30 feet in most of this area.

In the southern part of the area, the depth to shallow water has increased southwest of Westhaven and has decreased northeast of Westhaven. The areas in which the depth to water was less than 40 feet in 1951 had a shallower water table in 1965, but the rise has not been large because the water table was close to the land surface in 1951.

Water-table decline occurred in the area west of the Corcoran. The effects of water-table decline west of the Corcoran have resulted in water-table declines for as much as 5 miles east of the western boundary of the aquiclude and may have influenced the rates of water-table rise for even greater distances to the east. The area of 250 to more than 350 feet of water-table decline at the mouth of Los Gatos Creek coincides with the area of maximum depth to water shown in figure 25.

The overall pattern of water-table decline in the southern part of the area and of water-table rise in the northern part was the same as for the 1906–51 period.

Three hydrographs of water-table wells are shown in figure 27. Each of these water levels is believed to be representative of water-table conditions although part of the perforations may be opposite beds in which the water is semiconfined. Wells 14/13–11D3 and 16/15–34N5 are at the Mendota and Cantua recorder sites. Well 12/13–32A2 shows the steady rising trend that is characteristic of the water table in most of the northern part of the area. Well 14/13–11D3 had a rising water level until 1964; since then the water table has declined. Well 16/15–34N5 has had a fairly constant or slightly rising water table—a situation that apparently has existed at the Cantua site since at least 1952 (fig. 27) and possibly since 1906 (Mendenhall and others, 1916, plate 1) when the depth to water in shallow wells in the vicinity was about 165 feet.

THE UPPER-ZONE SEMICONFINED TO CONFINED AQUIFER SYSTEM

Roughly 25 percent of the water pumped in the Los

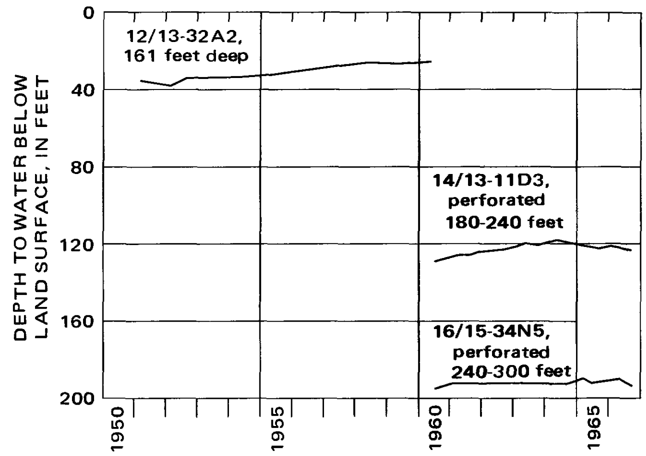


FIGURE 27.—Hydrographs of wells perforated in the unconfined zone.

Banos–Kettleman City area is withdrawn from the upper zone. The areal distribution of water withdrawal is not uniform, as is shown by figure 10. In some areas, water is pumped entirely from below the Corcoran, and in other areas water is pumped entirely from above the Corcoran. In most of the area, and particularly south of Five Points, water is pumped from both the lower and upper zones. Most of the lower-zone wells that have perforations in the upper zone are perforated immediately above the Corcoran. In general, there is an improvement in water quality and an increase in permeability of the deposits with depth in the upper zone, and in parts of the area the water obtained from immediately above the Corcoran is as usable for irrigation as the lower-zone waters.

In most of the area, a large downward head differential has developed across the Corcoran confining clay as a result of lower-zone pumping. Downward head differentials of 100–200 feet may be common in much of the northern part of the area. Water levels in wells tapping the lower zone and the base of the upper zone can be compared at two locations. Hydrographs for wells 15/14–15E3 (fig. 28), tapping the upper zone, and 15/14–14J1 (fig. 44), tapping the lower zone, suggest a downward head differential of about 120 feet in 1965. Farther east at the Tranquillity site, in 1967 the water level in a well perforated a short distance below the Corcoran was 120 feet deeper than a well tapping the base of the upper zone.

However, in the southern part of the area, head declines in the upper zone have been large where upper-zone water has been pumped intensively for irrigation. Observation wells tap both the upper and lower zones at the Westhaven site (figs. 3 and 14). The well tapping the sands (well 20/18–11Q1) immediately above the Corcoran has a deeper water level than the lower-zone wells (fig. 14). The record for well 11Q1 shows about the same seasonal fluctuation as for the lower-zone wells. This situation may represent pumping from a confined lense of sand of limited extent that is not connected with permeable beds leading to recharge areas. Upward gradients across the Corcoran may be fairly common in the southern part of the study area. At the Lemoore site, downward gradients of as much as 40 feet are present in the winter, but small upward gradients are present in the summer.

The degree of confinement southwest of the edge of the Corcoran is highly variable. The head differential, as of 1943, between the water table and water levels in deep irrigation wells suggests only moderate lower-zone confinement in the area west of Huron (Bull, 1974). Head differentials in this subarea ranged from less than 50 feet to more than 100 feet.

Hydrographs of three upper-zone Bureau of Reclamation piezometers are shown in figure 28. The three records are markedly different. The hydrographs illustrate the differences of confinement and separation of water bodies that occur in the upper zone as a result of heterogeneous lensing deposits derived from different sources. The summer low- and winter high-water levels have been used for the hydrographs.

Well 15E1 shows little seasonal fluctuation and shows a steady rise in water level. Although this well taps both unconfined and semiconfined water, the record represents chiefly semiconfined conditions. The water table at the location has risen twice as much during the same period.

Well 15E2 has a record of consistent seasonal fluctuations of 10–20 feet. The overall trend has been up, but the water-level rise has not been as much as in well 15E1. Deposits within the depth interval tapped by well 15E2 probably have a moderately good degree of confinement, but the amount of seasonal fluctuation is low because few nearby wells are perforated in this interval.

Well 15E3 has a record of erratic seasonal fluctuations that exceed 80 feet in some years. The fluctuations indicate that water levels in this confined depth interval are influenced by irrigation wells in the vicinity that are pumping in part from the basal upper zone. An overall decline of water levels has occurred for this zone, which is immediately above the Corcoran.

The hydrographs in figure 28 show why it is impossible to make water-level maps, or water-level change maps, for most of the upper zone, in an area that is as large as the Los Banos–Kettleman City area. Even if abundant water-level data were available for the many different units within the upper zone, consistent results could not be obtained for more than a few miles because

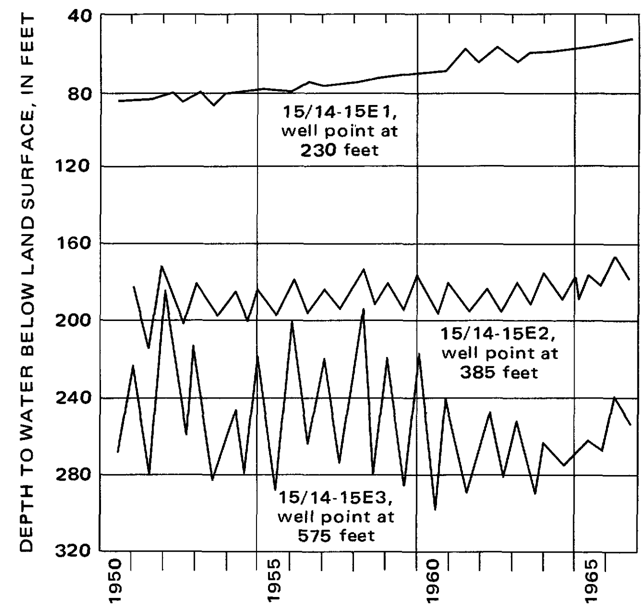


FIGURE 28.—Hydrographs of upper-zone piezometers at 15/14–15E. Data from the U.S. Bureau of Reclamation.

of the many semiconfining beds of low permeability.

Hydrographs of two unused irrigation wells perforated in the upper zone are shown in figure 29. The rising trend in the water levels of well 13/14–17N2 is a result of recharge from irrigation water, which in this area is obtained largely from surface-water sources. The shallow water level in 1959 appears to represent mainly water-table conditions. Later in the same year, however, the water level rose rapidly to a depth of only 8 feet, probably as a result of a casing break that permitted unconfined water to dominate the water level. The abrupt rise in water-level indicates that the water tapped by this well was semiconfined although the well is only 196 feet deep.

Well 15/16–20R1 was initially drilled to pump from both the upper and lower zones. Casing failures termi-

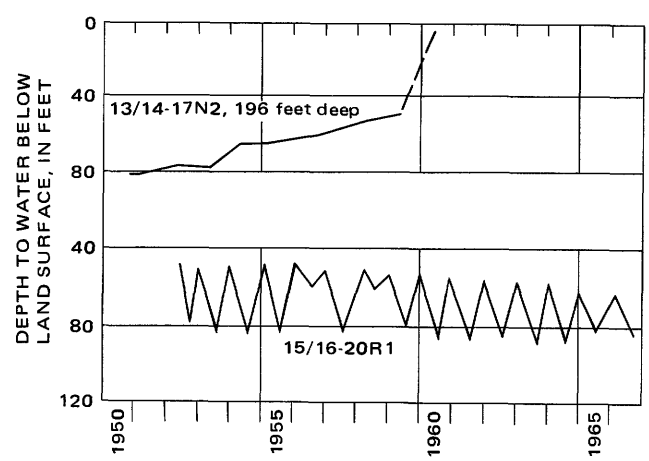


FIGURE 29.—Hydrographs of wells perforated in the upper zone.

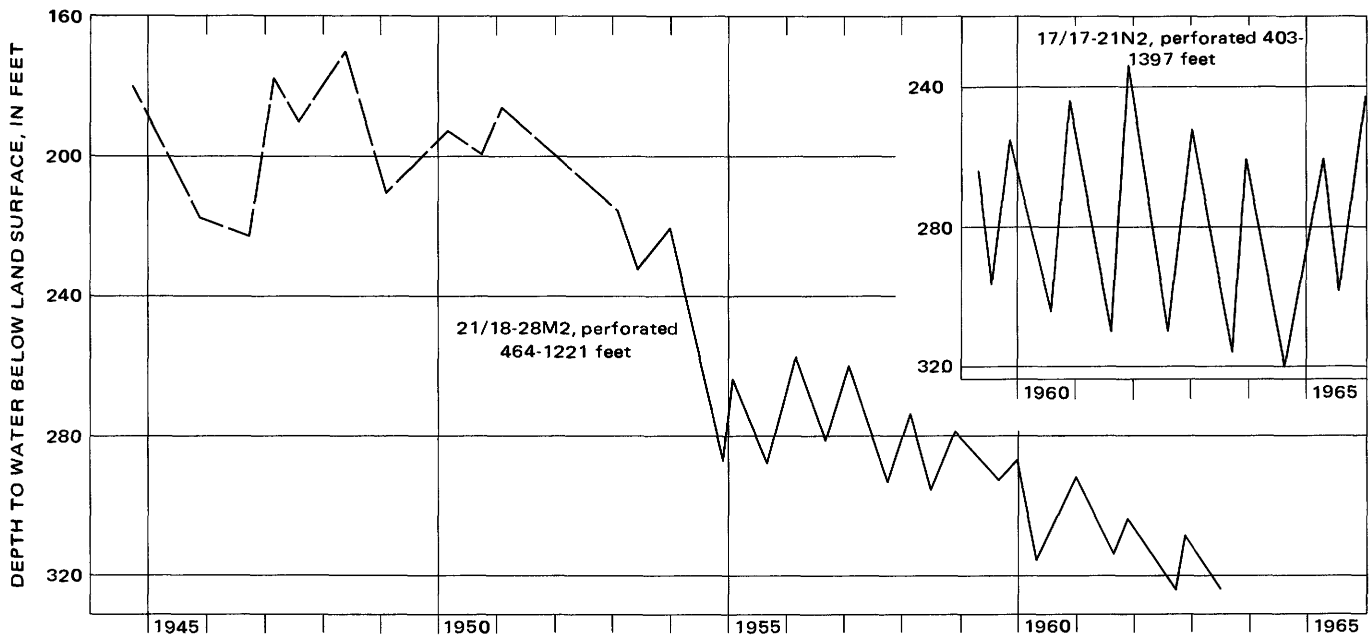


FIGURE 30.—Hydrographs of wells perforated in both the upper and lower zones.

nated the use of this well for irrigation purposes and apparently sealed off the lower-zone waters. Another well, 1 mile away, that is representative of the lower zone has a water level more than 100 feet deeper than that of well 20R1.

The winter high- and the summer low-water levels for well 20R1 have been obtained from a recorder that has been operating continuously since 1952. The consistent seasonal fluctuation of about 30 feet probably is representative of the upper zone, which is heavily pumped in the vicinity. The depth interval at which water moves in and out of the well casing is not known, but the large seasonal fluctuation indicates that the zone has good confinement. In 1956 and 1958, the summer low-water levels were abnormally high. These summers followed exceptionally wet winters. In these 2 years, a surplus of irrigation water from the Kings River was available for use in the vicinity, and apparently little ground water was pumped. The overall trend of the water level has been down—declining 10–13 feet in 12 years.

Water levels in wells that tap both the upper and lower zones are shown in figure 30. The large seasonal fluctuation in well 17/17–21N2 is characteristic of irrigation wells southwest of Five Points. A declining trend of water levels is characteristic of the lower zone in this part of the area (fig. 45B), but the record obtained from well 21N2 is too short to show a well-defined water-level decline. The availability of the unused well probably was in part due to the fact that it was no longer usable for irrigation purposes. Casing breaks that shut off production from the deeper aquifers are common in the area; therefore, the record for well 21N2 probably is representative of a much higher depth interval than indicated by the full perforated interval. As a result of the record obtained from this and other unused wells and the consistently high water levels noted in most unused irrigation wells during well rounds, it has been concluded that most unused wells are of dubious value for obtaining representative water-level records in a subsidence area.

The record for well 21/18–28M2 was obtained from the California Department of Water Resources. This well is adjacent to Kettleman Hills and near the west edge of the Corcoran. Water levels in this area did not decline until the early 1950's when agricultural development of the area near the Kettleman Hills expanded rapidly and numerous wells were drilled. A steady overall decline of about 6 feet per year has occurred between 1955 and 1963, and hydrographs of other wells in the vicinity (fig. 47) show that the decline was continued at about the same rate through 1965.

In general, not many mixed-zone wells were monitored because of the difficulty of determining the relative effects of the heads in the upper and lower zones. The differences in head and permeability of the various water-yielding beds make it difficult to use perforated interval in more than a general way to determine the effect of upper- or lower-zone head on the composite water levels or on the amounts of seasonal fluctuation.

THE LOWER-ZONE AQUIFER SYSTEM

The Corcoran Clay Member of the Tulare Formation provides excellent confinement for artesian pressures in nearly all of the Los Banos–Kettleman City area (see fig. 12). The thick sequence of alluvial deposits below the Corcoran furnishes roughly three-quarters of the irrigation water pumped in the area. Overdraft has resulted in large declines in head in the lower zone, and it is here in the lower zone that three-fourths of the compaction that causes subsidence occurs. Fortunately, a large amount of water-level data is available for the lower zone, and a measurement of a single well is likely to be representative of the potentiometric head in the vicinity because the hydraulic continuity within the lower zone is good in most of the area (fig. 14).

Changes In The Potentiometric Surface

The potentiometric surface was nearly flat prior to the pumping of ground water. On the basis of measurements made in 1906, Mendenhall, Dole, and Stabler (1916) estimated that the potentiometric surface sloped 2–5 feet per mile to the east and had a northward component of slope along the trough of the valley of about 1½ feet per mile.

By the time that Haehl and Forbes made their study for the Boston Land Co. in 1926, the potentiometric surface had been lowered, particularly in areas irrigated with lower-zone water. Generalized contours of the potentiometric surface in the southern part of the area as of 1926 are shown in figure 31. The three major depressions of the potentiometric surface coincide with the areas of early agricultural development (fig. 21). Similar pumping depressions probably existed in the areas of early development west of Mendota: these are indicated by scattered measurements made in about 1929. Unfortunately, the density of the control points is insufficient to permit contouring of the potentiometric surface north of the area studied by Haehl and Forbes.

With the expansion of agriculture, measurements were made available through the pump-efficiency tests made by the Pacific Gas and Electric Co. The static and 10-minute recovery levels made by this company in 1943 are numerous enough to permit preparation of a map of the lower-zone potentiometric surface (fig. 32).

The 1943 map shows that the trough of the potentiometric surface in the southern part of the area had moved west of the 1926 position and that a pronounced trough in the potentiometric surface extended from Tulare Lake bed to the Merced-Fresno County line. Part of the potentiometric surface southwest of Firebaugh had been depressed to below sea level. Pumping overdraft within the area had established a recharge gradient of 13–35 feet per mile along the east side of the area.

A widespread survey of the area was made by the U.S. Coast and Geodetic Survey in 1943. Thus, the 1943 vertical control and water-level control provide a base for comparison with more recent years.

By 1960 the gradient had steepened to 18–44 feet per mile, and the trough of the pumping depression had moved even further west (fig. 33). The westward migration of the trough of the pumping depression shown in figures 31–33, 35, and 36 is in the same direction as the increase in irrigated area shown in figure 22. By 1960 the potentiometric surface had been depressed below sea level in virtually all the area, and much of the area along the trough of deepest water levels was more than 250 feet below sea level.

Northwest of Mendota the potentiometric surface was not at its historic low in 1960 because initiation of surface-water deliveries by the Delta-Mendota Canal in 1954 had decreased the amount of ground water pumped, thereby causing water levels to rise locally. The minimum altitude of the potentiometric surface in the area northwest of Mendota is based on historic low-water levels measured prior to 1960—mainly in the middle 1950's.

The time of year in which the water levels are measured has a distinct influence on the altitude and configuration of the potentiometric surface. The lower-zone seasonal fluctuation within the study area ranges from less than 10 feet to more than 150 feet, therefore it is desirable to make water-level measurements in the area either at the winter high-recovery level or at the summer low-recovery level caused by intensive pumping. Numerous and well-spaced static measurements are much easier to obtain in December when most of the wells are shut down—a factor that contributes to an accurate map. Static measurements are not easy to obtain in August when most of the wells are pumping, but measurements made in August are more meaningful because they are made at the times of maximum applied stress and maximum compaction rates. Instead of summer static measurements, static levels (actually 10-minute recovery levels) made by the Pacific Gas and Electric Co. as part of pump-efficiency tests were used. By using selected measurements made in those months of the year in which there is intensive pumping (early spring and the summer), the minimum altitude of the potentiometric surface shown in figure 33 was obtained. The 1960 measurements were supplemented in part by measurements made in the summer of 1959, and in areas where no Pacific Gas and Electric Co. measurements were made, spring measurements made by the U.S. Geological Survey were used. Most of the spring

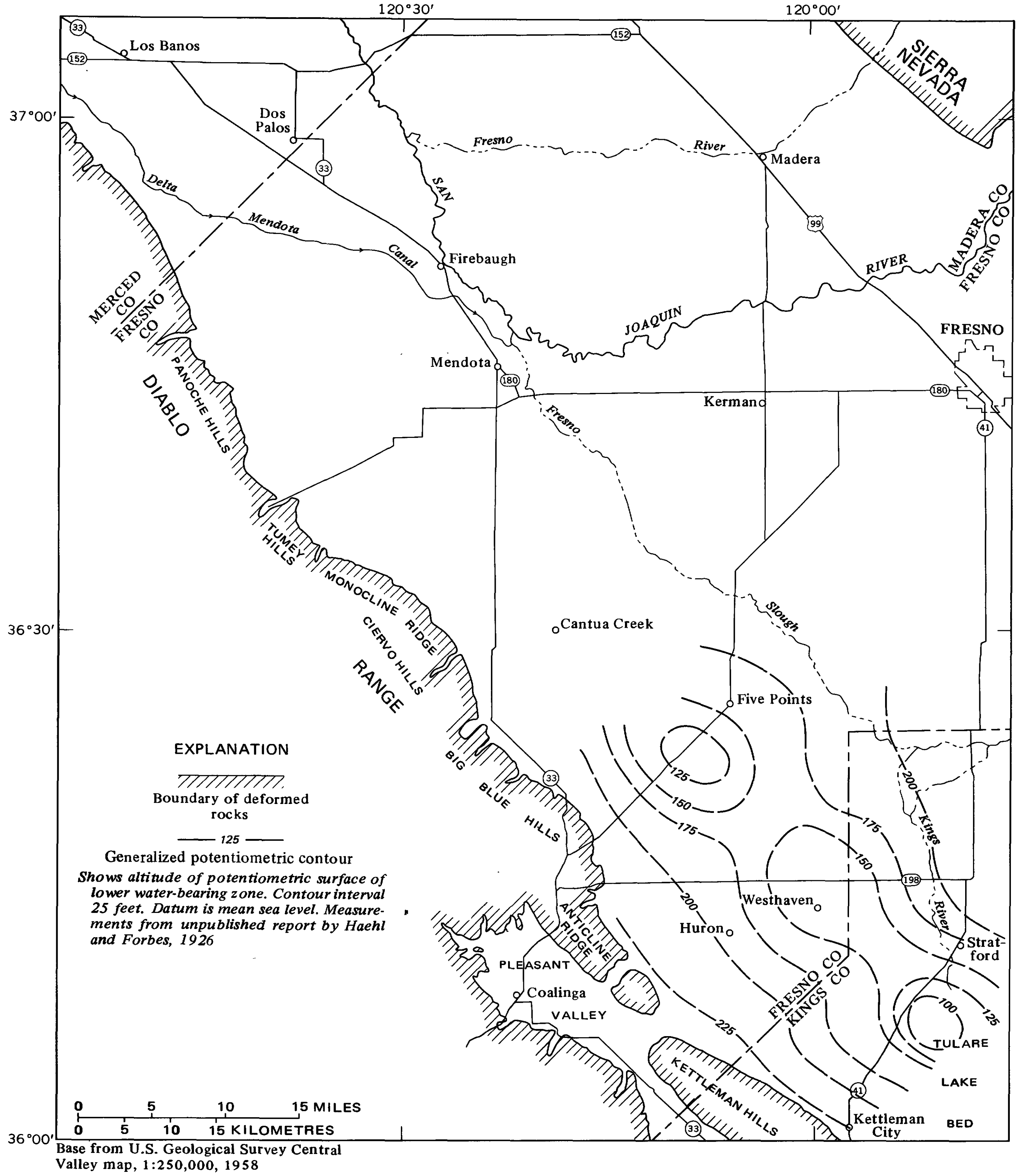


FIGURE 31.—Water-level contours for the lower zone or its stratigraphic equivalent, 1926.

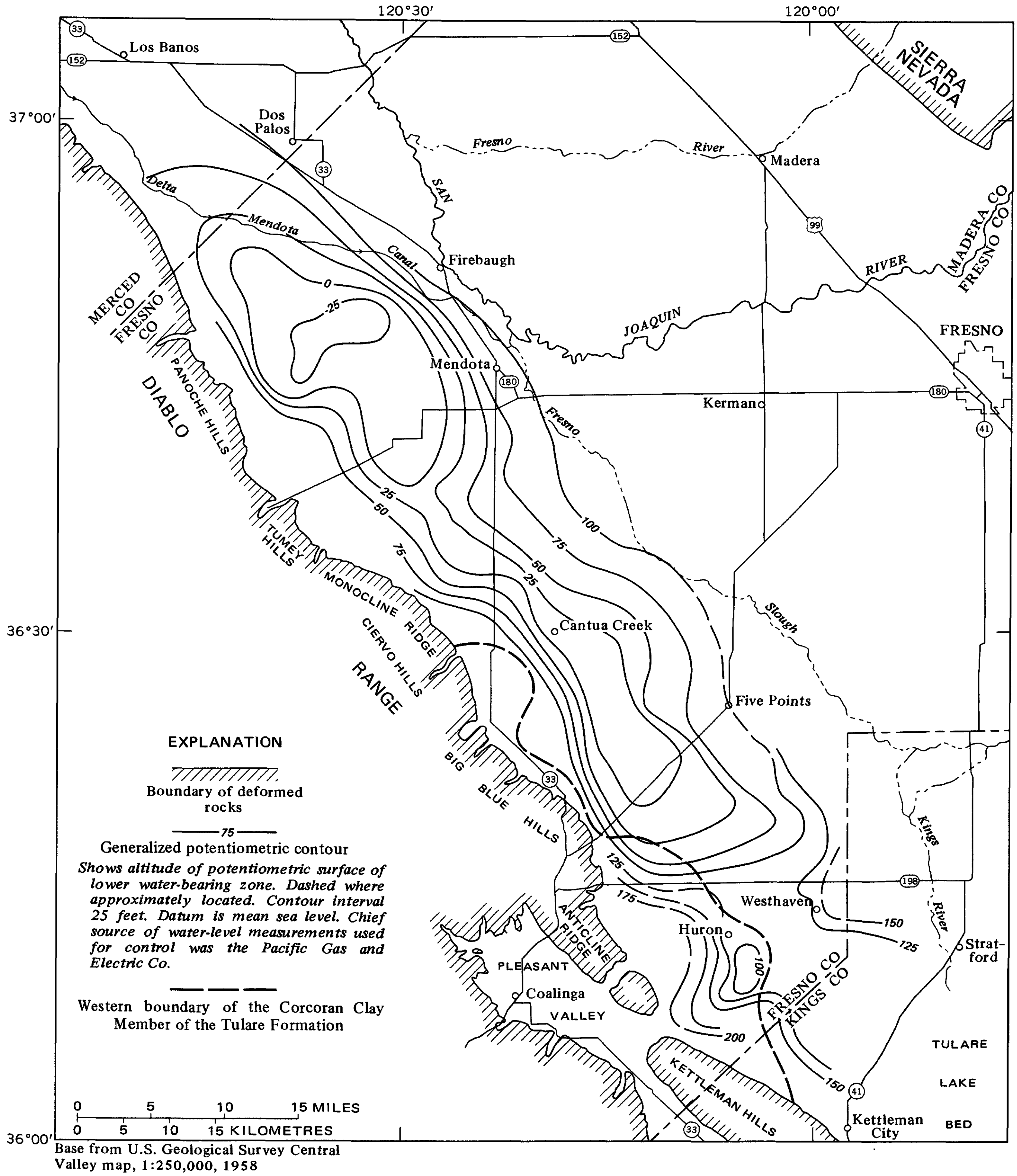
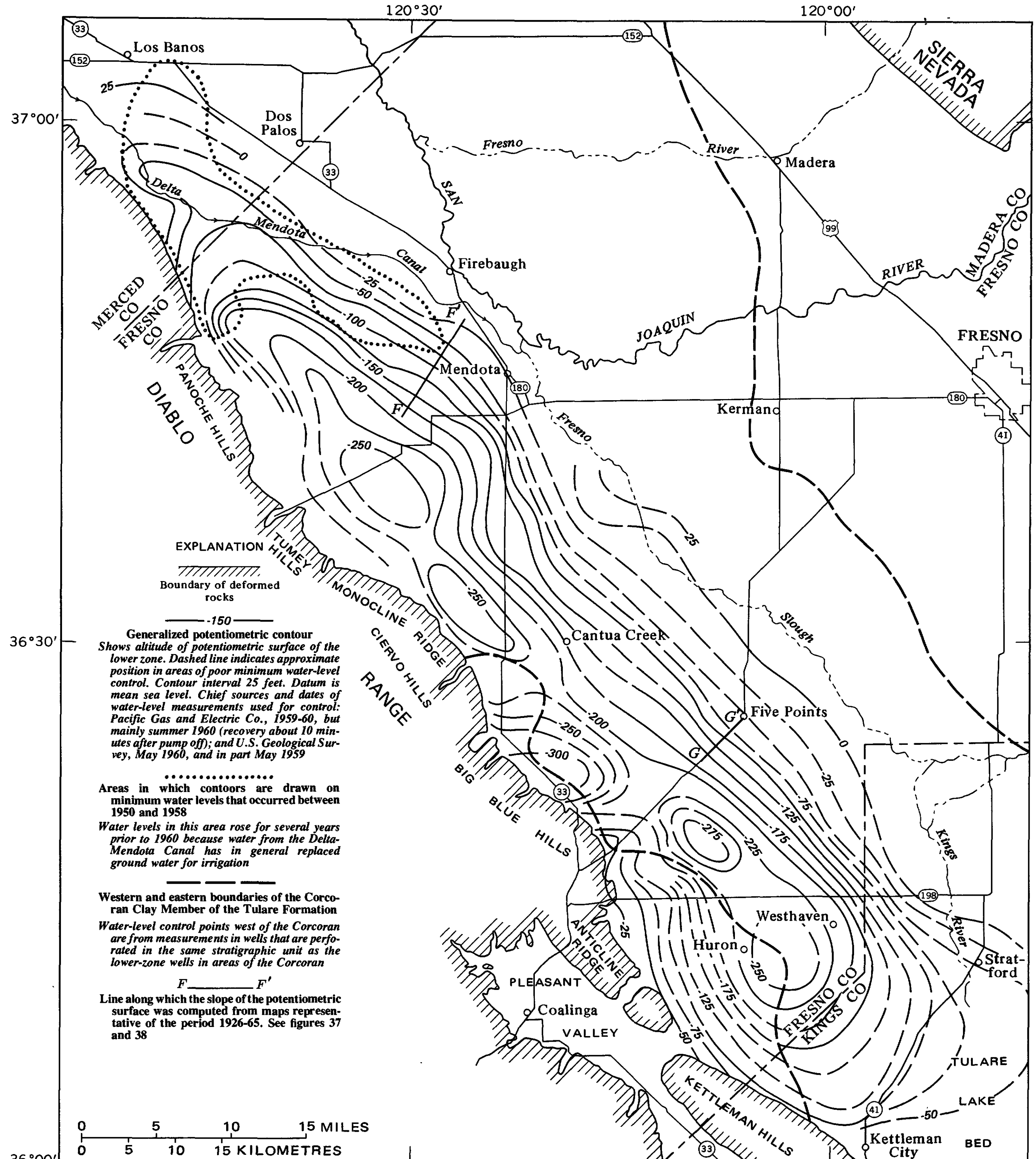


FIGURE 32.—Water-level contours for the lower water-bearing zone, 1943.



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

FIGURE 33.—Minimum altitude of the potentiometric surface of the lower zone as of 1960.

measurements were not made at times of maximum pumping, and those parts of the map are dashed.

The 1943 map is also based on measurements made by the Pacific Gas and Electric Co. The measurements were made at various times of the year, but mainly during times of maximum pumping. Thus, the 1943 map is more representative of the summer lows than of the winter highs.

Although the decline had been large as of 1960, sufficient pressure remained in the lower zone to cause water levels in wells to rise above the base of the Corcoran in most of the area. The artesian head of the lower zone as of May 1960—a time of seasonally high water levels—is shown in figure 34. Artesian head of 300–500 feet above the base of the Corcoran still existed in most of the study area. The amount of head present decreased to the southwest. In the southern part of the area, 200–400 feet of head was still present at the western boundary of the Corcoran. In the central part of the area, the lower-zone head was less than 100 feet near the mouth of Cantua Creek. The lower-zone water levels were more than 200 feet below the base of the Corcoran adjacent to the Diablo Range in the northern part of the area where the Corcoran has been strongly folded (fig. 13). Water-table conditions exist where the lower-zone water levels have declined below the base of the Corcoran if deeper confining beds are not present.

The decline of lower-zone water levels below the base of the Corcoran does not greatly change the rate of increase of stress being applied to the lower zone, however, the processes of stress increase are changed markedly. During water-level declines under confined conditions, increase in applied stress equal to 1 foot of water will occur for each foot of additional decline in artesian head. The process involved is one of increased seepage stress equal to the magnitude of the head differential. After the lower-zone water levels have declined below the Corcoran, further decline in head does not cause further increase in seepage stress. Instead the applied stresses are increased as a result of two other types of processes. Under the assumptions specified in the section "Stresses Tending to Cause Compaction," removal of buoyant support of the grains in the aquifers during the course of dewatering will cause an increase in applied stress equal to 0.6 foot of water for each foot of additional water-level decline. Added to this stress increase is 0.2 foot of water that results from part of the intergranular water changing from a neutral to an applied stress condition—the amount being equal to the water of specific retention.

The overall effect of lower-zone water levels dropping below the Corcoran and then continuing to decline is a decrease in the rate of stress application of about 0.2 foot per foot of additional water-level decline. The amount of increase in applied stress under such conditions has decreased from 1.0–0.8 foot of water per additional foot of lower-zone water-level decline.

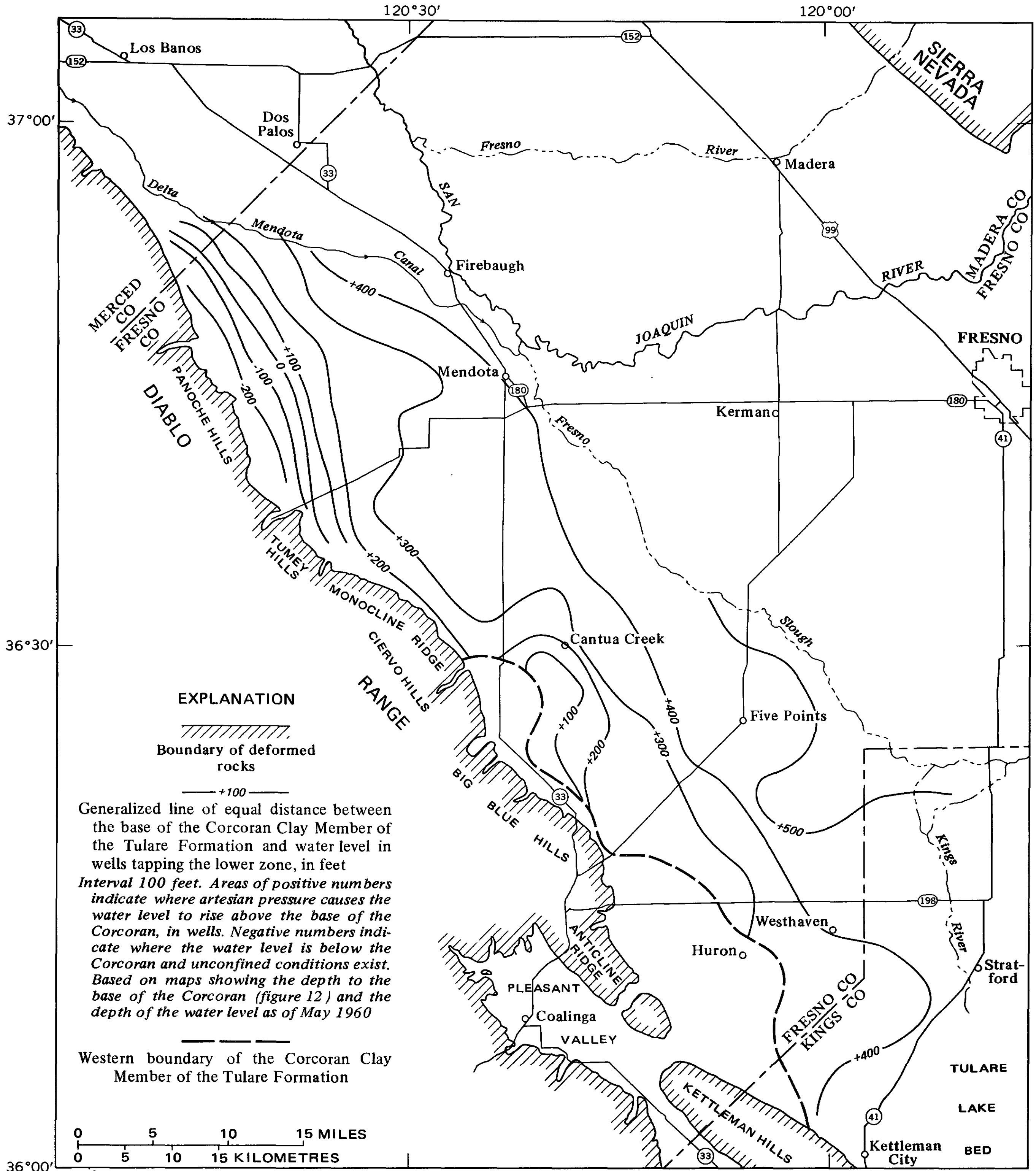
The 1962 map (fig. 35) is representative of the winter high in the potentiometric surface, and all the measurements were made in about a week. In most of the area, the December 1962 potentiometric surface is higher than in the summer of 1960.

The lowest part of the potentiometric surface was northeast of the Big Blue Hills where the surface was more than 325 feet below sea level. The gradient along the east side of the area was more uniform and had a more gentle slope than in the summers of 1943 and 1960. In December 1962, the gradient ranged from 22 to 33 feet per mile. The trough of the potentiometric surface was farther west than in earlier years, and it was narrower than the troughs in the summers of 1943 and 1960.

The water-level measurements of December 1962 and December 1965 were made 2–4 months before the bench-mark network was releveled by the Coast and Geodetic Survey. The potentiometric surface just before the 1966 releveling of the bench-mark network, is shown in figure 36. Comparison of the potentiometric surfaces at the time of the winter highs of 1962 and 1965 shows that the configuration and altitude of the potentiometric surface were virtually the same in 1965 as in 1962. All the maps for the previous years (most of which are not included in this paper) show a progressive decline of the potentiometric surface (figs. 39, 40), and a westward migration of the trough of maximum depth to the potentiometric surface. By 1965, winter water levels were slightly higher in part of the area than in 1962.

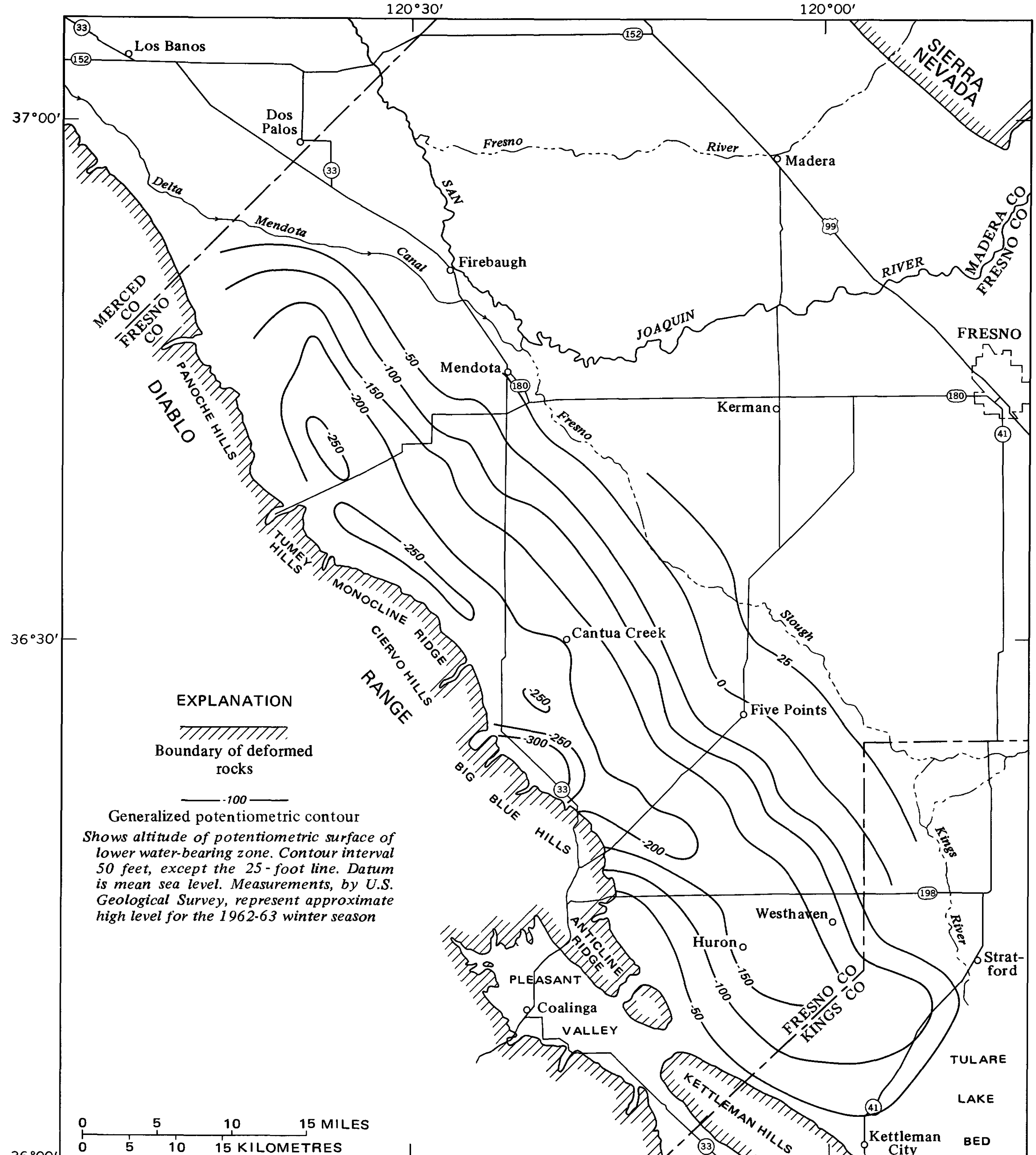
The overall similarity of the 1962 and 1965 maps suggests that a rough balance had been established between total pumpage, the amount of water derived from compaction, and the amount of subsurface recharge to the lower zone as a result of change in the gradient of the potentiometric surface along the northeast side of the study area.

The hydraulic gradient along the east side of the study area has steepened as a result of increased pumping of ground water to the west. Changes in the slope of the potentiometric surface along two section lines have been derived from maps of the potentiometric surface and are shown in figures 37 and 38. Line G–G', 4.3 miles long, extends southwest from Five Points. Line F–F',



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

FIGURE 34.—Artesian head of the lower zone as of May 1960.



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

FIGURE 35.—Water-level contours for the lower-water-bearing zone, December 1962.

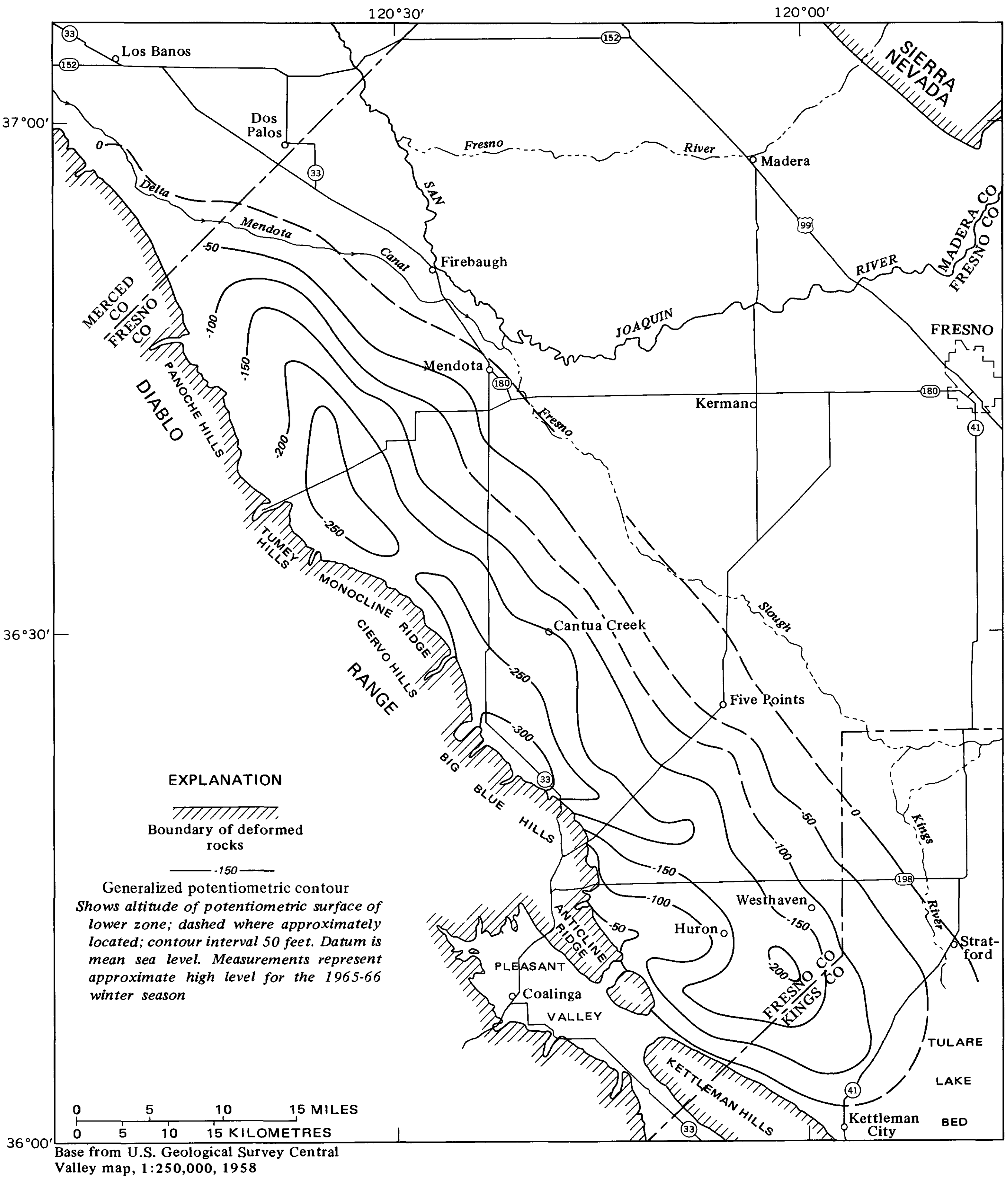


FIGURE 36.—Generalized water-level contours for the lower zone, December 1965.

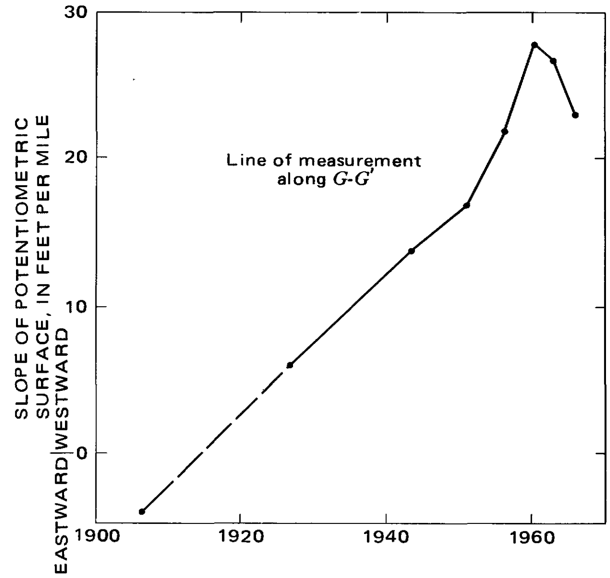


FIGURE 37.—Change in slope of the potentiometric surface of the lower zone southwest of Five Points, 1906–66. Line of section shown in figure 33.

7.7 miles long, extends to the southwest from a point midway between Firebaugh and Mendota, but distances of 4.0 and 5.6 miles had to be used for some periods. The location of the section lines are shown in figure 33. The head differential for each period along both lines has been corrected for the estimated post-1906 subsidence.

Mendenhall, Dole, and Stabler (1916) estimated that the slope of the lower-zone potentiometric surface in 1906 was 2–5 feet per mile to the east. A value of 4 feet per mile to the east has been used in both figures.

Both graphs indicate that the amount of underflow

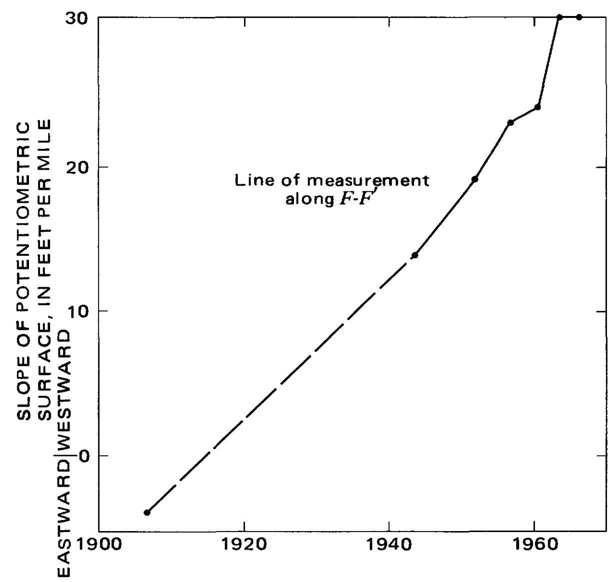


FIGURE 38.—Change in slope of the potentiometric surface of the lower zone southwest of Firebaugh, 1906–66. Line of section shown in figure 33.

from the east side of the San Joaquin Valley has increased substantially since about 1916. Unfortunately, as of 1968, the hydraulic conductivities of the lower-zone deposits are not known so the amount of change in underflow cannot be computed.

Along the span of section lines *F–F'* and *G–G'*, the westward steepening of the potentiometric surface appears to have ceased in the early 1960's—most likely because a general equilibrium between underflow, water of compaction, and withdrawal may have been approached. The rate of steepening of the potentiometric gradient decreased about a decade after the increase in total pumpage stopped (fig. 23). Part of the post-1960 change can be attributed to the fact that the 1962 and 1965 slopes were taken from maps of the winter high potentiometric level. The surface has a steeper slope in the summer than in the winter.

Profiles indicating the changes in the configuration of the potentiometric surface in the northern and southern parts of the area are shown in figures 39 and 40. All the data, except the 1943 data, are for times of seasonal recovery highs. The May recovery high is almost the same as the December recovery high, and for some years in the southern part of the area, May water levels are higher than December water levels.

The altitude of the potentiometric surface for the line of section between Tumey Hills and Mendota, measured six times between 1943 and December 1965, is shown in figure 39. A progressive deepening of the potentiometric surface is shown by the profiles. In 1943 most of the potentiometric surface was above sea level, but by 1966 the potentiometric level was as deep as 270 feet below sea level. The 1943 profile is symmetrical, but the 1953–65 profiles have varying degrees of asymmetry. The location of the troughs of the profiles have varied, but the trend has been an overall westward migration of the trough of the deepest water levels. The greater separation of the lines of profile in the western part of the line of section shows that greater head declines occurred between the various periods of measurement in the western part than in the eastern part of the line of section.

The altitude of the potentiometric surface for the line of section between Anticline Ridge and Fresno Slough, measured six times between 1943 and December 1965, is shown in figure 40. In contrast to the previous set of potentiometric levels shown in figure 39, the potentiometric levels have not deepened uniformly here. Most of the head decline occurred between 1943 and 1953. Since 1953 the overall trend has been toward a slow decline in artesian head, but the depth to water varies greatly for the individual years. All the profiles are asymmetrical and have steeper slopes in the western parts of the line of section than in the eastern. As in

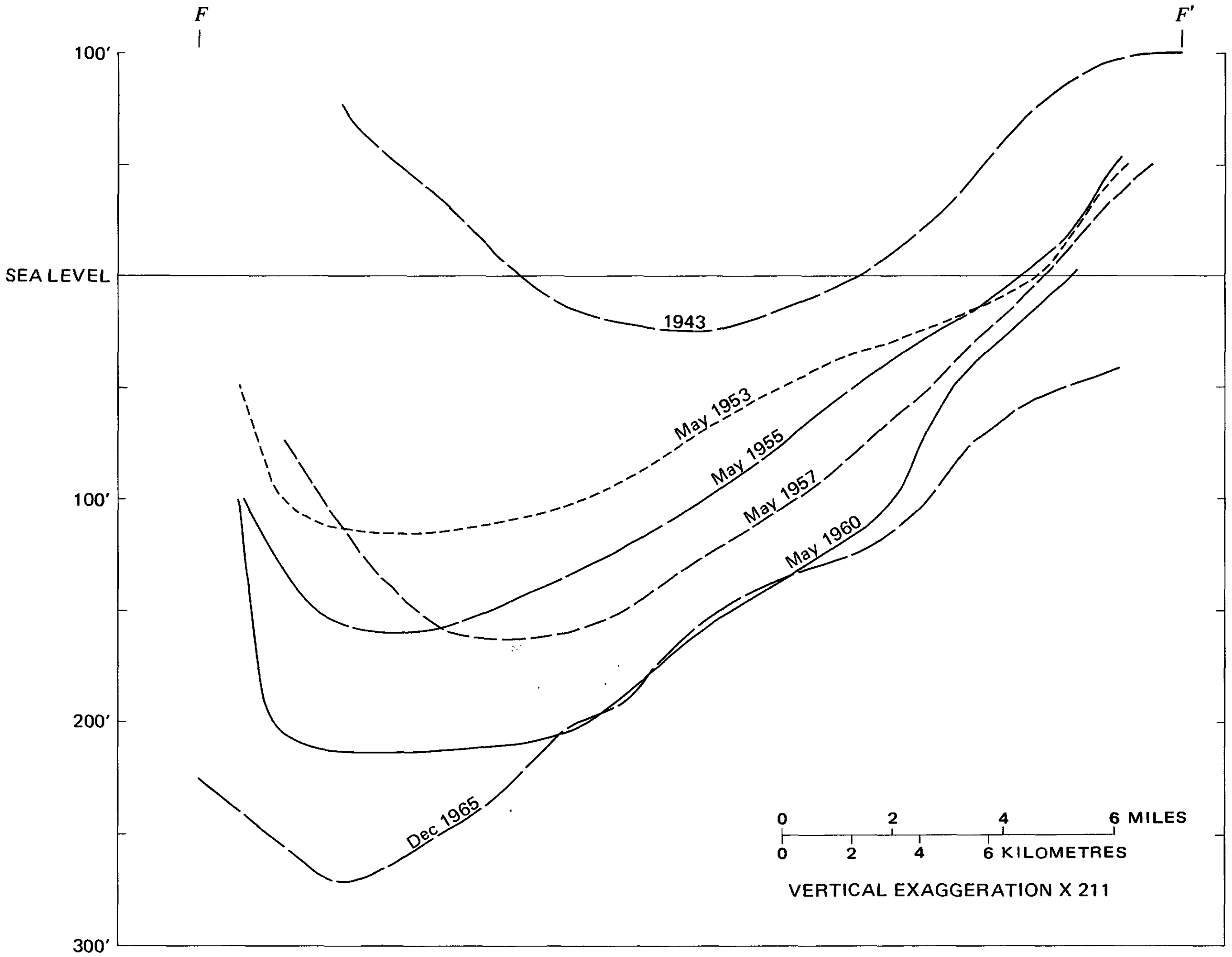


FIGURE 39.—Change in the altitude of the lower-zone potentiometric surface, 1943–66, Tumey Hills to Mendota. Line of section *F–F'* shown in figure 3.

figure 39, the trough of deepest water levels has migrated to the west, and the largest amounts of post-1943 head decline have been in the western part of the line of section.

The change in the potentiometric surface between 1943 and 1960 is shown in figure 41. The maximum head decline shown is northeast of the Big Blue Hills where the potentiometric surface had dropped more than 400 feet in the 17-year period—an average of about 25 feet per year. Areas of lesser head decline, such as along the road southwest of Five Points near Anticline Ridge, are largely the result of a low density of wells where less water has been pumped than in adjacent areas of more abundant wells.

In general, the decline in head was only 50–150 feet in the eastern and northern parts of the area, but more than 300 feet of head decline was common in areas close to the Diablo Range.

The amounts of head decline are in part a function of distance from the recharge area. The eastern and northern parts of the area are closest to the area of major recharge—the east side of the San Joaquin Valley. Very little recharge is derived from the Diablo Range, particularly lower-zone recharge. The areas near the Diablo Range have had the most severe head declines because they are farthest from the Sierra recharge water and because they are adjacent to a mountain front that approximates an impermeable boundary. Much of the recharge water from the east is intercepted by wells before it reaches areas near the Diablo Range.

In the southern part of the area, the maximum head decline is nearer Huron than the Diablo Range. The lower zone in the area between Huron and the Diablo Range is receiving undetermined amounts of recharge from intermittent flows of Los Gatos Creek. The Corcoran is poorly defined or absent in most of this area, thereby permitting recharge of the lower zone. The

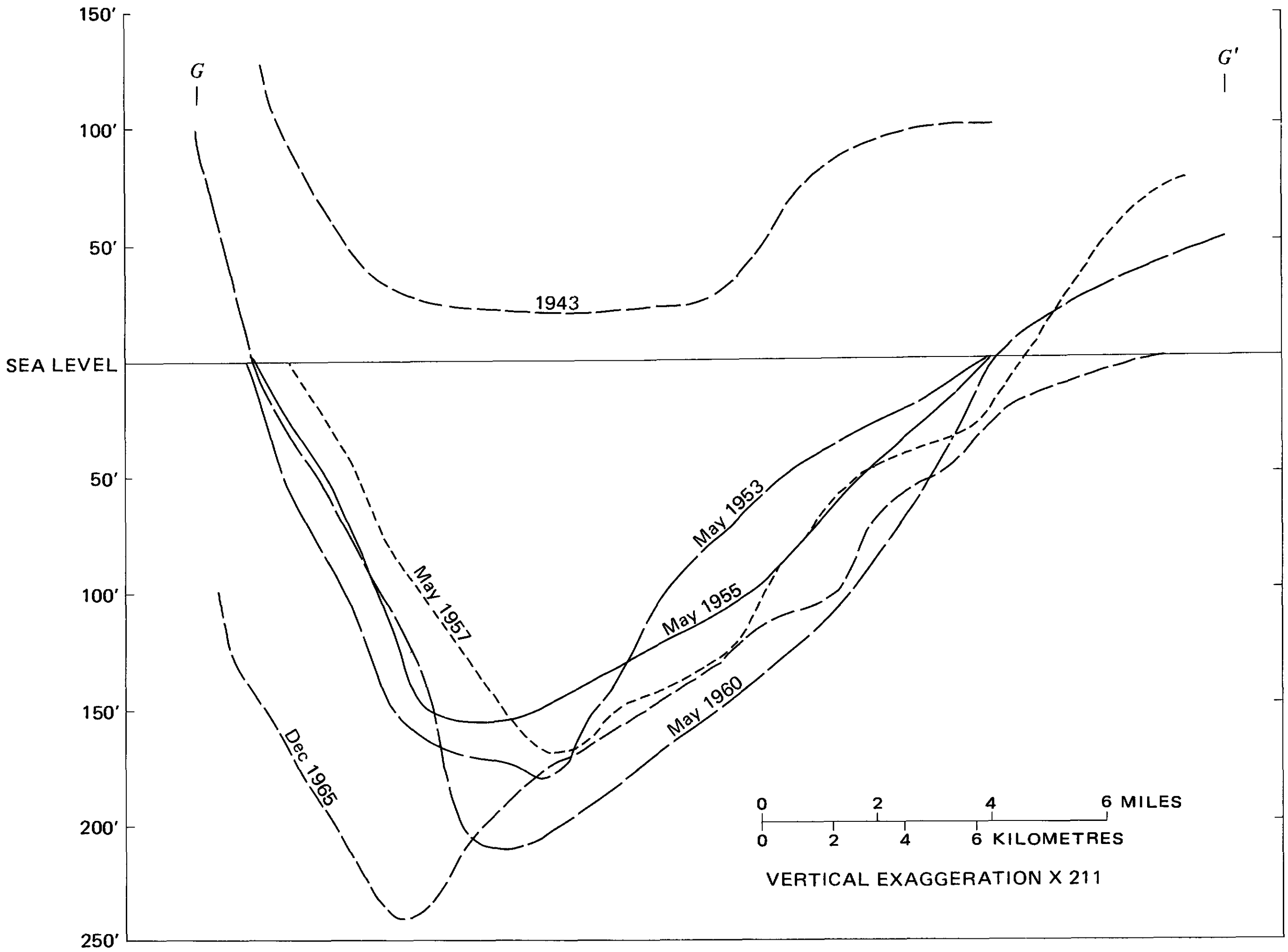


FIGURE 40.—Change in the altitude of the lower-zone potentiometric surface, 1943–66, Anticline Ridge to Fresno Slough. Line of section *G–G'* shown in figure 3.

1951–65 change in depth to water-table map (fig. 26) shows that the area southwest of Huron has had the maximum decline in the water table in the study area. This indicates that water in beds that are stratigraphically equivalent to beds in the upper zone east of Huron is moving down to partly recharge water withdrawn by the deep wells.

Another reason for the lesser amounts of head decline in the area west of Huron, as compared to the areas adjacent to the Diablo Range farther north in the study area, is the lack of an impermeable boundary. In this area, the impermeable boundary is actually the southwest side of Pleasant Valley because ground water can move from Pleasant Valley to the San Joaquin Valley through the gaps in the foothill belt.

In the area northeast of the Big Blue Hills and southwest of the town of Cantua Creek, the head declines in excess of 300 feet are due, in part, to the aquifers penetrated by the irrigation wells. The wells in this subarea are perforated in the Tulare Formation below the Corcoran and in the marine sands of the Etchegoin Formation. Although fresh water has largely replaced the salt water in the marine sands, very little recharge reaches the sands compared to the amount of recharge to the Tulare Formation. The lack of significant recharge to the Etchegoin sands probably is the main reason why this part of the study area has undergone the maximum decline in head between 1943 and 1960.

The change in altitude of the lower-zone potentiometric surface between December 1962 and December 1965 is shown in figure 42. In marked contrast to large head declines that occurred between 1943 and 1960, the recent 3-year period has been one of rise, as well as decline, in the potentiometric level. The extremes within

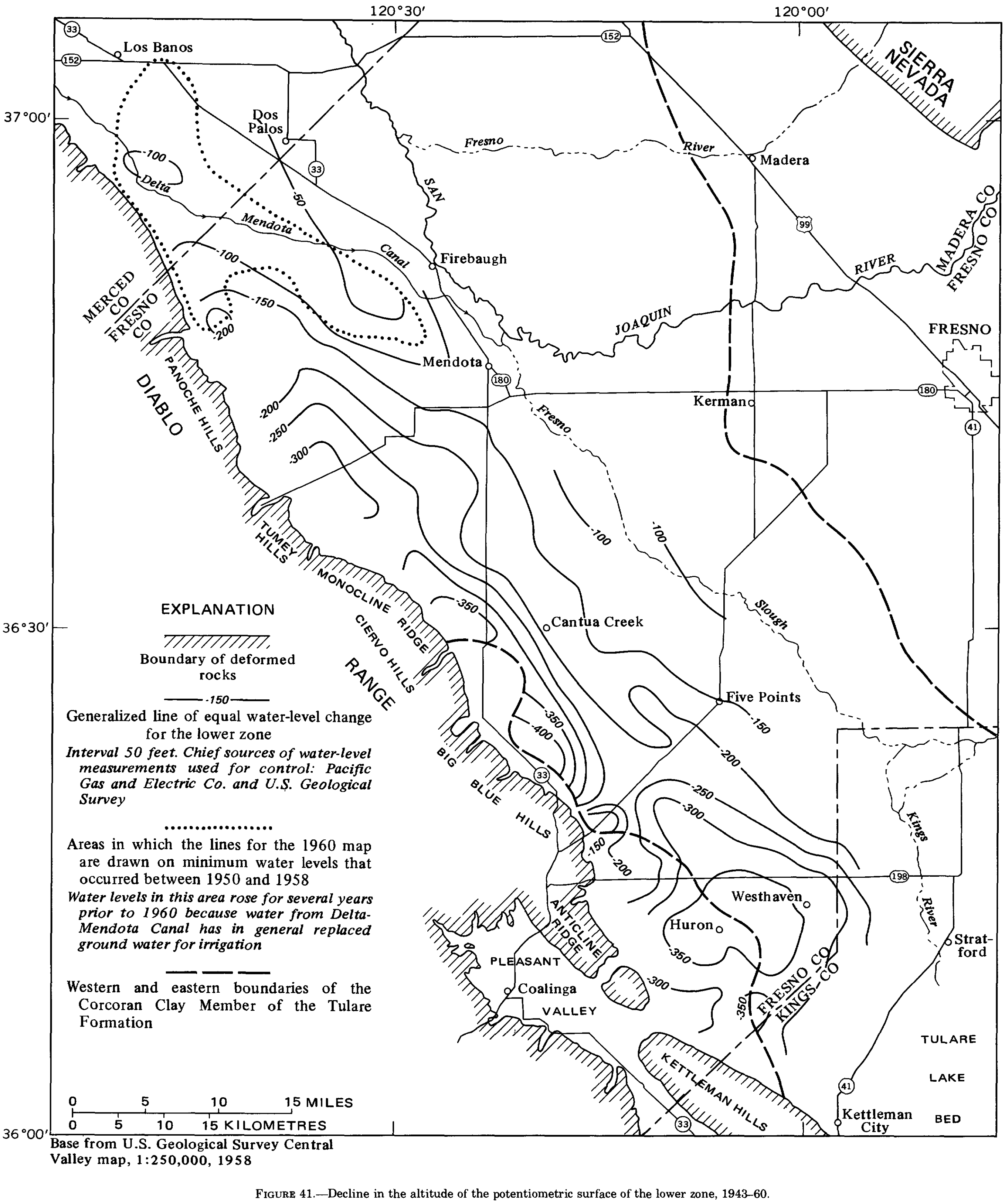


FIGURE 41.—Decline in the altitude of the potentiometric surface of the lower zone, 1943–60.

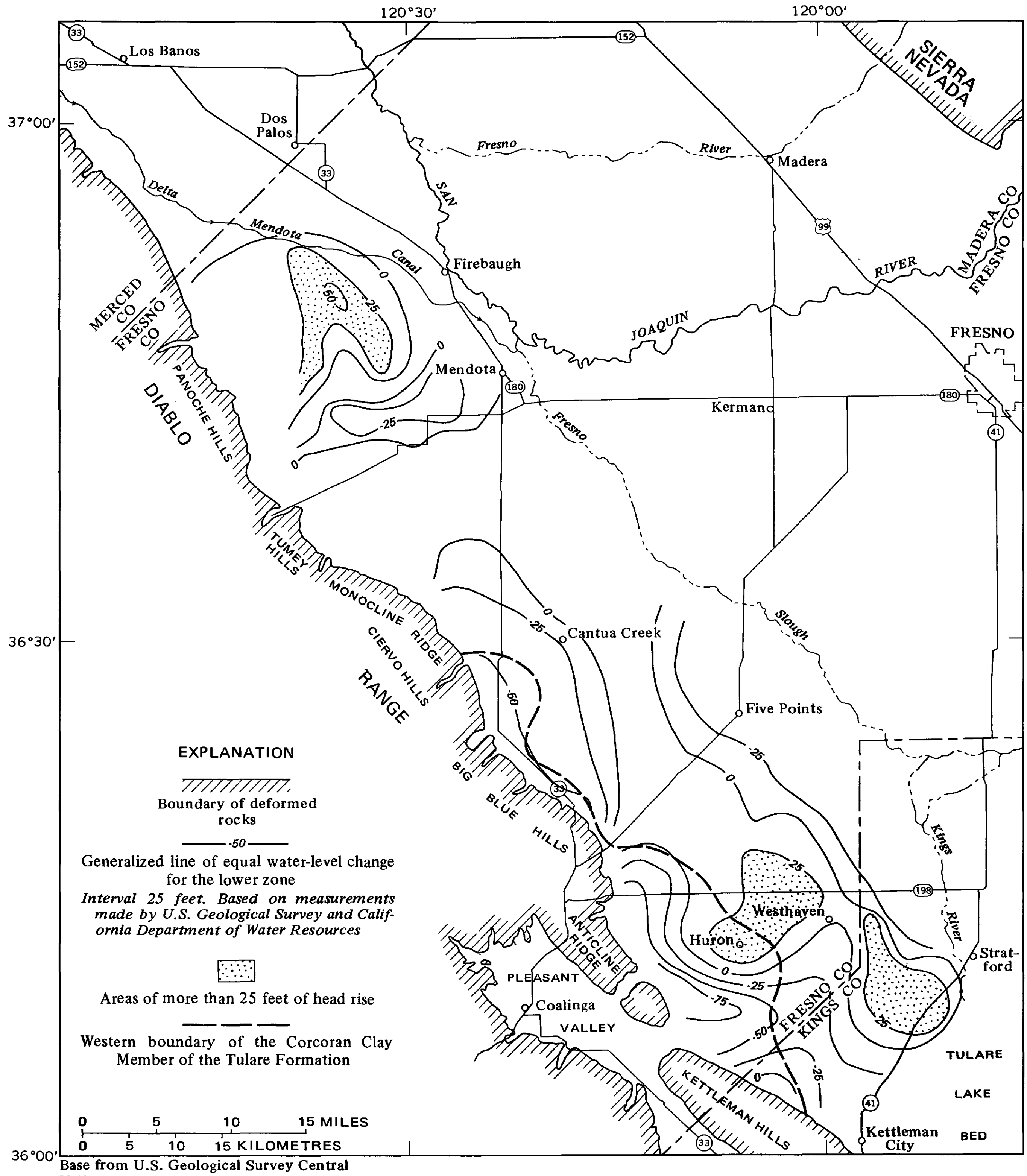


FIGURE 42.—Change in altitude of the lower-zone potentiometric surface between December 1962 and December 1965.

the study area are 50 feet of head rise west of Firebaugh, and 75 feet of head decline southwest of Huron. Locally, in areas such as southwest of Huron, and adjacent to the Big Blue Hills, lower-zone head decline was continuing at rates similar to those in the early 1950's—the period of maximum rates of head decline for much of the area. Between 1962 and 1965 pronounced head decline was occurring in only about 25 percent of the area. Areas of head rise of more than 25 feet totaled about 5 percent of the study area; the remaining 70 percent had little change in potentiometric level or underwent minor amounts of head rise. The areas of maximum head decline were farthest from the area of major recharge east of Fresno Slough. In the rest of the area, a rough balance between pumpage and sources of ground water appeared to have been achieved, as was noted in the discussion of the change in potentiometric slope.

Seasonal Fluctuation Of The Potentiometric Level

The trend in seasonal changes in the lower-zone artesian head is roughly the same throughout most of the Los Banos–Kettleman City area. After the summer, pumpage decreases during the fall as many crops are harvested. Some irrigation continues for the planting of winter grains. The winter recovery high occurs most commonly during the last part of December. Pumping during the first months of the year for preirrigation of summer crops causes the head to decline by the middle of March to almost the same level as the summer low. Little pumping occurs while the summer crops germinate, and by early May water levels in much of the area have recovered almost to the December high levels. Summer is the time of maximum pumping, and the lowest water levels usually occur during August. Thus, the typical seasonal trend of the lower-zone water levels has been to have two major fluctuations each year—low levels in March and August separated by periods of pronounced recovery that peak in May and December.

The pattern of seasonal head decline between December 1965 and August 1966 is shown in figure 43. In general, the trough of maximum seasonal fluctuation, about halfway between the topographic trough of the valley and the Diablo Range, is largely controlled by the density of well spacing. This is particularly true in the northern half of the study area.

In the southern half of the area, the gross lithologic properties of the lower zone are important in influencing the extremely large amounts of seasonal fluctuation. A lithofacies map (Part 2, fig. 68), based on the mean resistivity of the lower-zone deposits corrected to 100°F and 1,000 mg/l NaCl salinity, shows a remarkable similarity of pattern with the seasonal fluctuation map of figure 43. The arc of seasonal fluctuation in excess of 80 feet corresponds with an arc of minimum resistivity of the lower-zone deposits. Thus, the large seasonal fluctuations appear to be the result of the presence of thick fine-grained deposits of low permeability. In order to get sufficient yields, many pumps have to be operated with drawdowns of 50–100 feet. Northwest of Tulare Lake bed, farmers prefer to operate the pumps in this fashion instead of drilling wells 2,500–3,000 feet deep to tap the deeper fresh-water-bearing deposits (figs. 12, 17).

In the small area southwest of Mendota, seasonal fluctuation in excess of 80 feet is also influenced partly by lithology. This area is part of the area of intertonguing fine-grained facies of the Sierra and Diablo flood-plain deposits. It is also the area of lowest well-yield factors in the northern part of the study area (fig. 16).

The seasonal fluctuation map indicates the variation in applied stress during a given year. In those areas of 10–20 feet of seasonal fluctuation, the maps of the potentiometric surface made at the times of minimum applied stress, such as December 1962 and December 1965, are useful in determining the relation between change in applied stress and compaction. However, in much of the area, seasonal head declines of 60–150 feet result in substantially greater stresses being applied to the lower-zone deposits during times of maximum pumping than during times of minimum pumping. For this reason, the critical maps and hydrographs used in this series of papers for studies of the interrelations of hydrologic and geologic factors are based on changes between summer water levels.

The variation in seasonal fluctuation from east to west across the central part of the area is shown by the records of lower-zone observation wells 15/16–34E1, 15/14–14J1, and 16/14–16N1 in figure 44. Well 34E1 shows a fairly consistent seasonal fluctuation of 10–15 feet, particularly since 1959. Few, if any, wells pump from the lower zone in the vicinity. The seasonal fluctuation and the overall decline in artesian head at this site are chiefly the result of intensive lower-zone pumping farther west. Well 14J1 is in an area which has moderately high density of wells and where nearly all the irrigation water is pumped from the lower zone. The 40–70 feet of seasonal fluctuation is typical of other lower-zone wells in the vicinity that are deeper than well 14J1. Well 16N1 is only a mile east of the Diablo Range. The 40–50 feet of seasonal fluctuation is less

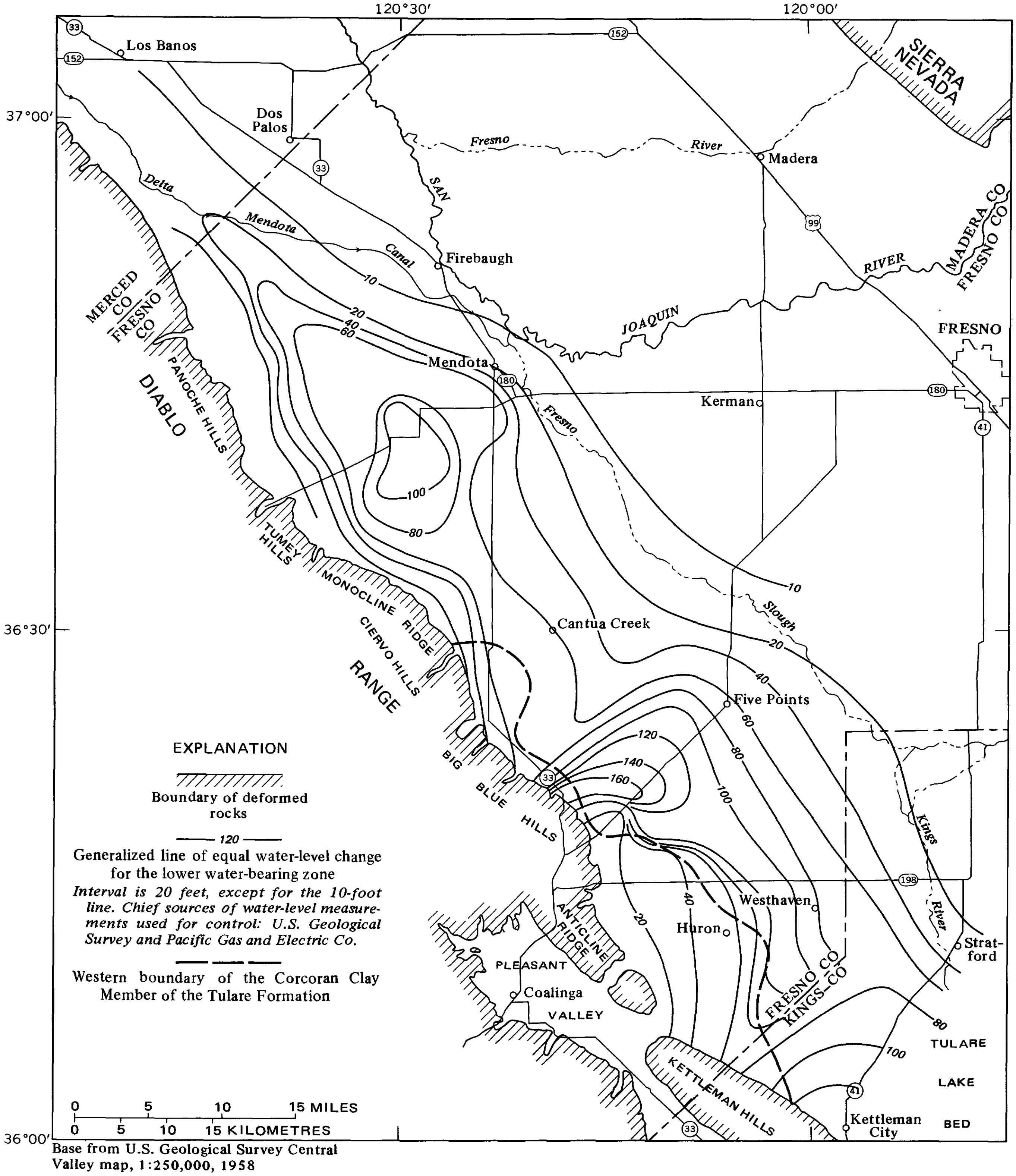


FIGURE 43.—Seasonal decline in the altitude of the potentiometric surface of the lower zone, December 1965 to August 1966.

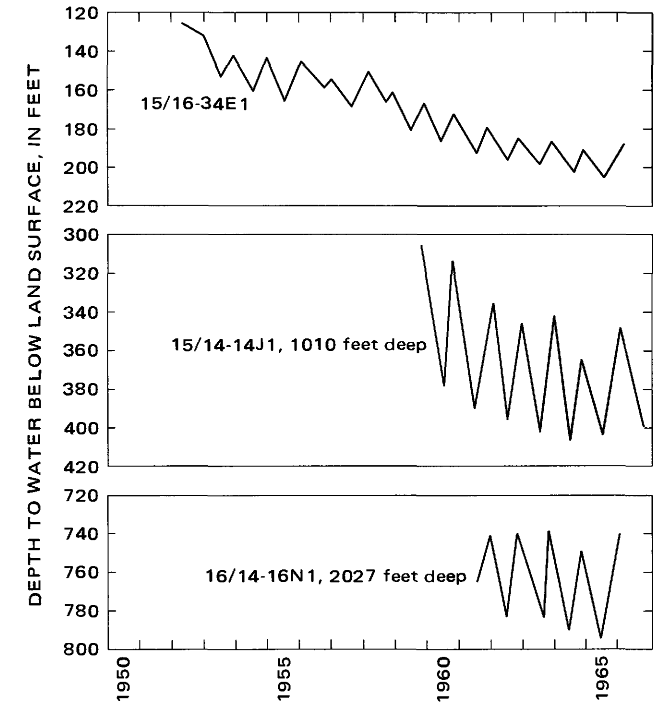


FIGURE 44.—Variation in seasonal fluctuation of water levels in lower-zone wells in the central part of the Los Banos-Kettleman City area.

than for well 14J1, despite the fact that well 16N1 is farther from areas of potential recharge. The smaller fluctuation at well 16N1 most likely is due to a lower density of wells in the vicinity. There were no irrigation wells west or southwest of well 16N1 during the period of record.

HISTORY OF HEAD DECLINE

In an area as complex as the Los Banos–Kettleman City area, the history of head decline is highly variable. Factors influencing the patterns of lower-zone head decline, as shown by hydrographs, include the rate of agricultural development, changes in the types of crops grown, recharge, hydraulic conductivity of the aquifer materials, and the amount of imported surface water available.

The trends of head decline within the area are separated into long-term and short-term records; the long-term hydrographs show trends from as early as the 1920's, and the short-term hydrographs show trends from the late 1940's through 1965. Nearly all the data are from the Pacific Gas and Electric Co. Pumping levels were used because they are much more abundant than static levels. The drawdown between static and pumping levels remains essentially the same for a given well over a period of years. This is because the well yield must be sufficient to supply the crop requirements of the fields being irrigated. If the yield declines because of head decline, a larger pump is installed, and the amounts of yield and drawdown for the well remain about the same as previously. Only those measurements made during times of widespread pumping were used. Winter high measurements were not used because not enough of them were available to show overall water-level trends within ranges of seasonal fluctuation as was done in figure 44. The use of occasional winter measurements would distort the overall trend in water levels. The use of summer and spring low pumping measurements wherever possible permits a smoother portrayal of the trends. Summer measurements also permit the trends to be based on the times of the year in which the potentiometric surfaces are at their lowest levels, maximum stresses are being applied to the aquifer system, and compaction rates are highest.

The five long-term hydrographs shown in figure 45 represent different trends, from the northern part of the area in figure 45*A*, to the southern part of the area in figure 45*C*. Additional long-term hydrographs have been paired with subsidence graphs in Part 3.

The 1932–66 lower-zone head decline near the Merced County line is shown in figure 45*A* (wells 12/12–34N1 and P1). The pre-1932 head decline in this area is estimated to be about 150 feet. A period of rapid decline ended in the late 1930's. Between 1937 and 1951 the head declined only 25 feet. The rate of head decline increased between 1951 and 1954. Since delivery of Delta-Mendota Canal water in 1954, the head has continued to decline, but at a decreasing rate. In contrast to the gradual decline in summer water levels since 1960, the winter levels have risen about 0–25 feet in the vicinity (fig. 42).

The other hydrographs shown in figure 45*A* are for wells about 8 miles southwest of Mendota. Well 14/14–30E1 was one of the first wells to be drilled in this part of the township, but several miles to the northeast pumpage of lower-zone water had occurred prior to 1924. After World War II many additional wells were drilled to the southwest, as agricultural development expanded rapidly. Well 30E2 was drilled to replace well 30E1. The rate of head decline was rapid before 1946, but it has been even more rapid since then. The 1937–63 head decline is almost 300 feet.

The hydrograph in figure 45*B* shows more than 200 feet of head decline in the 1937–56 period for the area southeast of the town of Cantua Creek. The rate of artesian-head decline increased fairly steadily between 1937 and 1952, and during the period 1946–52, the head declined an average of about 23 feet per year. Since 1952

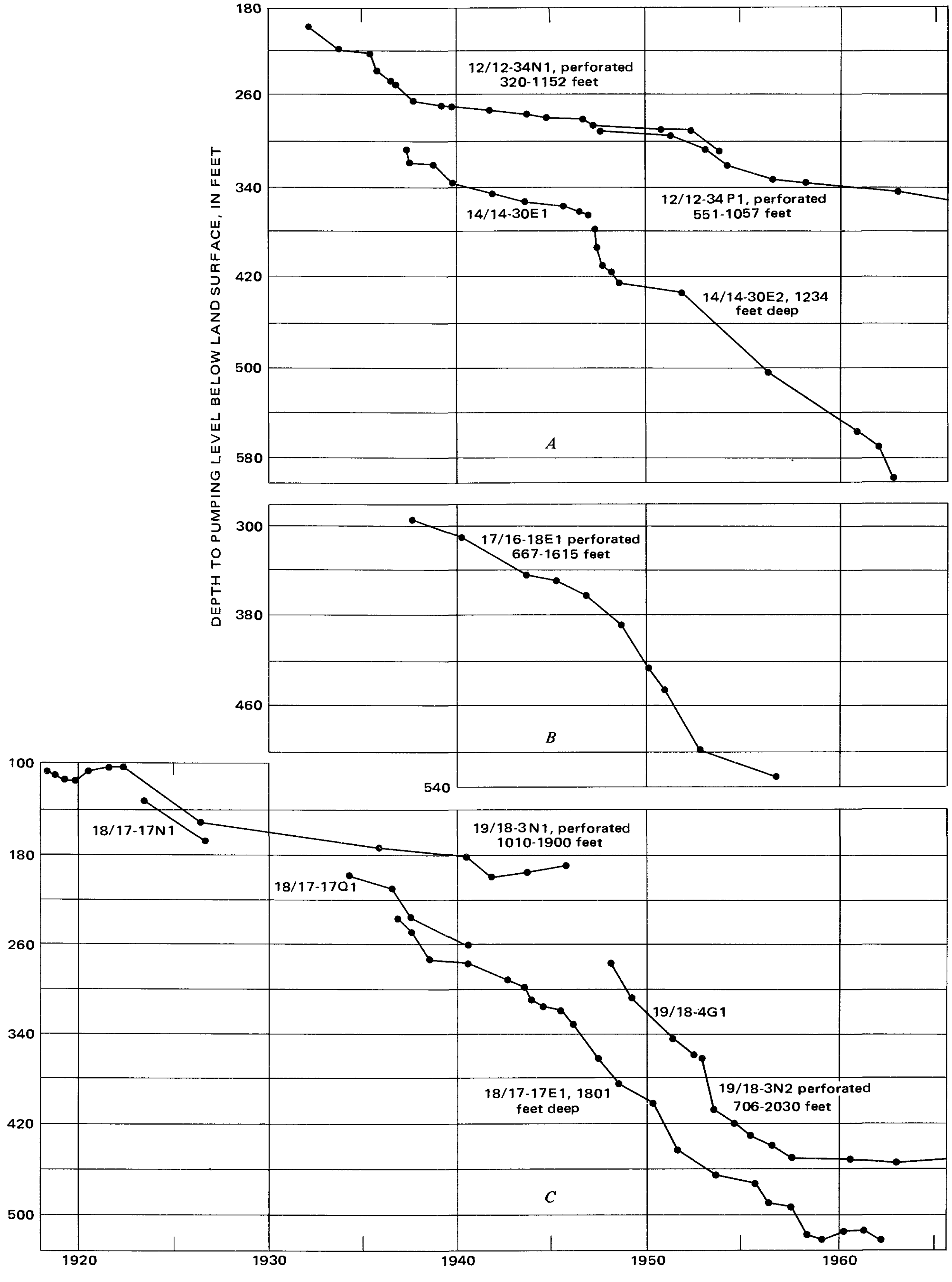


FIGURE 45.—Long-term hydrographs of lower-zone wells. *A*, Northern part of area. *B*, Central part of area. *C*, Southern part of area.

the potentiometric level has declined at a slower rate, as shown in figure 45*B*, and in the hydrograph for well 17/16–18Q2 (fig. 47).

The composite hydrograph of three wells southwest of Five Points in 18/17–17 is shown in the bottom of figure 45*C*. Although water levels in these wells are, in general, representative of the lower zone, a small portion of the perforated intervals may be in the basal part of the upper zone. The 1923 pumping level suggests that the potentiometric surface was only 10–30 feet below its estimated 1906 position. The record indicates that the head has declined 400 feet at a fairly constant rate over a 40-year period—about 10 feet per year.

The composite hydrograph of the three wells north of Westhaven in 19/18 (fig. 45*C*) shows a different pattern than that for the wells southwest of Five Points. North of Westhaven, it is apparent that water levels declined only moderately between 1918 and the end of World War II. After World War II the rapid development of nearby areas to the west and southwest caused the rate of head decline to accelerate. Since 1957, the trend in head decline has flattened. The measurements for the 1920's are from the unpublished Haehl and Forbes report. When pumping levels were only 100 feet below land surface, the potentiometric surface probably was about the same as in 1906. A similar long-term hydrograph for wells a few miles farther south has been paired with a bench-mark graph and is shown in Part 3.

Long-term records are not available for the area of heavy pumping from the marine sands of the Etchegoin Formation. An 8-year record for a well tapping the Etchegoin Formation adjacent to the Big Blue Hills is shown in figure 46. The nonpumping water levels in this well ranged between 800 and 940 feet below land surface. By the middle 1960's, wells adjacent to the Big Blue Hills were pumping from depths of more than 1,000 feet (see Part 3). Monthly measurements made between May 1960 and February 1961 outline a seasonal head recovery of 60 feet. Between December 1965 and August 1966, the seasonal head decline was 45 feet. The overall trend of water levels during the 1960's for this well has been a large and steady decline. From August 1960 to August 1967, the water level declined 64 feet—an average of 7 feet per year.

More than 600 feet of artesian-head decline has occurred at the site of well 18/15–5E1. The altitude of the land surface at the well is 529 feet, therefore the August 1967 static water level was at an altitude of −402 feet. The trough of the San Joaquin Valley opposite the well site has an altitude of 180 feet. The potentiometric surface was at least 20 feet above the land surface in 1906. Mendenhall, Dole, and Stabler (1916) reported that the gradient of the potentiometric surface west of the valley

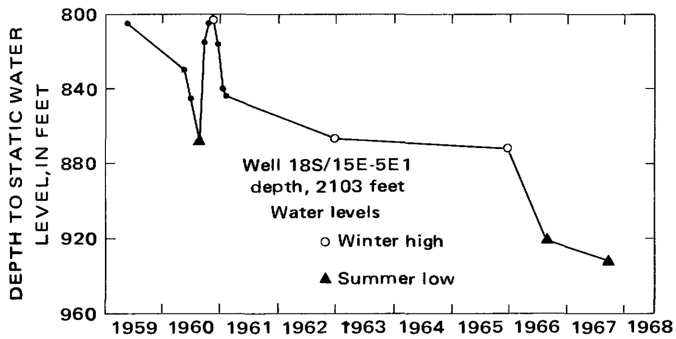


FIGURE 46.—Hydrograph of irrigation well tapping the Etchegoin and San Joaquin Formations.

trough was only 2–5 feet per mile. Assuming an initial gradient of 4 feet per mile to the east, the potentiometric surface was 80 feet higher (an altitude of +280 feet) at the well site than at the valley trough in 1906. Thus, in declining from about +280 feet to −400 feet, the potentiometric surface declined about 680 feet; if one assumed that no gradient was present in the potentiometric surface in 1906, 600 feet of head decline occurred.

The short-term trends of lower-zone pumping levels are shown in the 13 hydrographs in figure 47. These hydrographs have been placed on the map in order to facilitate comparison of the various trends and locations of the wells. Four of the wells—15/14–9E1, 20/17–33N1, 20/18–24D1, and 21/18–35N1—have had steadily declining water levels since 1951 or before. The continuing agricultural expansion to the southwest of wells 9E1 and 33N1 probably has influenced the trends in artesian head at these two sites. Well 35N1 is situated where little recharge can reach the well. No recharge is derived from the Kettleman Hills to the south and west, and the thick sequence of lake clays beneath Tulare Lake bed prevent recharge from the east. Recharge that might move towards the well from the north would be largely intercepted by other wells.

The other nine hydrographs all show a decreasing trend in the rate of artesian-head decline.

Well 12/11–13D2 is in an area that has had a reversal of pumping levels since 1958. The abrupt reduction in the rate of artesian-head decline between 1953 and 1959 is associated with the delivery of surface water in the vicinity of the well. Since 1953 ground water pumped from well 13D2 has been used to supplement the surface-water supply. In 1959 a large area to the south of the well started receiving surface water (Bull and Poland, 1974). The effect of surface-water imports both in 1954 and in 1959 is clearly shown in the hydrograph of well 13D2.

The other eight hydrographs that show a decreasing rate of artesian-head decline suggest a trend toward

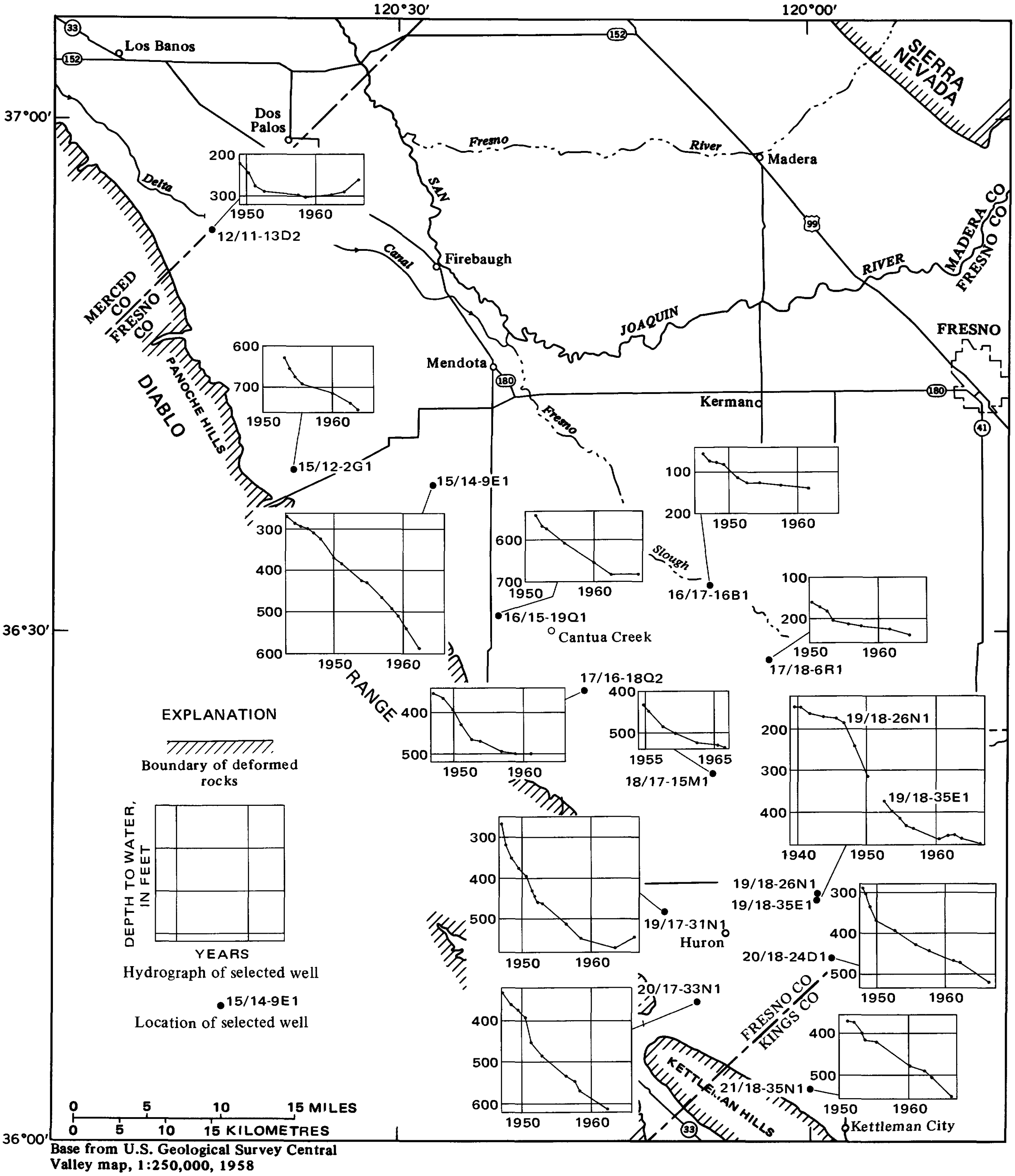


FIGURE 47.—Trends of lower-zone pumping levels.

equilibrium between pumpage and the various sources of water within the lower-zone aquifer system in most of the Los Banos–Kettleman City area. If the amount and distribution of pumpage within the area remained uniform, eventually the decline in water levels would establish a steep gradient that would permit sufficient recharge to the lower zone from the east side of the San Joaquin Valley to eliminate overdraft within the study area. Water levels would remain at low levels and would have large seasonal fluctuations in the areas of large lower-zone pumping, and the steep gradient of the potentiometric surface would be maintained around the borders of the study area.

Table 3 and figure 23 show that the amount of total pumpage within the area has not increased since 1952. The maps of the potentiometric surface between 1926 and 1965 (figs. 31–33, 35, 36) show a progressive steepening of the potentiometric surface along the east side of the study area. Thus, the above figures and figure 47 all support the conclusion that a strong tendency toward reduction of overdraft within the lower-zone aquifer system has been occurring.

SUMMARY AND CONCLUSIONS

The 500–3,500 feet of unconsolidated to poorly consolidated deposits that form the ground-water reservoir in the Los Banos–Kettleman City area consist of flood-plain, alluvial-fan, lacustrine, deltaic continental, and littoral and estuarine marine deposits. The sediments were derived from both the Diablo Range and the Sierra Nevada. The stratigraphy of such diverse genetic units is complex, but a simple three-part hydrologic classification can be made of the deposits penetrated by wells.

The upper zone extends from the land surface to the top of the principal confining clay. The upper zone, 100–900 feet thick, has a degree of confinement that ranges from unconfined in thick bedded sands to excellent confinement between extensive lacustrine clay beds. Much of the zone consists of lensing deposits in which the water is semiconfined. The primary aquifer consists of micaceous arkosic sands derived from the Sierra Nevada. The Sierra sands are almost 600 feet thick under the present valley trough but pinch out toward the west at distances of 5–15 miles from the eastern margin of the Diablo Range. Diablo alluvial-fan deposits make up most of the upper zone. Few wells tap the poor quality water in these deposits of low permeability. The upper-zone water, a calcium-magnesium sulfate water, commonly contains 3,000–4,000 mg/l total dissolved solids. Water quality improves with depth, and near the basal part of the zone, the total dissolved solids are about 1,500 mg/l. Most of the pumpage of upper-zone water is in the southeastern part of the study area and along Fresno Slough, south of the town of San Joaquin.

A widespread diatomaceous clay stratum, deposited in a fresh-water Pleistocene lake 600,000 years ago, is the second hydrologic unit. The Corcoran Clay Member of the Tulare Formation extends beneath the entire study area, except for an area adjacent to the foothills in the southwestern part. The Corcoran is the principal confining layer throughout much of the San Joaquin Valley, and locally it separates waters of greatly differing quality and head.

The Corcoran provides effective confinement for the third hydrologic unit—the lower zone. The lower zone, which supplies about three-fourths of the ground water in the study area, ranges from less than 500 to more than 2,000 feet thick. Although the zone contains many lensing aquitards, the overall hydraulic continuity between the basal and upper parts of the zone is good, except in the northern third of the area where a widespread clay layer acts as an effective separator within the lower zone.

The lower zone consists chiefly of the alluvial-fan, flood-plain, and lacustrine deposits of the Tulare Formation. In the southern part of the area, deltaic deposits are tapped also. Along the western margin of the valley, between the towns of Huron and Cantua Creek, wells are drilled still deeper to tap estuarine and littoral deposits of the San Joaquin and Etchegoin Formations. The alluvial-fan deposits, derived from the Diablo Range, consist of materials of low to moderate permeability. Individual beds within the Diablo flood-plain deposits give this unit a moderate to high overall permeability. Well-yield factors indicate that the flood-plain deposits are 3–5 times as permeable as the alluvial-fan deposits. The Sierra flood-plain deposits have the highest permeabilities because the sand beds are thicker, and they make up a greater porportion of a given section than do the Diablo flood-plain deposits.

The thickness of the fresh-water-bearing deposits and the perforated interval of the lower zone both range from 400 to more than 2,000 feet, but rarely are they the same in a given part of the area. In some areas, sufficient yields can be obtained without drilling to the base of the fresh water. Only 1,000–1,200 feet of the more than 2,000 feet of lower-zone fresh-water-bearing deposits are tapped northwest of Tulare Lake bed. Adjacent to the Big Blue Hills, sufficient quantities of water cannot be obtained from the continental deposits, and

3,000-foot wells obtain part of their water from brackish-water-bearing marine deposits to depths of as much as 200 feet below the base of the fresh water.

The total dissolved solids in the lower-zone water in most of the area west of the valley trough ranges from 800–1,500 mg/l, but locally they are more than 2,000 mg/l. The water is primarily a sodium-sulfate water with more bicarbonate than the upper-zone water.

The chemical character of the water indicates that water derived from the Diablo Range has flushed the connate waters out of the marine and Sierra sands. Maximum concentrations of dissolved solids occur opposite the mouths of Panoche and Los Gatos Creeks and in the area of maximum dependency of pumpage from the marine sands. Areas of low concentrations of dissolved solids occur between the mouths of the large streams.

Before the agricultural development of the central part of the San Joaquin Valley, the lower-zone potentiometric surface sloped gently towards the valley trough from both the Diablo Range and the Sierra Nevada. Because of the low permeability of the Corcoran, upward movement of lower zone water probably was very slow; and as a result, the potentiometric surface was more than 20 feet above the land surface in the valley-trough area.

Large-scale agricultural development has lowered the potentiometric surface on the west side of the valley to as much as 400 feet below sea level. Water-table conditions now exist below the Corcoran near the Diablo Range. The slope of the potentiometric surface has been reversed. By 1966, a belt only a few miles wide adjacent to the Diablo Range was still an area of eastern gradient for lower-zone water movement. Farther east, areas in which the potentiometric surface originally sloped eastward, locally had a westward gradient of as much as 40 feet per mile by 1960.

Disruption of the natural flow system by man has resulted from the pumping of more than 1,000,000 acre-feet of irrigation water per year since 1950. In 1924, the total estimated pumpage was only 35,000 acre-feet. By 1945, pumpage was 370,000 acre-feet and by 1953, 1,200,000 acre-feet. Total pumpage has not increased since 1953. The increase in pumpage has closely paralleled the agricultural growth in the area from a few wells to irrigate pasture to a modern complex of large-scale diversified farming that occupies nearly all the area.

Changes in the upper-zone water levels have not been pronounced in the northern and central parts of the area, but in the southeastern part of the area, where large amounts of upper-zone water is pumped, both the water table and the water levels in the confined aquifer system have declined. Locally the water table has declined more than 300 feet, and elsewhere the artesian head at the base of the upper zone has declined more than 300 feet. North of Five Points, the water table has risen from less than 25 feet to more than 100 feet, and much of the area may be threatened with insufficient drainage for crops. In the northern area, water levels representative of the semiconfined zone have risen in some areas and have declined in others, depending on local variations in the amount of water pumped in the upper zone.

The changes in the hydrologic environment have been the greatest in the lower zone. Flowing wells once were common along the trough of the valley. In other areas where the potentiometric surface initially was less than 100 feet below the land surface, static levels were at depths of about 500 feet by the 1960's. Overall head declines of 300 to more than 400 feet are common in much of the area, and an estimated 600 feet of head decline has occurred next to the Big Blue Hills.

The lower-zone aquifer system has responded to the changes imposed by man by developing a steep gradient in the potentiometric surface around the trough of maximum pumping. In 1906, the potentiometric surface sloped 2–5 feet per mile to the east; by 1926, 6 feet per mile to the west; by 1943, 14 feet per mile; and by 1960, 30 feet per mile to the west. As the gradient became steeper and total pumpage stopped increasing, recharge from the east side of the San Joaquin Valley increased sufficiently to roughly balance the large overdraft from the lower zone. As a result, the rate of head decline has become progressively less since 1955 throughout most of the area. The records of many wells for the 1960–66 period show a seasonal fluctuation of 60–120 feet but less than 5 feet of year-to-year head decline.

Most of the compaction has occurred in the lower zone as a direct result of the head decline that has occurred within it. Water-table changes also have affected the amounts of lower-zone compaction but only to a minor extent. Lower-zone applied stresses and compaction have been increased in areas of water-table rise and have been decreased in areas of water-table decline.

Decline of the lower-zone water levels below the base of the Corcoran decreases the change in applied stress from 1.0–0.8 foot of water per additional foot of water-level decline. The processes of applied-stress increase are changed from that of seepage stress equal to head differentials, to those of loss of buoyancy and transfer of part of the contained water from a neutral to an applied-stress condition as the deposits are dewatered.

REFERENCES CITED

American Geological Institute, 1972, Glossary of geology: Washington, D.C., Am. Geol. Inst. 805 p.

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

———1972, Prehistoric near-surface subsidence cracks in western Fresno County, California: U.S. Geol. Survey Prof. Paper 437–C, 85 p.

———1974, Land subsidence due to ground-water withdrawal in the Los Banos-Kettleman City area, California—Part 2, Subsidence and compaction of deposits: U.S. Geol. Survey Prof. Paper 437–F (in press).

Bull, W. B., and Poland, J. F., 1974, Land subsidence due to ground-water withdrawal in the Los Banos-Kettleman City area, California—Part 3, Interrelations of water-level change, change in aquifer-system thickness, and subsidence: U.S. Geol. Survey Prof. Paper 437–G (in press).

Croft, M. G., 1972, Subsurface geology of the late Tertiary and Quaternary water-bearing deposits of the southern part of the San Joaquin Valley, California: U.S. Geol. Survey Water-Supply Paper 1999–H, 29 p.

Davis, G. H., Green, J. H., Olmsted, F. H., and Brown, D. W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U.S. Geol. Survey Water-Supply Paper 1469, 287 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, p. 409–588.

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

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., Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, Calif., open-file report, 60 p.

———1958, Progress report on land-subsidence investigations in the San Joaquin Valley, California, through 1957: Sacramento, Calif., Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, Calif., open-file report, 160 p.

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

Janda, R. J., 1965, Quaternary alluvium near Friant, Calif., *in* Guidebook for Field Conference I, Northern Great Basin and California—Internat. Assoc. Quaternary Research, 7th Cong., U.S.A., 1965: Lincoln, Nebr., Nebraska Acad. Sci., p. 128–133.

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.

Lofgren, B. E., 1960, Near-surface land subsidence in western San Joaquin Valley, California: Jour. Geophys. Research, v. 65, no. 3, p. 1053–1062.

———1968, Analysis of stresses causing land subsidence, *in* Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600–B, p. B219–B225.

———1969, Land subsidence due to the application of water, *in* Varnes, D. J., and Kiersch, George, eds., Reviews in Engineering Geology, Volume II: Boulder, Colo., Geol. Soc. America, p. 271–303.

Lohman, S. W., and others, 1972, Definitions of selected ground-water terms, Revisions and conceptual refinements: U.S. Geol. Survey Water-Supply Paper 1988, 21 p.

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

Ogilbee, William, and Rose, M. A., 1969, Ground-water pumpage on the west side of the San Joaquin Valley, Calif., 1962–66: U.S. Geol. Survey basic-data compilation, 7 p.

Page, R. W., 1971, Base of fresh ground water (approximately 3,000 micromhos) San Joaquin Valley, California: U.S. Geol. Survey open-file report, 13 p.

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, 257 p.

Poland, J. F., and Davis, G. H., 1969, Land subsidence due to withdrawal of fluids, *in* Varnes, D. J., and Kiersch, George, eds., Reviews in Engineering Geology, Volume II: Boulder, Colo., Geol. Soc. America, p. 187–269.

Poland, J. F., Lofgren, B. E., and Riley, F. S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U.S. Geol. Survey Water-Supply Paper 2025, 9 p.

Terzaghi, Karl, and Peck, R. B., 1948, Soil mechanics in engineering practice: New York, John Wiley and Sons, Inc., 566 p.

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