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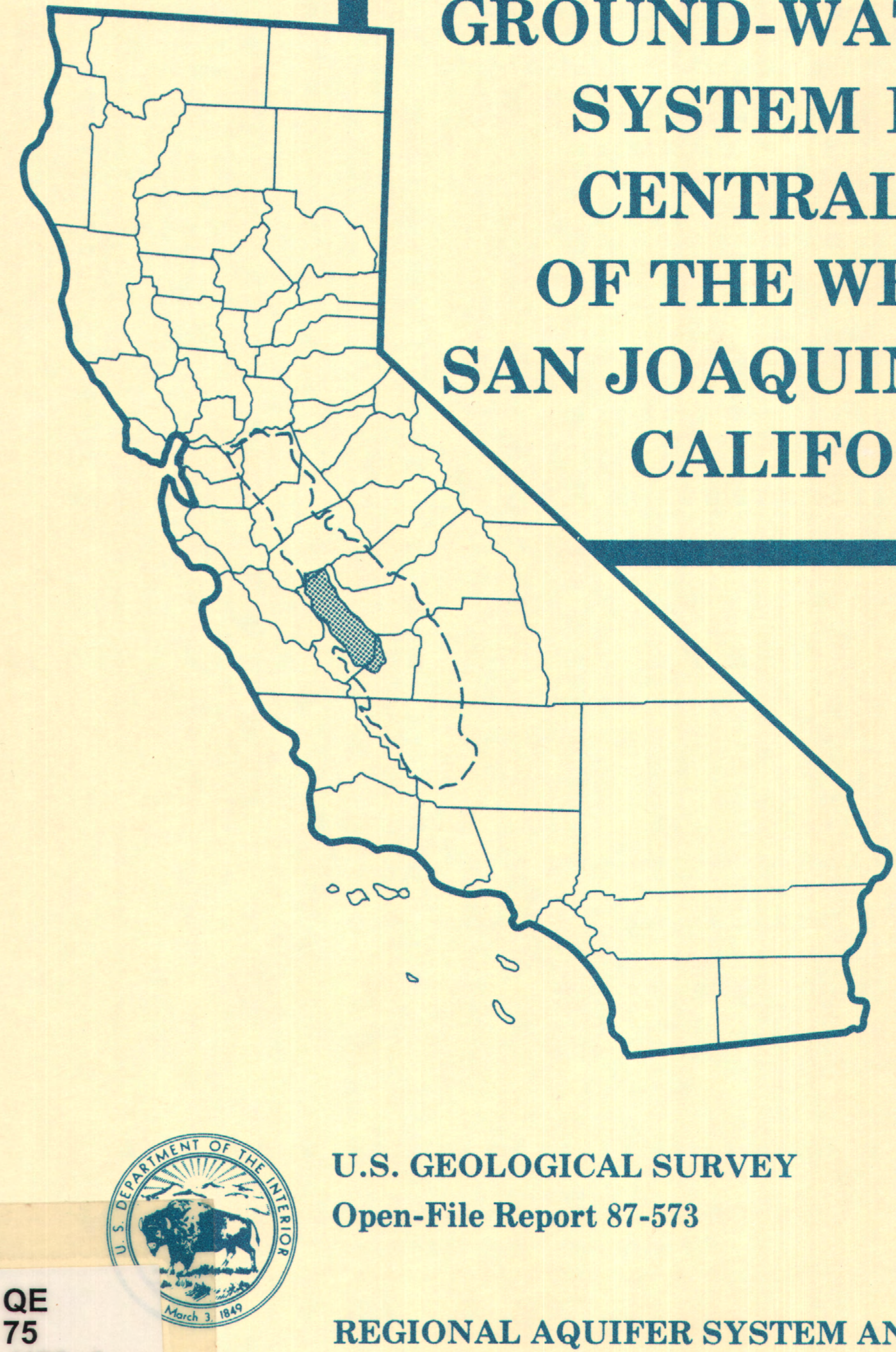
CHARACTER AND EVOLUTION OF THE GROUND-WATER FLOW SYSTEM IN THE CENTRAL PART OF THE WESTERN SAN JOAQUIN VALLEY, CALIFORNIA



U.S. DEPARTMENT OF THE INTERIOR
March 3 1849

U.S. GEOLOGICAL SURVEY
Open-File Report 87-573

REGIONAL AQUIFER SYSTEM ANALYSIS

Prepared in cooperation with the
SAN JOAQUIN VALLEY DRAINAGE PROGRAM

This report was prepared by the U.S. Geological Survey in cooperation with the San Joaquin Valley Drainage Program and as part of the Regional Aquifer System Analysis Program of the U.S. Geological Survey.

The San Joaquin Valley Drainage Program was established in mid-1984 and is a cooperative effort of the U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, California Department of Fish and Game, and California Department of Water Resources. The purposes of the Program are to investigate the problems associated with the drainage of agricultural lands in the San Joaquin Valley and to develop solutions to those problems. Consistent with these purposes, program objectives address the following key areas: (1) Public health, (2) surface- and ground-water resources, (3) agricultural productivity, and (4) fish and wildlife resources.

Inquiries concerning the San Joaquin Valley Drainage Program may be directed to:

San Joaquin Valley Drainage Program
Federal-State Interagency Study Team
2800 Cottage Way, Room W-2143
Sacramento, California 95825-1898

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

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1988

DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

The inch-pound system of units is used in this report. For those readers who prefer to use metric (International System) of units rather than inch-pound units, the conversion factors for the units used in this report are listed below.

Multiply inch-pound unit	By	To obtain metric unit
acres	0.4047	square hectometers
acre-feet per year	0.001233	cubic hectometers per year
feet	0.3048	meters
feet per mile	0.1894	meter per kilometer
cubic feet per year per square foot	0.3048	cubic meter per annum per square meter
miles	1.609	kilometers
square miles	2.590	square kilometers

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

CHARACTER AND EVOLUTION OF THE GROUND-WATER FLOW SYSTEM IN THE CENTRAL PART OF THE WESTERN SAN JOAQUIN VALLEY, CALIFORNIA

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ABSTRACT

The occurrence of selenium in agricultural drain water derived from the western San Joaquin Valley, California, has focused concern on the ground-water flow system of the western valley. In this investigation, previous work and recently collected texture and water-level data are used to evaluate the character and evolution of the regional ground-water flow system in the central part of the western valley, with particular emphasis on the deposits overlying the Corcoran Clay Member of the Tulare Formation.

The Corcoran Clay Member, where present, divides the flow system into an upper semiconfined zone and a lower confined zone. Above the Corcoran, three hydrogeologic units can be recognized: Coast Range alluvium, Sierran sand, and flood-basin deposits. These units differ in texture, hydrologic properties, and oxidation state.

The development of irrigated agriculture in the central part of the western valley has significantly altered the flow system. Percolation of irrigation water past crop roots has caused a rise in the altitude of the water table in midfan and distal-fan areas. Pumpage of ground water from wells has caused a lowering of the water table beneath parts of the fanheads and a lowering of the potentiometric surface of the confined zone over much of the western valley. The combination of percolation and pumpage has resulted in development of a large downward hydraulic head gradient in the semiconfined zone and has created a ground-water divide along the western margin of the valley. Surface-water deliveries from the California Aqueduct have allowed a decrease in pumpage and a consequent recovery in hydraulic head throughout the system.

INTRODUCTION

Saline conditions and associated high levels of selenium and other soluble trace elements are prevalent in soils, ground water, and agricultural drain water of the western San Joaquin Valley, California (Deverel and others, 1984; Tidball and others, 1986). The occurrence and movement of selenium and other dissolved constituents through the hydrologic system of the western valley is closely related to the movement of ground water. Therefore, an understanding of the ground-water flow system should help provide insight into the sources, occurrence, and movement of selenium and other solutes in the system. In addition, an increased understanding of the ground-water flow system will provide resource managers with information that will be helpful in managing the system.

Purpose and Scope

The objective of this report is to present an overview of the ground-water flow system in the central part of the western San Joaquin Valley, with particular emphasis on the deposits and flow system that overlie the Corcoran Clay Member of the Tulare Formation. The primary study area is shown in figure 1, though some information given in this report extends beyond those boundaries.

The study area includes those parts of the western valley containing the highest levels of selenium in soil (Tidball and others, 1986), ground water, and agricultural drain water (Deverel and others, 1984). Although there have been several reports on the ground-water hydrology of the western valley, few have focused on the flow system in the deposits that overlie the Corcoran. Moreover, the flow system has undergone considerable change since those reports have been written. The present investigation synthesizes previous work with ongoing investigations to describe (1) the geology of the regional flow system, (2) the evolution of the flow system since the development of irrigated agriculture, and (3) the present day flow system. Such a synthesis will provide valuable information to current investigators and planners and will serve as a foundation for subsequent quantitative studies of the flow system at both local and regional scales.

This study is part of a comprehensive investigation by the U.S. Geological Survey of the hydrology and geochemistry of the San Joaquin Valley. The studies are being done as part of the Regional Aquifer System Analysis Program of the U.S. Geological Survey and in cooperation with the San Joaquin Valley Drainage Program.

Previous Investigations

Several geologic and hydrologic studies have focused on or included the central part of the western San Joaquin Valley. Davis and Poland (1957) recognized three bodies of ground water in the western San Joaquin Valley: (1) an unconfined and semiconfined zone of fresh water above the Corcoran Clay Member of the Tulare Formation, (2) a confined zone of fresh water beneath the Corcoran Clay Member, and (3) a saline body of water underlying the confined fresh water. Davis and Poland (1957) and Davis and others (1959) noted that the deposits overlying the Corcoran Clay Member are derived from the Coast Range to the west and the Sierra Nevada to the east. Miller and others (1971) mapped the thickness and extent of the deposits derived from each of these sources. Miller and others (1971) and Bull and Miller (1975) noted that the deposits derived from the Coast Range that overlie the Corcoran are typically of low permeability and those derived from the Sierra Nevada are generally of higher permeability. Historically, agricultural wells in the western valley primarily have tapped the confined zone except in the valley trough, where the wells also tap the Sierran sands. The geology of the freshwater bearing deposits is extensively discussed by Miller and others (1971), Croft (1972), Hotchkiss (1972), and Page (1986).

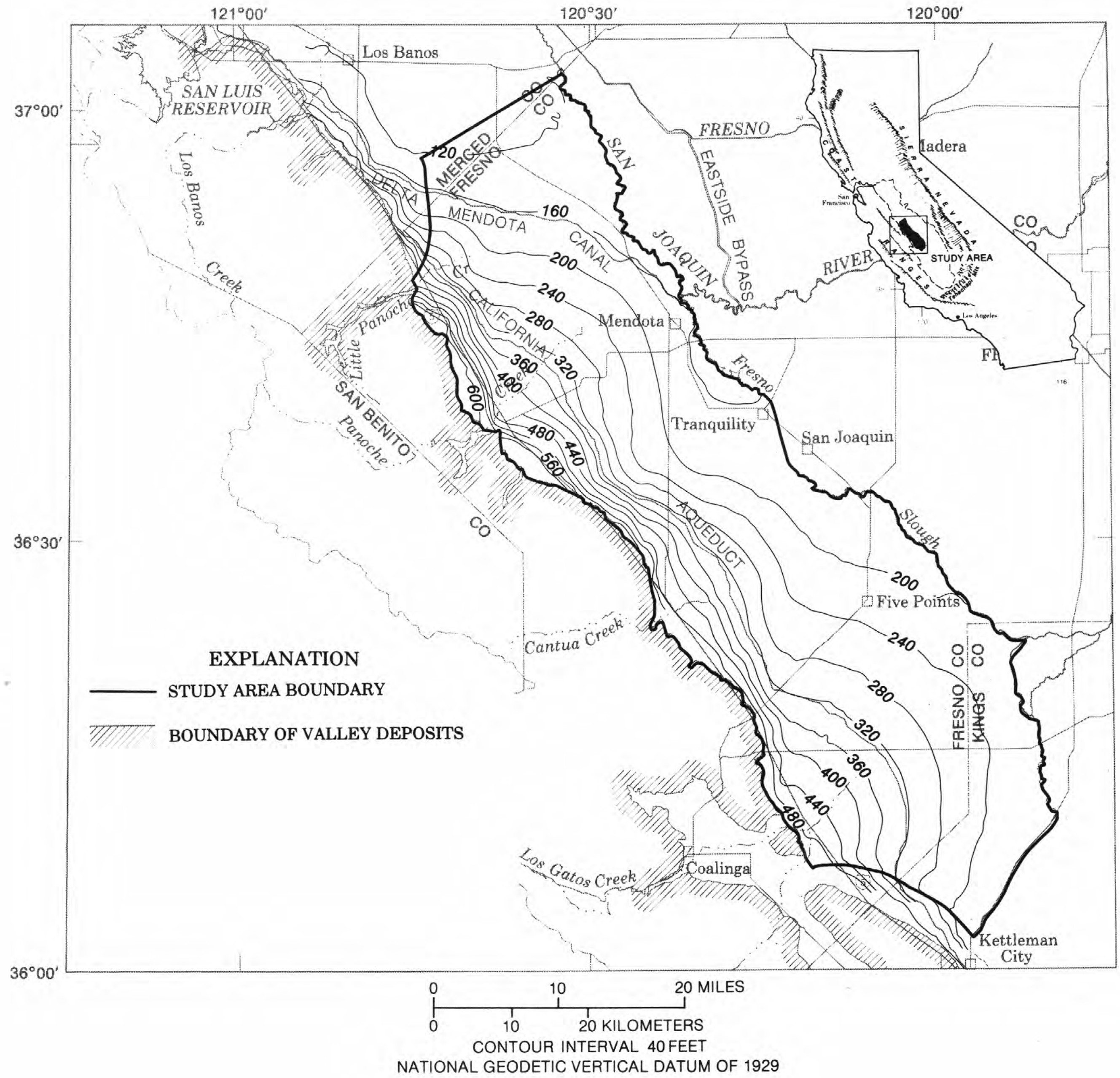

FIGURE 1. — Location and topography of the study area.

Several of the previous studies have assessed the ground-water flow system at a particular period in time. The earliest assessment of ground water in the western valley was by Mendenhall (1908) and by Mendenhall and others (1916). Their work provides documentation of the system during the earliest stages of agricultural development. Davis and Poland (1957) and Davis and others (1959) provide documentation of the flow system during a period of rapid expansion of irrigated acreage. These authors used the work of Mendenhall and others (1916) to assess the natural flow system and evaluate the changes in the natural system resulting from agricultural development. Bull and Miller (1975) also investigated changes in the flow system arising from agricultural development and related those changes to land subsidence. The U.S. Bureau of Reclamation (1965) prepared maps, cross sections, and hydrographs, which document the geology and hydrology prior to the completion of the California Aqueduct. Hotchkiss and Balding (1971) assessed the geology, hydrology, and water quality of the freshwater bearing deposits in the northern part of the western valley. Ireland and others (1984) present a large number of maps and hydrographs that document water levels and the evolution of the flow system.

Most recently, Williamson (1982), Diamond and Williamson (1983), and Williamson and others (1985) conducted a comprehensive investigation of the flow system for the entire Central Valley. That study, which was part of the Regional Aquifer System Analysis (RASA) program of the U.S. Geological Survey, provides an assessment of the flow system in the Central Valley under natural conditions and for 1961-77.

Acknowledgments

The preparation and completion of this report were made possible by the cooperation and assistance of several agencies and individuals. The U.S. Bureau of Reclamation, the California Department of Water Resources, and the Westlands Water District provided data and maps essential to this investigation. Steven Phillips and Jo Ann Murashige, of the U.S. Geological Survey, assisted the author in the reduction of data and preparation of maps. The author would especially like to thank Frederick Heimes and John Carlson of the Survey for their production of the maps presented in this report.

GEOLOGY

The San Joaquin Valley is an asymmetrical basin bounded by the Coast Ranges to the west, the Tehachapi Mountains to the south, the Sierra Nevada to the east, and the delta of the San Joaquin and Sacramento Rivers to the north. The axis of the valley trough is closer to the Coast Ranges than to the Sierra Nevada. The study area shown in figure 1 is defined by the Coast Ranges to the west, by the San Joaquin River and Fresno Slough in the trough of the San Joaquin Valley to the east and, to the north and south, by the lateral extent of prominent alluvial fans derived from the Coast Ranges.

Bull (1964a, 1964b, 1972) identified 21 alluvial fans in the central part of western Fresno County ranging in area from less than 1 square mile to more than 250 square miles. Deposits associated with the two largest fans, Los Gatos Creek fan and Panoche Creek fan, occupy more than one-half the total area. Many of the fans identified by Bull (1964a, 1964b, 1972) are of limited areal extent and coalesce with large neighboring fans.

The Pleistocene Corcoran Clay Member of the Tulare Formation divides the ground-water flow system into a lower confined zone and an upper semiconfined zone. The deposits of the semiconfined zone can be divided into three hydrogeologic units: Coast Range alluvium, Sierran sands, and flood-basin deposits. These units differ in texture, hydrologic properties, and oxidation state.

The Coast Range alluvium is derived from the Coast Range to the west. The alluvial deposits are generally oxidized (Davis and others, 1959) and range in thickness from 850 feet (Page, 1986) along the Coast Range to 0 feet along the valley trough (fig. 2). The texture of the alluvium is largely a function of relative position on the alluvial fan. Alluvial fans are commonly divided into three parts (Blissenbach, 1954; Reineck and Singh, 1980): the apex of the alluvial fan (the fanhead), the area between the fanhead and the lower margins of the fan (the midfan), and the outermost, lowest altitudes of the fan, where the fan often coalesces with other fans (distal fan). The deposits are significantly coarser at the fanheads than at

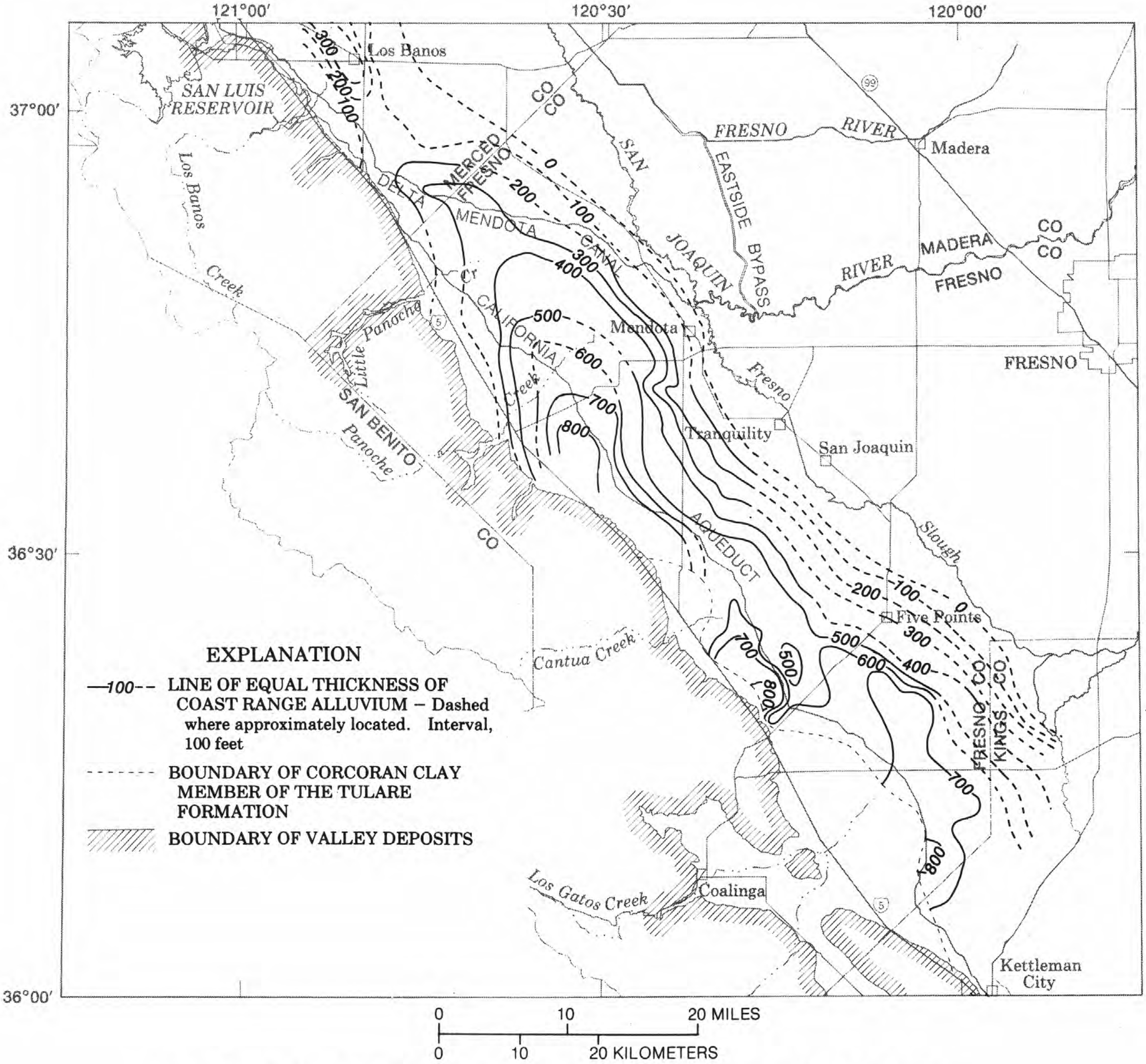

FIGURE 2. — **Thickness of Coast Range alluvium that overlies the Corcoran Clay Member of the Tulare Formation. (Adapted from Miller and others, 1971.)**

midfan and distal-fan locations. Textural analysis of the alluvial deposits (J.A. Laudon, U.S. Geological Survey, written commun., 1987) indicates that the fanhead deposits are typically 80 to 100 percent sand and gravel and less than 20 percent silt and clay. The distal-fan deposits typically contain less than 20 percent sand and gravel and more than 80 percent silt and clay. The midfan deposits are typically coarse textured along present-day stream channels and paleochannels and finer grained between channels.

Bull (1964b) recognized two types of deposits in the alluvium: mudflow and water-laid deposits. The mudflow deposits typically are poorly sorted and are in close proximity to the Coast Range. The water-laid deposits are better sorted and are more areally extensive than the mudflow deposits.

The alluvium derived from the Coast Range interfingers eastward with material derived from the Sierra Nevada to the east. In the trough of the valley, the deposits derived from the Sierra Nevada are predominantly well-sorted micaceous sands (Miller and others, 1971). The Sierran sands are 400 to 500 feet thick in the valley trough and thin eastward and westward (fig. 3). The Sierran sands differ from the Coast Range alluvium in texture as well as oxidation state. In contrast to Coast Range alluvium, the Sierran sands are reduced in the valley trough (Davis and others, 1959). The Sierran deposits are highly permeable and historically have been tapped by wells as a source of irrigation water.

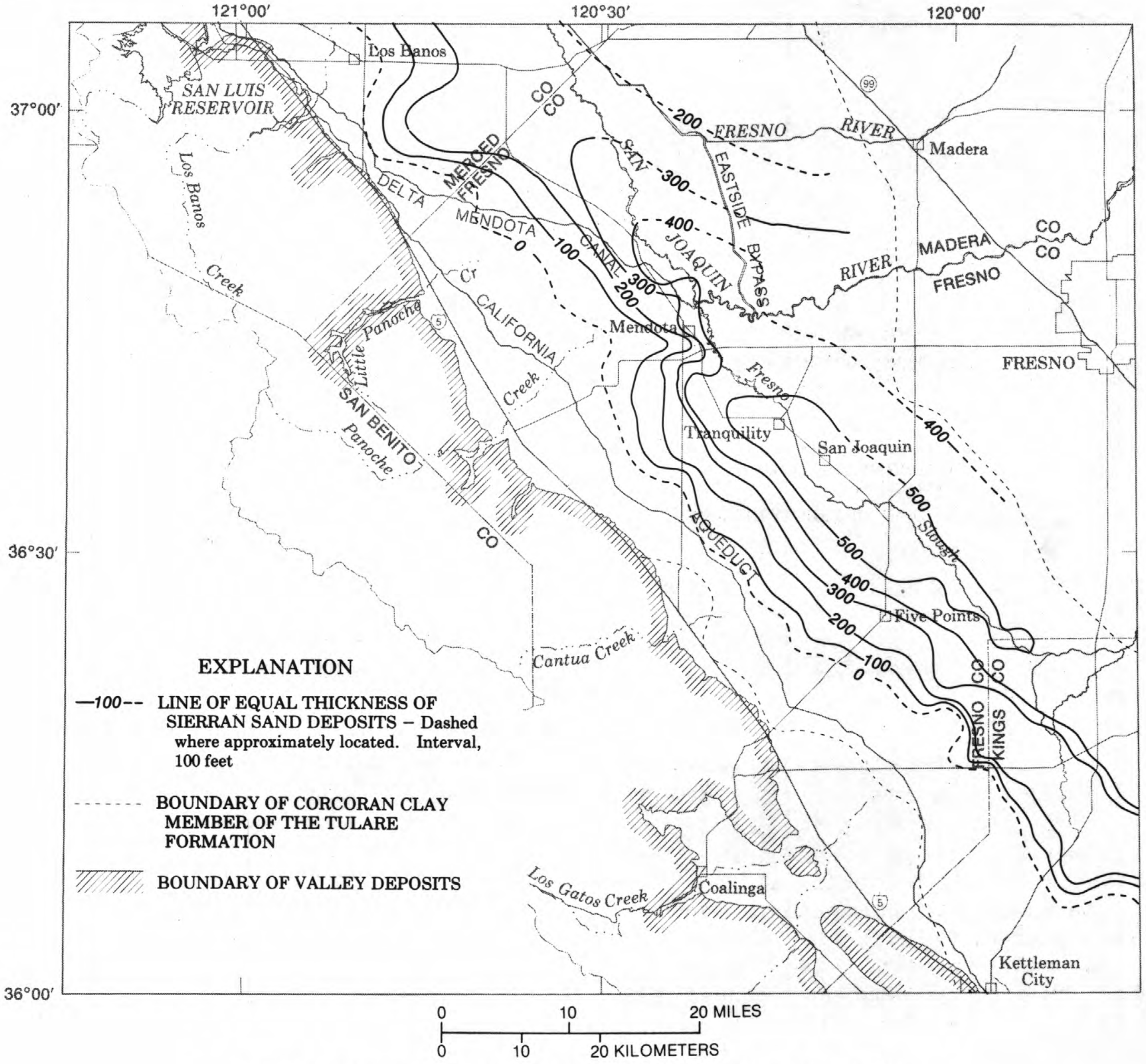

FIGURE 3. – Thickness and extent of Sierran sands. (Adapted from Miller and others, 1971.)

In the valley trough, the Sierran sands are overlain by a veneer of flood-basin deposits (fig. 4). The basin deposits are derived from the Coast Range to the west and the Sierra Nevada to the east. The deposits are of variable thickness (typically 5 to 35 feet) and texture but consist primarily of fine-textured, moderate to densely compacted clays. The basin clays are of low permeability and greatly impede the downward movement of water. The oxidation state of the flood-basin deposits is variable, reflecting the variability of depositional conditions and perhaps changes in oxidation state attributable to agricultural activity.

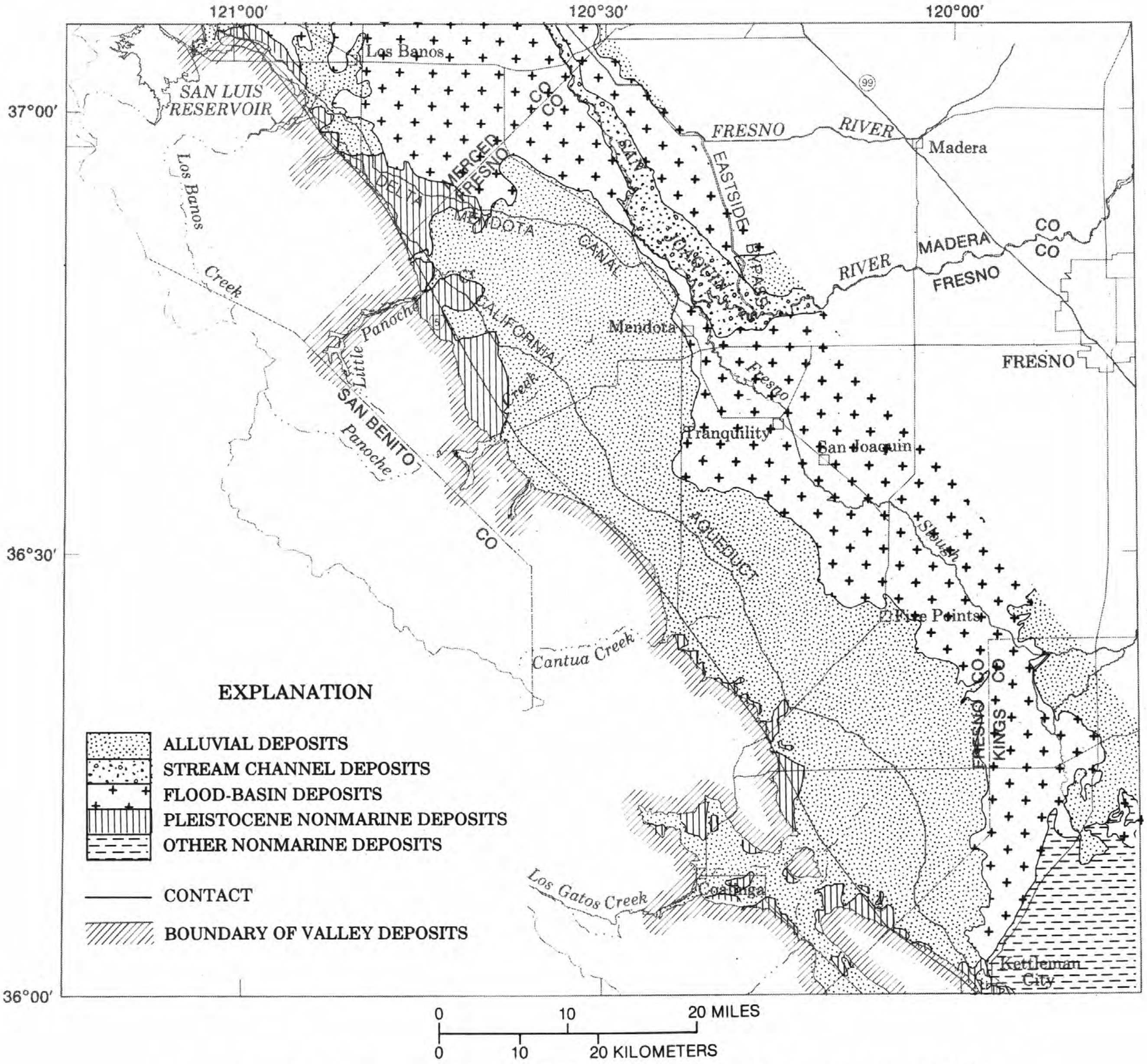

FIGURE 4. — Surficial geology. (Adapted from California Division of Mines and Geology, 1959, 1965, and 1966.)

An understanding of the flow system above the Corcoran Clay Member of the Tulare Formation requires, to a certain extent, an understanding of the Corcoran and of the flow system below the Corcoran. The Corcoran Clay Member is an extensive lacustrine deposit of low permeability (Johnson and others, 1968). The base of the unit ranges in depth from 400 feet in the valley trough to more than 900 feet along the Coast Range (fig. 5) and the unit ranges in thickness from 20 to 120 feet (fig. 6). Recent mapping of the Corcoran Clay Member (Page, 1986) indicates that the structure and thickness of the Corcoran is more variable than indicated in figures 5 and 6. The general trends, however, illustrated in figures 5 and 6 are confirmed by the work of Page (1986). The upper two-thirds of the Corcoran Clay Member consists of thin-bedded clayey

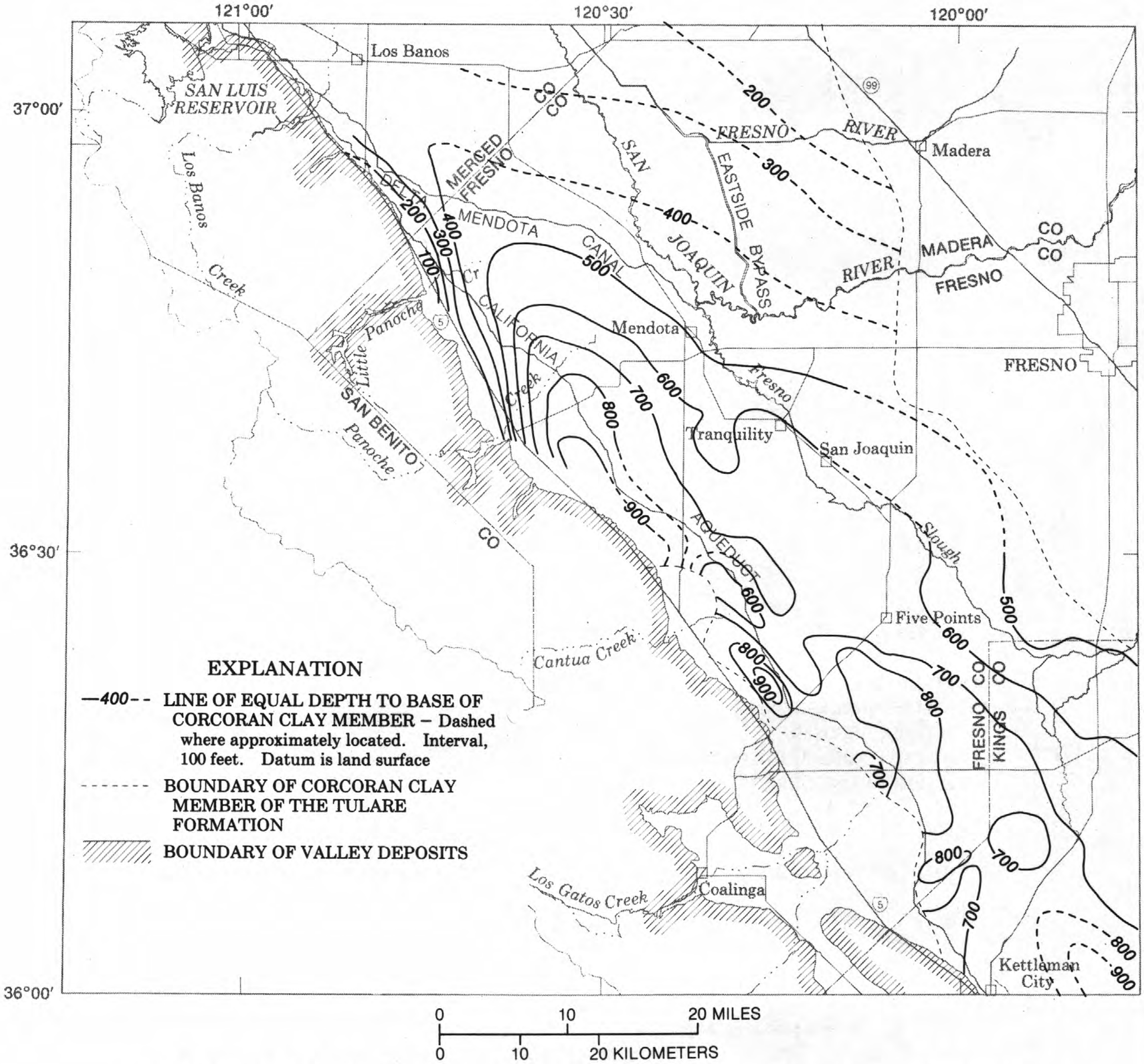

FIGURE 5. — Depth to the base of the Corcoran Clay Member of the Tulare Formation. (Adapted from Bull and Miller, 1975.)

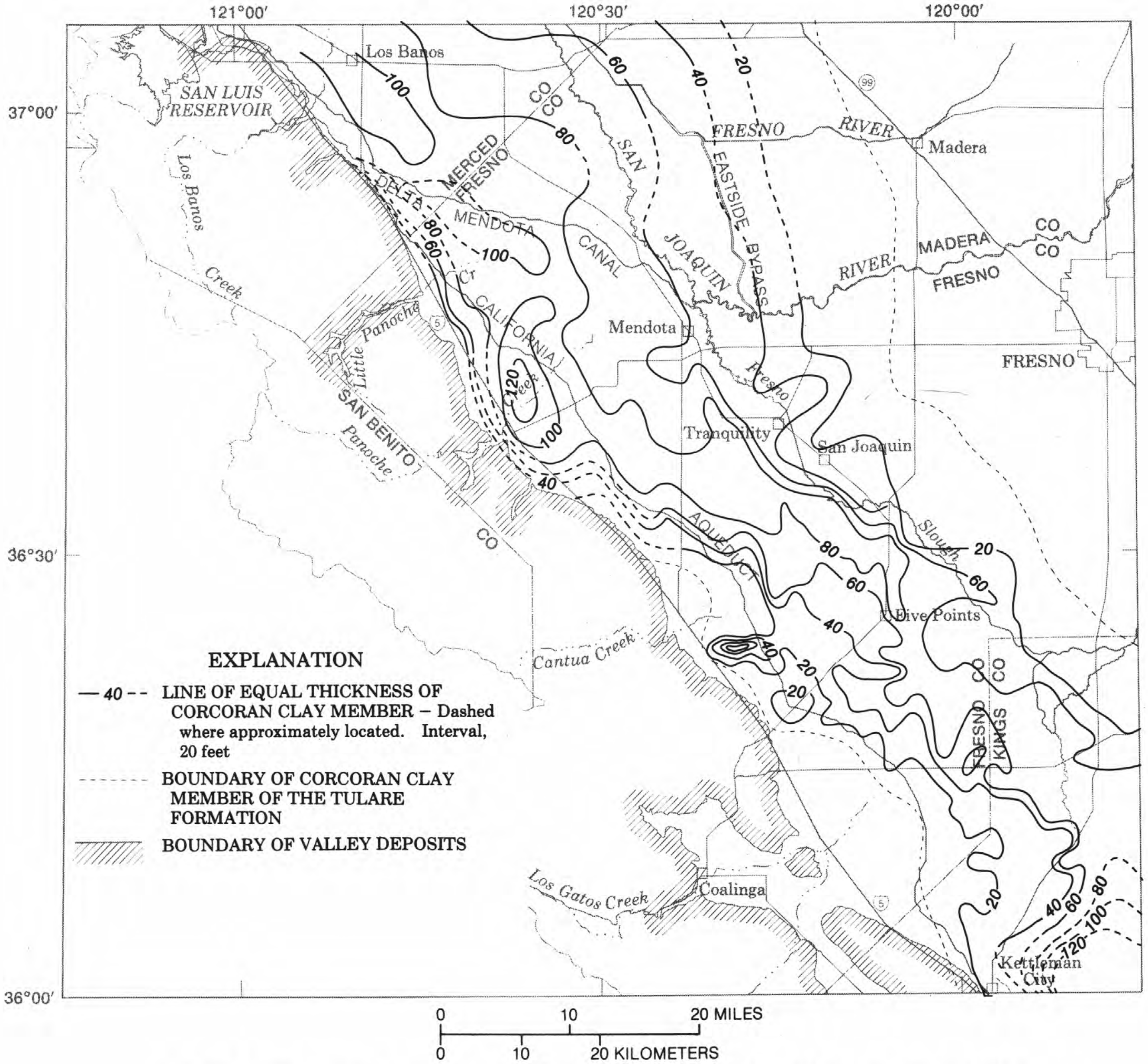

FIGURE 6. — Thickness of the Corcoran Clay Member of the Tulare Formation. (Adapted from Miller and others, 1971.)

silt and silty clay and the lower one-third consists of interbedded sand-silt-clay and clayey silt (Bull, 1975). The Corcoran is chemically reduced except in the extreme western part of the study area where it has been uplifted and partially oxidized.

Historically, many of the agricultural production wells in the study area have been perforated below the Corcoran Clay Member. The lower confined zone consists of poorly consolidated flood-plain, deltaic, alluvial-fan, and lacustrine deposits of the Tulare Formation. The lower confined zone has been the subject of numerous investigations, many of which focused on land subsidence (for a review, see Poland and others, 1975).

GROUND-WATER FLOW SYSTEM

The ground-water flow system of the western San Joaquin Valley has undergone considerable change since the development of irrigated agriculture. The present-day flow system is in a transient state and is responding to stresses imposed on it in both the past and the present. Therefore, it is useful to understand the natural flow system and the evolution of the flow system since the development of irrigated agriculture in the western valley. Because the focus of this paper is on the semiconfined zone, it is of particular importance to understand those activities that have affected the semiconfined zone. These activities include percolation of irrigation water past crop roots, historic pumpage of ground water from below the Corcoran Clay Member of the Tulare Formation, delivery of surface water, and installation of a regional subsurface tile-drain system. As will be discussed in the following sections, the response of the semiconfined zone to these activities is partly dependent on the texture of the subsurface deposits.

Predevelopment Flow System

Under natural conditions, recharge was primarily from infiltration of stream water from intermittent streams and, perhaps, from smaller ephemeral streams. The intermittent streams (Little Panoche, Panoche, Cantua, and Los Gatos Creeks) flow seasonally during the winter rainy season and the smaller ephemeral streams flow only after storms (Bull, 1964a). None of the stream courses reach the San Joaquin River or Fresno Slough in the trough of the valley. The streams lose their flow through evaporation and infiltration before reaching the valley floor. Davis and Poland (1957) estimated that the four intermittent creeks typically have a total flow of about 50,000 acre-feet per year (acre-ft/yr), of which 30,000 to 40,000 acre-ft/yr infiltrates and recharges the ground water. Davis and Poland (1957) and subsequent workers assumed that rainfall was an insignificant mechanism for recharging the system under natural conditions.

Soil-salinity and soil-compaction data support the view that recharge was limited primarily to areas traversed by the intermittent streams. A soil-salinity map prepared by Harradine (1950; fig. 7) indicates that the highest soil salinities are associated with the midfan and distal-fan, areas which historically have not been traversed by intermittent streams. The lowest soil salinities are associated with the fanhead areas and with the midfan areas, where they are traversed by the major creeks. The absence of saline soils along the contact between the Coast Range and the alluvium along much of the western valley suggests that the numerous minor drainages may have contributed recharge to the ground-water flow system in the geologic past. In contrast, the distribution of soils that have been or would likely be susceptible to near-surface subsidence resulting from soil compaction caused by application of water at the surface (fig. 8) indicates that recharge was small in the areas between the large alluvial fans of the intermittent creeks. Bull (1964b) noted that the interfan areas were built up from mudflow deposits, which are subject to compaction when wetted. The presence of deposits compacted prior to agricultural development in the fanhead areas and of deposits that have been compacted as a result of irrigation (or would likely be compacted if wetted) in the interfan areas suggests that recharge occurred under natural conditions at the fanheads and did not occur in the interfan areas.

Discharge from the system under natural conditions was primarily by evapotranspiration and streamflow along the valley trough. Early geologic surveys of the valley (Hamilton, 1916) indicate the presence of marshland along most of the valley trough. Mendenhall and others' (1916) map of water levels in the semiconfined zone (fig. 9) indicates that

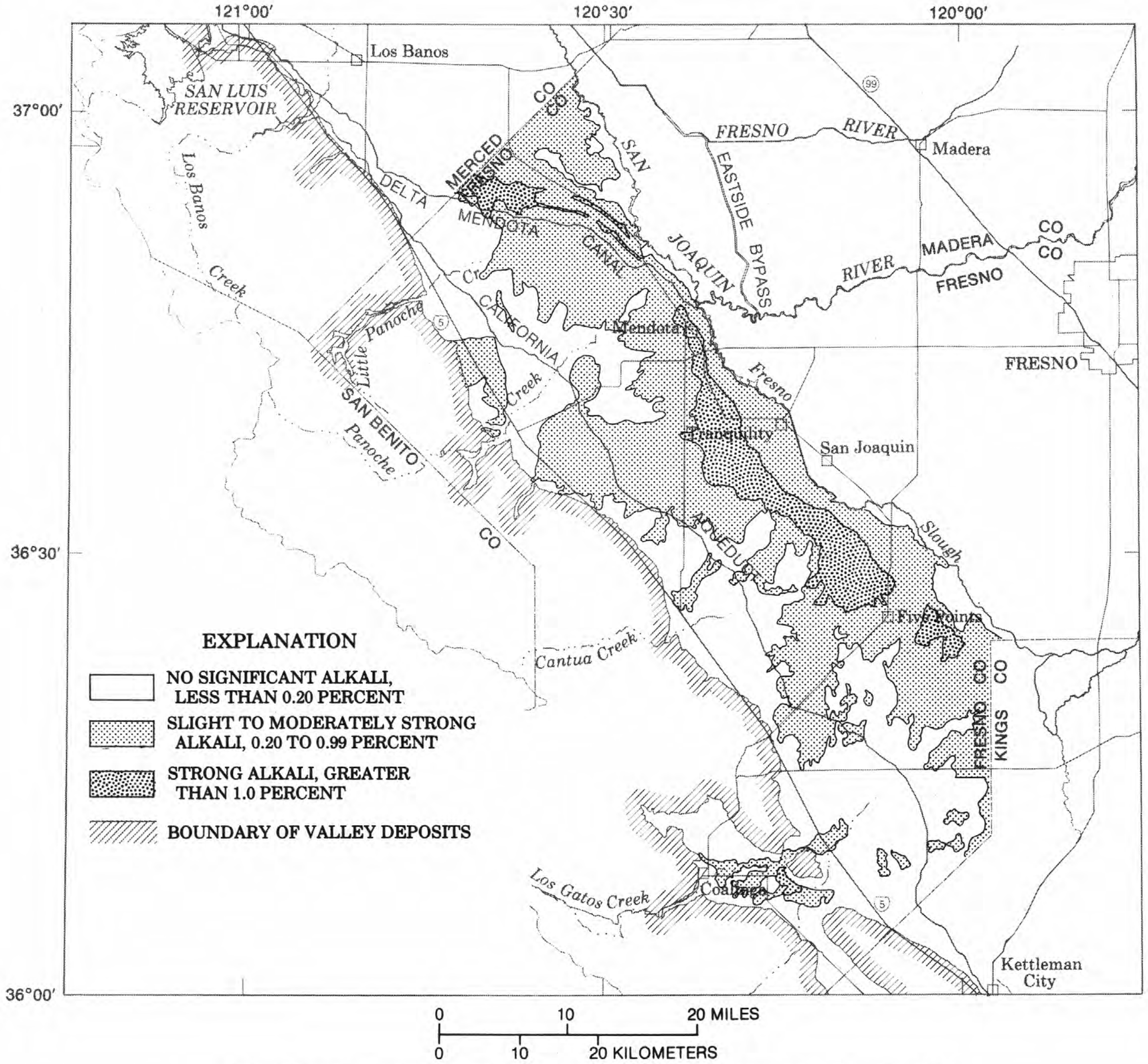

FIGURE 7. — Distribution of alkali in soils in western Fresno County. (Adapted from Harradine, 1950.)

artesian conditions prevailed along a broad stretch of the valley trough. The presence of marshlands in the arid to semiarid Central Valley and the extensive artesian conditions indicate that the valley trough was a discharge area under predevelopment conditions.

Mendenhall's map is based on water levels in wells perforated in the semiconfined zone. His map indicates that ground-water gradients in the semiconfined zone were from the southwest to the northeast, reflecting the general topographic trend of the area. Gradients typically were 1 to 3 feet per mile, reflecting the arid climate and low rates of recharge to the system. Mathematical simulation of the ground-water flow system (Williamson and others, 1985) indicates that the hydraulic head distribution in the confined zone beneath the

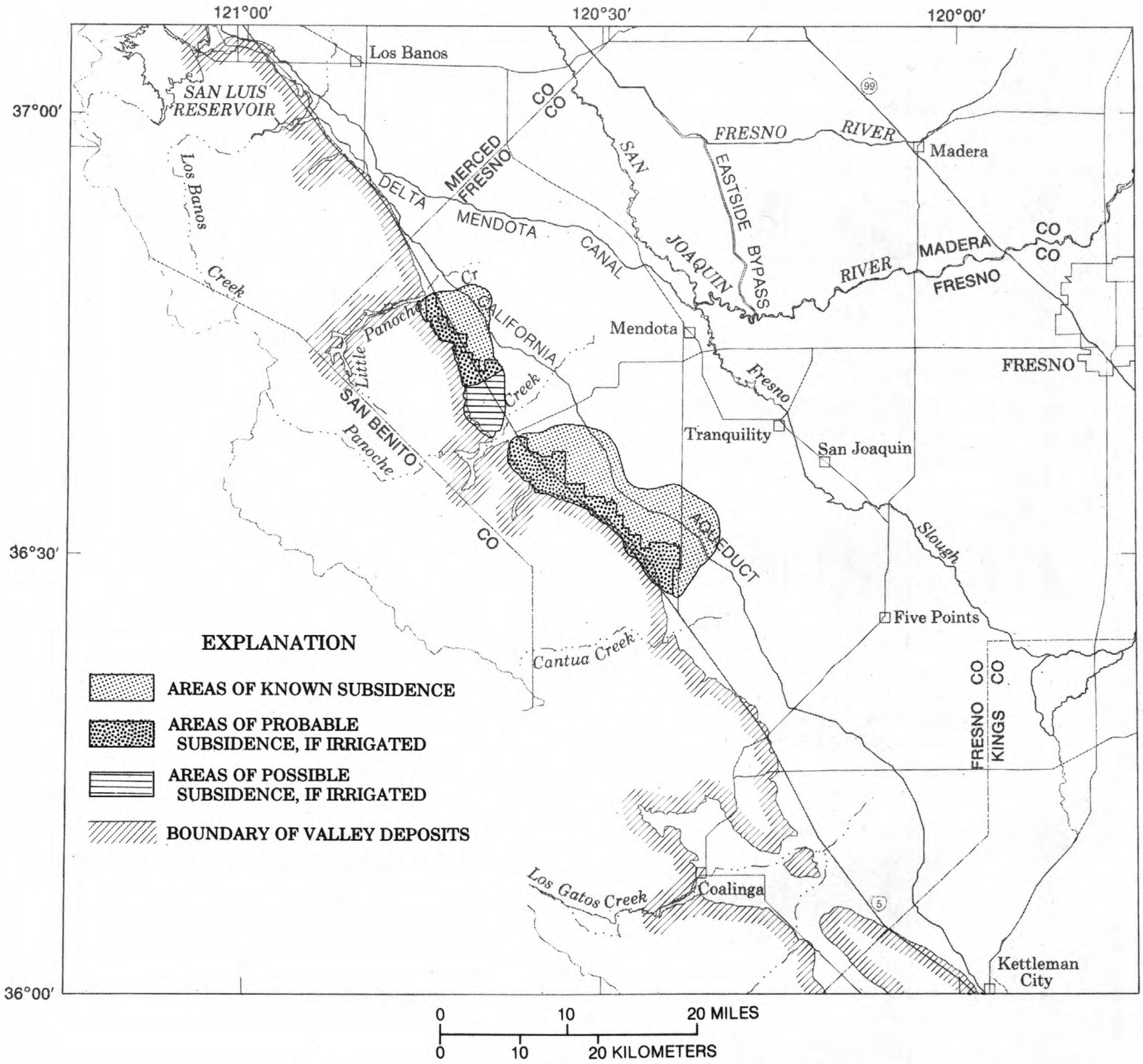

FIGURE 8. — Boundaries of near-surface subsidence areas. (Adapted from Bull, 1964b.)

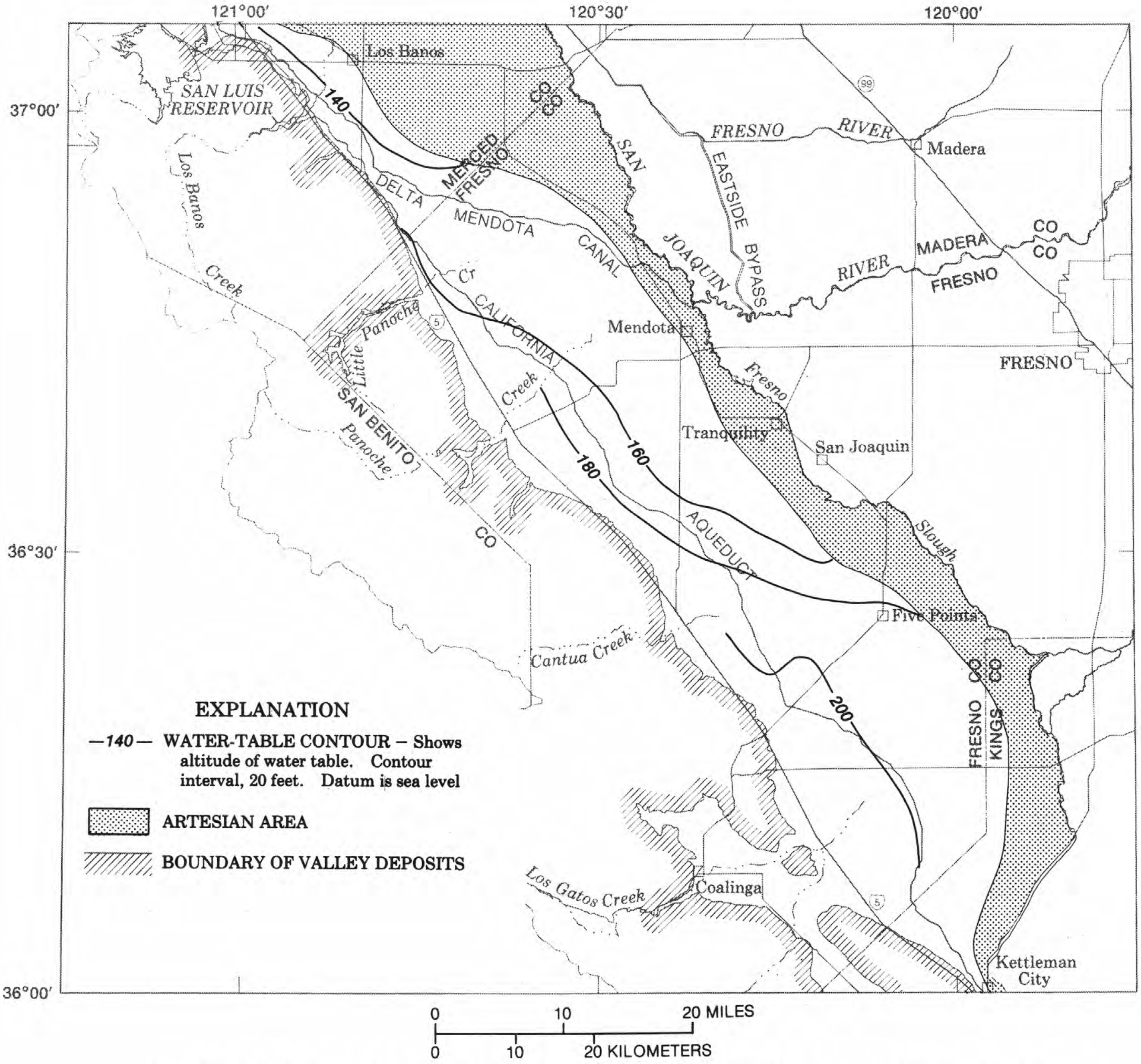

FIGURE 9. — Estimated water-table altitude and extent of artesian areas, 1908. (Adapted from Mendenhall and others, 1916.)

Corcoran Clay Member of the Tulare Formation was quite similar to the hydraulic head distribution in the upper semiconfined zone. The numerical simulation model of Williamson and others (1985) indicates that hydraulic head in the lower confined zone was typically 10 to 20 feet lower then the hydraulic head in the upper semiconfined zone along the Coast Range and 0 to 10 feet higher along the valley trough.

Agricultural Development and System Response

Agricultural activity in the study area began as early as the 1870's, but large-scale farming and irrigation did not occur until the First World War (Davis and Poland, 1957; Bull and Miller, 1975). Irrigation with ground water expanded rapidly in the 1920's and steadily increased until World War II. After World War II, the price of commodities stimulated increased agricultural growth (Davis and Poland, 1957), and by the early 1950's nearly 1 million acre-feet of water was being pumped from the aquifer system (fig. 10). Most of the water was pumped from beneath the Corcoran Clay Member of the Tulare Formation. The increase in irrigated acreage (fig. 11) and in pumping significantly altered the ground-water flow system. Percolation of irrigation water past crop roots greatly exceeded infiltration of intermittent stream water and replaced the latter as the primary mechanism of recharge. Discharge of water through wells and evapotranspiration from crops replaced natural evapotranspiration as the primary mechanism of discharge. Williamson and others (1985) concluded that overall postdevelopment recharge during 1961-77 was more than 40 times greater than the estimated predevelopment values for the Central Valley.

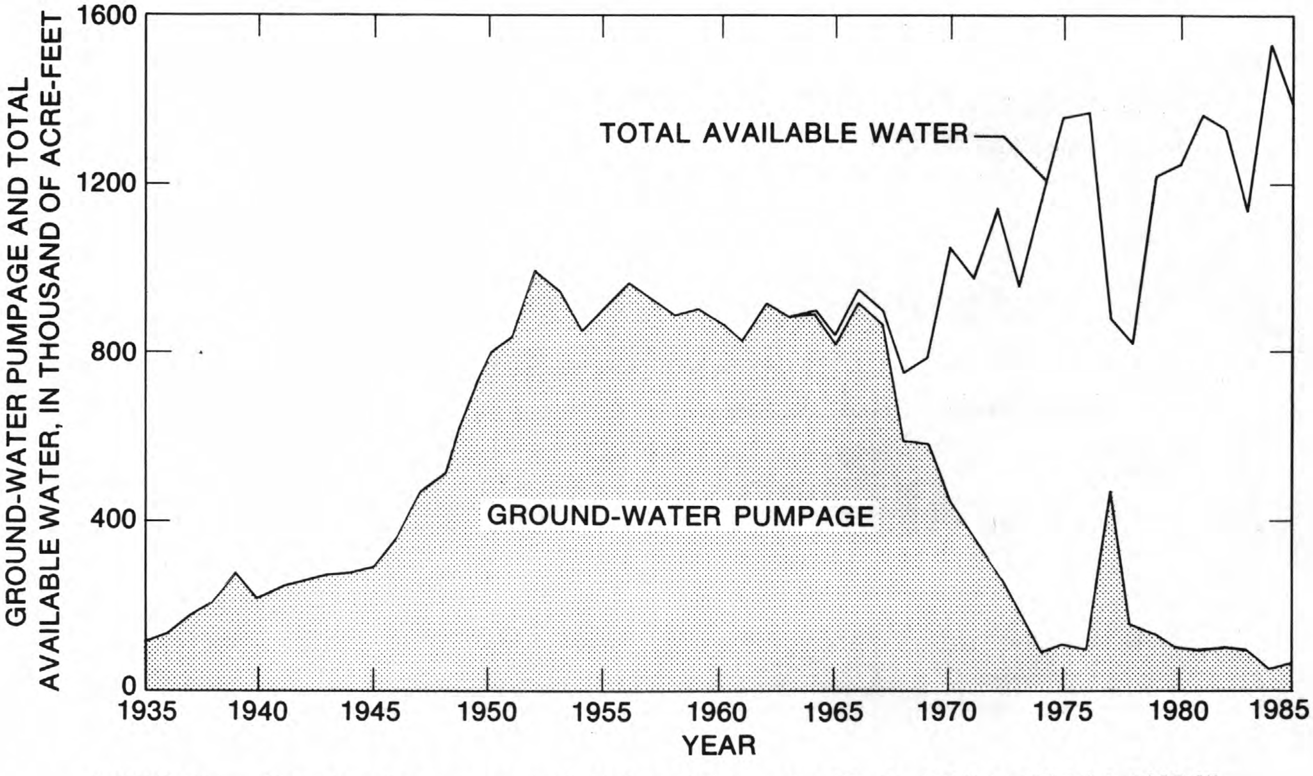

FIGURE 10. — Ground-water pumpage and total available water, Westlands Water District, 1935-85.

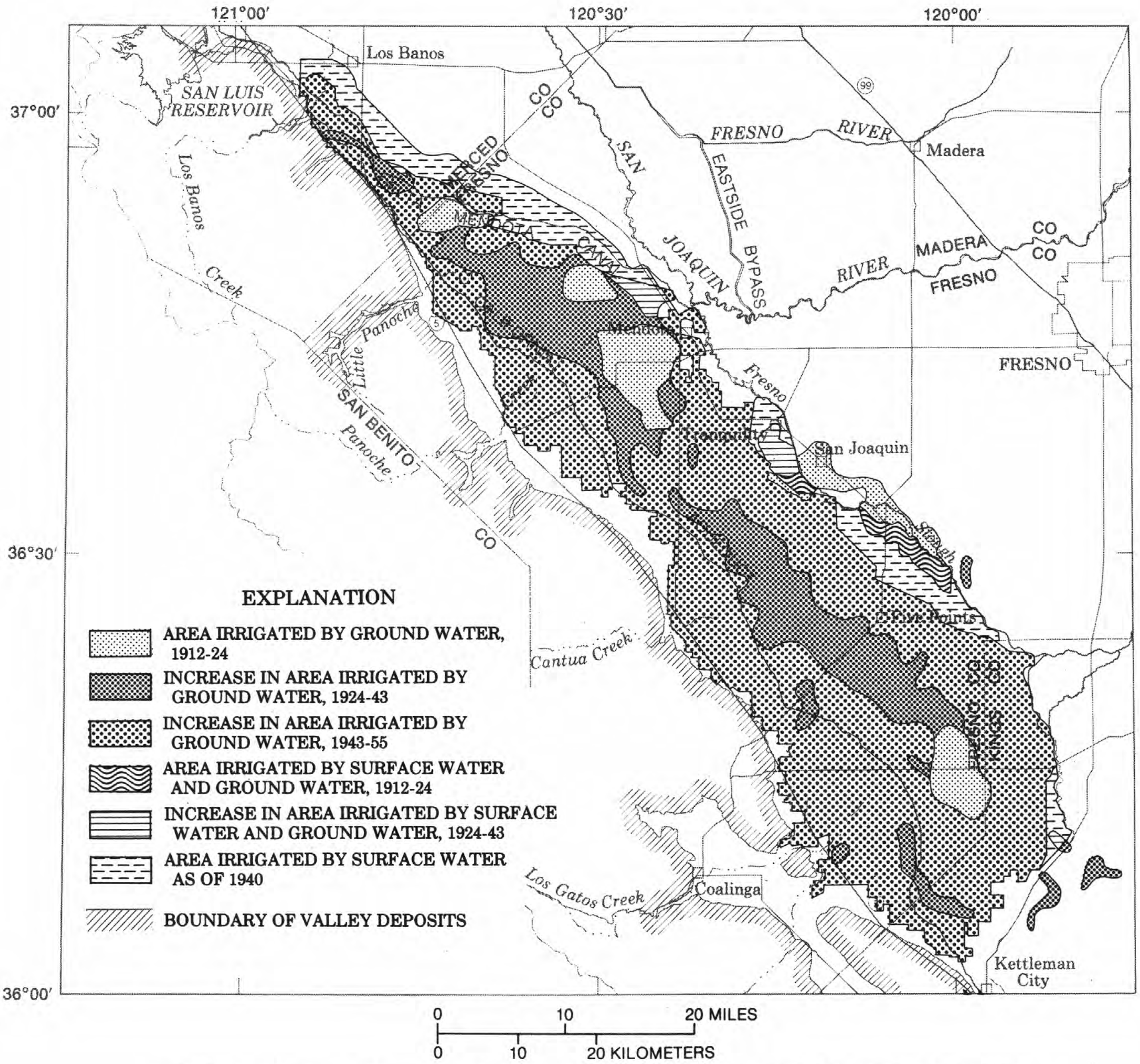

FIGURE 11. — Areal extent of areas irrigated with ground water and surface water. (Modified from Bull and Miller, 1975.)

Pumping of ground water in the central part of the western valley affected the hydraulic head and the direction of flow in the system. The most pronounced changes occurred in the lower confined zone. By 1952, the potentiometric surface of the confined zone (fig. 12) was drawn down 100 to 200 feet from the presumed predevelopment altitude. The large drawdown in hydraulic head created a reversal in the direction of flow in the lower confined zone from eastward to westward, and also caused a significant component of vertical flow from the overlying semiconfined zone.

The changes in the altitude of the water table were less marked than the changes in hydraulic head in the confined zone during the early period of intensive

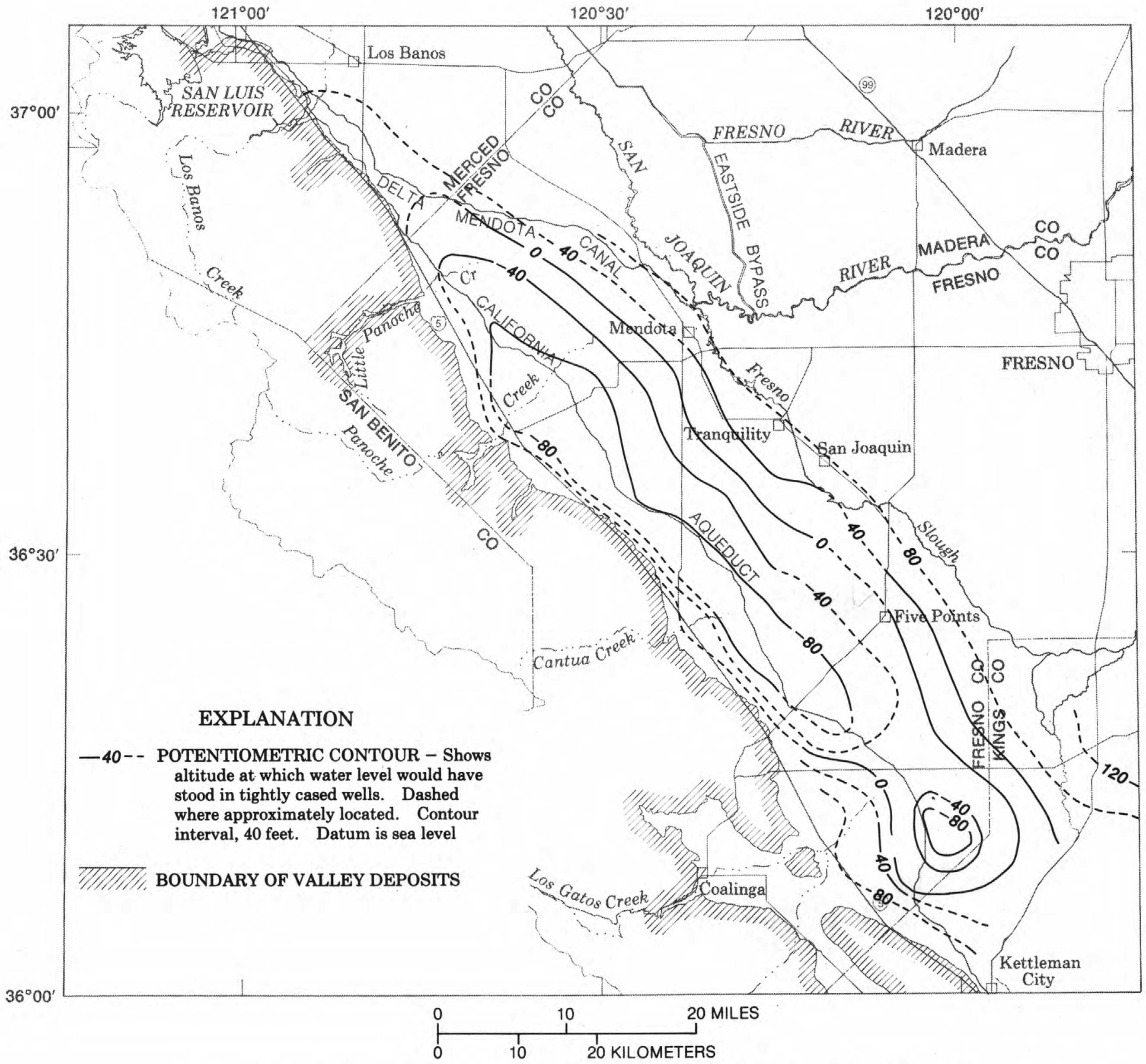

FIGURE 12. — Potentiometric surface of the confined zone, 1952. (Adapted from Davis and others, 1959.)

development. Comparison of maps of the altitude of the water table in 1952 (Davis and others, 1959; fig. 13) and in 1908 (Mendenhall and others, 1916; fig. 9) indicates a lowering of the water table along the distal-fan margins and the valley trough. Water-table declines in these areas were probably the result of pumping from the Sierran sands. In contrast to the lowering of the water table along the distal-fan margins and the valley trough, the altitude of the water table seems unchanged to slightly elevated (Davis and Poland, 1957) along the western part of the area from 1906 to 1952, except for the development of an oblate mound southeast of the Panoche Creek. It is possible, however, that this mound was not actually present. Davis and others' (1959) map probably was

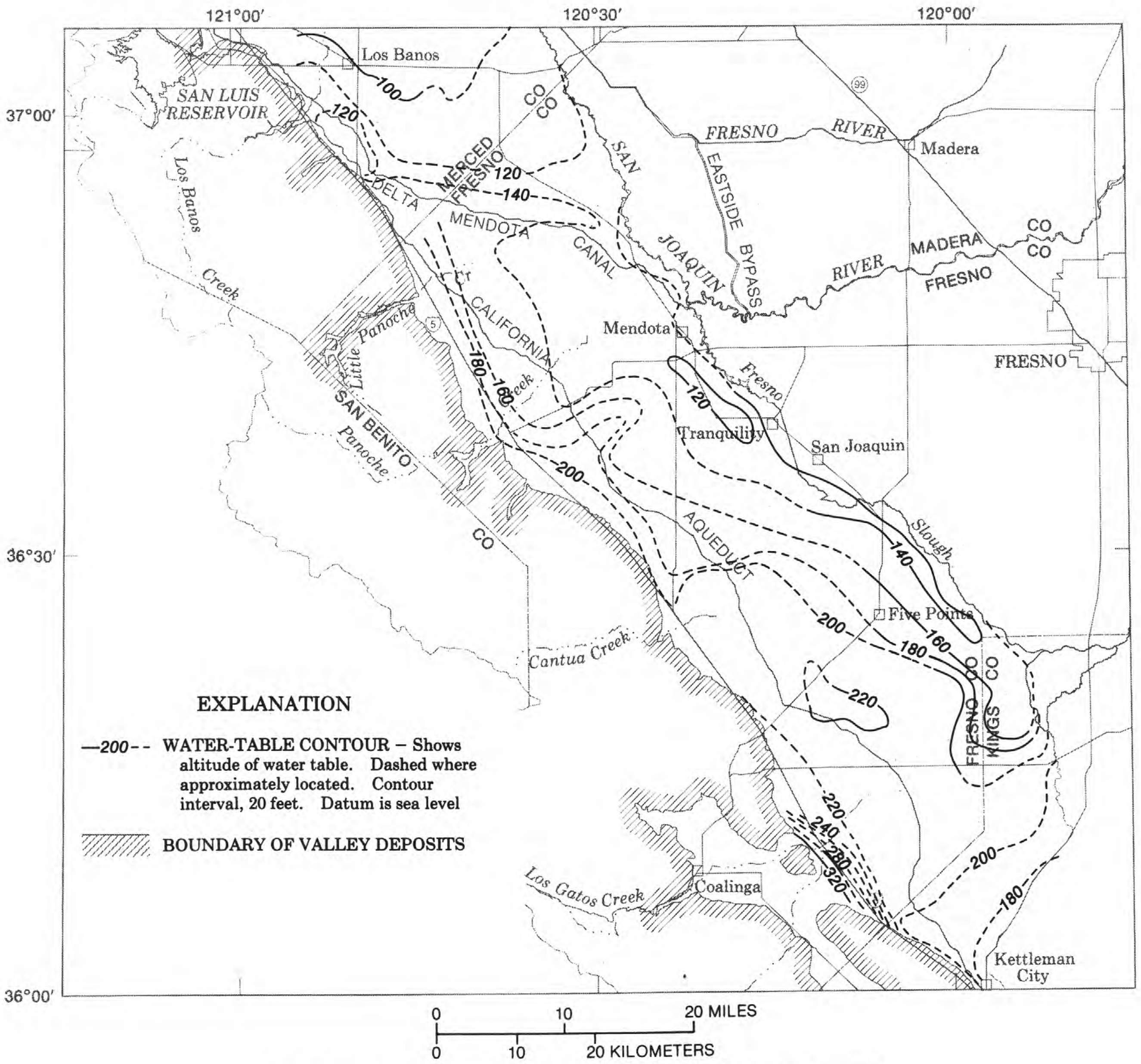

FIGURE 13. — Water-table altitude, spring 1952. (Adapted from Davis and others, 1959.)

not corrected for land subsidence, which was already substantial by the time their map was prepared. The apparent mound is in the area of greatest subsidence.

Agricultural pumping in excess of recharge continued for more than a decade after 1952 and led to continued lowering of the potentiometric surface of the confined zone. By 1967, the potentiometric surface (fig. 14) had been lowered hundreds of feet over much of the western valley. The large quantities of ground water pumped from the aquifer system had several significant effects, including steepening of westward gradients in the confined zone, substantial increase in pumping lifts, and land subsidence (fig. 15). Pumping lifts exceeded 800 feet over parts of

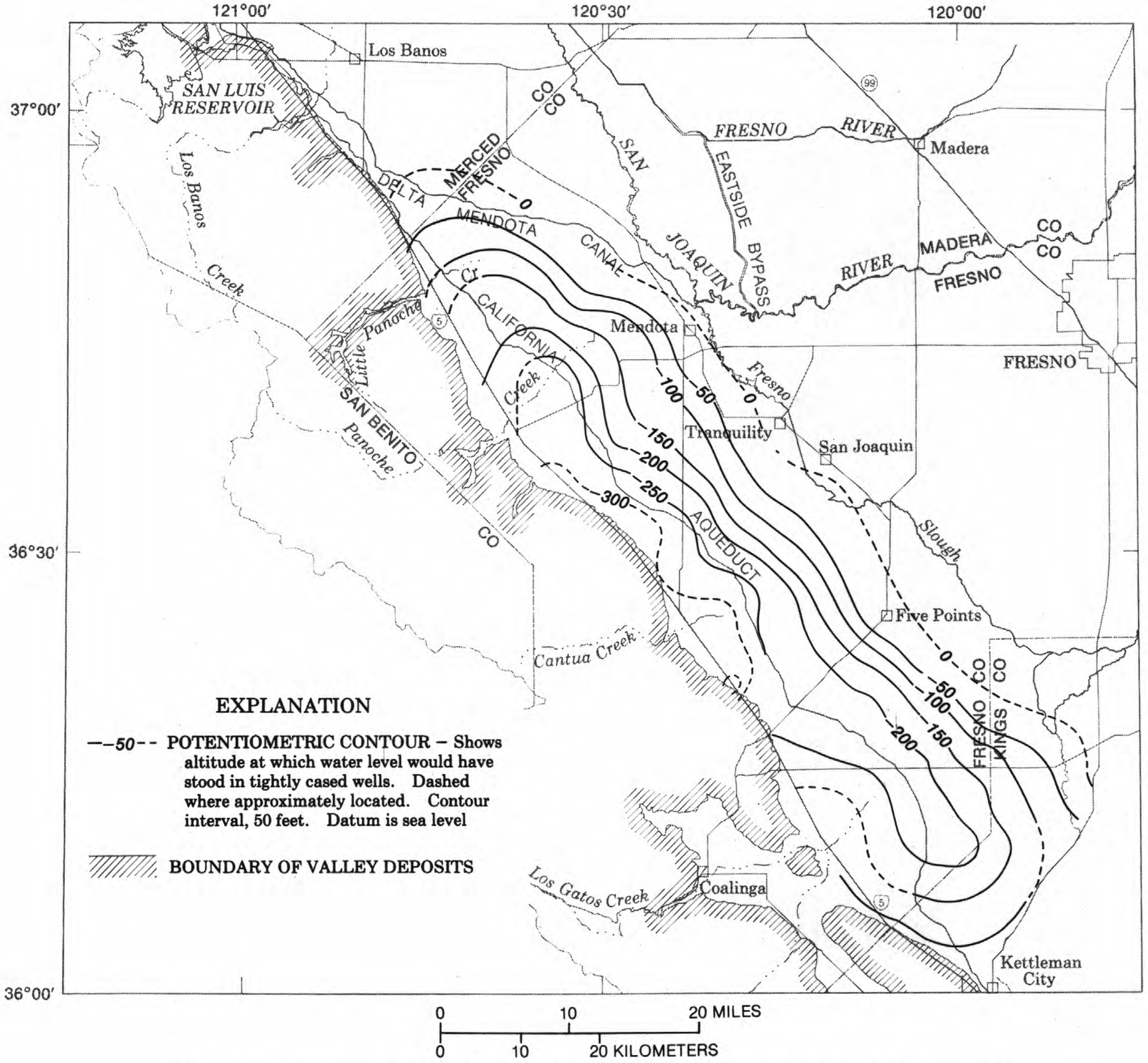

FIGURE 14. — Potentiometric surface of the confined zone, December 1967. (Adapted from Ireland and others, 1984.)

the area and land subsidence of more than 2 feet occurred throughout the study area, with local subsidence reaching as much as 28 feet by 1972.

As a result of land subsidence, increased pumping lifts, and water-quality limitations, surface water was imported to the western valley in order to decrease pumpage from the aquifer system. Beginning in 1967, surface water imported via the California Aqueduct began to replace pumped water as the primary source of irrigation supply in the area south of Mendota. The availability of surface water has led to an increase in the total quantity of water applied while the quantity of water removed from the system by wells has been decreased (fig. 10). The marked decrease in pumpage has allowed a recovery in hydraulic head throughout the aquifer

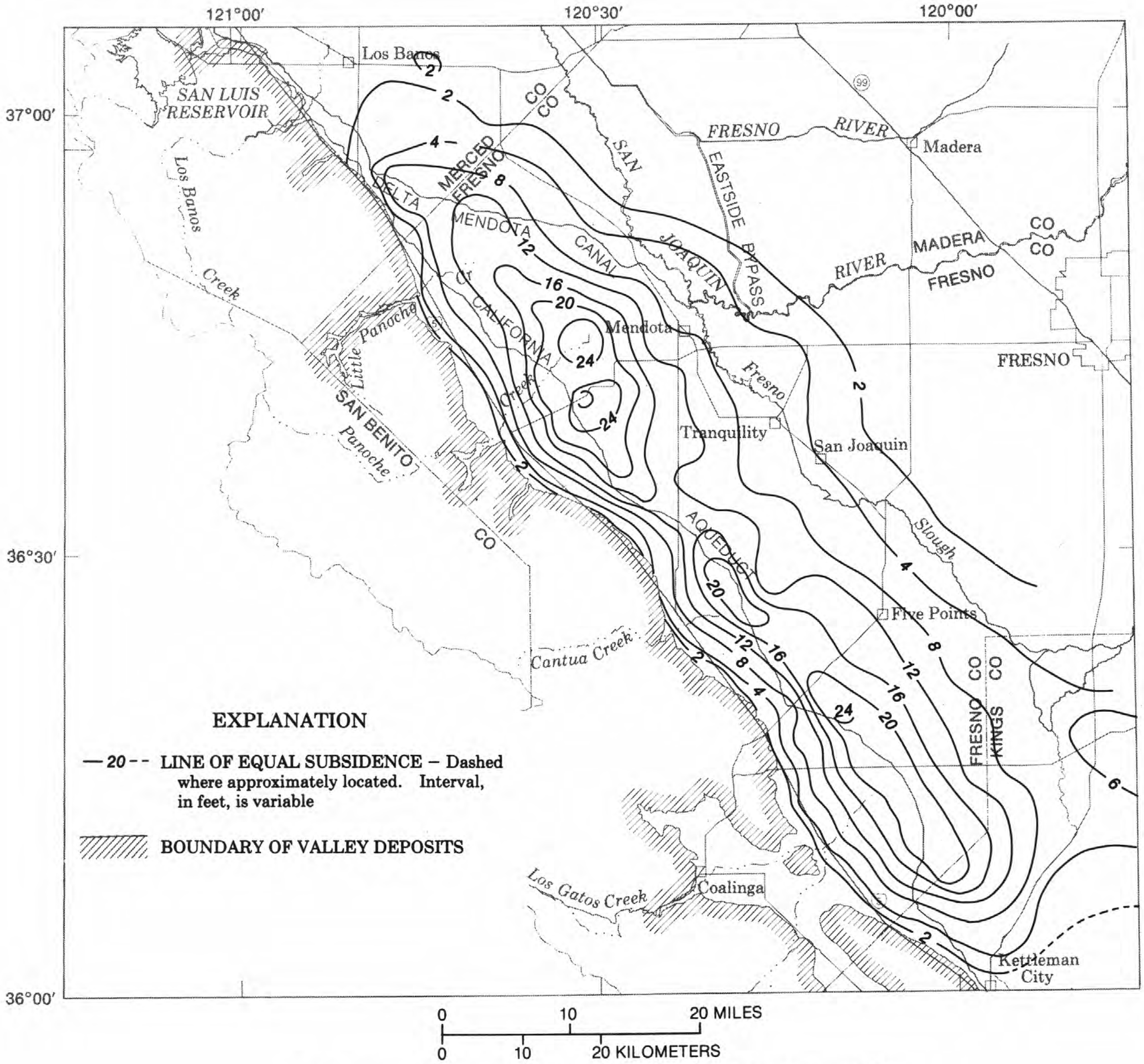

FIGURE 15. — Land subsidence, 1926-72. (Adapted from Ireland and others, 1984.)

system. Figures 14 and 16 show the potentiometric surface for the confined zone in 1967 and 1984. Comparison of those maps indicates that hydraulic head in the confined zone has risen 200 to 300 feet from 1967 to 1984 along the western part of the study area in areas previously characterized by the largest drawdown. Hydraulic head in the valley trough has typically risen 100 feet along the valley trough. Overall, the rise in the potentiometric surface from 1967 to 1984 has been nearly one-half the drawdown that occurred from predevelopment conditions to 1967.

Agricultural development also has affected the semiconfined zone which overlies the Corcoran Clay Member. Increased rates of recharge resulting from percolation of irrigation water (as compared to predevelopment recharge rates),

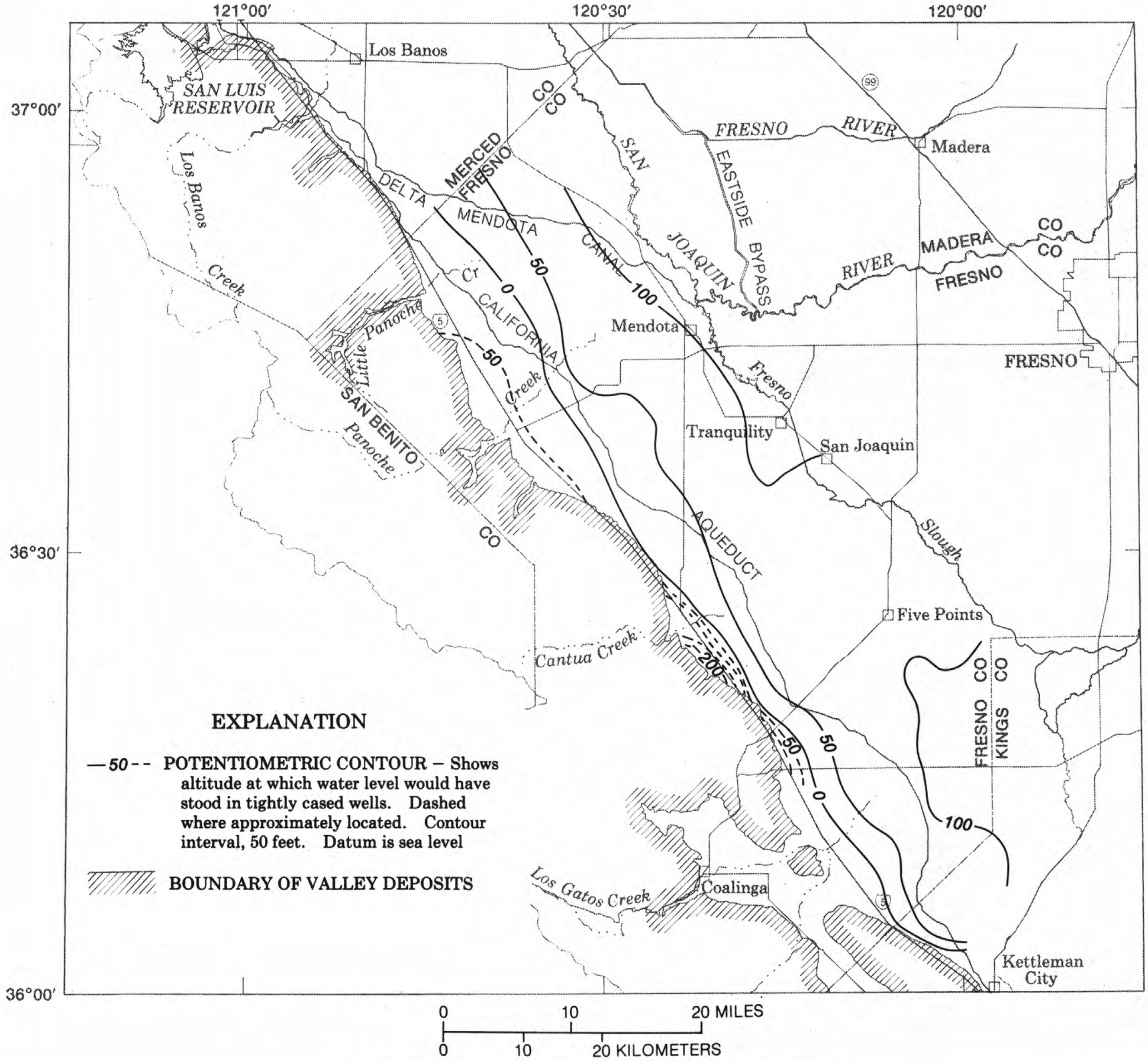

FIGURE 16. — Potentiometric surface of the confined zone, spring 1984.

combined with the rapid post-1967 decrease in pumpage, have caused a rise in the altitude of the water table over much of the western valley. Comparison of maps of the depth to the water table in 1952 (fig. 17) and 1984 (figs. 18 and 19) indicates this marked change in the system. In 1984, about one-half of the

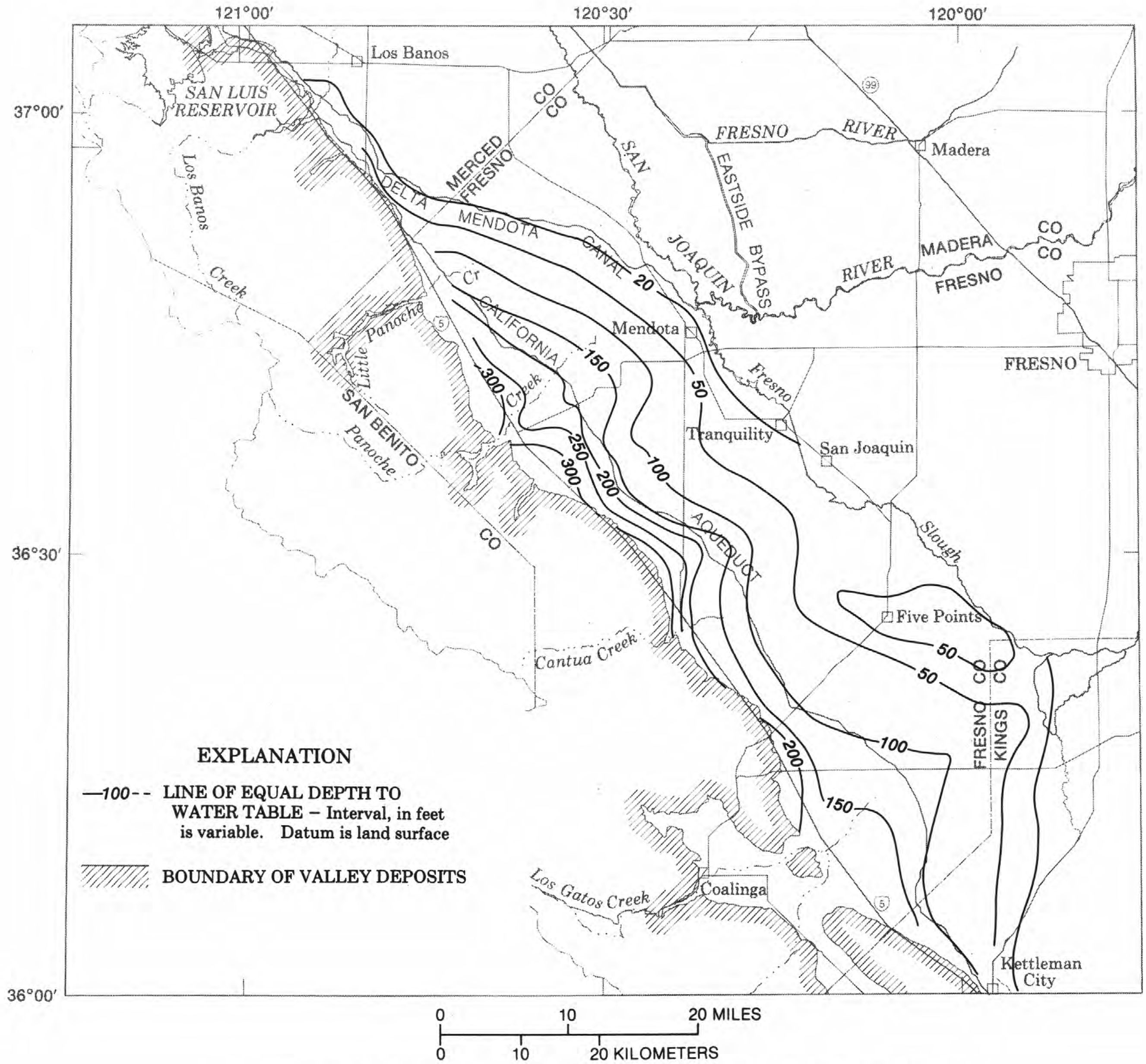

FIGURE 17. — Depth to water table, spring 1952. (Adapted from Davis and others, 1959.)

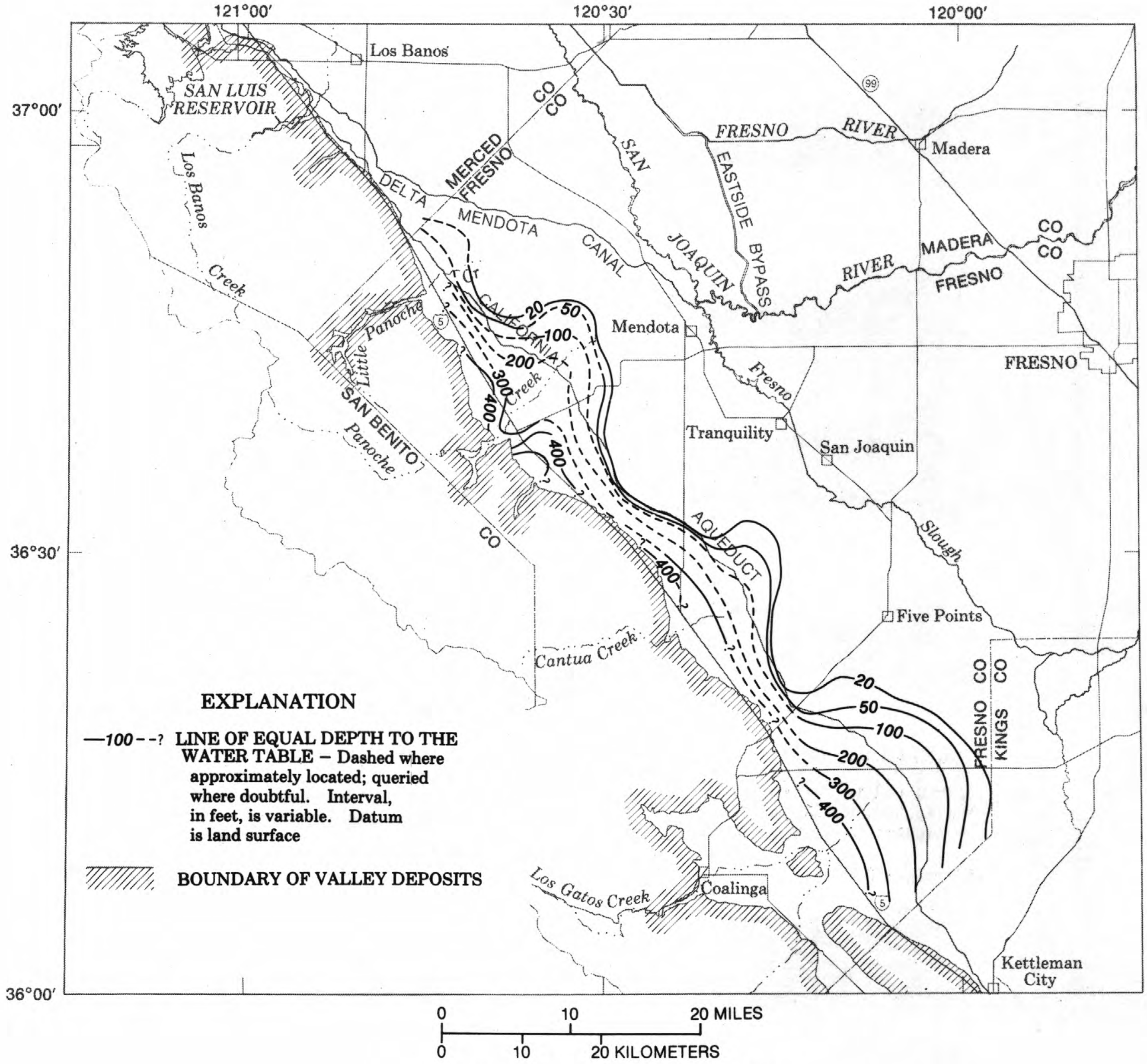

FIGURE 18. – Depth to water table, October 1984.

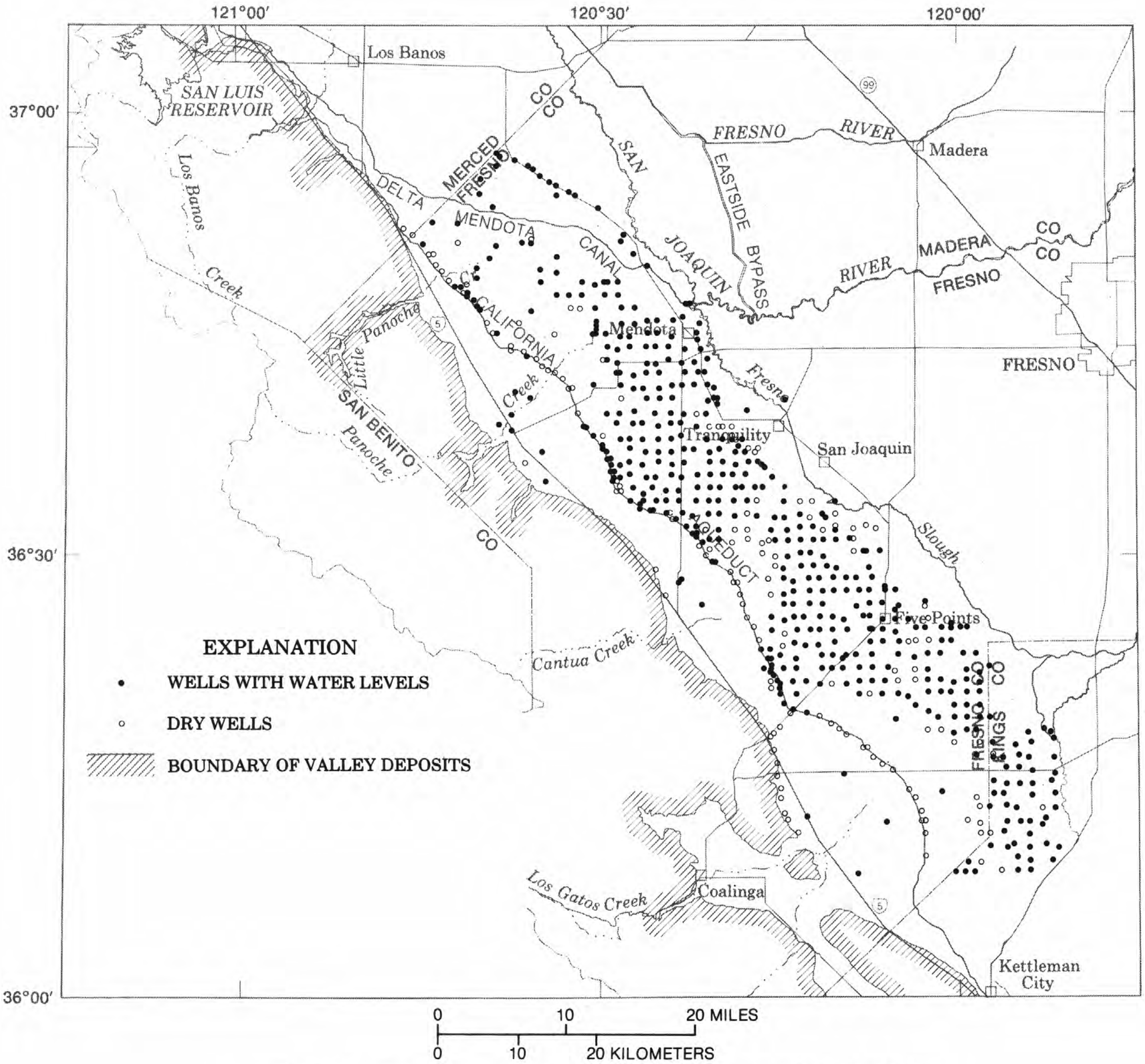

FIGURE 19. — Wells used to map the depth to and altitude of the water table, October 1984.

study area was characterized by a water table within 20 feet of the land surface, whereas in 1952 only a small percentage of the western valley was underlain by shallow ground water. Indeed, much of the present-day area underlain by a water table within 20 feet of the land surface was characterized by a water table at depths of 100 to 200 feet in 1952. The development and growth of areas with a shallow water table and resulting drainage problems has been a key concern of agricultural interests in the area.

Wells completed in the deepest parts of the semiconfined zone indicate that the rise in hydraulic head is larger in the deeper parts of the semiconfined zone than for the shallower parts. Figure 20 shows hydrographs for two wells near the California Aqueduct. Both wells are at a land-surface altitude of 320 feet but are drilled to different depths. From 1975 to 1984, the shallow well shows a rise in water level of about 20 feet and the deep well shows a rise of 40 feet. Moreover, the hydraulic head rise in the confined zone has been about 100 feet at that location during the same time period. These observations indicate that the downward head gradient is decreasing with time. This decrease is probably due to the decrease in pumpage from beneath the Corcoran Clay Member.

In contrast to most of the study area, comparison of the depth to the water table in 1952 (fig. 17) and 1984 (fig. 18) along the western margin of the alluvial fans indicates that the water-table altitude has declined along most of the western part of the alluvial fans. In 1952, the water table was generally within 200 feet of the land surface along the western margins of the alluvial fans, whereas, in 1984, the water table was typically more than 300 feet beneath the land surface in those areas. The increase in depth to the water table is especially pronounced beneath the fanhead of the Los Gatos Creek alluvial fan where in 1952, the water table was within 200 feet of the land surface over most of the fanhead. In contrast, the depth to the water table in 1984 was more than 400 feet over parts of the fanhead of the Los Gatos Creek alluvial fan. It is important to note that the map of the depth to the water table in 1952 was constructed, in part, by using electrical resistivity logs and that the map is considered approximate (Davis and others, 1959). Therefore, the numerical values of water-table decline cited in this study also need to be considered approximate.

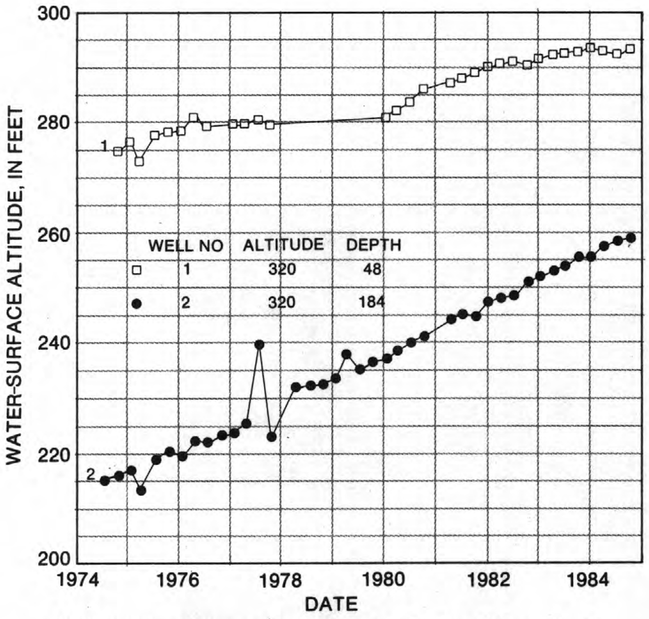

FIGURE 20. — Hydrographs of two wells drilled to different depths in the semiconfined zone. Well locations are shown on figure 21.

The decline of the water table from 1952 to 1984 is probably a result of the large overdraft from the confined zone that occurred prior to the importation of surface water. The areas of water-table decline along the western part of the alluvial fans are correlative to the areas of greatest drawdown in the confined zone. Indeed, the greatest depth to the water table occurs within the fanhead of the Los Gatos Creek fan where the Corcoran Clay Member is absent over a large area (fig. 5); the absence of the Corcoran allows for enhanced hydraulic connection between the semiconfined and confined zones. Inspection of hydrographs in the areas of water-table decline indicates that water levels in wells completed in the semiconfined zone have been rising since 1967. The overall decline of the water table from 1952 to 1984 along the western margin of the alluvial fans indicate that although the water table is rising in those areas, those parts of the system have not yet recovered to the 1952 levels.

A regional tile-drain collector system, which was installed in 1980-81, also has had significant effects on the ground-water flow system. The regional tile-drain collector system underlies about 42,000 acres (65.6 square miles) of land west and southwest of Mendota (fig. 21). During 1981-84, the drains collected an average of 6,900 acre-feet per year (0.15 cubic foot per year per square foot). By diverting water that may have

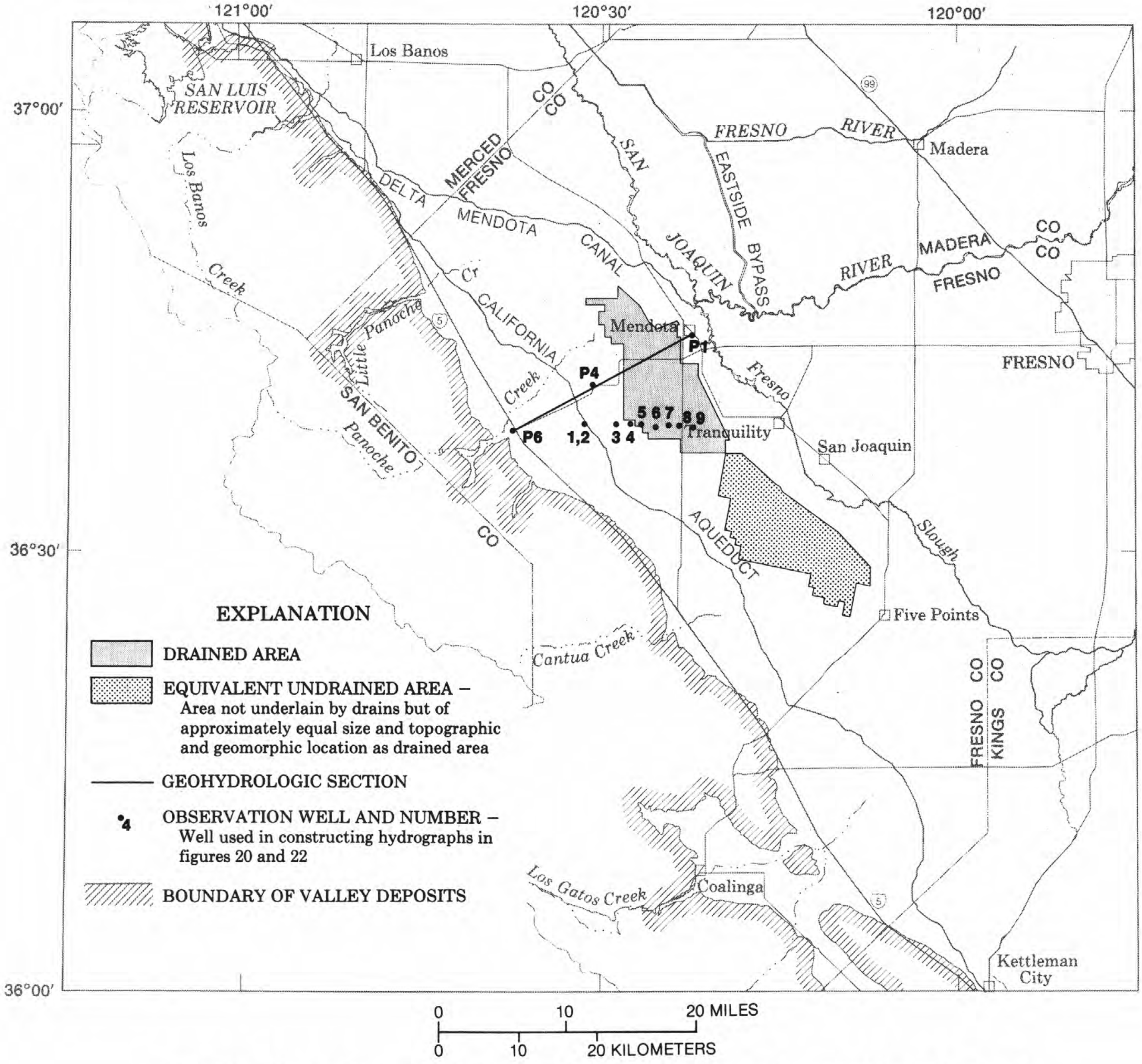

FIGURE 21. – Location of area serviced by the regional tile-drain system and an area of approximately equivalent size and topographic and geomorphic location.

otherwise recharged the ground-water flow system, the drains have lowered water levels in the drained area from 1 to 3 feet on a regional scale and up to 5 feet on a local scale. In addition, the drains have decreased seasonal variation in water levels in the drained area.

By lowering water levels 1 to 3 feet in the drained area, the tile-drain collector system has been effective in decreasing the total area characterized by a water table within 5 feet of the land surface. Maps of depth to the water table (Westlands Water District, written commun., 1986) indicate that in April 1976 about 27 square miles of the area later serviced by drains had a water table within 5 feet of the land surface. In April 1984, the size of the area underlain by a water table within 5 feet of the land surface had been reduced to 4 square miles. In contrast, in an area of equivalent size and topographic and geomorphic location but not underlain by regional tile drains (fig. 21), the size of the area underlain by a water table within 5 feet of the land surface increased from 8 square miles in April 1976 to 18 square miles in April 1984. These large changes in area reflect changes in water levels of only 1 to 3 feet.

Figure 22 shows hydrographs of eight wells along a west to east line through an area where the Panoche Creek and Cantua Creek alluvial fans coalesce (fig. 21). The west-to-east line is nearly perpendicular to the contours of the altitude of the water table and thus nearly corresponds to the lateral component of a flow line. The hydrographs illustrate the effects of the drains on the ground-water flow system, and also illustrate the local-scale variability of the ground-water flow system. In general, shallow wells in the drained area (more than 50) show smaller seasonal variation in water levels since the drains were installed than before and also show smaller seasonal variation than several hundred shallow wells in the area not underlain by drains. In addition, water levels in the drained area have been steady since the drains were installed, whereas wells in the undrained areas commonly show a rise in water levels. Wells 7, 8 and 9 (fig. 22) are in the drained area and show smaller seasonal variation in water levels since the drains were installed than before and show constant water levels since 1981. Well 6 is at the edge of the drained area but the water levels in that well seem unaffected by the installation of the drains in 1980-81. Wells 1, 3, and 4 are in areas not underlain by drains and show rising water levels with time. Wells, 1, 3, and 4 also show seasonal variations in water levels of 1 to 5 feet. Well 1 is in close proximity to the California Aqueduct and does not show seasonal variation in water levels for the period of record. Water-level changes in the study area are quite variable and many wells deviate from the general trends.

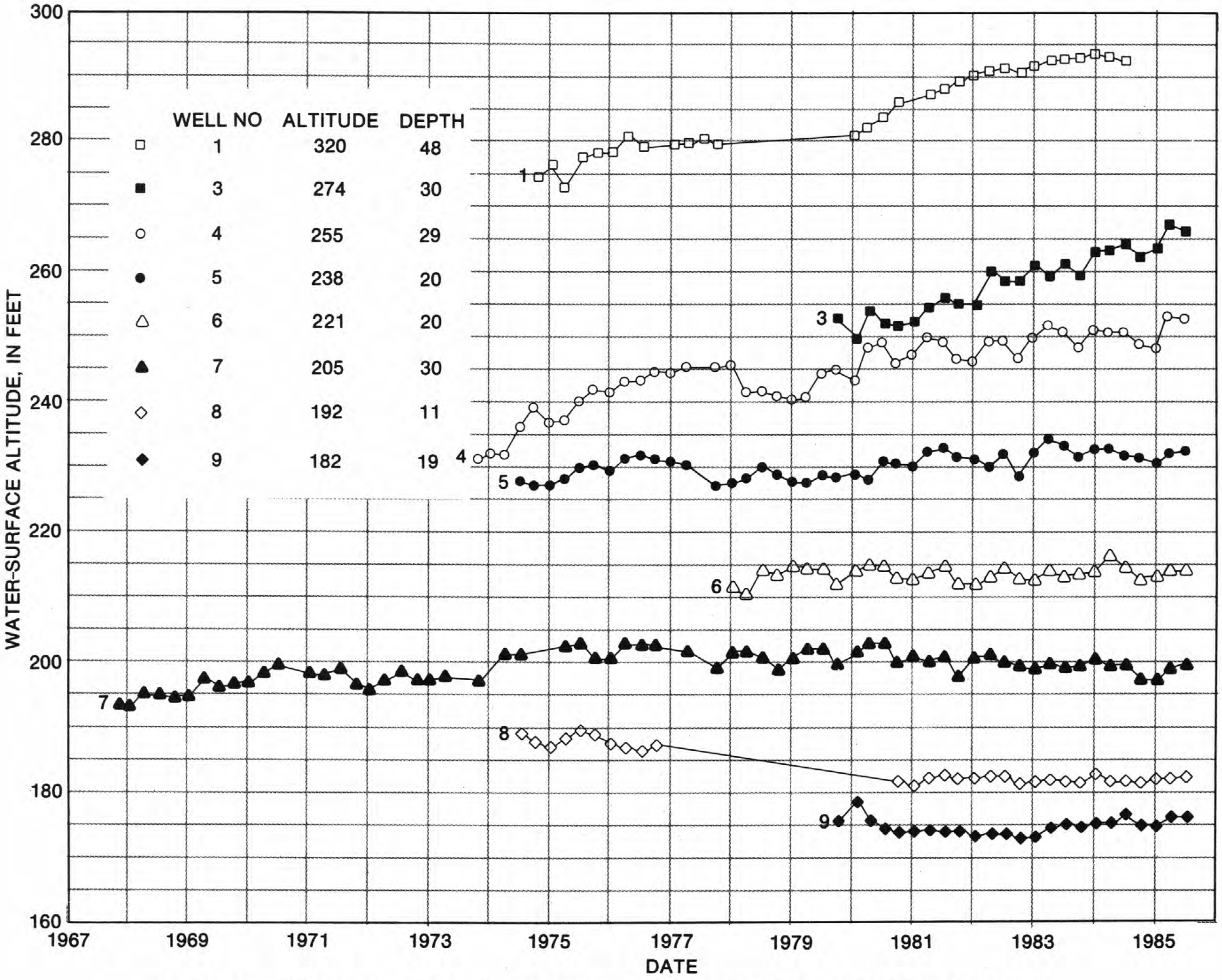

FIGURE 22. — Hydrographs of eight wells along an approximate flow line. Well locations shown on figure 21.

Present-Day Configuration of the Water Table

The present-day configuration of the altitude of the water table is shown in figure 23. The water table demarcates the top of the zone of saturation. In many investigations, flow is assumed to be horizontal and equipotential lines vertical. If these assumptions were true, then the areal distribution of the altitude of the water table could be taken as representative of the areal distribution of hydraulic head for the aquifer. In the western San Joaquin Valley, vertical flow is substantial, and thus the altitude of the water table is not representative of the hydraulic head at other depths. The map showing altitude of the water table can be used to determine the general direction of the lateral component of flow in the semiconfined zone.

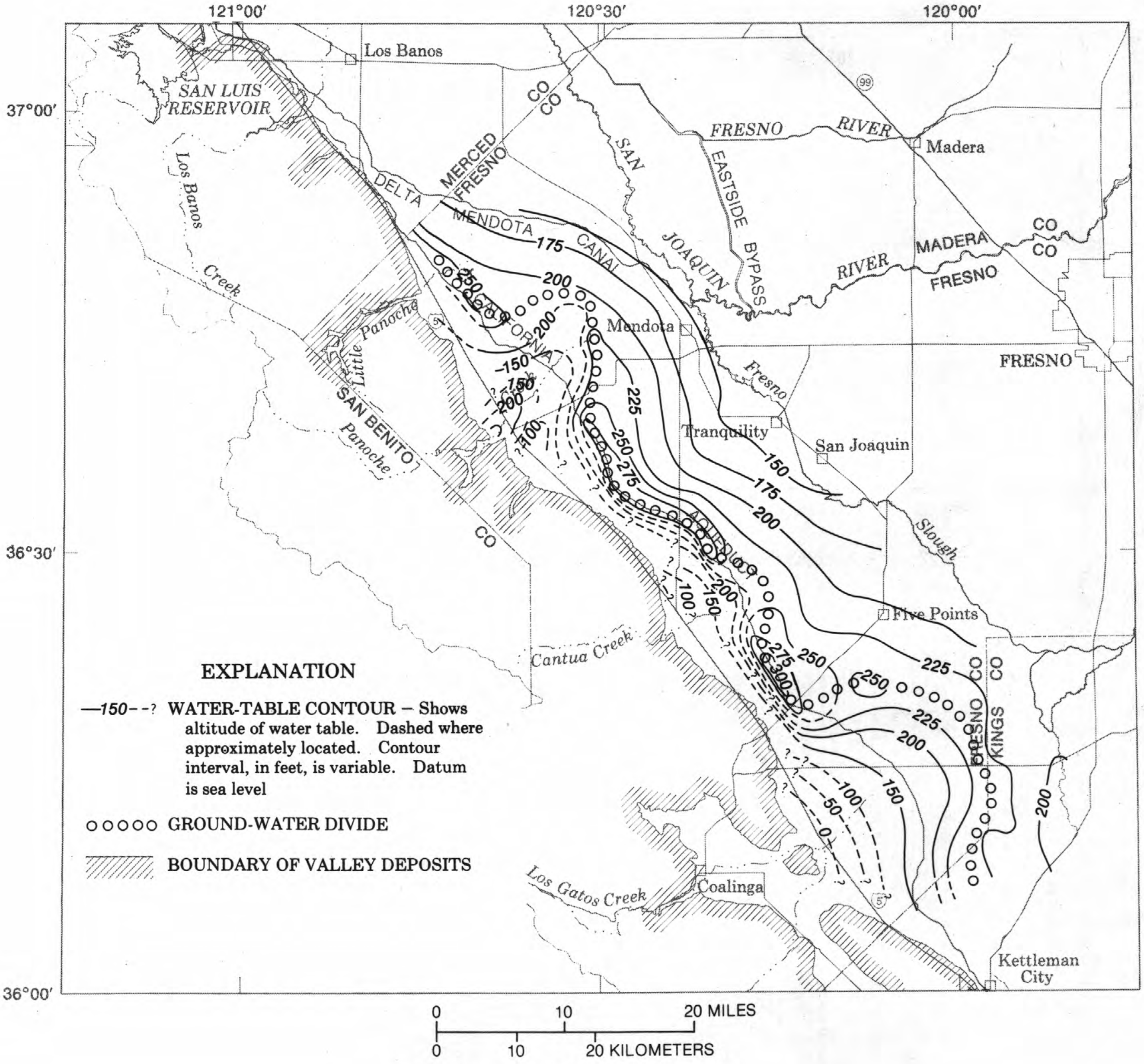

FIGURE 23. — Water-table altitude, October 1984.

One of the most notable features of the water table is the ground-water divide that more or less parallels the western boundary of the alluvial fans. The ground-water divide shifts westward between the fanheads of the major alluvial fans and shifts eastward near the fanheads. To the east of the ground-water divide, the water table lies at shallow depths and is a subdued replica of the topography. East of the divide, flow is eastward and northeastward, reflecting the general trend of the topography. In part of the study area, there is a component of flow eastward across the valley trough toward pumping wells perforated in the Sierran sands. To the west of the ground-water divide, the water table slopes steeply to the west, opposite in direction to the land surface. West of the divide, flow is toward the Coast Range and toward the fanhead areas.

The existence of the ground-water divide is related to historical agricultural activity in the area and to the texture of the subsurface deposits. Comparison of the present-day altitude of the water table (fig. 23) with the altitude in 1952 (fig. 13) indicates a lowering of the water table over at least part of the area to the west of the divide and a rise in the water table over much of the area to the east of the divide. The area of the lowered water table along the western boundary of the alluvial fans corresponds to the area of maximum drawdown in hydraulic head in the confined zone; both can be related to historic pumpage which occurred primarily from the confined zone. The rise in the water table to the east of the divide is probably related to increased rates of recharge to the system arising from percolation of irrigation water past crop roots.

The location of the ground-water divide is partly affected by the texture of the subsurface sediments. The ground-water divide shifts eastward in the fanhead areas where the sediments are coarsest and shifts westward in the interfan areas where the sediments are finest grained. The altitude of the water table is the lowest, and the ground-water divide farthest to the east, beneath the fanhead of the Los Gatos Creek alluvial fan. The area of low altitude of the water table beneath the fanhead of the Los Gatos Creek fan corresponds to the area where the Corcoran Clay Member of the Tulare Formation is not present. The absence of the Corcoran results in better hydraulic connection between the semiconfined and confined zones.

Since texture affects the specific yield and the permeability of the deposits, texture affects system response to hydraulic stresses. The dominant boundary conditions on the semiconfined zone are percolation of irrigation water past crop roots from above and the hydraulic head of the confined zone from below (which is in turn affected by pumping). Percolation of irrigation water past crop roots has resulted in accretion to the water table over a large area. Because fine-grained deposits tend to have smaller specific yield than coarse-grained deposits, the water table accretion tends to be largest in areas of fine-grained deposits, such as interfan areas. The combined effect of pumping from below the Corcoran and percolation from above the water table has been development of a large downward flow gradient in the semiconfined zone. Because the fine-grained sediments tend to have lower permeability than the coarse-grained sediments, a larger vertical head gradient is required to transmit a given quantity of water through the fine-grained deposits than through the coarse-grained deposits. Consequently, the interfan areas have larger vertical head gradients than the fanhead areas. The larger vertical head gradient translates to a thicker saturated column in the interfan areas and hence shallower depth to ground water than in the fanhead areas.

Vertical Gradients

Under natural conditions, the groundwater flow system of the western San Joaquin Valley was characterized by horizontal flow over most of the area. Numerical simulation of the flow system by Williamson and others (1985) indicates that vertical gradients were small and limited to the fanhead areas (where there was a downward gradient) and to the valley trough (where there was an upward gradient). Presently, the flow system above the Corcoran Clay Member of the Tulare Formation is characterized by a large component of vertical flow over most of the study area.

Vertical gradients of hydraulic head were calculated at 37 locations in the study area. At locations with two or more wells, the gradient was calculated by dividing the difference in water levels by the distance between the midpoints of the perforated intervals. At locations with a single deep well, gradients were calculated only at sites where shallow water levels could be interpolated to within 3 feet with a fair degree of confidence from the water table map (fig. 23). Vertical gradients during 1984-86 ranged from 0.003 to 1.1. In contrast, horizontal head gradients in the western valley typically ranged from 0.001 to 0.02.

Vertical gradients in hydraulic head are lower in the coarse-textured Sierran sands and fanhead alluvium than in the finer textured midfan, distal-fan, and flood-basin deposits. The highest gradients occur beneath the California Aqueduct in areas of fine-grained deposits and in the flood-basin clays in areas where there is pumping-induced drawdown in the Sierran sands. Vertical gradients within the coarse-textured Sierran sands and fanhead alluvium ranged from 0.003 to 0.07 in 1984-86. Gradients in the midfan areas ranged from 0.07 to 0.32 in 1984-86 except beneath the California Aqueduct where gradients ranged from 0.08 to 1.0. Gradients in the fine-textured flood-basin deposits ranged from 0.10 to 1.1.

Gradients near to one and equal to one beneath the aqueduct may be indicative of local perched conditions, in which saturated deposits overlie unsaturated deposits. The possible perching may be the result of preconstruction ponding along the canal right-of-way and from leakage from the canal. Gradients near to one and larger than one in the valley trough in the vicinity of San Joaquin and Tranquility may be indicative of perching over a larger area. Pumping of ground water from the Sierran deposits has lowered water levels in the Sierran sands below the altitude of the interface between the overlying flood-plain deposits and Sierran sands producing an unsaturated zone between the fine-grained flood-plain deposits and the Sierran sands. The low diffusivity of the clays in the flood-plain deposits has allowed these deposits to remain saturated as the water table in the semiconfined zone declined below the interface.

Pumping from the Sierran sands was greater in the past than it is presently. The present-day (1987) extent of the perched zone probably is smaller than it has been in the past and the area of perched conditions will continue to decrease with a continued decrease in pumping.

Generalized Geohydrologic Section Through the Flow System

A generalized geohydrologic section through the flow system is shown in figure 24. The cross section extends from the fanhead of the Panoche Creek alluvial fan to Mendota (fig. 21). The section shows the generalized geology and distribution of hydraulic head. The geology of the section was interpreted from published maps and sections (Page, 1986; U.S. Bureau of Reclamation, 1965). Direct observations of hydraulic head are available from several sources. Observations of the vertical distribution of head in the semiconfined zone and across

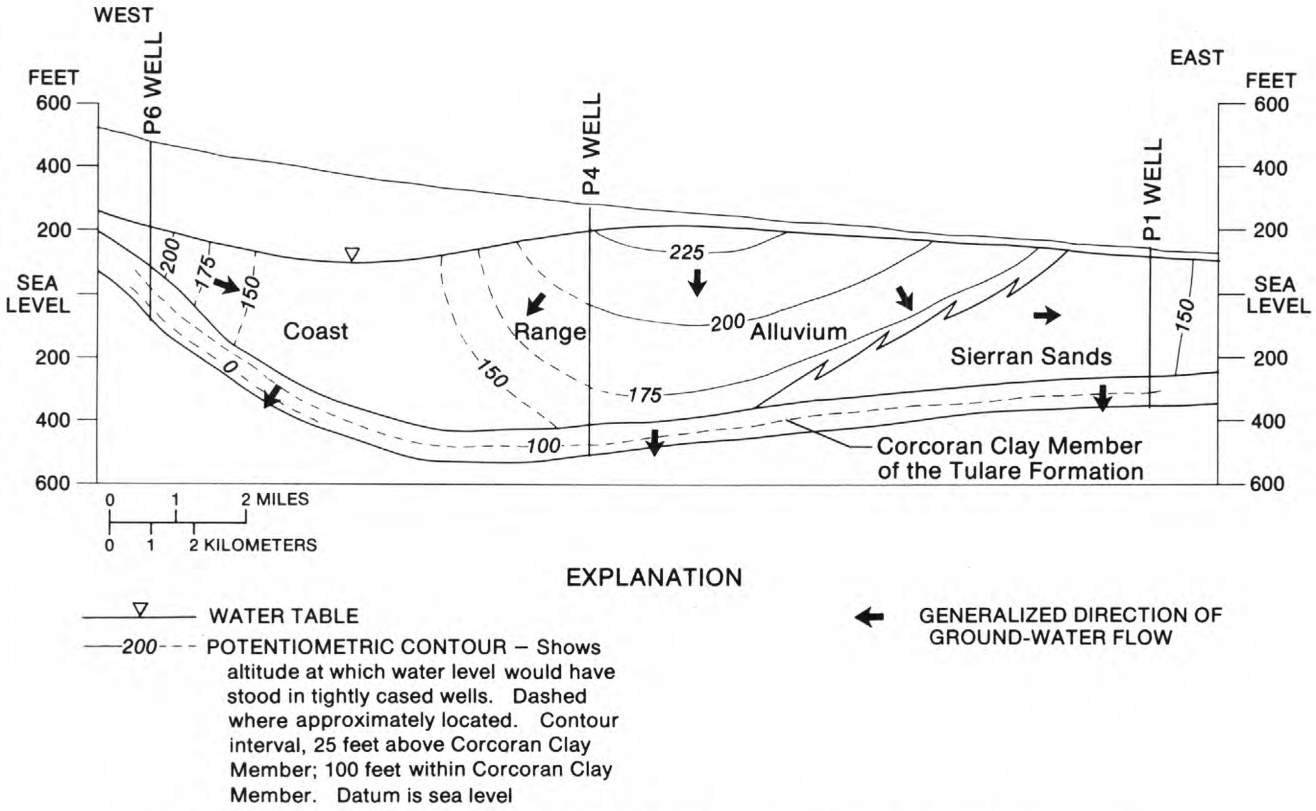

FIGURE 24. — Generalized geohydrologic section through the flow system. Location of section shown on figure 21.

the Corcoran Clay Member of the Tulare Formation are available from wells drilled to multiple depths by the U.S. Geological Survey at three sites: P6, P4, and P1 (fig. 21). The altitude of the water table is well documented in areas where the water table is within 20 feet of the land surface because the Westlands Water District maintains a network of shallow wells to monitor the water table in those areas. The distribution of hydraulic head beneath the Corcoran Clay Member is known from maps of the potentiometric surface of the confined zone prepared by the Westlands Water District and by the California Department of Water Resources, and from wells drilled by the U.S. Geological Survey.

The distribution of hydraulic head within the semiconfined zone in regions without wells was inferred by interpolation between wells and based on the hydrogeology of the system. In particular, the orientation of the equipotential lines in the area between the P6 and P4 sites was drawn to reflect the distribution of electrical resistivity as mapped by R. Bisdorf (U.S. Geological Survey, written commun., 1986). The equipotential lines were contoured more vertically where the resistivity is indicative of coarse-grained deposits and were contoured more horizontally where the resistivity is indicative of fine-grained deposits. The distribution of hydraulic head in the Corcoran reflects the known and interpreted values of hydraulic head both above and below the clay.

The section as drawn shows a nearly vertical equipotential line in the Sierran sands. Time-series data for the wells at the Mendota Airport indicate that the vertical gradient varies seasonally at that site. During the late autumn and winter, the vertical head gradient is as low as 0.003 and in the late spring and summer, the head gradient is as high as 0.07. The increased vertical head gradient during the late spring and summer is probably attributable to nearby pumping.

Generalized arrows are drawn on the section to indicate the general directions of ground-water flow. The arrows illustrate several major aspects of the flow system. Ground water east of the ground-water divide flows downward toward the confined zone and eastward toward pumping wells in and located east of the valley trough. The orientation of the arrows east of the ground-water divide reflects the contrast in hydraulic properties between the Coast Range alluvium and Sierran sands. The more vertically oriented arrow in the Coast Range alluvium is refracted toward the horizontal upon entering the Sierran sands. Ground water west of the ground-water divide flows toward a trough in the water table and downward toward the confined zone. The eastward-pointing arrow near the fanhead of the Panoche fan reflects the effects of the ground-water mound beneath the Panoche Creek (fig. 23). The arrows also indicate downward flow across the Corcoran Clay Member from the semiconfined zone to the confined zone.

CONCLUSIONS

The Pleistocene Corcoran Clay Member of the Tulare Formation divides the ground-water flow system of the western San Joaquin Valley into an upper semiconfined zone and a lower confined zone. The deposits of the semiconfined zone can be divided into three hydrogeologic units: Coast Range alluvium, Sierran sands, and flood-basin deposits. The texture of the Coast Range alluvium varies as a function of position on the alluvial fans. The deposits are coarse textured at the heads of fans and along present-day stream channels and paleo-channels. The deposits are fine textured between channels and at the distal-fan margins. The Coast Range alluvial sediments were deposited under arid conditions and are generally oxidized. The Sierran sands, in the valley trough, are reduced deposits of coarse texture. The flood-basin deposits are predominantly fine textured, moderate to densely compacted clays; the oxidation state of these deposits is variable.

Agricultural development has significantly altered the ground-water flow system in the central part of the western San Joaquin Valley. Percolation of irrigation water past crop roots greatly exceeds and has replaced infiltration of intermittent streamflow as the primary mechanism of recharge. Pumpage of ground water from wells and crop evapotranspiration have replaced natural evapotranspiration and seepage to streams in the valley trough as the primary mechanisms of discharge. Historic pumpage of ground water from beneath the Corcoran Clay Member has lowered the potentiometric surface in the confined zone hundreds of feet over much of the western valley and has lowered the water table beneath parts of the fanheads of the alluvial fans. Percolation of irrigation water past crop roots has caused the water table to rise over a large part of the western valley since 1952. Surface-water deliveries from the California Aqueduct have caused a decrease in pumpage since 1967 and a consequent recovery in hydraulic head throughout the aquifer system.

Increased recharge by percolation of irrigation water past crop roots and historic pumpage of ground water from beneath the Corcoran Clay Member have created a ground-water divide along the western margin of the valley. The divide is more or less parallel with the Coast Range but is closer to the Coast Range in fine-textured interfan areas and farther from the Coast Range in coarse-textured fanhead areas. The combination of percolation and pumpage also has resulted in development of a downward component of flow in the semiconfined zone. The downward component of flow is decreasing with time in response to reduced pumping. The present-day flow system is in a transient state and is adjusting to stresses placed upon it in both the past and present.

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