

# Land Subsidence in the San Joaquin Valley, California, As of 1972

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 437-H

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



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By J. F. POLAND, B. E. LOFGREN, R. L. IRELAND, and R. G. PUGH

STUDIES OF LAND SUBSIDENCE

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

*A history of land subsidence  
caused by water-level decline  
in the San Joaquin Valley,  
from the 1920's to 1972*



UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

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## METRIC CONVERSION TABLE

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<i>English unit</i>	<i>Symbol</i>	<i>Equivalent (multiply by-)</i>	<i>Metric unit</i>	<i>Symbol</i>	<i>English unit</i>	<i>Symbol</i>	<i>Equivalent (multiply by-)</i>	<i>Metric unit</i>	<i>Symbol</i>
Inch	(in.)	2.54	Centimetres	(cm)	U.S. gallon	(gal)	3.785	Litres	-----
Foot	(ft)	0.3048	Metre	(m)	Acre-foot	(acre-ft)	1,233.5	Cubic metres	(m <sup>3</sup> )
Mile	(mi)	1.609	Kilometres	(km)	U.S. gallon per minute	(g/m)	0.0631	Litres per second	(l/s)
Acre	-----	0.405	Hectare	-----	Cubic feet per second	(ft <sup>3</sup> /s)	1.699	Cubic metres per minute	(m <sup>3</sup> /min)
Square mile	(mi <sup>2</sup> )	2.590	Square kilometre	(km <sup>2</sup> )					



## STUDIES OF LAND SUBSIDENCE

# LAND SUBSIDENCE IN THE SAN JOAQUIN VALLEY, CALIFORNIA, AS OF 1972

By J.F. POLAND, B. E. LOFGREN, R. L. IRELAND, and R. G. PUGH

### ABSTRACT

Land subsidence which began in the mid-1920's due to ground-water overdraft in the San Joaquin Valley has caused widespread concern for the past two decades. Withdrawals for irrigation increased from 3 million acre-feet in 1942 to 10 million acre-feet in 1966. Water levels declined at unprecedented rates during the 1950's and early 1960's. Pumping lifts became inordinately high, well casings failed at alarming rates, and differential settlement caused numerous farming and engineering problems. By 1970, 5,200 square miles of valley land had been affected, and maximum subsidence exceeded 28 feet. The valleywide volume of subsidence totaled 15.6 million acre-feet—one-half the initial storage capacity of Lake Mead. This subsidence represents one of the great environmental changes imposed by man.

Importation of surface water to the northwestern and eastern areas of overdraft in the valley began in the 1950's and to the much larger western and southern areas in the late 1960's. Canal imports have largely replaced ground-water pumpage in these areas. As of 1973, after three decades of continued declining water levels, many hundreds of irrigation wells are idle and water levels are rising. Throughout much of the valley, artesian pressures are recovering toward their presubsidence levels, and elevations of the subsiding land surface are stabilizing.

Basic-data graphs and computer-plotted stress-strain relationships constitute a major part of this report. They are based on 10–13 years of detailed field measurements of both water-level change and compaction collected by the U.S. Geological Survey at 20 selected locations in the San Joaquin Valley.

The recharge characteristics of a ground-water reservoir are indicated roughly by the volume ratio, which is subsidence/pumpage. In the Los Banos–Kettleman City area, the values of this ratio range from less than 0.2 near the perimeter to more than 0.6 in the central part of the area. In the corresponding parts of the Arvin-Maricopa area, the ratio ranges from near 0 to more than 0.4.

### INTRODUCTION

#### THE SUBSIDENCE PROBLEM

Land subsidence in the San Joaquin Valley, Calif., represents one of the great changes man has imposed on the environment. About 5,200 square miles of irrigable land, one-half the entire valley, has been affected by subsidence, and maximum subsidence exceeded 28 feet in 1970; by 1972 subsidence was about 29 feet. Throughout most of the area, subsidence has occurred so slowly and over such a broad area that its effects have gone largely unnoticed by most residents. It has created serious and costly problems, however, in construction and maintenance of water-transport structures; also,

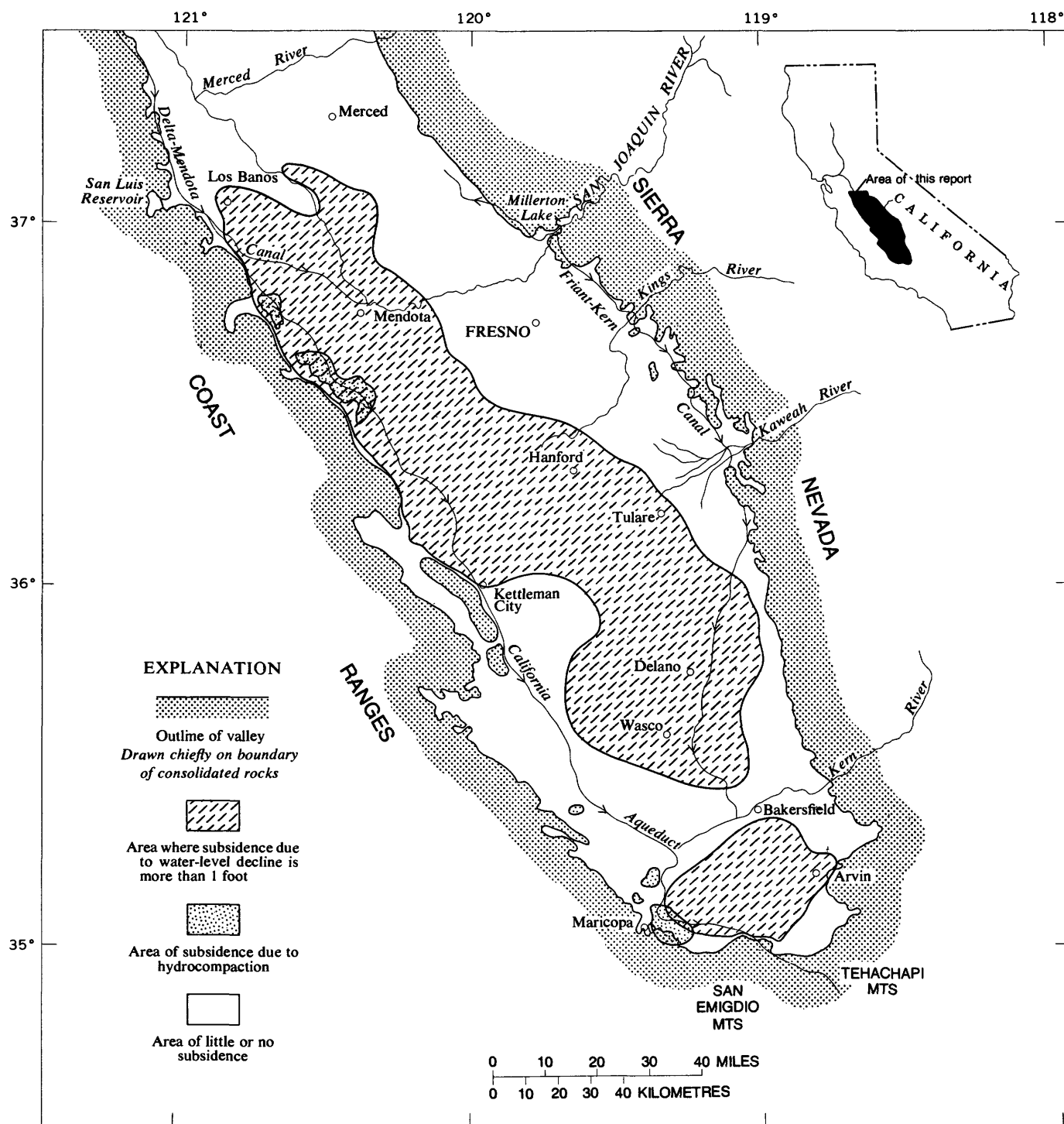
many millions of dollars have been spent on the repair or replacement of deep water wells because of ruptured casings.

The San Joaquin Valley (fig. 1) is a broad alluviated structural trough constituting the southern two-thirds of the Central Valley of California. It is about 250 miles long, averages about 35 miles in width, and encompasses 10,000 square miles, excluding the rolling foothills that skirt the valley on three sides. Figure 1, showing the pertinent geographic features of the area discussed in this report, covers the southern four-fifths of the valley.

Agricultural development in the San Joaquin Valley has been intensive, especially since World War I. In the eastern part of the valley from the Kings River north, surface streams from the Sierra Nevada supply most of the irrigation needs, but are supplemented by ground water, especially after midsummer when streamflow is deficient. From the Kaweah River south—except for the Kern River and its alluvial fan—and in the west-central area from Mendota to Kettleman City, local surface-water supplies have been small to negligible. Prior to the construction of major canals or aqueducts, irrigation was almost wholly from thousands of large and deep irrigation wells; conditions of ground-water overdraft have prevailed since the 1930's. Extractions of ground water in the San Joaquin Valley for irrigation increased from 3 million acre-feet in 1942 to at least 10 million acre-feet in 1964 (Poland and Evenson, 1966) and in 1966 (Ogilbee and Rose, 1969a, b; Mitten and Ogilbee, 1971).

The trend of declining water levels was well established long before the problems or the causes of subsidence were recognized. Few areas had sufficient leveling control to reveal the subtle land-surface changes; however, induced by greater and deeper pumping, the subsidence that began in several centers of overdraft in the 1920's became of widespread concern in the late 1940's and early 1950's. Through the 1950's and early 1960's, water levels declined at an unprecedented rate throughout much of the area. Pumping lifts became inordinately high, well casings failed at an alarming rate, and differential settlement of the land surface





Base from U.S. Geological Survey  
1:1,000,000, State base map, 1940

FIGURE 1.—Pertinent geographic features of central and southern San Joaquin Valley and areas affected by subsidence.

caused numerous farming and engineering problems. Clearly, remedial action was urgently needed.

Importation of surface water to areas of serious overdraft began in 1950 when water from the San Joaquin

River was brought south through the Friant-Kern Canal, which extends to the Kern River (fig. 1). Of the average annual deliveries of about 1 million acre-feet of water from this canal, about 80 percent has been

supplied to irrigation districts south of the Kaweah River. Importation from the Friant-Kern Canal to the east side area south of the Kern River did not begin until 1966. Surface-water imports to the northwestern part of the area via the Delta-Mendota Canal began in the early 1950's.

Additional large surface-water imports from the Sacramento-San Joaquin Delta to deficient areas on the west side and to the south end of the valley are being provided by the California Aqueduct and its joint-use reach between Los Banos and Kettleman City. This joint-use facility serves the San Luis project area of the Bureau of Reclamation and transports State water south to Kettleman City. The joint-use reach was completed in 1968, and water deliveries from the aqueduct to the San Luis project area increased from 200,000 acre-feet in 1968 to 865,000 in 1972. After completion of the distribution system in the middle 1970's, a maximum of about 1.2 million acre-feet of water can be delivered annually to the San Luis project area. The California Aqueduct was completed south to the Tehachapi Mountains in 1970, delivered 570,000 acre-feet to the southern part of the San Joaquin Valley in 1971, and eventually will supply 1.35 million acre-feet per year to the San Joaquin Valley south of Kettleman City under long-term contracts.

Surface-water imports to subsiding areas through the Friant-Kern Canal and the California Aqueduct through 1972 are given in tables 3-5.

As a result of the importation of large surface-water supplies, pumping of ground water has been reduced, and the rapid decline of artesian head has been reversed in parts of the areas of overdraft. By the end of 1971, many hundreds of irrigation wells were idle, and subsidence trends were leveling out as stresses on the deposits were reduced. Today (1973), after three decades of overdraft, much of the overdrawn area of the San Joaquin ground-water basin is returning to a stable water budget, and artesian pressures are recovering toward their presubsidence levels.

Although subsidence has caused serious and costly problems, not all its effects have been bad. The deposits of the ground-water basin are now largely "preconsolidated" to their historic low water levels, and thus the basin can be managed for cyclic storage nearly to the historic low levels without the threat of serious subsidence. Also, the basin has provided a field laboratory for testing compression characteristics of complex aquifer systems, in situ, and for measuring mechanical and storage parameters of aquifer systems under a wide range of loading stresses. An incidental minor economic benefit is that the depth to water and hence the pumping lift have increased more slowly than if comparable volumes of water had been withdrawn from a less compressible aquifer system.

#### PURPOSE OF REPORT

This report is part of a study of land subsidence in California in financial cooperation with the California Department of Water Resources; the study is closely interrelated with a concurrent Federal research investigation of the mechanics of aquifer systems. Subsidence in the San Joaquin Valley has been studied in this cooperative program since 1956. This report is intended to present an up-to-date factual summary of recorded land subsidence in the valley. More specifically, the purpose is to show the overall extent and magnitude of subsidence for the full period of available vertical control, to describe the several causes of subsidence, to present the latest available information on magnitude and rates of subsidence in the principal subsiding areas, to report on the volume of subsidence and, where possible, its relation to pumping draft, and to show the relationship between water-level change (stress change), measured compaction, and subsidence, chiefly by use of computer plots of Geological Survey field data.

These computer graphs contain the essence of 13 years of field measurements by the Geological Survey. From these data, the stress-strain characteristics of complex aquifer systems can be obtained and their relation to the magnitude, rate, and causes of subsidence studied. The report incorporates field data through December 1970 and demonstrates that water levels at many of the observation sites are in the transition from a declining to a rising trend.

#### ACKNOWLEDGMENTS

The writers acknowledge the cooperation of Federal, State, and local agencies, irrigation districts, private companies, and individuals. All leveling data used in the preparation of the various subsidence maps and graphs and in calculating magnitudes and rates of subsidence were by the National Geodetic Survey, a component of the National Ocean Survey<sup>1</sup> (formerly the U.S. Coast and Geodetic Survey). Water-level data utilized in this report were chiefly from field measurements by the Geological Survey, but some records were from the Bureau of Reclamation, the California Department of Water Resources, the Pacific Gas and Electric Co., and irrigation districts. Many Survey workers have contributed to this continuing research program; some of these are listed in the section "Annotated Bibliography."

#### WELL-NUMBERING SYSTEM

The well-numbering system (fig. 2) used in California

<sup>1</sup>The agency requests that all inquiries for geodetic control data (including vertical-control data) be directed to the National Geodetic Survey, Rockville, Md. 20852 and advises that this name will replace Coast and Geodetic Survey on future publications. Accordingly, subsequent reference in this report is to the National Geodetic Survey.

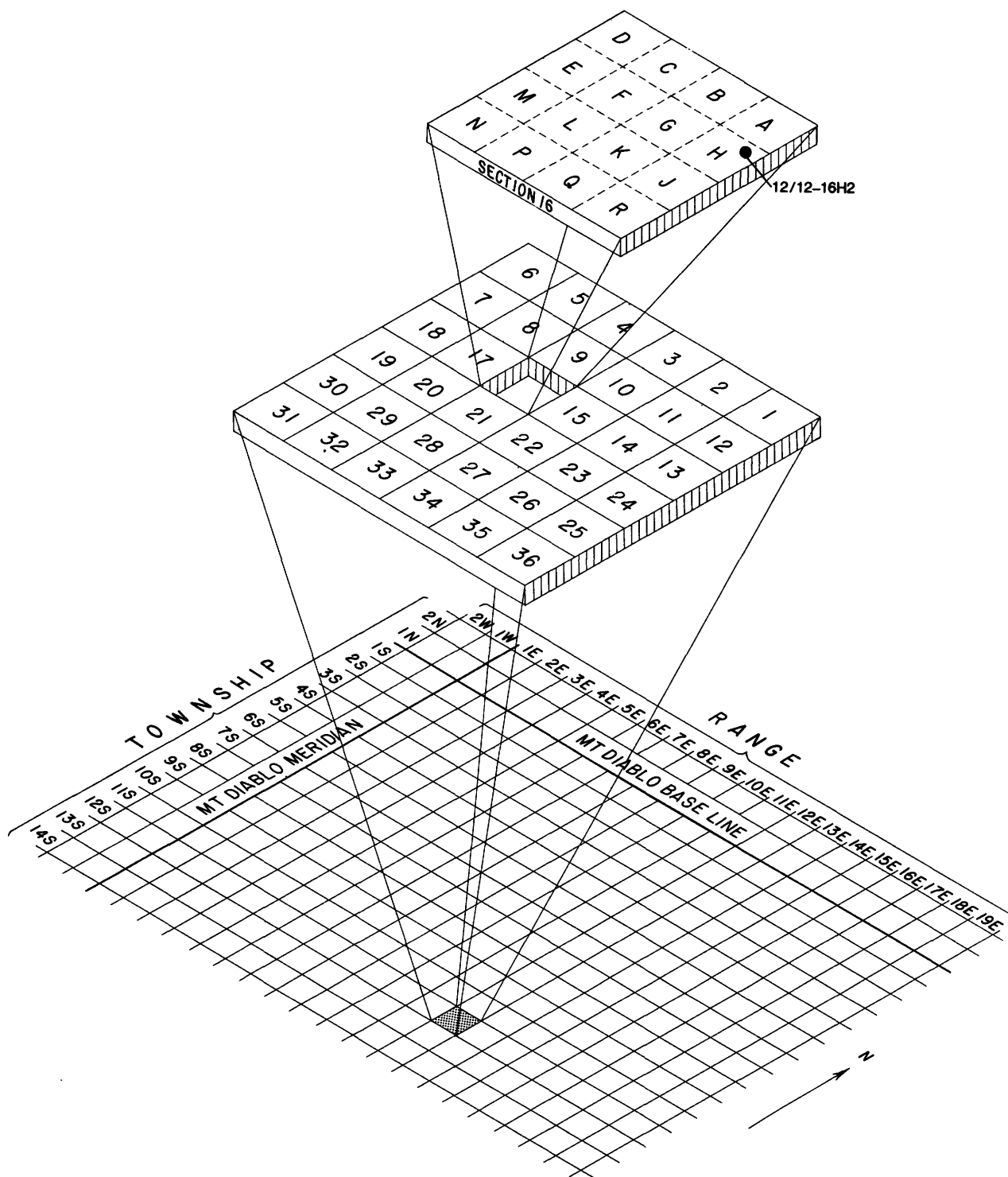


FIGURE 2.—Well-numbering system.

by the Geological Survey and the State of California shows the locations of wells according to the rectangular system for the subdivision of public lands. For example, in the number 12/12-16H2, the part of the number preceding the slash indicates the township (T. 12 S.), the part between the slash and the hyphen shows

the range (R. 12 E.), the number between the hyphen and the letter indicates the section (sec. 16), and the letter following the section number indicates the 40-acre subdivision of the section as shown in figure 2. Within each 40-acre tract, wells are numbered serially as indicated by the final digit of the well number. Thus,

well 12/12-16H2 is the second well listed in the SE¼ of the NE¼ of sec. 16, T. 12 S., R. 12 E. Except for the extreme south end of the valley which is referenced to the San Bernardino base and meridian, all wells are referenced to the Mount Diablo base and meridian.

#### REPORTS BY THE GEOLOGICAL SURVEY

In December 1954, concerned Federal and State agencies formed an Inter-Agency Committee on Land Subsidence in the San Joaquin Valley to plan and coordinate subsidence studies. The first major activity of this Committee was the preparation of a proposed program of investigation (Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1955). As one product of the inter-agency planning, the Geological Survey began in 1956 an intensive study of the extent, rates, and causes of subsidence in the San Joaquin Valley, in financial cooperation with the California Department of Water Resources. At the same time, a companion federally financed study of the mechanics of aquifer systems was initiated to determine the principles controlling the compaction and expansion of aquifer systems under pumping stresses and to determine hydrologic storage parameters from field measurements. These two projects, cooperative and Federal, have resulted in a number of published or open-filed research reports. An annotated bibliography of the more significant contributions resulting from this research follows under the following five topic headings: (1) valleywide investigations, (2) Los Banos-Kettleman City area, (3) Tulare-Wasco area, (4) Arvin-Maricopa area, and (5) special studies. Professional Papers in the 437 number series represent products of the cooperative program on land subsidence; those in the 497 number series are products of the Federal program on mechanics of aquifer systems.

At the end of this report, complete bibliographic citations are given. Many additional shorter papers have been published or open filed. Some of these are referred to in the text and cited under references.

#### ANNOTATED BIBLIOGRAPHY

##### VALLEYWIDE INVESTIGATIONS

Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, "Progress report on land-subsidence investigations in the San Joaquin Valley, California, through 1957." Prepared chiefly by J. F. Poland, G. H. Davis, and B. E. Lofgren of the Geological Survey (1958). Reviews the program of the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley and describes the work accomplished through 1957. Includes maps and graphs showing results of precise leveling in the

Los Banos-Kettleman City and Tulare-Wasco areas. Includes maps of areas of shallow subsidence (hydrocompaction) and reports on construction and operation of test plots. Summarizes geologic and hydrologic aspects of subsidence due to artesian-head decline.

Professional Paper 497-A, "Physical and hydrologic properties of water-bearing deposits in subsiding areas in central California," by A. I. Johnson, R. P. Moston, and D. A. Morris (1968). To provide information on the water-bearing deposits in the principal subsiding areas, six core holes were drilled in the San Joaquin Valley as part of the program of the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley. In all, 462 samples from these core holes were tested by the U.S. Geological Survey for physical and hydrologic properties, and 86 samples were tested by the U.S. Bureau of Reclamation for engineering properties, including one-dimensional consolidation tests. This report presents core-hole logs and laboratory data in tabular and graphic form, describes methods of laboratory analysis, and shows interrelationships of some of the physical and hydrologic properties.

Professional Paper 497-C, "Petrology of sediments underlying areas of land subsidence in central California," by R. H. Meade (1967). Describes petrologic characteristics that influence compaction of sediments in the San Joaquin and Santa Clara Valleys, including particle size, clay minerals, and associated ions. Tabular presentation of results of laboratory tests from four core holes in the Los Banos-Kettleman City area, two each in the Tulare-Wasco area and Santa Clara Valley, and from one in the Arvin-Maricopa area. Montmorillonite is the principal clay mineral in each area.

Professional Paper 497-D, "Compaction of sediments underlying areas of land subsidence in central California," by R. H. Meade (1968). This report relates, partly by statistical analysis, the variation in overburden load and petrologic factors to variations in the pore volume and fabric of the water-bearing sediments in subsiding areas in the San Joaquin and Santa Clara Valleys. These sediments have been compacted by effective overburden loads ranging from 3 to 70 kilograms per square centimetre (40-1,000 lbs. in <sup>-2</sup>).

##### LOS BANOS-KETTLEMAN CITY AREA

Professional Paper 437-A, "Alluvial fans and near-surface subsidence in western Fresno County, California," by W. B. Bull (1964a). A study of compaction caused by water percolating through moisture-deficient alluvial-fan deposits above the

water table for the first time since burial. Detailed description of surficial deposits on alluvial fans in west-central San Joaquin Valley, where about 124 square miles of deposits has subsided or probably would subside if irrigated. Tests on surface samples under hygroscopic conditions indicate that maximum compaction occurs at a clay content of about 12 percent.

Professional Paper 497-E, "Geology of the compacting deposits in the Los Banos-Kettleman City subsidence area, California," by R. E. Miller, J. H. Green, and G. H. Davis (1971). This report describes the geology of the deposits undergoing compaction due to head decline, including source, type, physical character, and mode of deposition and the hydrologic framework so developed. In a series of subsurface maps and sections based on electric logs and core records, the Tulare Formation and overlying younger deposits are subdivided into alluvial-fan, flood-plain, deltaic, and lacustrine deposits and are identified as from the Sierra Nevada or the Diablo Range.

Professional Paper 437-E, "Land subsidence due to groundwater withdrawal in the Los Banos-Kettleman City area, California. Part 1, Changes in the hydrologic environment conducive to subsidence," by W. B. Bull and R. E. Miller (1975). Withdrawing water for agriculture and thus increasing the stress tending to compact unconsolidated deposits by as much as 50 percent has created in the west-central part of the San Joaquin Valley what is believed to be the world's largest area of intense land subsidence. More than a million acre-feet has been pumped from the ground-water reservoir each year during the period 1951-65, lowering the potentiometric surface as much as 600 feet, reversing the eastward gradient of 2-5 feet per mile to a westward gradient of 30 feet per mile, and causing water levels to decline below the base of the Corcoran Clay Member of the Tulare Formation adjacent to the Diablo Range.

Professional Paper 437-F, "Land subsidence due to ground-water withdrawal in the Los Banos-Kettleman City area, California. Part 2, Subsidence and compaction of deposits," by W. B. Bull (1975). In the west-central San Joaquin Valley, Calif., as of 1966, 2,000 square miles had subsided more than 1 foot, and the area that had subsided more than 10 feet was 70 miles long. Maximum subsidence was 26 feet. The rates, amounts, and distribution of subsidence within the area are described and are shown to be highly dependent on regional variations of certain geologic factors influencing the compaction of unconsolidated deposits. The report describes the measurement of compaction, the rates

and amounts occurring within specified depth intervals, and the proportions of subsidence being measured, and then assesses the geologic factors influencing compaction.

Professional Paper 437-G, "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," by W. B. Bull and J. F. Poland (1975). This report relates changes in thickness of the aquifer-system skeleton to water-level changes. Reviews analysis of stresses and change in stress. Describes various parameters necessary for a better understanding of the mechanics of aquifer systems and the compaction of sediments and for the development of criteria for predicting future subsidence.

#### TULARE-WASCO AREA

Professional Paper 437-B, "Land subsidence due to ground-water withdrawal, Tulare-Wasco area, California," by B. E. Lofgren and R. L. Klausning (1969). More than 800 square miles of irrigable land has subsided in the Tulare-Wasco area, owing to intensive pumping of ground water. The magnitude and rate of subsidence are directly related to the change in effective stress within the various beds that results from water-level changes and to the thickness and compressibility of the compacting deposits. In the southeastern part of the area, subsidence nearly stopped in the late 1950's, when water levels recovered as much as 130 feet in response to reduced pumping and increased recharge resulting from importation of water through the Friant-Kern Canal.

#### ARVIN-MARICOPA AREA

Professional Paper 437-D, "Land subsidence due to ground-water withdrawal, Arvin-Maricopa area, California," by B. E. Lofgren (1975). As of 1970, 700 square miles of irrigable land—roughly 60 percent of the area—had subsided owing to intensive pumping of ground water. Maximum subsidence exceeded 9 feet, and the total volume (1926-70) is about 1 million acre-feet. The report describes four types of subsidence occurring in the Arvin-Maricopa area and develops criteria that may be applied to estimate the amount of subsidence that will occur under assumed hydrologic change.

#### SPECIAL STUDIES

Professional Paper 437-C, "Prehistoric near-surface subsidence cracks in western Fresno County, California," by W. B. Bull (1972). During the excavation for the California Aqueduct, thousands of

clay-filled tension cracks were found in the alluvial fans of western Fresno County which raised the possibility of postconstruction tensional rupture of the canal. Many filled near-surface subsidence cracks occur in the small fans, and evidence is presented to show that many of these are historic. They have a mean spacing of less than one per hundred feet of canal length. On the other hand, the thousands of filled near-surface subsidence cracks in the large fans have a mean spacing of two to six per 100 feet of canal. The study revealed that virtually all the cracks in the large fans are prehistoric and that the possibility of future near-surface subsidence which would cause damage to the California Aqueduct is slight.

Professional Paper 497-B, "Removal of water and rearrangement of particles during the compaction of clayey sediments—review," by R. H. Meade (1964). Review of pertinent literature on the factors influencing the water content and clay-particle fabric of clayey sediments under increasing overburden pressures.

Professional Paper 497-G, "Land-surface tilting near Wheeler Ridge, southern San Joaquin Valley, California," by F. S. Riley (1970). Two continuous-recording liquid-level tiltmeters and three associated borehole extensometers recorded tilt at land surface and compaction of the upper 150 feet of alluvial-fan deposits at the site of a future pumping plant of the California Aqueduct. The site bordered a large bowl of land subsidence due to ground-water overdraft and overlay deposits susceptible to hydrocompaction. Repeated releveled of an array of surface bench marks agreed with the tiltmeter data in defining two principal periods of northward tilting per year.

Professional Paper 497-H, "Application of the modified theory of leaky aquifers to a compressible multiple-aquifer system," by F. S. Riley and E. J. McClelland (open file, 1972). Detailed description of practical procedures, based on the Hantush "modified theory of leaky aquifers," for analyzing pumping-test data. Application of the Hantush function is illustrated by the analysis of one recovery and five drawdown tests made near Pixley in the San Joaquin Valley, in a heterogeneous alluvial aquifer system.

Water-Supply Paper 2025, "Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal," by J. F. Poland, B. E. Lofgren, and F. S. Riley (1972). The glossary defines 25 terms as they are used in Geological Survey research reports concerned with the mechanics of stressed aquifer systems and of land subsidence. Most are terms that

have appeared in engineering or hydrologic literature, but several have been introduced as a result of the Survey's studies.

Geological Society of America, Reviews in Engineering Geology II, "Land subsidence due to the application of water," by B. E. Lofgren (1969). Hydrocompaction has produced widespread subsidence in low density moisture-deficient deposits and is of serious concern in the design and construction of many engineering structures. Deposits susceptible to hydrocompaction worldwide are described. In western and southern San Joaquin Valley, probably 200 square miles of irrigated farm land is subsiding because of the application of water, and at least another 50 square miles of susceptible land has not yet been irrigated. Preconsolidation before construction begins usually minimizes damage.

Geological Society of America, Reviews in Engineering Geology II, "Land subsidence due to withdrawal of fluids," by J. F. Poland and G. H. Davis (1969). A review of the known (1963) examples of appreciable land subsidence due to fluid withdrawal throughout the world, with a brief examination of the principles involved in the compaction of sediments and of aquifer systems as a result of increased effective stress. Special emphasis is given to studies in the San Joaquin Valley. Other areas in California affected by subsidence due to withdrawal of fluids are Santa Clara Valley, Wilmington, Lancaster, and La Verne. Several ways to alleviate subsidence are mentioned.

Professional Paper 352-E, "Geomorphology of segmented alluvial fans in western Fresno County, California," by W. B. Bull (1964). A study of the interrelations of alluvial-fan morphology, drainage-basin characteristics, and tectonic and climatic events. This study presents data on the geomorphology of alluvial fans in the west-central part of the San Joaquin Valley. It provides information concerning deposition and erosion of the fans as well as the relations of fan size and slope to drainage-basin area and lithology. The overall shape of the fans was studied by means of radial and cross-fan profiles. Fan segmentation, revealed by the radial profiles, was used to decipher tectonic history.

#### CAUSES OF SUBSIDENCE

Four types of subsidence are known to occur in the San Joaquin Valley. In order of their magnitude, they are (1) subsidence caused by water-level decline and the consequent compaction of aquifer systems, (2) subsidence related to the hydrocompaction of moisture-deficient deposits above the water table, (3) subsidence related to fluid withdrawal from oil and gas fields, and

(4) deep-seated tectonic settlement. A fifth type, subsidence caused by the oxidation and compaction of peat soils, occurs in the Sacramento-San Joaquin Delta area and is not considered in this report.

Figure 1 shows the principal areas affected by subsidence caused by water-level decline and hydrocompaction. These areas are principally in the western and southern parts of the valley, where runoff from surface streams is minimal. Subsidence due to hydrocompaction (also called near-surface or shallow subsidence) has occurred in two areas southwest of Mendota (Bull, 1964b) and in five areas south and southwest of Bakersfield (California Department of Water Resources, 1964a, pl. 2; Lofgren, 1975, pl. 3C). The total area susceptible to hydrocompaction is about 210 square miles, of which about 130 is north of Kettleman City.

Oil-field subsidence is known to occur in a few small areas south and west of Bakersfield (Lofgren, 1975). For the most part, this type of subsidence has been less than 1 foot during the period of leveling control and is restricted to local areas. Present subsidence rates are generally very low. During earlier periods of maximum production, however, subsidence rates in some oil fields undoubtedly were much greater than during the period of measurement. This type of subsidence has little effect on the long-term subsidence trends in the valley and is not considered further in this report.

Little information is available on rates of tectonic downwarping occurring in the San Joaquin Valley. Davis and Green (1962, p. D-90) postulated that post-depositional downwarping was responsible for 300 feet of deformation of the Corcoran Clay Member of the Tulare Formation beneath Tulare Lake bed. Carbon-14 dates used to calculate average depositional rates south of Kettleman City (Lofgren, 1975) indicate that if structural downwarping has been occurring uniformly since the Pleistocene, tectonic subsidence would have been so slow that it would not have affected bench marks appreciably during the historical span of leveling control. Of particular significance, however, are the evidences of tectonic movement of "stable bedrock" bench marks in the Coast Ranges to the west and the Tehachapi Mountains to the south. Apparent tectonic movements of as much as 0.8 foot in these bedrock tie points has affected the computed elevations of many of the bench marks in the valley. The magnitudes of these movements are not precisely measurable with present methods and instruments, but probably represent several tenths of a foot for many bench marks during the period of record.

#### SUBSIDENCE DUE TO WATER-LEVEL DECLINE

##### SAN JOAQUIN VALLEY

In 1956 when this cooperative investigation was in-

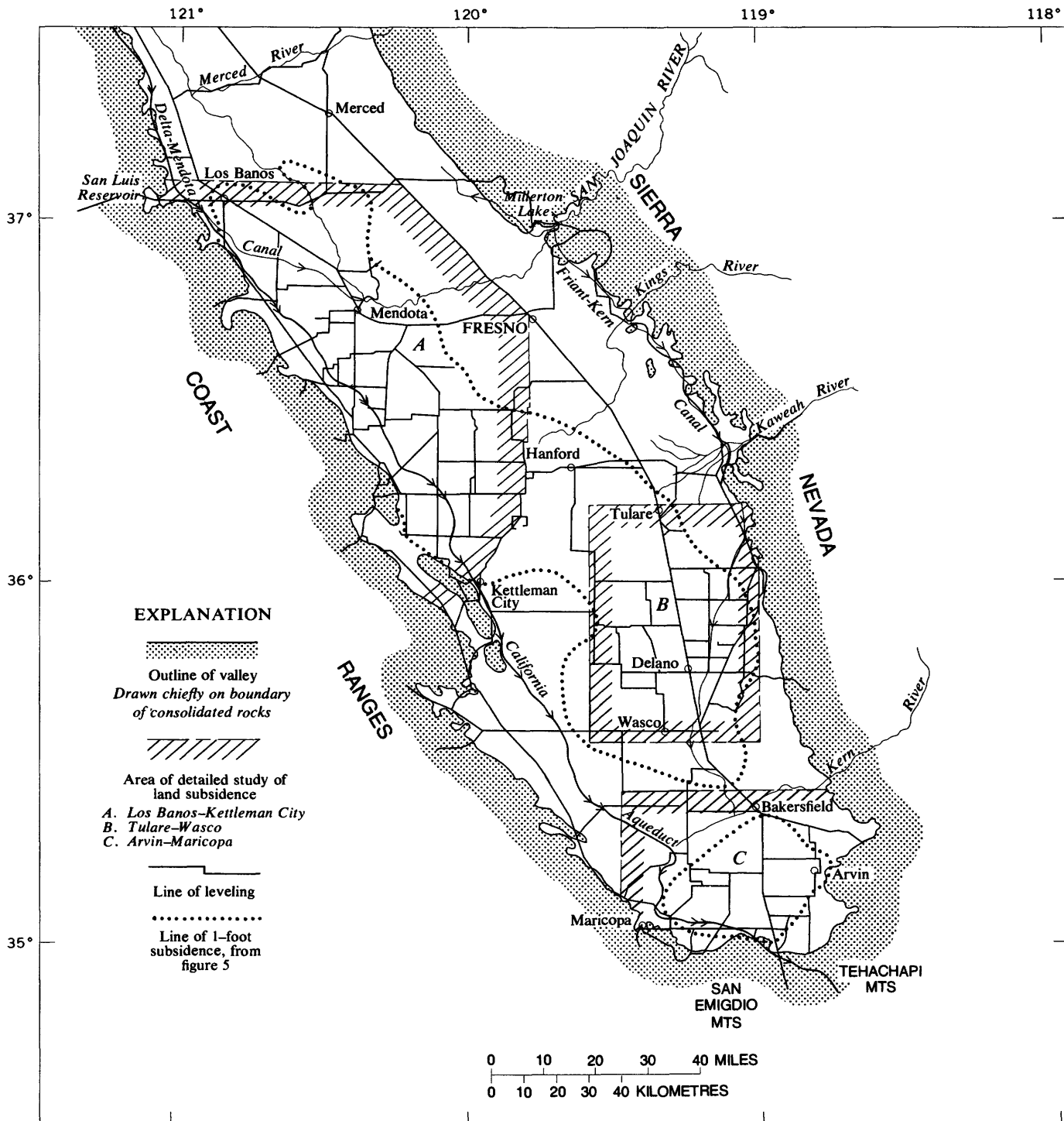
itiated, subsidence centered in three broad areas of known pumping overdraft. These were designated (fig. 3) (A) the Los Banos-Kettleman City area, (B) the Tulare-Wasco area, and (C) the Arvin-Maricopa area, and most of the subsequent studies and reports have considered these separately. As of 1956, a valleywide bench-mark network of leveling control, with some precise leveling dating back to 1902, was available. A bench-mark network had been established in the Tulare-Wasco subsidence area in 1948 through the efforts of the Geological Survey, the National Geodetic Survey, the Bureau of Reclamation, and other interested agencies. Similar networks were established in the Los Banos-Kettleman City area in 1955 and in the Arvin-Maricopa area in 1957 (Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958, pls. 4-6).

Figure 3 shows the network of leveling control, periodically resurveyed by the National Geodetic Survey. The control is concentrated in the three subsidence areas and ties to a dozen "stable bedrock" reference bench marks around the perimeter of the valley. Table 1 shows for each of the three subsidence areas the date the network was first established and the years of releveling of the network.

Significantly, most of the subsiding area in the San Joaquin Valley is underlain by a continuous and extensive confining bed (aquiclude). Most of the pumping overdraft and most of the compaction occurs in the artesian aquifer system beneath this confining bed. The boundary of this bed, where known, is shown in figure 4 (Lofgren and Klausning, 1969; Miller and others, 1971; Croft, 1972). North of the vicinity of Wasco, the confining bed is the Corcoran Clay Member of the Tulare Formation which also has been called the E clay by Croft (1972). Figure 4 also shows the location of selected observation wells and nearby bench marks discussed in this report.

Figure 5 shows the magnitude and extent of subsidence exceeding 1 foot in the San Joaquin Valley from 1926 to 1970 (1926-69 in the Los Banos-Kettleman City area). Three centers of subsidence stand out on the map. The most prominent is the long narrow trough west of Fresno that extends 90 miles from Los Banos to Kettleman City. Maximum subsidence in this area to 1969 was 28 feet, 10 miles southwest of Mendota. The second center, between Tulare and Wasco, is defined by two closed 12-foot lines, 20 and 30 miles south of Tulare, respectively. The depression near Delano had subsided 12 feet by 1954 (Lofgren and Klausning, 1969, fig. 43); subsidence of the northern depression has doubled since 1954. The third center, 20 miles south of Bakersfield, has subsided a maximum of about 9 feet, mostly since World War II.

Manmade subsidence began in the San Joaquin Valley in the middle 1920's, but the cumulative volume of



Base from U.S. Geological Survey  
1:1,000,000, State base map, 1940

FIGURE 3.—Network of leveling by the National Geodetic Survey and three areas of detailed studies of land subsidence.

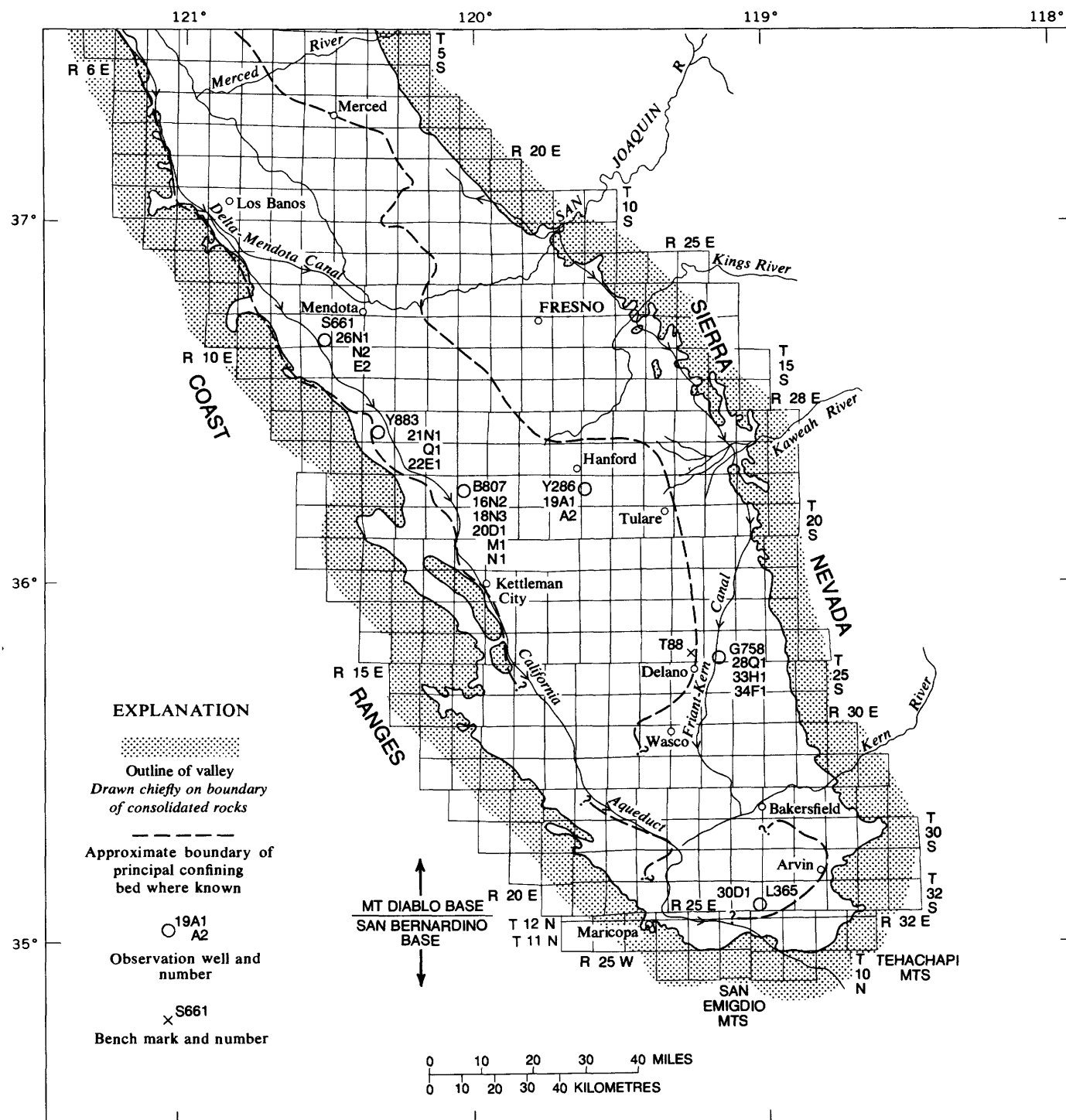
subsidence (fig. 6) remained small until after World War II. By 1970, the total volume of subsidence for the 44-year period (table 2) was 15.6 million acre-feet, having doubled since 1957. This volume is equal to one-half

the initial storage capacity of Lake Mead. The volume of subsidence for any interval of leveling control is obtained by planimetry of the subsidence map for that period. The cumulative volume for the entire valley (fig.



TABLE 1.—Years of leveling control of the network of bench marks in three subsidence areas by the National Geodetic Survey

Los Banos-Kettleman City	Tulare-Wasco	Arvin-Maricopa	Los Banos-Kettleman City	Tulare-Wasco	Arvin-Maricopa
----- 1955 1957-58 1959-60	<sup>1</sup> 1948 1953 1957 1958-59	----- 1957 1958-59	1963 1966 1969 1971-72	1962 <sup>2</sup> 1964 1969-70 -----	1962 1965 1970 -----

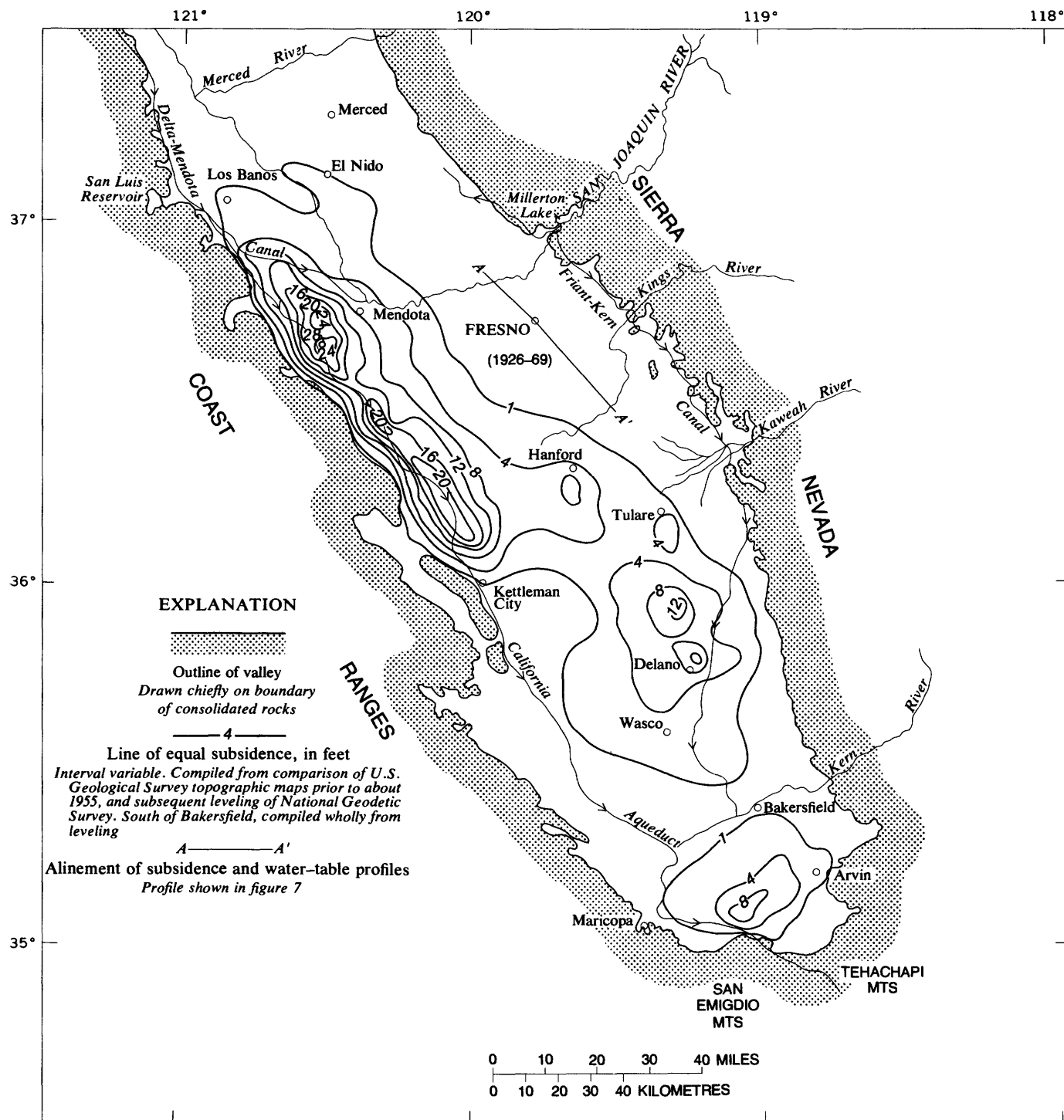
<sup>1</sup>Year network established.<sup>2</sup>Partial releveing of net.

Base from U.S. Geological Survey  
1:1,000,000, State base map, 1940

FIGURE 4.—Location of selected observation wells, nearby bench marks, and boundary of the principal confining beds.

6) is derived by addition of the volumes for individual areas. Figure 5 shows the areal distribution of this 15.6 million acre-feet of subsidence. However, figure 5 only defines the extent of subsidence that exceeds 1 foot, an area of 4,300 square miles. Extrapolation of the magnitude-area graphs for the four areas given in table

2 (such as fig. 20 for the Los Banos-Kettleman City area) to zero subsidence suggests that the total area affected by subsidence is about 5,200 square miles (table 2) and hence that the area in which subsidence is less than 1 foot but greater than zero is 900 square miles.



Base from U.S. Geological Survey  
1:1,000,000, State base map, 1940

FIGURE 5.—Land subsidence, 1926-70. Compiled from comparison of U.S. Geological Survey topographic maps prior to about 1955 and subsequent leveling of National Geodetic Survey. South of Bakersfield, compiled wholly from leveling.

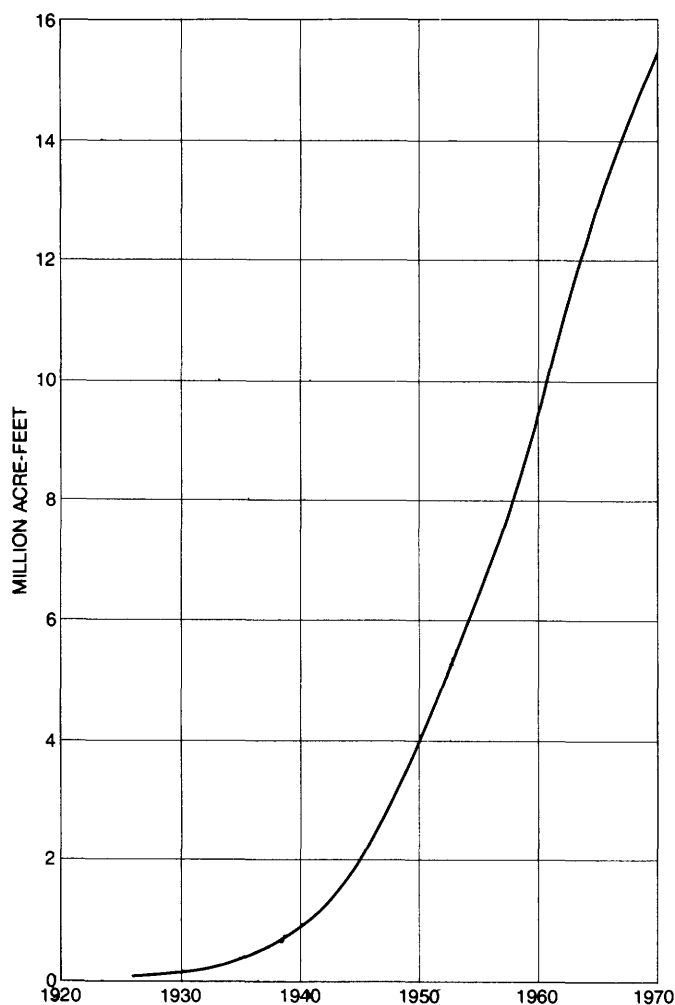


FIGURE 6.—Cumulative volume of subsidence, 1926–70.

TABLE 2.—Summary of extent and volume of subsidence, 1926–70, San Joaquin Valley

Area	Area where subsidence exceeds 1 foot		Total area affected <sup>1</sup>		Volume Acre-feet $\times 10^6$
	Acres $\times 10^3$	Square miles	Acres $\times 10^3$	Square miles	
Los Banos-Kettleman City <sup>2</sup> .....	1,300	2,030	1,530	2,400	9.92
Hanford .....	350	550	435	680	1.31
Tulare-Wasco .....	800	1,250	910	1,420	3.32
Arvin-Maricopa .....	320	500	450	700	1.06
Total (rounded) .....	2,750	4,300	3,300	5,200	15.6

<sup>1</sup>Extrapolated graphically to zero subsidence.<sup>2</sup>Subsidence, 1926–69.

Probably more than 900 square miles has been affected by subsidence, but falls outside the 1-foot line of figure 5. Certainly, elevation differences of 0.05–0.3 foot are indicated along many bench-mark lines which have been resurveyed 10–40 years after the first survey. However, most leveling surveys are not that precise. Complications that include distance to bedrock ties, stability of bedrock ties, instruments used, order of ac-

curacy required, adjustment procedures, and other problems lead to the conclusion that comparative elevation changes at individual bench marks (from surveys tens of years apart) which do not exceed 0.2–0.3 foot are of questionable value as indicators of subsidence trends. For this reason, we have not attempted to map overall subsidence in the valley to limits of less than 1 foot, although we have mapped subsidence in active subsidence areas to 0.1 foot under favorable conditions.

As shown later, generally there is a close correlation between subsidence and water-level trends. When this correlation does not exist, other causes or spurious data are suspected. Figure 7 is an example of small apparent subsidence that does not correlate with water-level decline and which may not be real. The water-level and subsidence profiles are along the Southern Pacific Railroad, between the San Joaquin and the Kings Rivers (for alignment, see section A–A', fig. 5). The water-level profiles are from 1960 data of the California Department of Water Resources (California Department of Water Resources, 1963, 1964b) and from its predecessor (California Division of Water Resources, 1931, pl. 13; 1921 and 1929 autumn levels); the subsidence profiles are from bench-mark surveys by the National Geodetic Survey. This profile alignment is along the upper reaches of the alluvial fans of the San Joaquin and Kings Rivers. To the depths of 150–300 feet tapped by water wells, these deposits are primarily coarse sand and gravel, and the ground-water body at these depths is unconfined (Page and LeBlanc, 1969, pls. 8, 10).

The indicated subsidence from the 1930 base as of 1952–53 averaged about 0.06 foot (max 0.10) and as of 1959–60 ranged from 0.02 to 0.20 foot. However, the maximum indicated subsidence from 1930 to 1960 was between Fowler and Selma, in the area of only 10–15 feet of water-table decline (autumn low level, 1929 and 1960), whereas the reach of maximum water-table decline of 40 feet in the city of Fresno subsided only half as much (0.08–0.09 ft) in the 30 years. Thus, the apparent subsidence does not correlate with water-table decline; except for three bench marks, the 30-year subsidence is less than 0.1 foot and thus may represent adjustment procedures from different bedrock ties. It is possible that vibrations caused by the passage of several thousand trains per year might cause differential compaction of as much as 0.1 foot between bench marks 1–3 miles apart in a period of 30 years.

Two long reaches of the California Aqueduct traverse the west side of the valley north and south of the Los Banos-Kettleman City subsidence area. The magnitude and extent of historical subsidence in these two areas is of interest. To the north, the area between Los Banos and Tracy (57 miles northwest; not shown) has been irrigated primarily with surface water since the

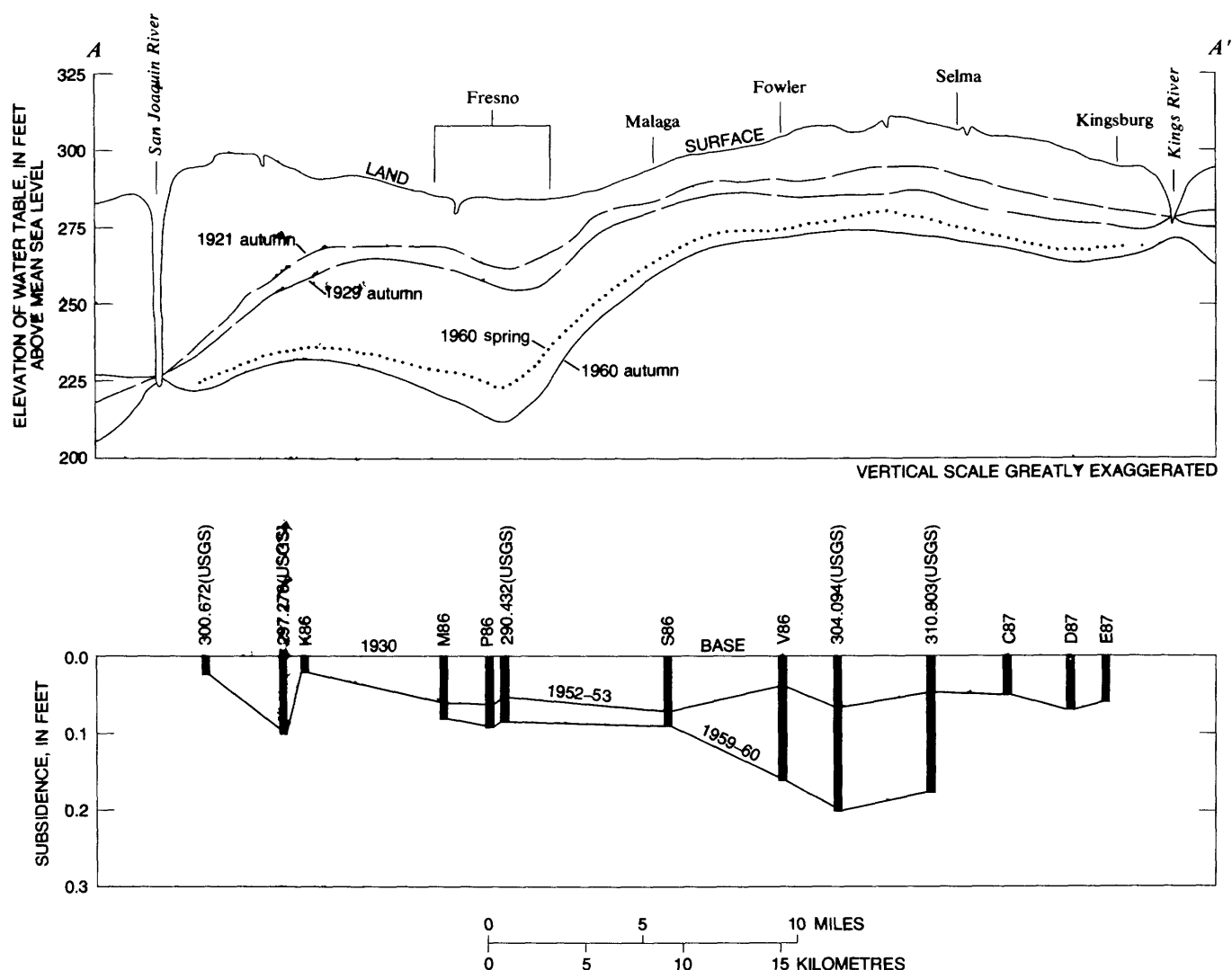


FIGURE 7.—Apparent subsidence and water-table decline along the Southern Pacific Railroad between the San Joaquin and Kings Rivers.

Delta-Mendota Canal was completed in 1951. During 1962–66, one-quarter of the irrigation water in this northern area (about 300,000 acre-ft/yr) was supplied from wells, and three-quarters (900,000 acre-ft/yr) from canals (Hotchkiss and Balding, 1971). In general, water levels in wells have been rising for the past two decades, and so subsidence would not be anticipated to be a current problem. On the other hand, the area traversed by the California Aqueduct between Kettleman City and T. 30 S. (fig. 4) never had been developed agriculturally prior to canal deliveries in 1970 because inferior quality of the ground water had discouraged well development (Wood and Davis, 1959). Here also, subsidence from water-level decline would not be anticipated.

In 1966, the California Department of Water Resources made a brief analysis of bench-mark surveys by the National Geodetic Survey north of Los Banos and

between Kettleman City and Tupman (in T. 30 S., R. 24 E., sec. 24; fig. 4). The purpose was to appraise historical land subsidence in these areas, with respect to State water facilities—the California Aqueduct then under construction and the proposed Master Drain. From Tracy to 50 miles southeast to within 5 miles of Los Banos, the maximum historical subsidence (1935–66) along the Southern Pacific Railroad was about 0.5 foot, and the rate of subsidence was lowest in the 1960's (Marvin V. Damm, written commun., June 29, 1966).

From Kettleman City south to Tupman (in T. 30 S., R. 24 E.; see fig. 4), subsidence along the general California Aqueduct alignment did not exceed 0.2 foot in the period between the first leveling control of the National Geodetic Survey (in 1935 or 1942) and 1966 (Marvin V. Damm, written commun., July 12, 1966). Leveling by the National Geodetic Survey in 1969–70 southeast of Kettleman City shows only a few hundredths of a foot of

increased subsidence along the aqueduct alignment in this reach. However, it should be noted that two bench marks on U.S. Highway 466 at the axis of the Lost Hills oil field (SW. cor. sec. 33, T. 26 S., R. 21 E.) subsided 2.24 feet, 1935-66, and 1.04 feet, 1954-66. Evidently this local subsidence was caused by fluid production from the oil field, but it represents no hazard to the aqueduct which is about 2 miles to the east.

#### LOS BANOS-KETTLEMAN CITY AREA

Roughly 2,400 square miles of the Los Banos-Kettleman City area (fig. 3) has been affected by subsidence, of which 1,500 square miles is west of the valley trough as defined by the San Joaquin River and Fresno Slough. For a detailed discussion of the geology, hydrology, and characteristics of the compacting aquifer systems, reference is made to comprehensive reports listed in the section "Annotated Bibliography."

Figures 8, 9, and 10 are comparative records of subsidence and change in artesian head of the lower zone

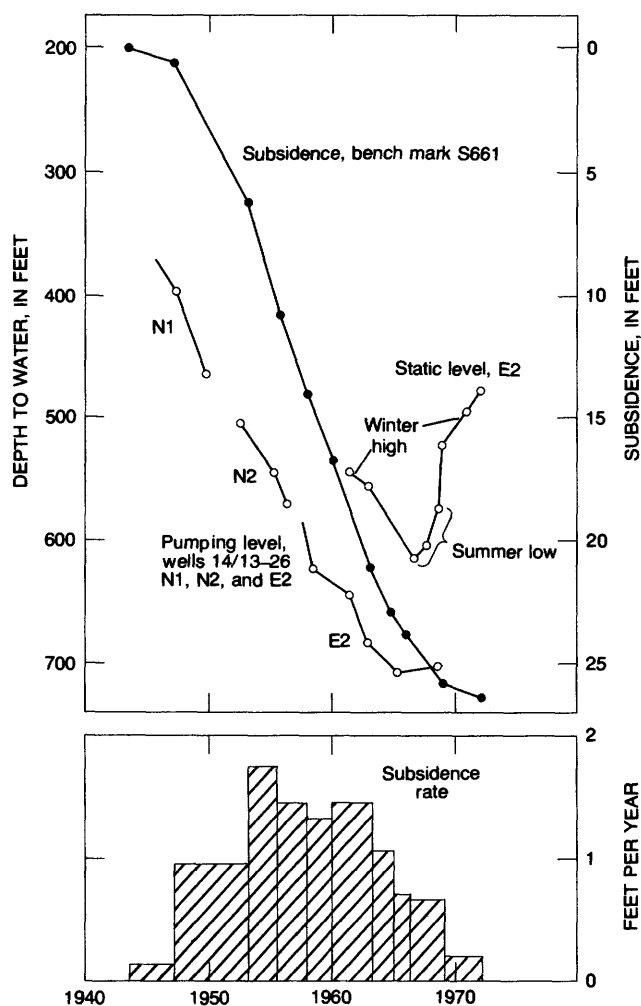


FIGURE 8.—Subsidence and artesian-head change 10 miles southwest of Mendota.

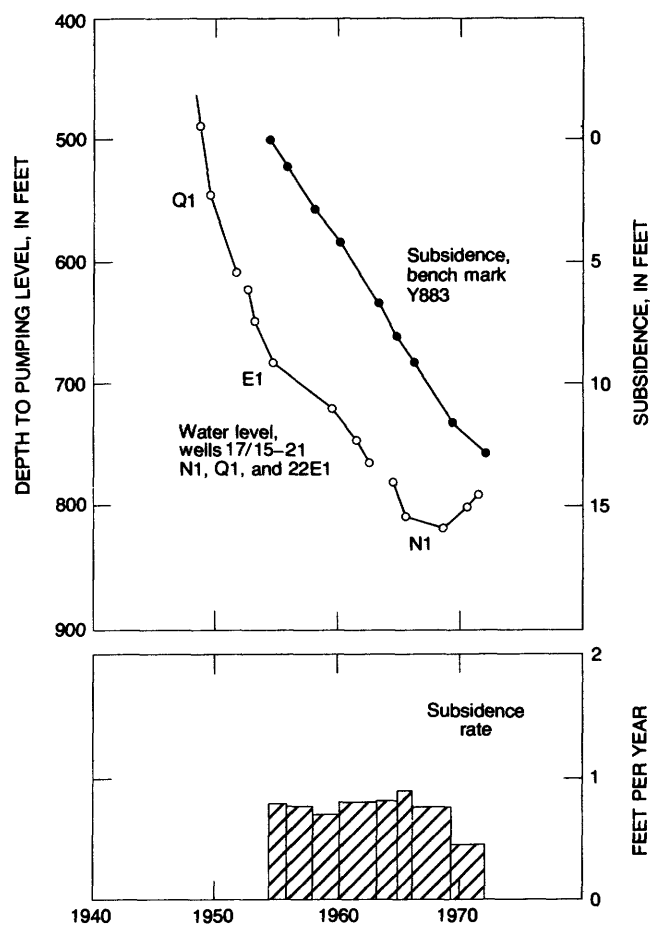


FIGURE 9.—Subsidence and artesian-head change near Cantua Creek.

(confined aquifer system) at three centers of rapid subsidence. (For location of these wells and bench marks, see fig. 4.) At each location, an extended period of water-level decline accompanied by rapid subsidence was followed by a few years of water-level rise. The Federal San Luis Project area includes most of the agricultural land in Fresno County west of Fresno Slough (fig. 13); surface-water deliveries to this area from the joint-use reach of the California Aqueduct increased from an initial 200,000 acre-feet in 1968 to 865,000 in 1972. As shown by the bar diagrams in the three figures, the rate of subsidence in 1966-69 compared with the rate in the early 1960's decreased markedly southwest of Mendota (fig. 8) and appreciably near Huron (fig. 10), but registered little change near Cantua Creek (fig. 9). Southwest of Mendota, by 1966-69 the yearly rate had decreased to 38 percent of the maximum rate in 1953-55.

The average rate of subsidence in 1969-72 decreased drastically at all three sites because of the rapid rise in artesian head caused by the increase in surface-water imports (table 3) and the resulting decrease in groundwater draft. For example, southwest of Mendota the

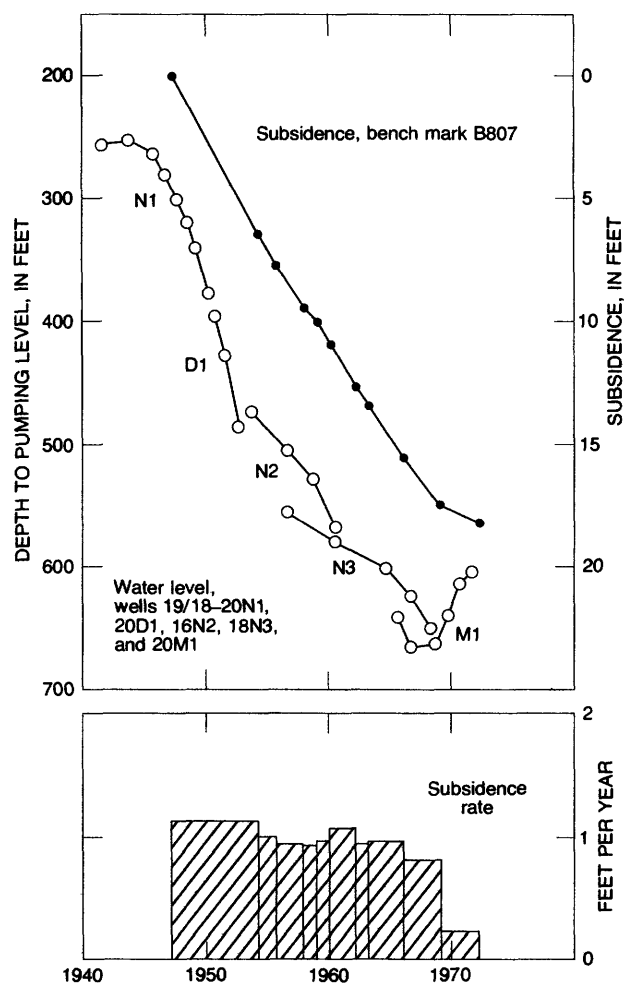


FIGURE 10.—Subsidence and artesian-head change near Huron.

average rate of 0.2 foot per year in 1969–72 was only 11 percent of the 1953–55 maximum; near Huron the average rate was only 22 percent of the 1960 average.

Figure 11 shows the trends of subsidence and head decline in two zones near Hanford (for location, see fig. 4). The upper zone is above the principal confining bed—the Corcoran Clay Member of the Tulare Formation—and the lower zone is below. This location is outside the Los Banos–Kettleman City area (fig. 3), but in general the same effects of overpumping have occurred. About 8 feet of subsidence has been measured in this area (fig. 5), mostly since 1953. At bench mark Y286, the maximum subsidence rate of 0.6 foot per year (lower graph, fig. 11) was measured in 1959–62. The average rate in 1966–69 was less than half this amount. Of the two water levels, the hydrograph of shallow well 19/22–19A2 (110 ft deep) seems to more closely parallel the subsidence trend, although the deep summer low levels registered in observation well 19/22–19A1 (well point set at 559 ft) undoubtedly contributed to the subsidence.

Figure 12 shows the magnitude and areal extent of subsidence in the Los Banos–Kettleman City area during the 3 years 1966–69. The construction of the California Aqueduct south to Kettleman City was completed early in 1968. About 230,000 acre-feet of surface water had been imported by the end of 1968 (see table 3), thereby causing about 20 percent reduction in pumpage and about a 20-foot average recovery of the artesian head of the lower zone. Hence, the rate of subsidence must have decreased substantially during 1968, but even so, the 3-year total exceeded 2.5 feet along a 4-mile stretch of the aqueduct west of Cantua Creek and exceeded 2 feet for an aggregate length of 32 miles.

The average yearly rate of subsidence during 1966–69 (fig. 13) was derived by dividing the values of figure 12 by three. The average rates shown undoubtedly are lower than the actual rates of 1966 and higher than the actual rates of 1968. Nevertheless, the map indicates that for 60 miles from west of Mendota to 3 miles north of Kettleman City the average yearly rate of subsidence along the central subsidence trough exceeded 0.4 foot per year.

Figure 14 shows the total subsidence in the 14 years since the bench-mark network was established in 1955. The maximum subsidence of 14 feet was 10 miles southwest of Mendota. More than 10 feet of subsidence occurred during the mapped period in a 50-mile reach extending from west of Mendota southeast past the Kings County line.

The total subsidence due to man's overall increase of subsurface stresses from 1926 to 1969 is shown in figure 15. By 1969, maximum subsidence exceeding 28 feet affected an area of about 1 square mile, 10 miles southwest of Mendota. Subsidence exceeded 10 feet in about 600 square miles and 4 feet in 1,200 square miles. Figures 12 through 15 delineate by a dotted outline the areas west and northwest of Cantua Creek (town) and 16–19 miles west of Mendota where hydrocompaction has been a problem for many years.

In December 1972, after the draft of this summary report was completed, the National Geodetic Survey supplied a tentative adjustment of bench-mark elevations for the survey of November 1971–March 1972. Adjustments were made on the same basis as for the surveys of 1966 and 1969. During the 3-year period 1969–71, the increasing importation of surface water through the California Aqueduct (fig. 46) and the consequent decrease in ground-water pumpage greatly decreased the stress applied to the fine-grained beds (aquitards). Imports during this period totaled 1,434,000 acre-feet (see table 3), and the artesian head of the lower water-bearing zone rose an average of 42 feet, in contrast to the previous 3-year period, 1966–68, when imports totaled 228,000 acre-feet (92 percent of

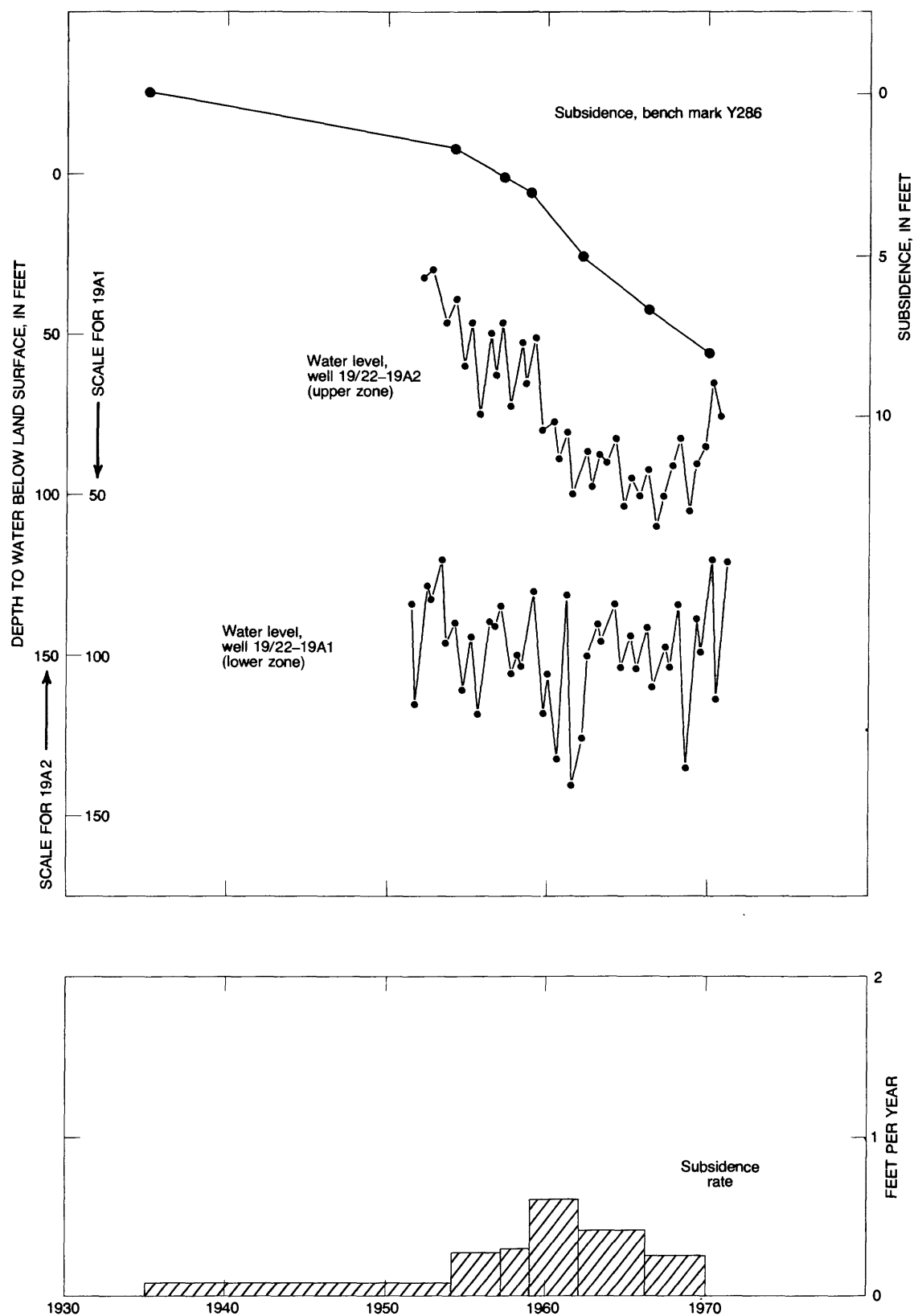


FIGURE 11.—Subsidence and head change in two zones near Hanford.

this was in 1968) and net change in artesian head was small.

Figure 16 shows the subsidence from 1969 to 1972. (Because of the late availability of the 1971-72 bench-

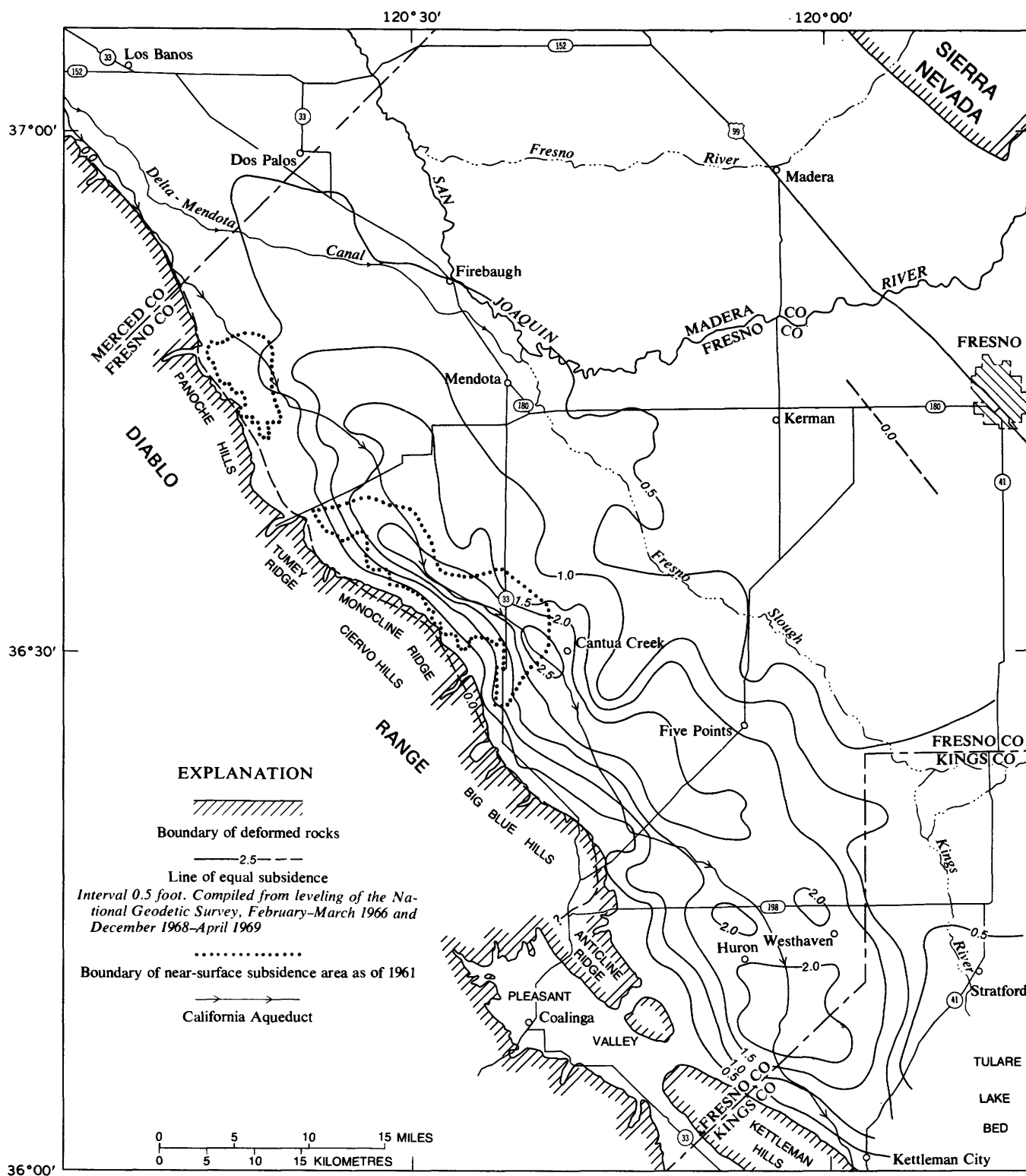
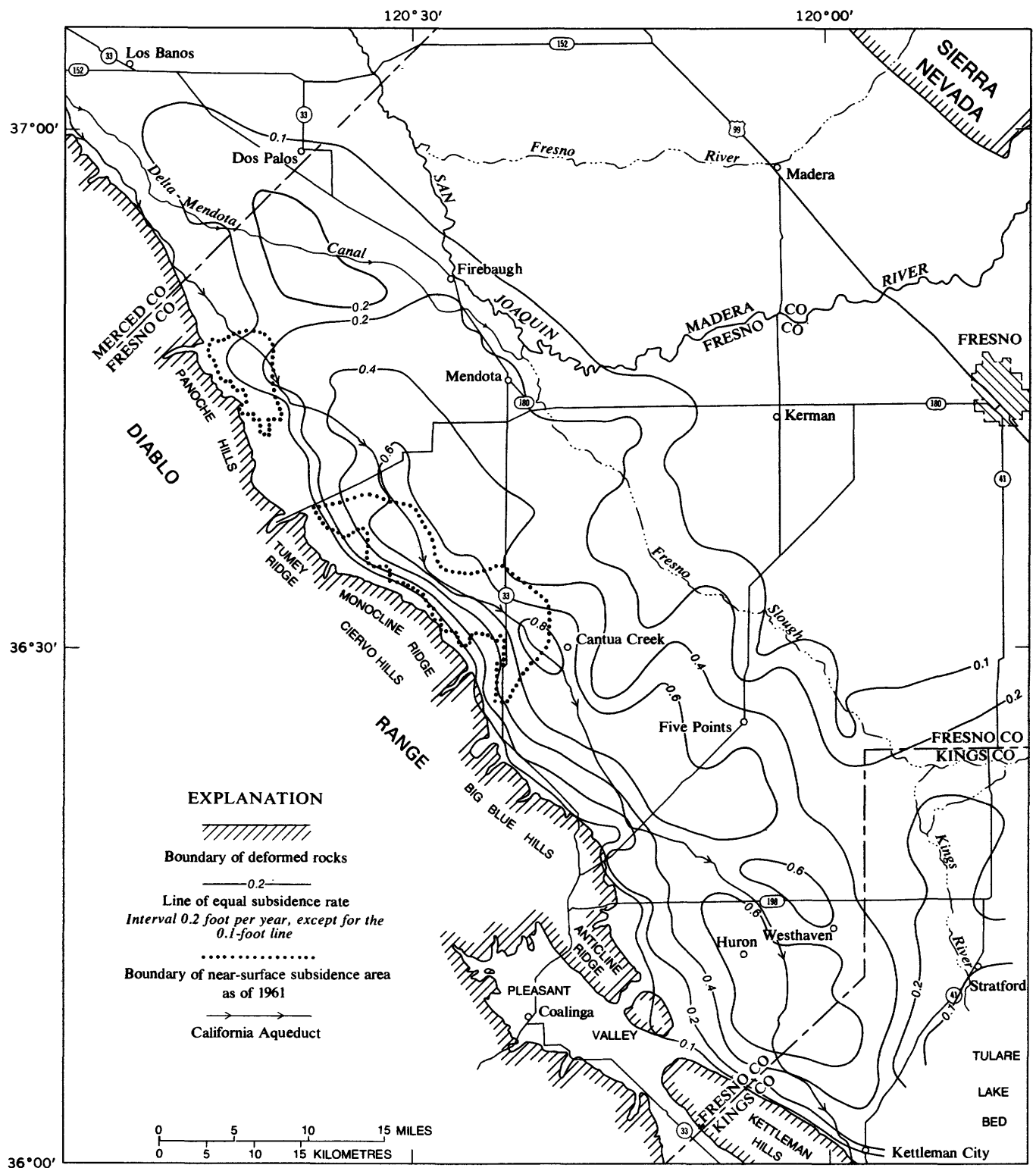


FIGURE 12.—Land subsidence, 1966–69, Los Banos–Kettleman City area. Compiled from leveling of the National Geodetic Survey, February–March 1966 and December 1968–April 1969.

mark elevations, we have not attempted to update other subsidence graphs or maps beyond the 1969 data except figures 8–10 and 18, but we have added figures 16 and

17.) The 1969–72 change in both magnitude and pattern of subsidence, from 1966–69 (fig. 12) is striking. Maximum subsidence of about 1.6 feet occurred on the

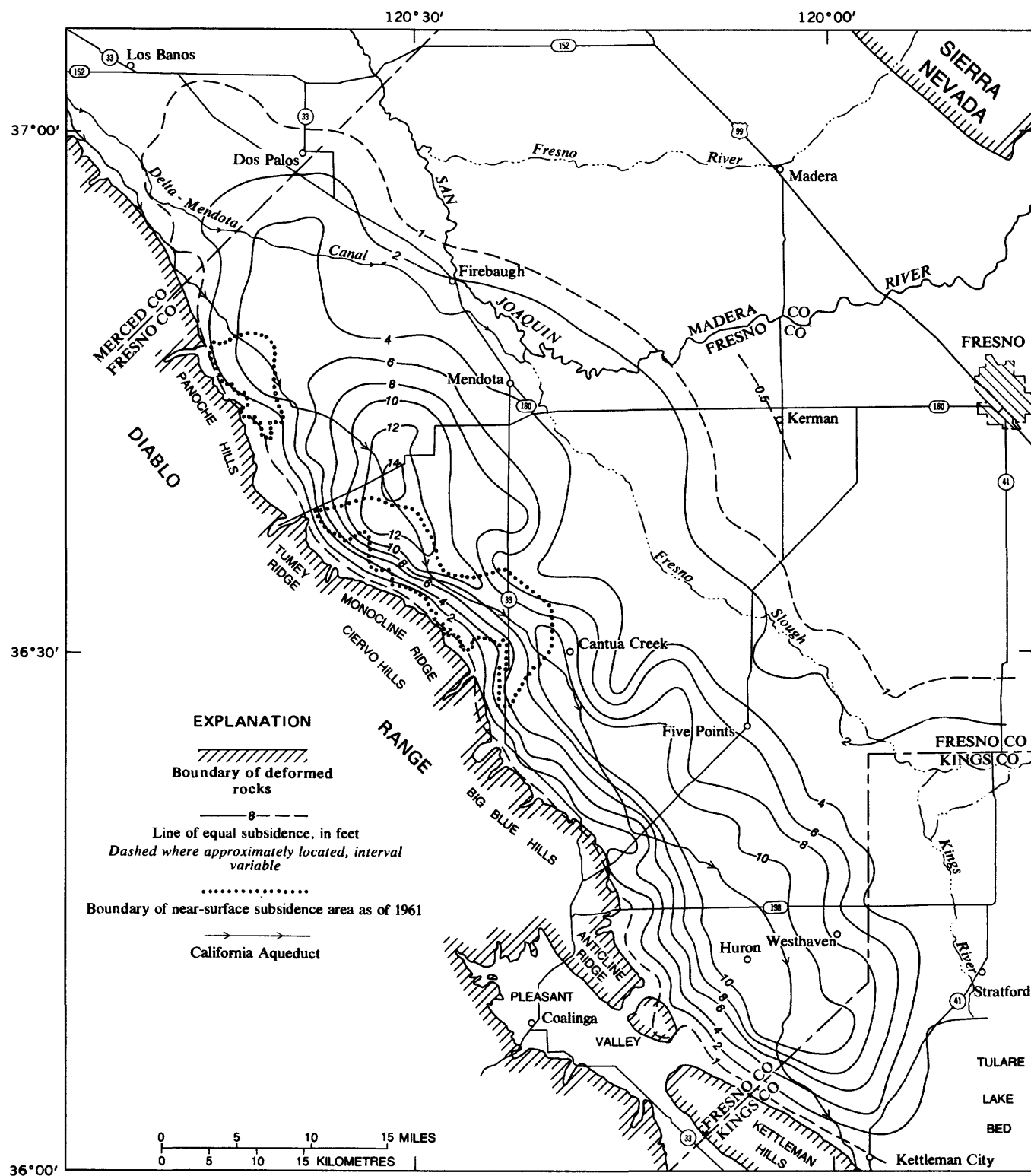




Base from U.S. Geological Survey Central Valley map, 1:250,000, 1958

FIGURE 13.—Average yearly rate of subsidence, 1966–69, Los Banos–Kettleman City area. Based on control data of figure 12.

aqueduct 2 miles west of Cantua Creek (town), compared with 2.7 feet in 1966–69. Everywhere the 1969–72 | subsidence shows a decrease in the magnitude compared with 1966–69, but the ratio ranges widely from



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

FIGURE 14.—Land subsidence, 1955–69, Los Banos–Kettleman City area. Compiled from leveling of the National Geodetic Survey, September–November 1955 and December 1968–April 1969.

1/5 to as much as 4/5. The irregularity of the lines of equal subsidence in figure 16, in contrast to the smooth pattern of figure 12, reflects the progressive completion of the irrigation distribution system in the area, caus-

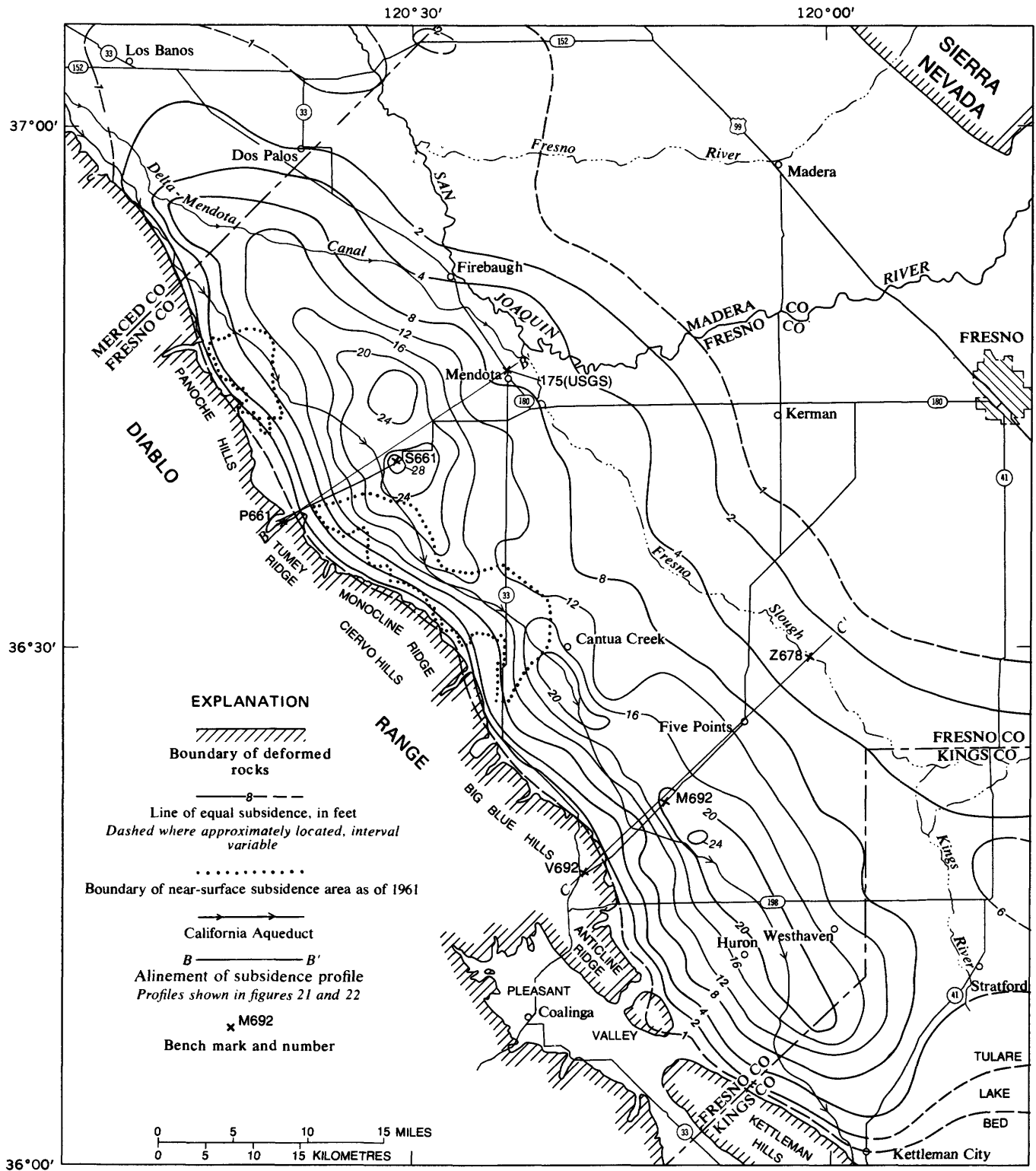


FIGURE 15.—Land subsidence, 1926–69, Los Banos–Kettleman City area. Compiled chiefly as the sum of (1) a comparison of topographic mapping by the U.S. Geological Survey done between 1920–28 and in 1955 and (2) leveling of the National Geodetic Survey in 1955 and 1969.

ing an irregular pattern of surface-water deliveries and hence of irrigation well shutdown and artesian-head recovery.

Figure 17 shows the subsidence from 1926 to 1972. By 1972, maximum subsidence had reached 29 feet, 10 miles southwest of Mendota. Because subsidence in

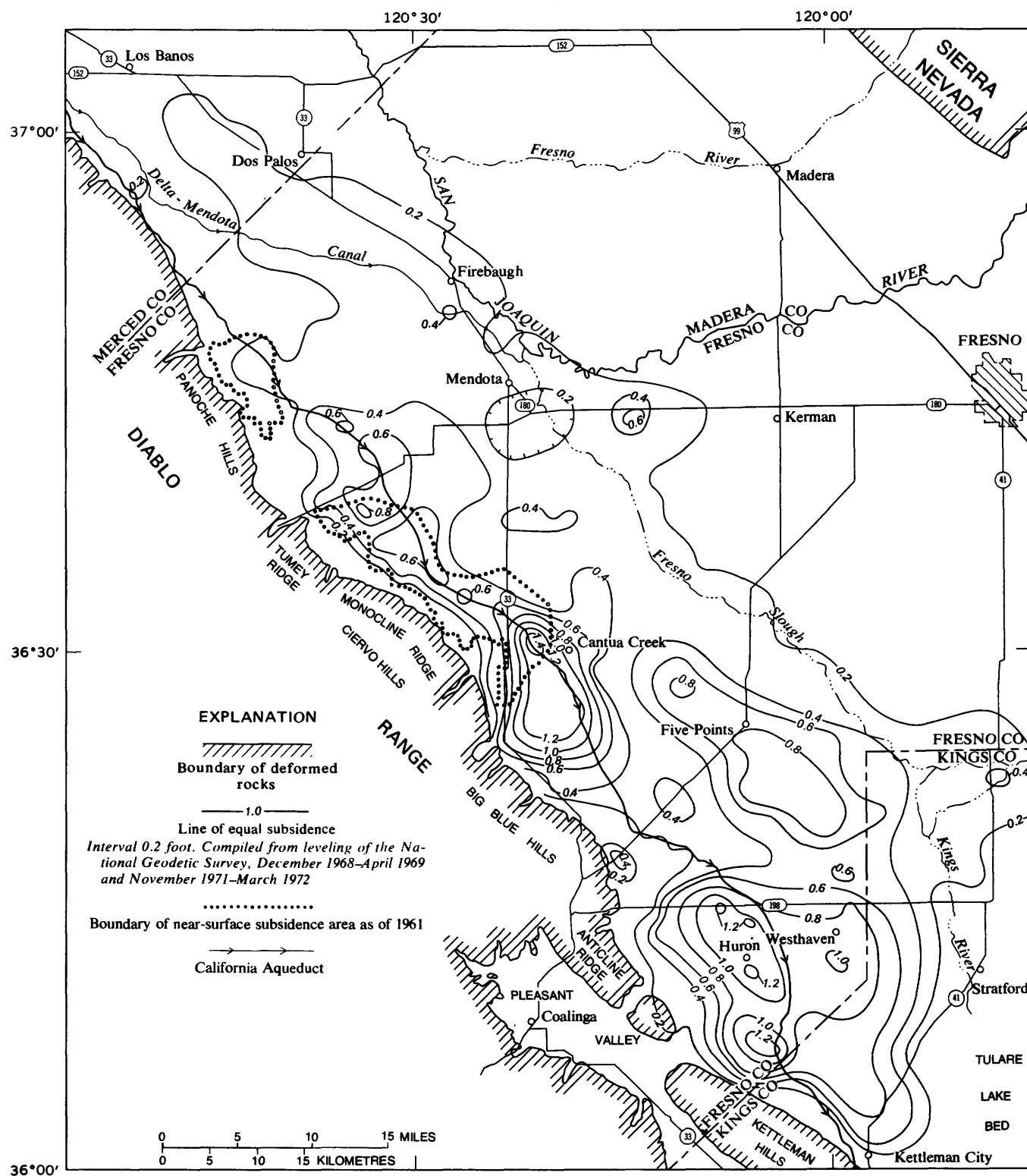


FIGURE 16.—Land subsidence, 1969–72, Los Banos–Kettleman City area. Compiled from leveling of the National Geodetic Survey, December 1968–April 1969 and November 1971–March 1972.

1969–72 (fig. 16) exceeded 1 foot only in two small areas, the configuration of the lines of equal subsidence in figure 17 differs little from that in figure 15, except in

the El Nido area, at the north edge of the map. Subsidence in the El Nido area is controlled by leveling of the National Geodetic Survey along Highway 152 at five

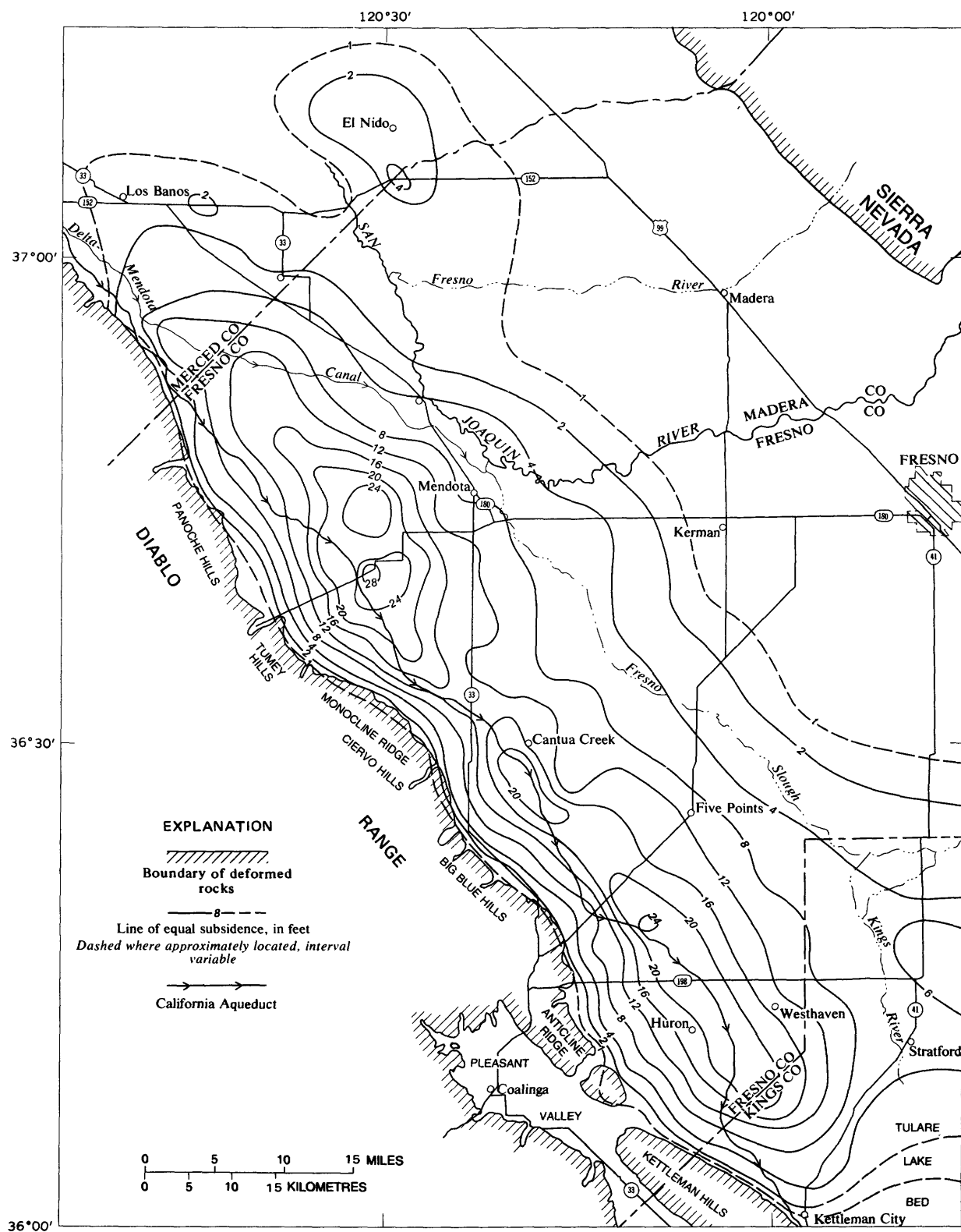


FIGURE 17.—Land subsidence, 1926-72, Los Banos-Kettleman City area. Compiled as sum of subsidence for 1926-69 (fig. 15) and for 1969-72 (fig. 16).

times between 1933 and 1972 and north through El Nido in 1958 and 1972.

The average yearly rates of subsidence, in acre-feet per year, during the nine periods of vertical control between 1926 and 1972 are illustrated by the rectangular bars in figure 18. They were obtained by dividing the computed volume of subsidence for the period by the number of years between times of vertical control. The dashed line represents the estimated probable rate of subsidence which varies with time. The probable subsidence rate increased fairly uniformly from the 1920's to 1957, reached a maximum of about 450,000 acre-feet per year in 1961, and declined to about 100,000 acre-feet per year in 1972. The pumping draft in the area west of Fresno Slough and south of the Merced County line reached its peak of 1.275 million acre-feet in 1952, about 10 years before the maximum subsidence rate. Pumpage in 1960-62 averaged 1.075 million acre-feet per year (Bull and Miller, 1975, table 3).

Figure 19 indicates that after subsidence began in the middle 1920's the volume increased slowly to 1 million acre-feet by 1942, then rose rapidly in the postwar years to 4 million acre-feet at the end of 1953. By 1969, the total volume of subsidence related to ground-water pumpage west of Fresno Slough was 9.6 million acre-feet, nearly two-thirds of the cumulative total for the San Joaquin Valley (fig. 6). The cumulative ground-water pumpage in the Los Banos-Kettleman City area (west of Fresno Slough and the San Joaquin River) through March 1969 is estimated as 28.5 million acre-feet. This cumulative pumpage has been plotted annu-

ally in figure 19 to show the relation between subsidence volume and pumpage. At a scale ratio of 1 to 3, the correlation is remarkably consistent, indicating that throughout the 43 years since subsidence began (1926 into 1969) about one-third of the water pumped has been water of compaction derived from the compaction of the aquifer systems.

As of 1969, about 1.3 million acres (2,030 sq mi) had subsided more than 1 foot (fig. 20), and the total area affected by subsidence was 1.53 million acres (2,400 sq mi). About 400,000 acres had subsided more than 10 feet, and 80,000 acres more than 20 feet.

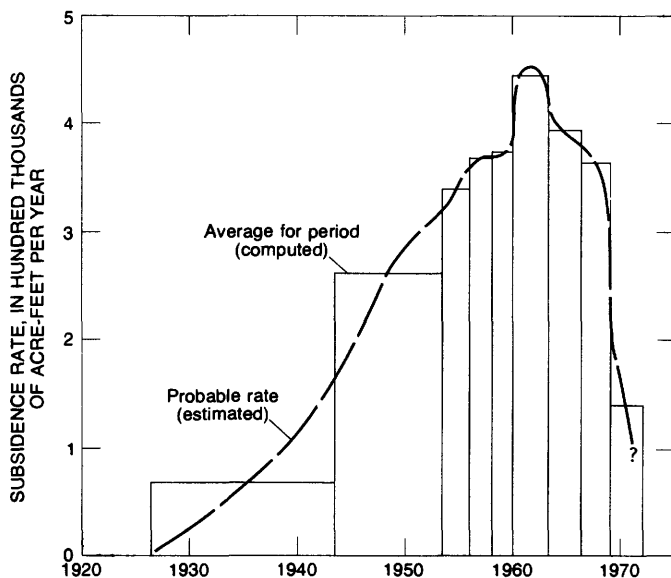


FIGURE 18.—Rate of subsidence in the Los Banos-Kettleman City area, 1926-72.

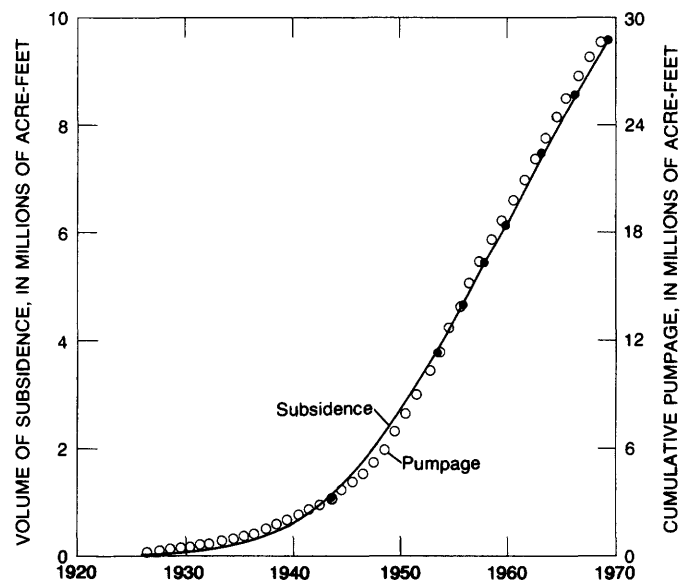


FIGURE 19.—Cumulative volumes of subsidence and pumpage, 1926-69, Los Banos-Kettleman City area. Points on subsidence curve indicate times of leveling control.

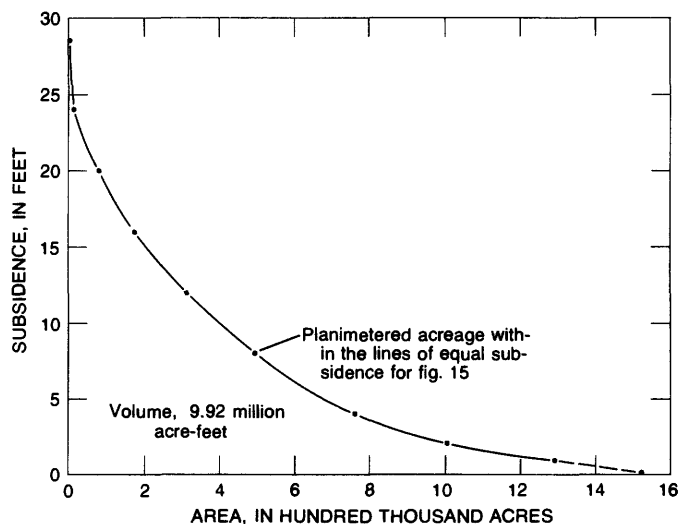


FIGURE 20.—Relation of magnitude to area of subsidence, 1926-69, Los Banos-Kettleman City area.

Two transverse subsidence profiles illustrate the history of subsidence from 1943 to 1969 southwest of Mendota and along Five Points Road (for location, see fig. 15). Along both profiles the subsidence is caused wholly by water-level decline. Profile B-B' (fig. 21) extends from the foothills of the Diablo Range through Mendota, passing close to the site of maximum subsidence (bench mark S661). It shows subsidence during eight periods since 1943, with the 1943 control used as a horizontal reference base. The center of subsidence migrated southwest about 3.4 miles from 1947 to 1957 in response to the major westward extension of ground-water development from 1940 to 1950 (Bull and Miller, 1975, fig. 22).

Profile C-C' (fig. 22) extends northeast along the Five Points Road from Anticline Ridge to Fresno Slough. Maximum subsidence from 1943 to 1969 was 21 feet at bench mark M692. About 1 mile northeast of the California Aqueduct alignment, the subsidence profiles steepen dramatically, suggesting a fourfold increase in the compressibility of the deposits tapped by wells, a rapid thickening of compactible deposits, or a greater historic drawdown of artesian head, or, more probably, the combined effect of all three factors.

#### TULARE-WASCO AREA

Subsidence was first recognized in the Tulare-Wasco area in 1935. As of 1970, an estimated 1,420 square

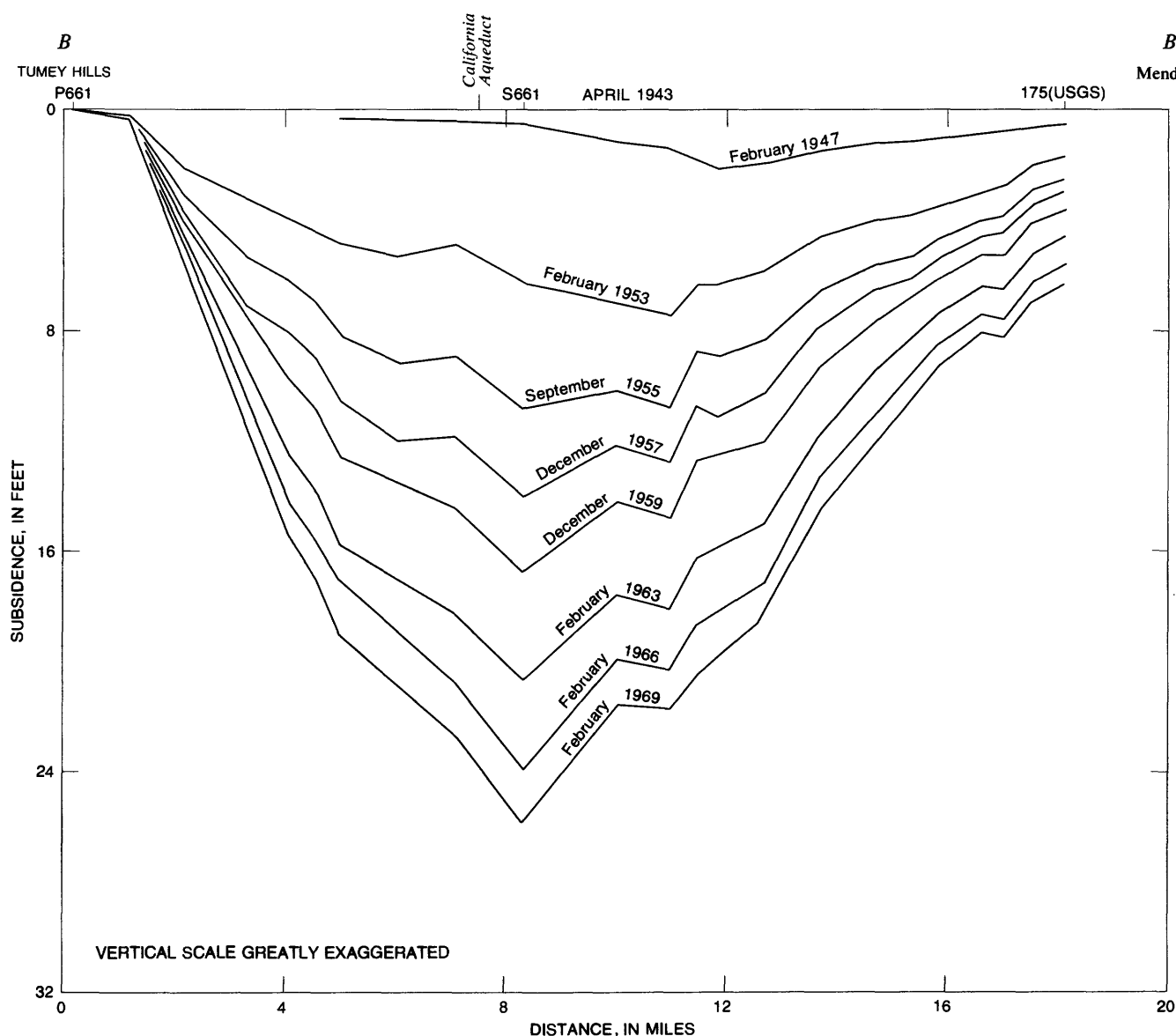


FIGURE 21.—Profiles of subsidence, 1943-69, Tumey Hills to Mendota.

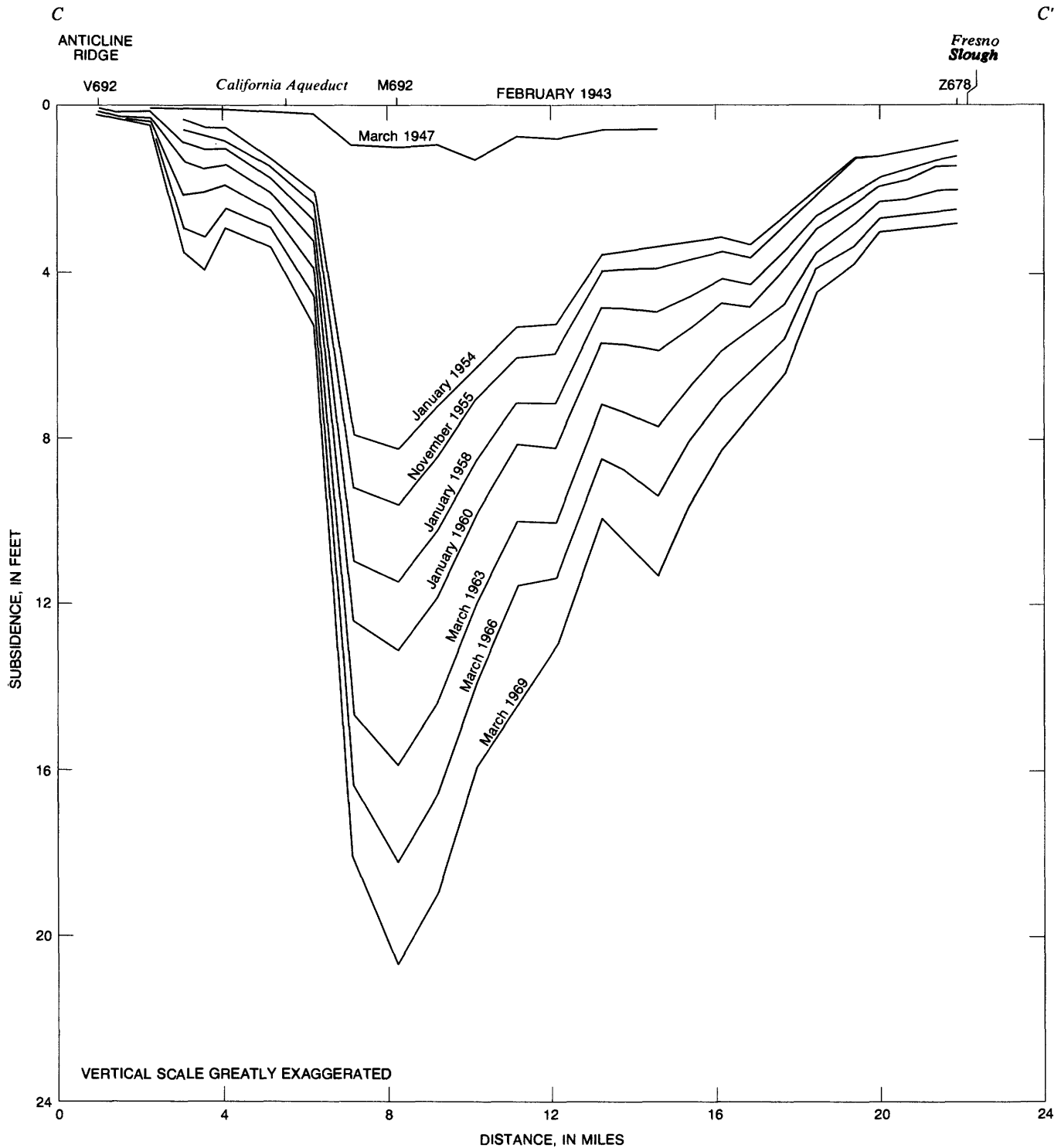


FIGURE 22.—Profiles of subsidence, 1943-69, Anticline Ridge to Fresno Slough.

miles (fig. 3; table 2) had been affected by subsidence, about 1,220 square miles had subsided more than 1 foot, and 300 square miles had subsided more than 5 feet. Lofgren and Klausing (1969) described in considerable detail the pertinent geologic framework of the ground-

water reservoir, the hydrologic units, the history of water-level trends and subsidence of the land surface and the measured compaction of the water-bearing deposits to the end of 1964, computed compaction at Pixley (computed from laboratory consolidation tests and



generalized trend of water-level decline), and parameters for estimating subsidence under assumed hydrologic change.

Historically, water levels in wells in the area have responded differently depending on whether the wells tapped the confined system west of Delano (fig. 4) or tapped the semiconfined to confined system to the east (Lofgren and Klausing, 1969, figs. 13, 45, table 3). Water levels in wells tapping the confined system west of Delano have declined throughout the period of record (Lofgren and Klausing, 1969, figs. 34, 35). Water levels in wells to the east, in much of the service area of the Friant-Kern Canal, declined from 1920 to 1951, but have recovered substantially in the past two decades as

surface-water imports through the Friant-Kern Canal permitted reduction of pumping and increased recharge. The decline and recovery pattern is well demonstrated by the multiple hydrograph of figure 23 for three wells northeast of Delano (fig. 4). The water level of 1970 (well 34F1) was equal to that of 1930 (33H1), following a recovery of 230 feet from the low level of 1950. This recovery has stopped the subsidence of bench mark G758 since 1962. The most rapid average rate of subsidence at bench mark T88 was 0.54 foot per year during 1948-54, when water levels reached their historic low. From 1962 to 1970, however, the average rate at that bench mark was only 0.04 foot per year (fig. 23).

Figure 24 shows the magnitude and extent of subsid-

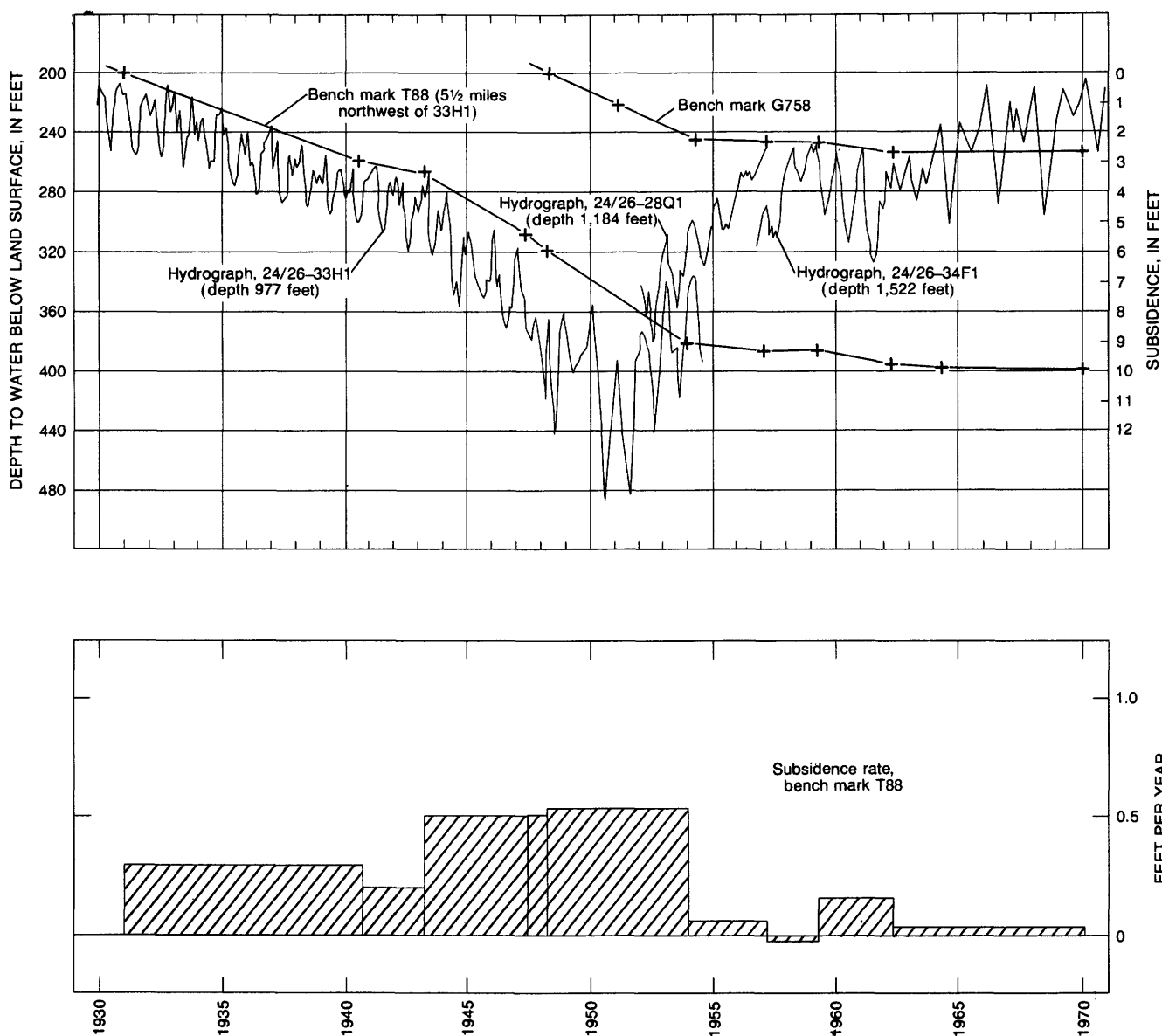


FIGURE 23.—Subsidence and water-level fluctuations northeast of Delano.

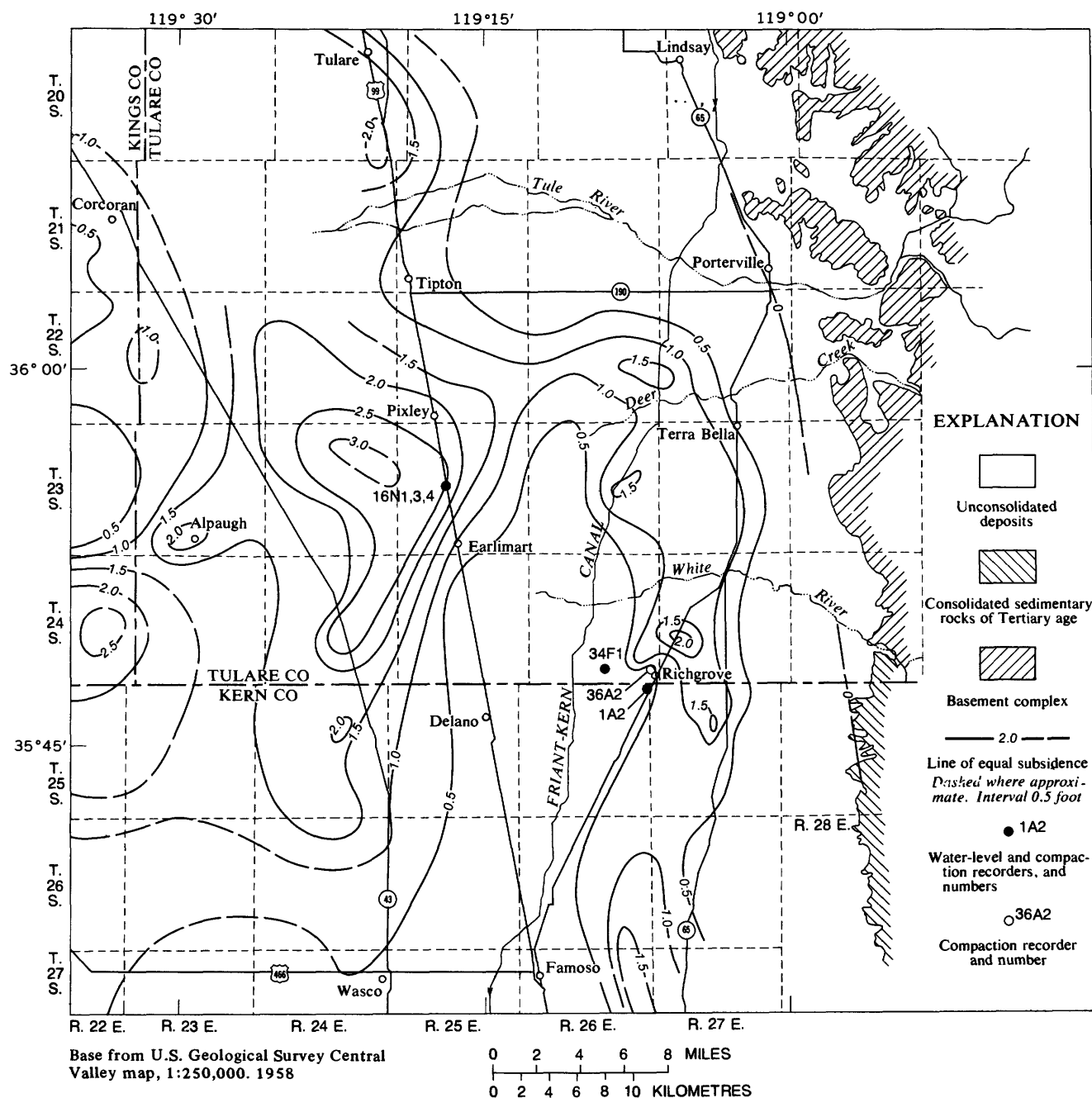


FIGURE 24.—Land subsidence, 1962–70, Tulare-Wasco area. Compiled from leveling of the National Geodetic Survey, January–April 1962 and November 1969–February 1970.

ence in the Tulare-Wasco area during the latest period of control, from 1962 to 1970. Two features are noteworthy. First, the map is pockmarked with subsidence "holes," indicating areas of continued intensive pumping. The biggest "hole," exceeding 3 feet during the 8-year period, is southwest of Pixley, an area irrigated mostly from wells. Second, the beneficial effects of substituting surface water from the Friant-Kern Canal for well water are demonstrated by the area of nearly 200 square miles in the south-central part of the map, between Earlimart and Famoso, that subsided less than

0.5 foot in the 8 years. About half of that area subsided less than 0.3 foot.

The average yearly rate of subsidence from 1962 to 1970 exceeded 0.1 foot in about half (800 sq mi) of the Tulare-Wasco area (fig. 25), mostly in the west half within lands not served by the Friant-Kern Canal. Only in two areas, southwest of Pixley and southwest of Alpaugh, did the average yearly rate of subsidence exceed 0.3 foot.

The leveling network was established in 1948, shortly before surface-water imports through the Friant-

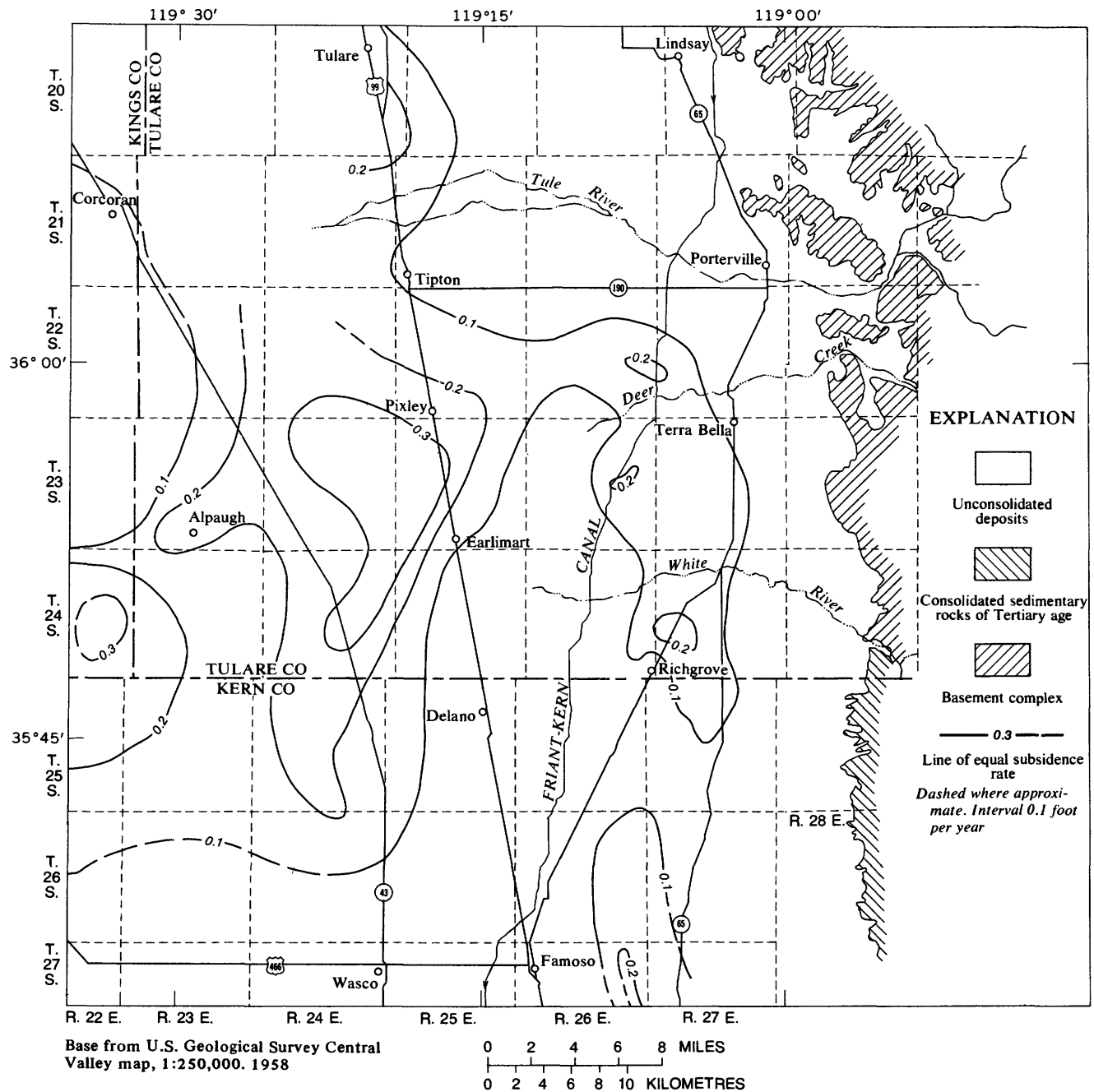


FIGURE 25.—Average yearly rate of subsidence, 1962–70, Tulare-Wasco area. Based on control data of figure 24.

Kern Canal began in 1950 and 1951. In the 22 years from 1948 to 1970, a major subsidence "hole," centered 3 miles south of Pixley (fig. 26), developed in an area irrigated chiefly by ground water. This major sink extended 9 miles north to Tipton and 12 miles west to Alpaugh and was a maximum at bench mark N88R (for location, see fig. 27), which subsided 11.7 feet. Subsidence at a second much smaller depression, centered 1 mile west of Richgrove, was more than 6 feet in the 22 years. More than half of this subsidence in Richgrove developed between 1948 and 1954 because of increased

pumping from new deep wells (Lofgren and Klausning, 1969, fig. 44 and p. B58).

The long-term subsidence from 1926 to 1970 (fig. 27) is characterized by two major subsidence "holes" along U.S. Highway 99; the 6-foot subsidence line encloses both. The "hole" south of Pixley is slightly larger and deeper than that in figure 26. Bench mark N88R had subsided 12.8 feet since its establishment in 1940, and total subsidence at this site was over 14 feet. By 1970, the land surface in the southern "hole," centering 3 miles north of Delano, had subsided more than 12 feet.

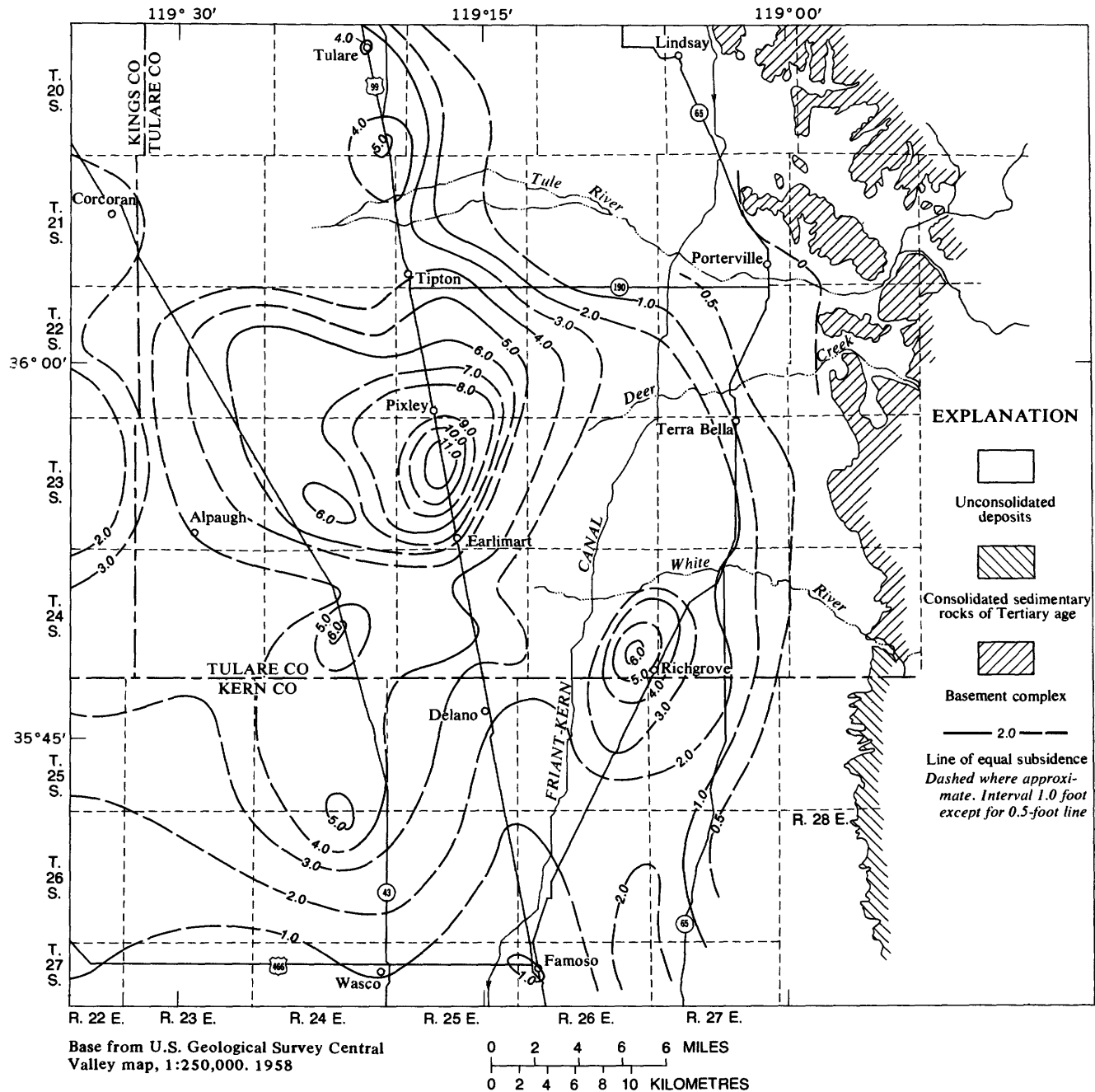


FIGURE 26.—Land subsidence 1948–70, Tulare-Wasco area. Compiled from leveling of the National Geodetic Survey, February–May 1948 and November 1969–February 1970.

Ingerson demonstrated (1941, fig. 7) that this "hole" was about half developed by 1940. (See also Lofgren and Klausing, 1969, p. B49, fig. 36.) A comparison of topographic maps of the Geological Survey made in 1926 and 1953–54 (Lofgren and Klausing, 1969, fig. 43) indicates that the land surface in this subsidence "hole" north of Delano had subsided more than 12 feet by 1954.

The average yearly rates of subsidence during the seven periods of control between 1926 and 1970 are shown by the bars in figure 28. The dashed line represents the estimated probable rate of subsidence at any

particular time. During 1948–54, the subsidence rate increased to 1950, owing to expanding ground-water use and then decreased rapidly as surface water from the Friant-Kern Canal replaced ground water. The highest yearly rate of subsidence—that from 1959 into 1962—occurred during a drought period. The cumulative volume of subsidence from 1926 to 1970 was 3.32 million acre-feet (fig. 29). Almost half of this subsidence occurred since 1960.

The area affected by subsidence from 1926 to 1970 was about 1,420 square miles or  $9.1 \times 10^5$  acres (fig. 30),

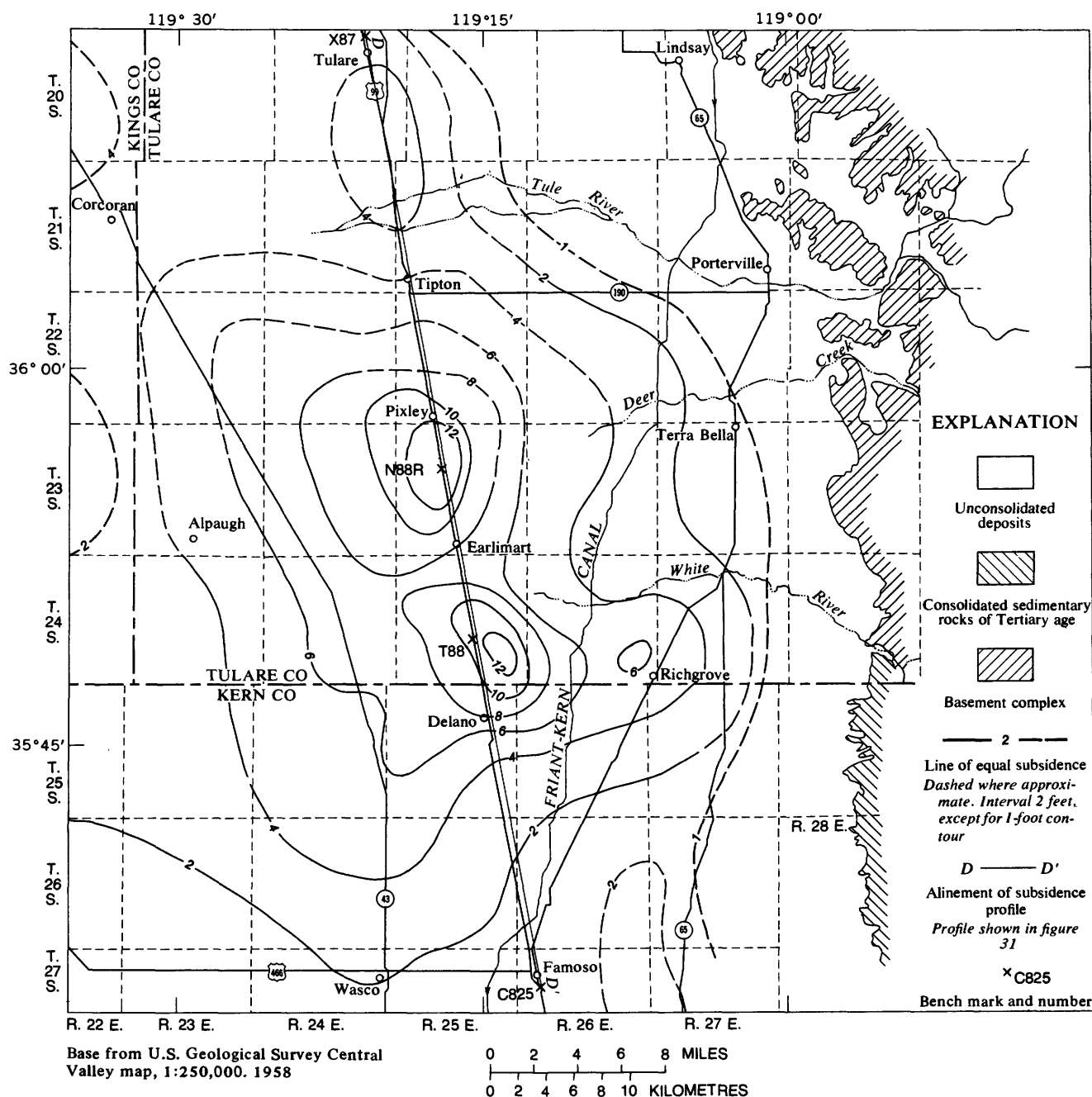


FIGURE 27.—Land subsidence, 1926–70, and location of subsidence profile, Tulare-Wasco area. Compiled from (1) 1948–70 subsidence (fig. 26 this report), (2) 1926–62 subsidence (Lofgren and Klausing, 1969, fig. 50), and (3) 1962–70 subsidence (fig. 24 this report).

based on planimetry of figure 27. Of this area, about 200,000 acres had subsided more than 5 feet, and 20,000 acres had subsided 10 feet or more.

Land-subsidence profiles from Tulare to Famoso (fig. 31) illustrate subsidence along a 44-mile reach of the Southern Pacific railroad for 10 periods since 1931. Leveling for these profiles was by the National Geodetic Survey, and the 1931 control has been used as the reference datum. Changes since the 1901–2 leveling of the Geological Survey are shown above the 1931 datum for

the eight bench marks recovered in 1931. Maximum subsidence since 1901–2 is 14.2 feet at bench mark N88 between Pixley and Earlimart. This site has been the center of maximum subsidence continuously since 1953–54.

#### ARVIN-MARICOPA AREA

As of 1970, about 700 square miles in the Arvin-Maricopa area (fig. 3) had been affected by subsidence, and 100 square miles had subsided more than 5 feet.

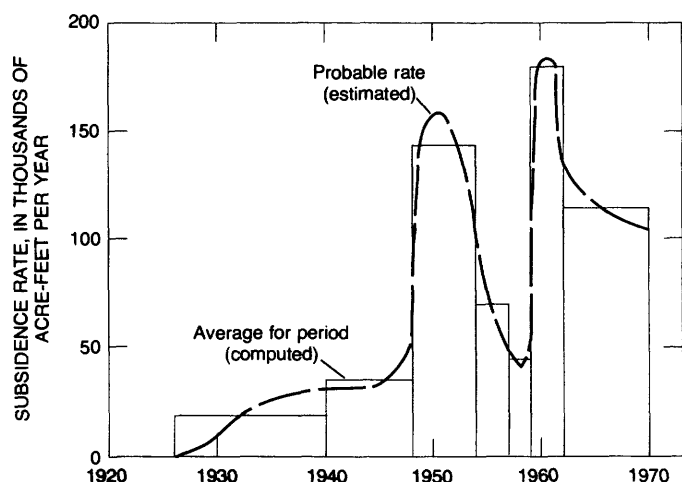


FIGURE 28.—Rate of subsidence in the Tulare-Wasco area, 1926-70.

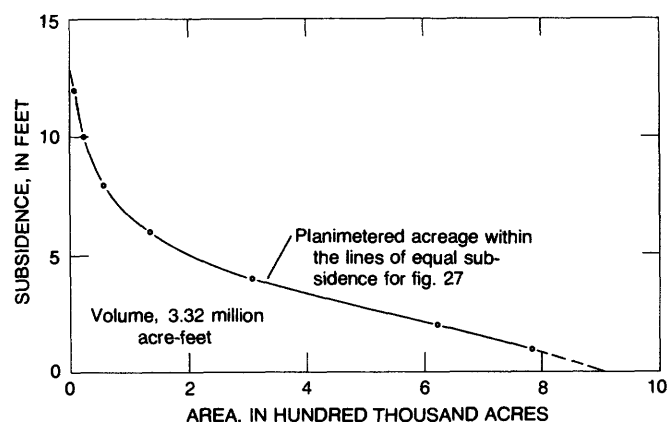


FIGURE 30.—Relation of magnitude to area of subsidence, 1926-70, Tulare-Wasco area.

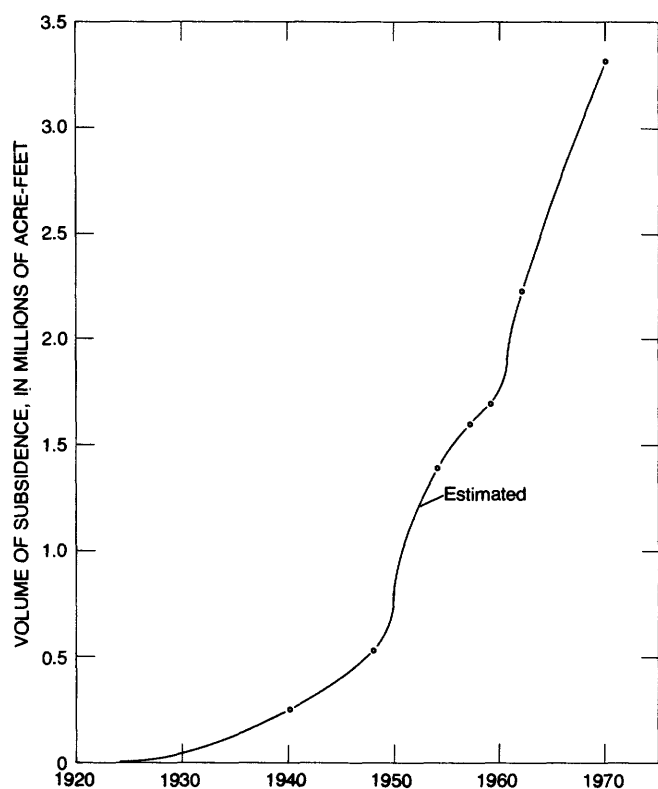


FIGURE 29.—Cumulative volume of subsidence in the Tulare-Wasco area, 1926-70. Points indicate times of leveling control.

Lofgren (1975) described the geologic and hydrologic setting, the history of water-level decline, the available records of subsidence, and the compaction that has been measured in several wells to 1970.

The development of ground water south and east of the Kern River alluvial fan was described in some detail by Wood and Dale (1964). Although there was substantial development of ground water in the Arvin-Edison area by 1930, development in the area south of T. 31 S. was small until 1945. By 1950, most of the productive

land was under cultivation, and many wells had been drilled to depths of 1,000-1,500 feet.

Figure 32 shows the water-level trend for three piezometers at 32S/28E-30D1 and the plot of subsidence at bench mark L365 near the center of the subsiding area (fig. 36). These piezometers, completed with well points at the depths indicated, were installed by the Bureau of Reclamation in 1952. The water levels in the three piezometers declined rapidly into 1957. The level in the shallow zone (No. 1) was about constant from 1957 to the end of record in 1961. The winter high water level for the intermediate zone (No. 2) at 611 feet declined 75 feet from 1957 to 1967 at a nearly uniform rate and then was about uniform into 1970. The level for the deep zone (No. 4) 1,220 feet below the land surface declined at roughly the same rate as No. 2 until 1962, although its peak water level was 2-3 months later than that in No. 2. In 1962, the level fell rapidly about 94 feet to 47 feet below the level in No. 2 piezometer, and the seasonal fluctuation nearly tripled, suggesting the onset of pumping draft from new and nearby irrigation wells. Since 1967, however, the winter high has been about constant. At bench mark L365, the average rate of subsidence (lower graph, fig. 32) for the period 1962-65 was equal to that of 1953-57, but from 1965 to 1970 the average rate decreased noticeably in response to the lack of water-level decline in 1967-70.

The latest leveling of the bench-mark net in the Arvin-Maricopa area was in 1970. Figure 33 shows the magnitude and areal extent of subsidence for 1965-70. The maximum subsidence in the 5 years, centered 6 miles northwest of Mettler, was 2.2 feet (fig. 33). A small secondary center of 0.4 foot enclosed the town of Arvin. About 530 square miles of land subsided more than 0.2 foot in the period. The volume of subsidence in the 5 years was 230,000 acre-feet. The average annual rate of subsidence in this 5 years was 0.44 foot at the center (fig. 34).

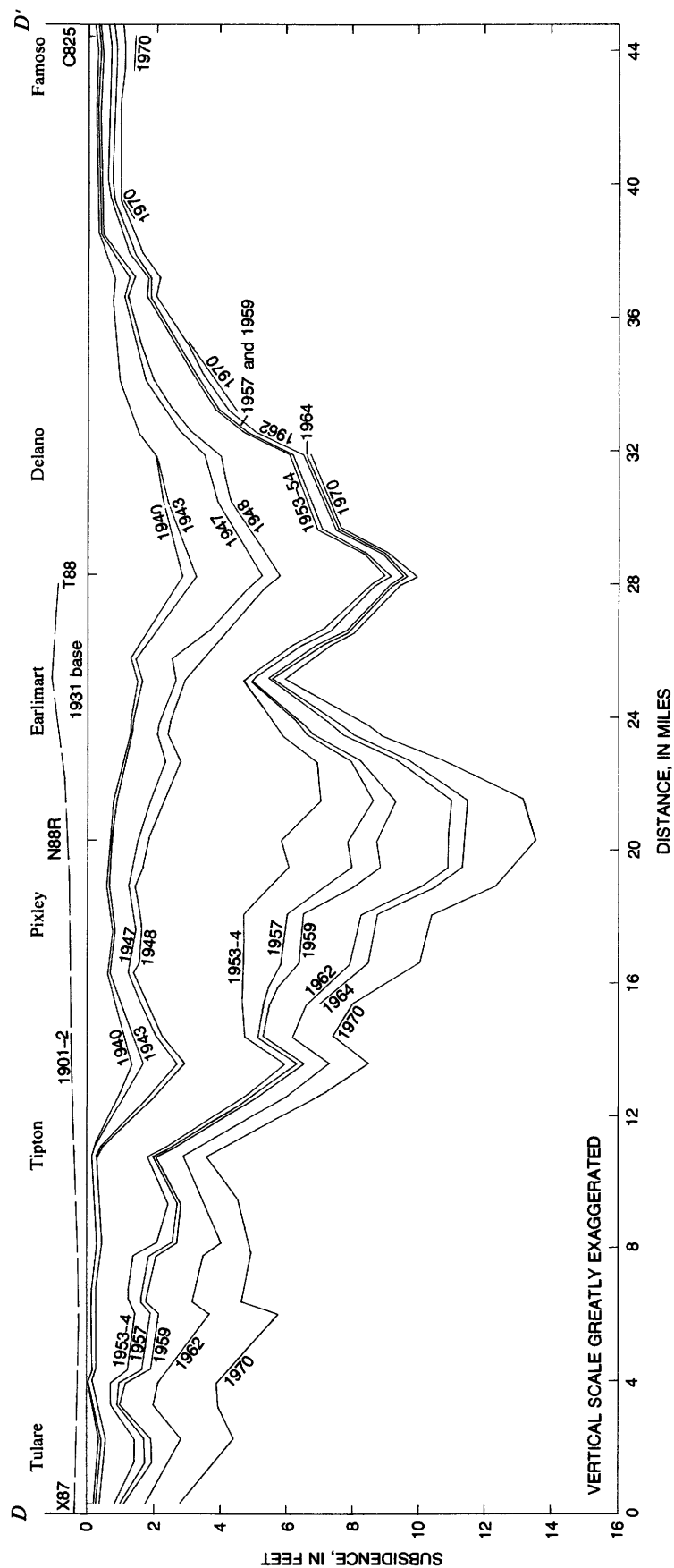


FIGURE 31.—Land-subsidence profiles D-D' along U.S. Highway 99 from Tulare to Famoso, 1901-2 to 1970. For location, see figure 27.

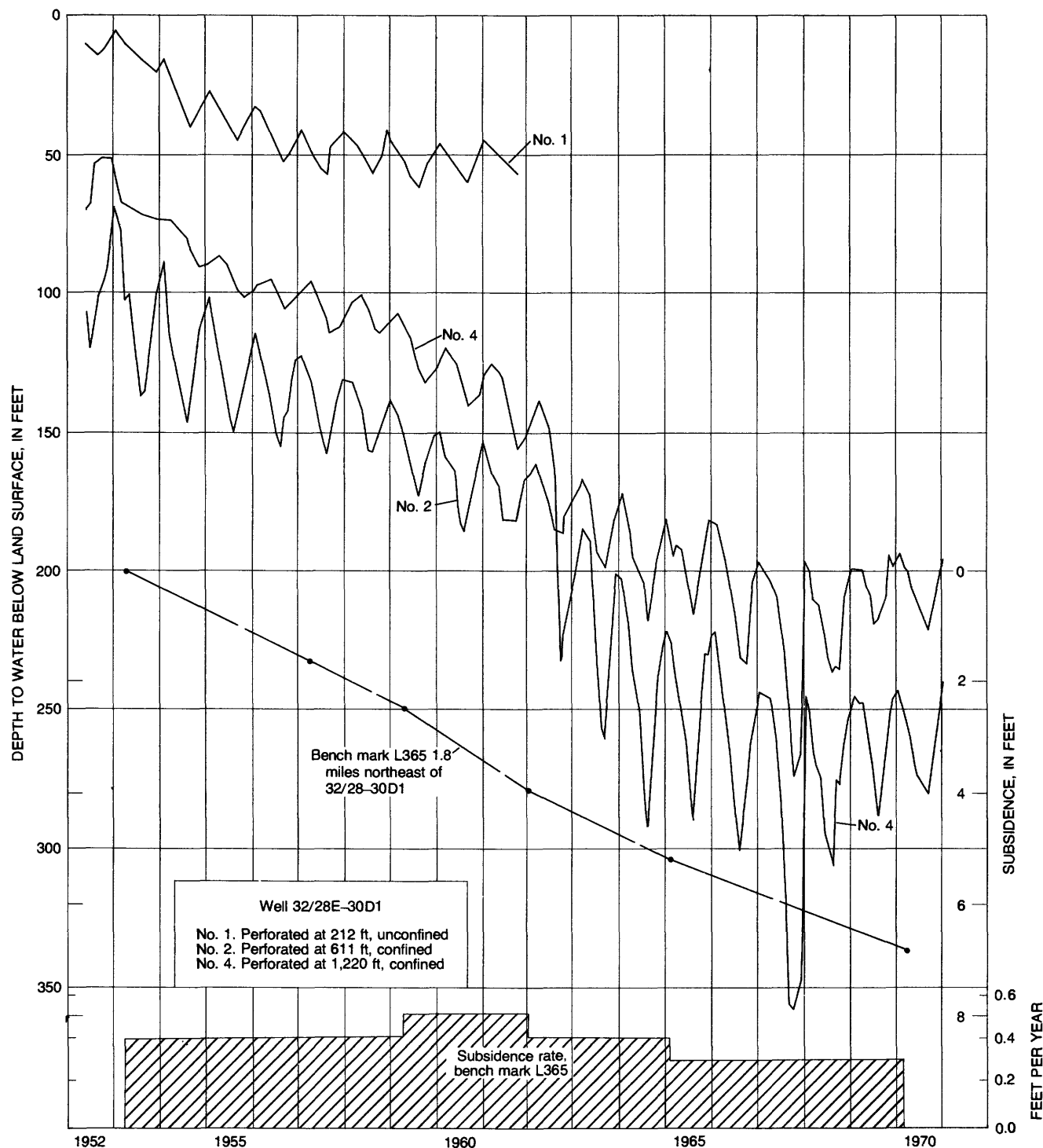


FIGURE 32.—Hydrographs of three piezometers at 32S/28E-30D1 in the center of the Arvin-Maricopa subsidence area and the subsidence graph of a nearby bench mark. See figure 4 for location of piezometers and bench mark.

From 1957 when the bench-mark net was established to 1970, subsidence exceeded 6 feet at the center 5 miles north of Wheeler Ridge (fig. 35). About 430 square miles of land extending from Bakersfield south to Wheeler Ridge and from Buena Vista Lake bed to 3 miles east of Arvin subsided more than 0.5 foot in the 13 years, and

about 160 square miles subsided more than 2 feet. The volume of subsidence in this period was 630,000 acre-feet.

The maximum subsidence from 1926 to 1970 (fig. 36) exceeded 9 feet at the center, and an area of 500 square miles had sunk more than 1 foot. The total area affected



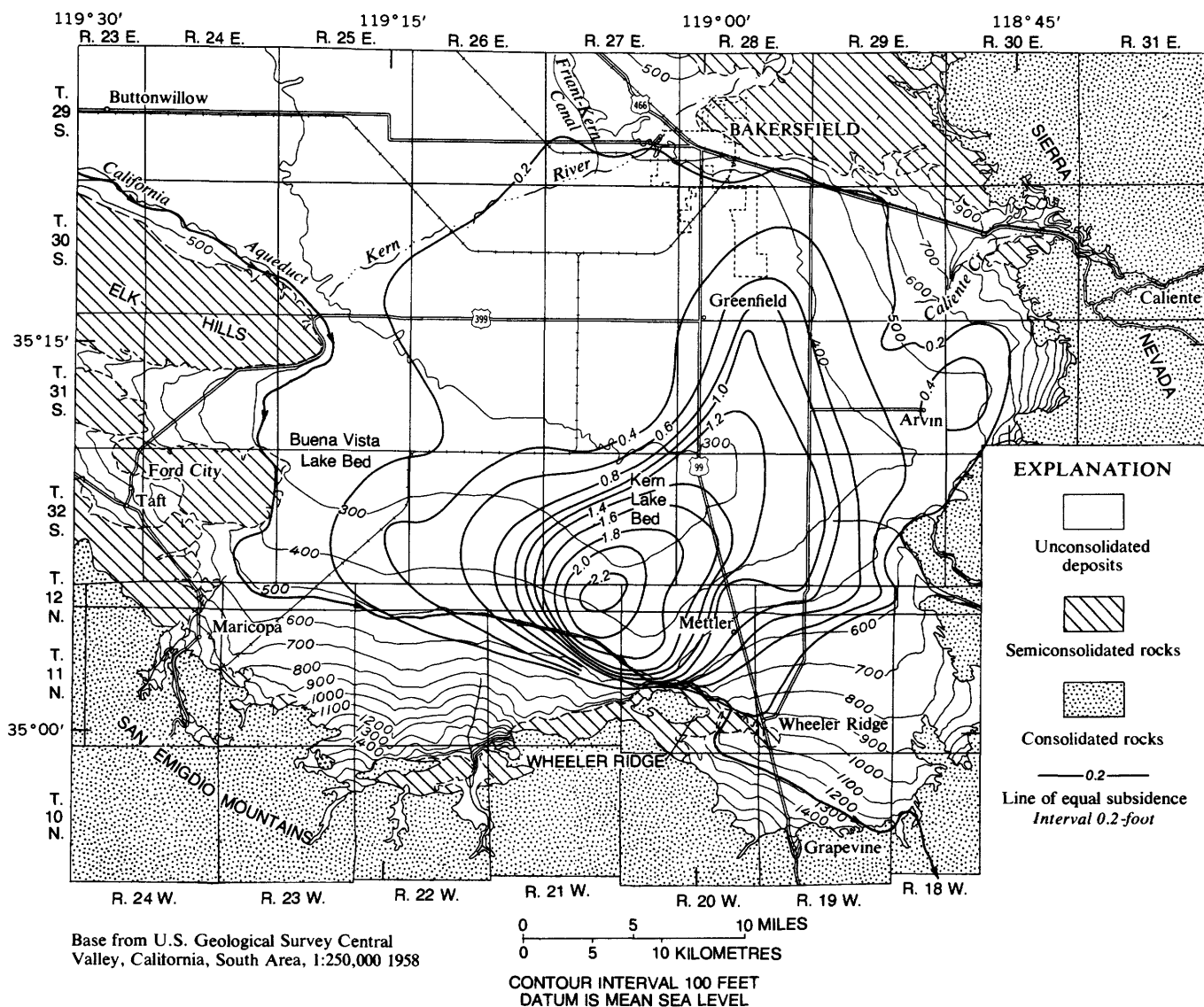


FIGURE 33.—Land subsidence, 1965–70, in the Arvin-Maricopa area. Compiled from leveling of the National Geodetic Survey, March 1965 and January–May 1970.

was about 700 square miles. Using the leveling data for pre-1957 subsidence and figure 35 for post-1957 subsidence, figure 36 is an approximation of the total man-made subsidence in the Arvin-Maricopa area. The total volume of subsidence is estimated to be 1.06 million acre-feet, based on planimetry of figure 36.

The average rate of subsidence for the seven periods of leveling control beginning in 1926 is illustrated by the bar diagram of figure 37.

As already noted, bench marks along U.S. Highway 99 from Bakersfield to Grapevine were first leveled in 1926 and releveled periodically thereafter. The areal network was first leveled in 1957. To approximate the rate of subsidence for time intervals prior to 1957, the assumption was made that the volume of subsidence for the Arvin-Maricopa area increased proportionately to the respective areas under the 1926–57 subsidence

profiles along U.S. Highway 99 (fig. 40). Thus, the three approximate rate bars of figure 37 prior to 1957 were derived from the respective estimated volumes. The four since 1957 were by planimetry of the subsidence maps. The probable rate (dashed line) increased about sixfold from 1942 to 1948, was fairly constant to 1959, and increased to the maximum rate of 60,000 acre-feet per year in 1960 (owing to very deficient rainfall and runoff in 1959–61). From 1962 to 1970 the yearly rate has been about 48,000 acre-feet. Up to the time of the 1970 leveling, no irrigation water had been delivered to the subsiding area through the California Aqueduct. Deliveries started in 1971 and water levels started to recover as a result of decreased pumping of ground water. As a result of decreasing stress, the subsidence rate began decreasing in 1971 as shown by the compaction record at well 11N/21W–3B1.

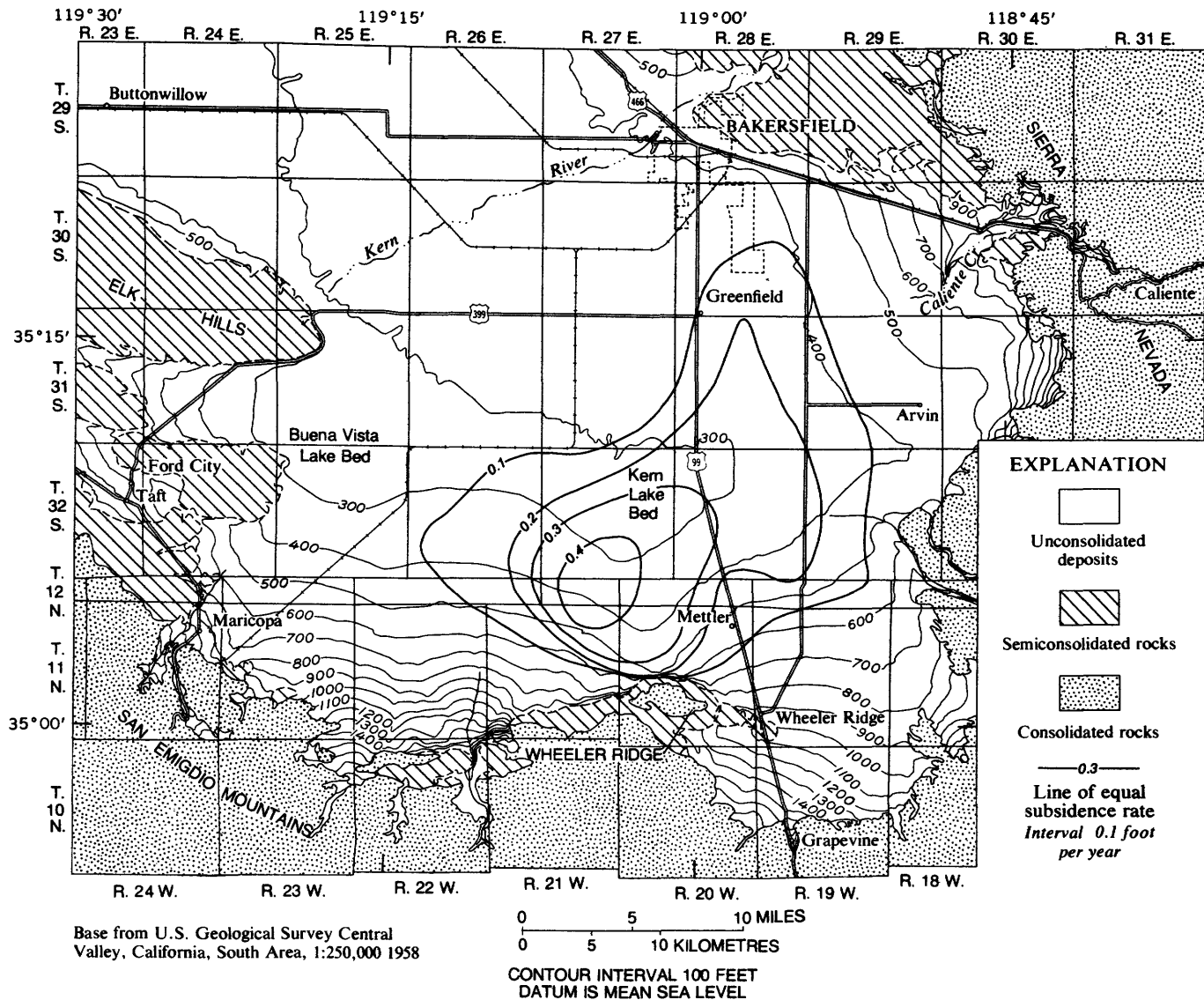


FIGURE 34.—Average annual rate of subsidence, 1965–70, Arvin-Maricopa area. Based on control data of figure 33.

As of 1970 the cumulative volume of subsidence since 1926 was 1.06 million acre-feet (fig. 38). About 80 percent of the subsidence has occurred since 1950, and 44 percent since 1960.

Figure 39 illustrates that the area affected by subsidence as of 1970 is about 700 square miles (450,000 acres). About 500 square miles (320,000 acres) has sunk more than 1 foot, and 100 square miles (64,000 acres) has sunk 5 feet or more.

The rate, magnitude, and distribution of subsidence are well displayed in subsidence profiles. Two profile alignments are shown for the Arvin-Maricopa area (for location, see fig. 36): one extends from Bakersfield south to Grapevine (fig. 40); the second, about perpendicular to the first, extends from Maricopa east along the Maricopa Road (fig. 41).

In figure 40, the 1926 leveling used as a base was followed by partial releveing in 1935–39, 1942, and 1947 and then by six releveings from 1953 to 1970 extending across the full 32-mile reach. The 1957 leveling marked the establishment of the bench-mark net over the full subsiding area. The profiles demonstrate that the axis of maximum subsidence has shifted northward slightly through the years and in 1970 was close to bench mark L365. Maximum subsidence was insignificant until 1942, increased to an average rate of 0.35 foot per year in 1947–53, and 0.45 foot per year in 1959–62.

The profiles of figure 41 extend 28 miles east from Maricopa to 3 miles east of U.S. Highway 99 and define an axis of subsidence at bench mark K367. Subsidence at this bench mark has been about 8.5 feet since the

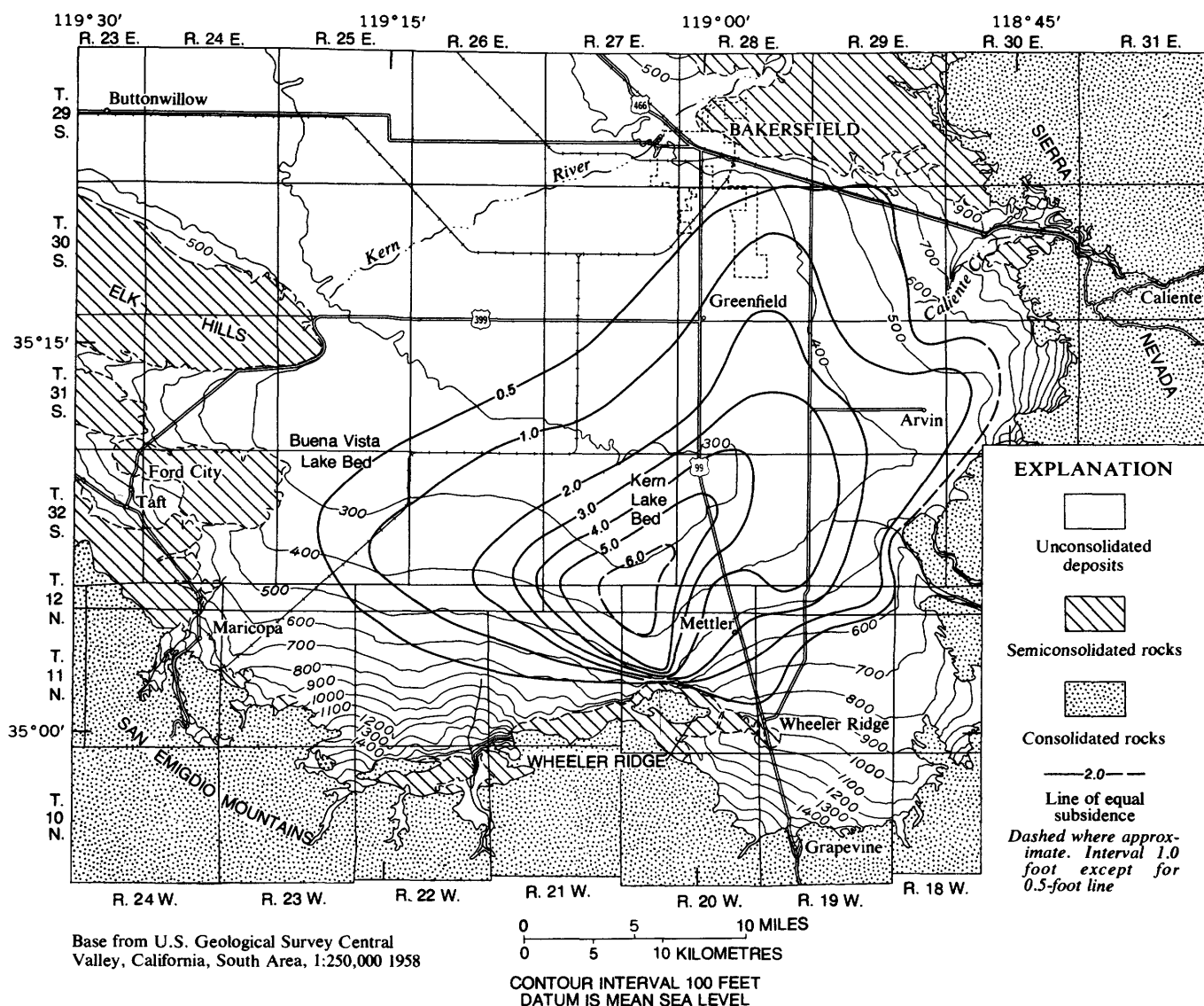


FIGURE 35.—Land subsidence, 1957–70, Arvin-Maricopa area. Compiled from leveling of the National Geodetic Survey, January–February 1957 and January to May 1970.

1935–39 base and was most rapid from 1959 to 1965, averaging about 0.5 foot per year. From 1965 to 1970 the rate of subsidence averaged 0.38 foot per year.

#### RELATION OF SUBSIDENCE TO PUMPAGE

Recently, quantitative estimates of ground-water pumpage for agricultural use, based chiefly on metered electric power consumption and computed average power per acre-foot, have become available for the years 1962–66 (Ogilbee and Rose, 1969a; Mitten and Ogilbee, 1971). These estimates provide the data to compare areally the volumes of subsidence and pumpage for a common 3-year period in both the Los Banos-Kettleman City and the Arvin-Maricopa areas. From these data, subsidence/pumpage ratio maps have been derived, this ratio being an approximation of the

proportion of pumpage derived from water of compaction (assumed equal to the subsidence volume).

#### LOS BANOS-KETTLEMAN CITY AREA

In the Los Banos-Kettleman City area, the pumpage and subsidence were compared on an areal basis for the 3-year period March 1963 to March 1966. In this appraisal, pumpage (Ogilbee and Rose, 1969b) was summed by unit area for the 3 years 1963–65 (agricultural power year April 1–March 31), expressed in feet of water. The average subsidence for the same period (Bull, 1975, fig. 13), derived from leveling of the bench-mark net by the National Geodetic Survey in March 1963 and March 1966, was visually assigned to each unit area. A ratio of subsidence to pumpage was then derived for each unit area from the two sets of

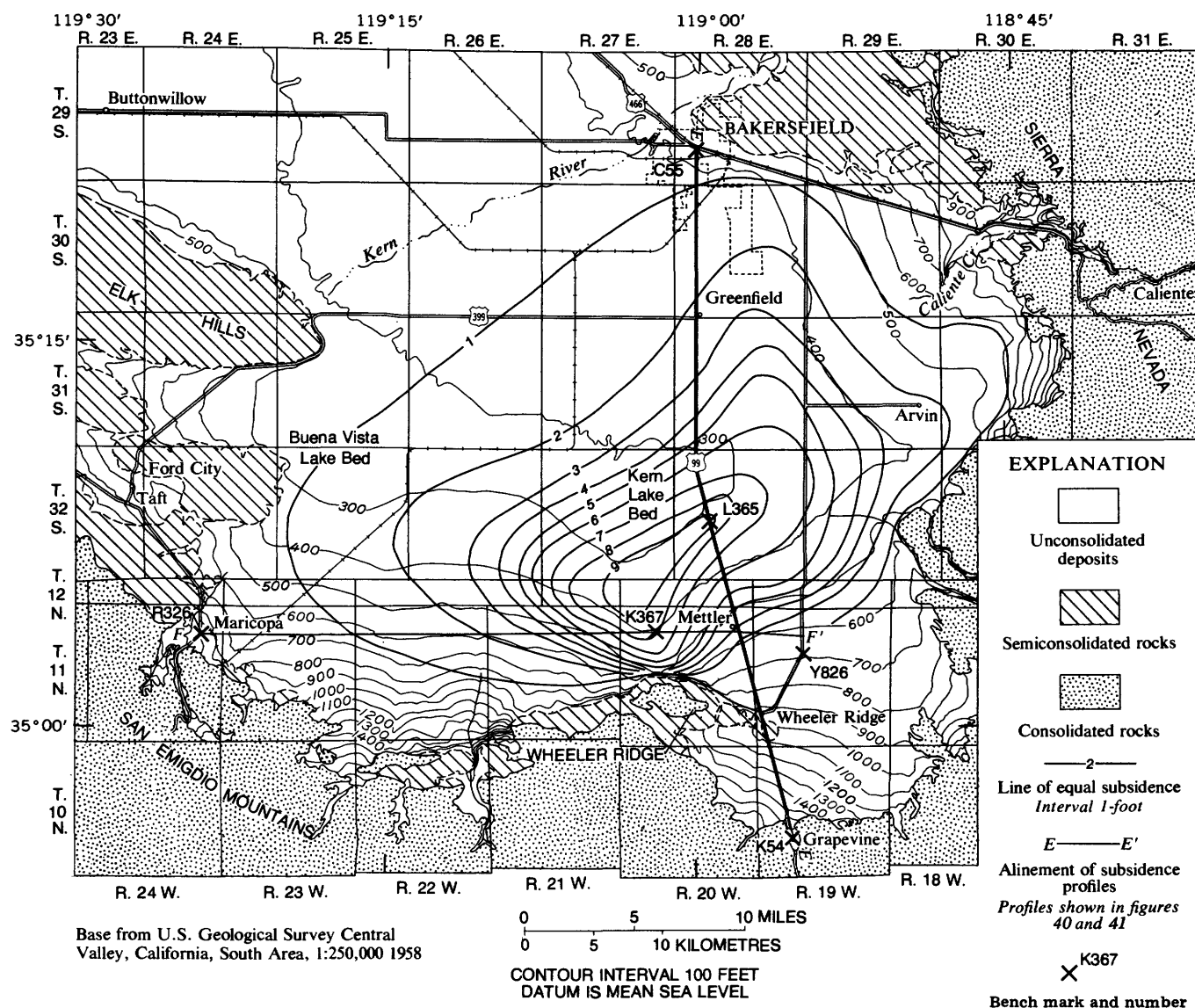


FIGURE 36.—Land subsidence, 1926–70, and location of subsidence profiles, Arvin-Maricopa area. Compiled chiefly as the sum of (1) approximated subsidence from 1926 to 1957 from leveling data of the National Geodetic Survey along U.S. Highway 99 and along Maricopa Road and (2) 1957–70 subsidence from figure 35.

numbers. The ratio values, entered in the center of each unit area, were then contoured to construct the lines of equal subsidence/pumpage ratio shown in figure 42.

The ratio in figure 42 ranges from less than 0.2 to more than 0.6, indicating that the percentage of pumpage derived from "water of compaction" ranged from a few percent to more than 60 percent. This ratio is related to the recharge characteristics of the compacting aquifer systems in the subsiding area and to the magnitude of delayed compaction occurring in response to prior water-level decline.

In figure 42, the ratio exceeds 0.6 both near the north end and at the south end of the map. In the northern area between Los Banos and Mendota where the ratio exceeds 0.6, the subsidence was small, ranging from 0.3

to 1.0 foot in the 3 years, and was largely in response to earlier head decline. But the pumpage also was small because much of this area is irrigated with surface water. Therefore the ratio far exceeded unity in some unit areas where pumpage was very small. In the southern area between Kettleman City and Stratford, the subsidence ranged from 0.4 to 2.0 feet in the 3 years. In several of the unit areas, pumpage was very small, in part because of surface-water irrigation from the Kings River. In years of abundant surface-water supply, the ratio would be higher than in years of deficient supply because the quantity of ground water pumped varies more significantly than the subsidence on a year-to-year basis. Also, the rate of water-level decline in response to pumping in this area, and hence the rate of

# STUDIES OF LAND SUBSIDENCE

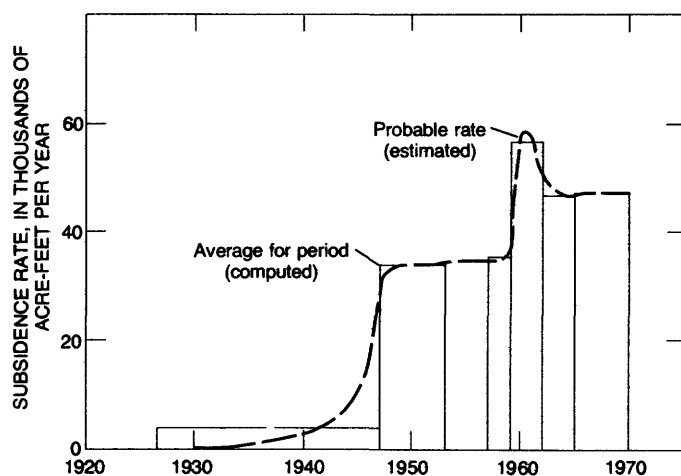


FIGURE 37.—Rate of subsidence in the Arvin-Maricopa area, 1926-70.

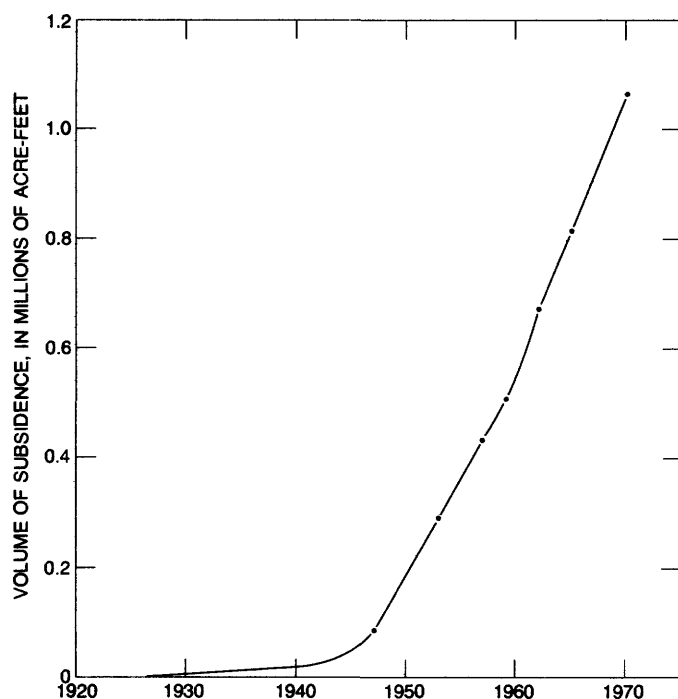


FIGURE 38.—Cumulative volume of subsidence in the Arvin-Maricopa area, 1926-70. Points indicate times of leveling control.

subsidence, is increased by the barrier effect of the fine-grained deposits beneath Tulare Lake bed which inhibit recharge from the east.

In the remainder of the mapped area of figure 42, the ratio is irregular, without any specific pattern. Nearly all the recharge moves southwest across the trough (Fresno Slough) as underflow. Subsidence decreases rapidly to the east of Fresno Slough, as historic head-decline decreases. Therefore, as would be expected, the ratio is less than 0.2 along much of the valley trough. The two central areas along Fresno Slough where the ratio is greater than 0.4 are irrigated chiefly with sur-

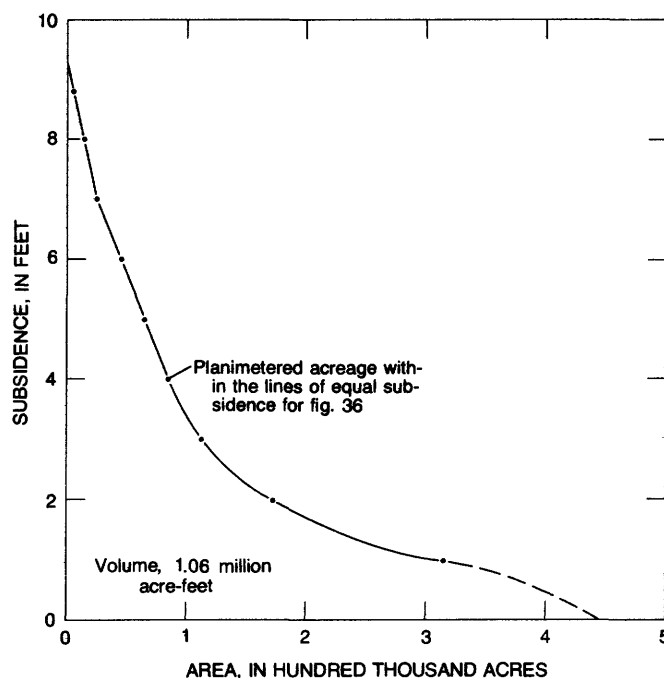


FIGURE 39.—Relation of magnitude to area of subsidence, 1926-70, Arvin-Maricopa area.

face water. For this reason the ground-water pumpage is low, which explains the high ratio.

In several areas bordering the foothills, the ratio is less than 0.2. These low ratios are related chiefly to small values of subsidence in an area where the subsidence/head-decline ratio has been very low (Bull and Poland, 1975, fig. 32), even though the historic head decline has been many hundreds of feet. In general, water wells adjacent to the foothills tap older deposits than wells to the east at equal depths. These older deposits have substantially lower average compressibilities than the younger deposits to the east, and therefore the subsidence/pumpage ratios also tend to be low.

The total pumpage from the area for which the subsidence/pumpage ratio is mapped in figure 42 was about 3.7 million acre-feet in the 3 years. The subsidence in the same area was about 1.1 million acre-feet. Thus, the average "water of compaction" for the 3 years was approximately 30 percent of the pumpage.

## ARVIN-MARICOPA AREA

In the Arvin-Maricopa area, the pumpage and subsidence were compared for the 3-year period March 1962 to March 1965. Pumpage estimates (Ogilbee and Rose, 1969a) are available for this exact period, and a subsidence map is available from leveling of the bench-mark net by the National Geodetic Survey in January 1962 and March 1965 (Lofgren, 1975, pl. 4C).

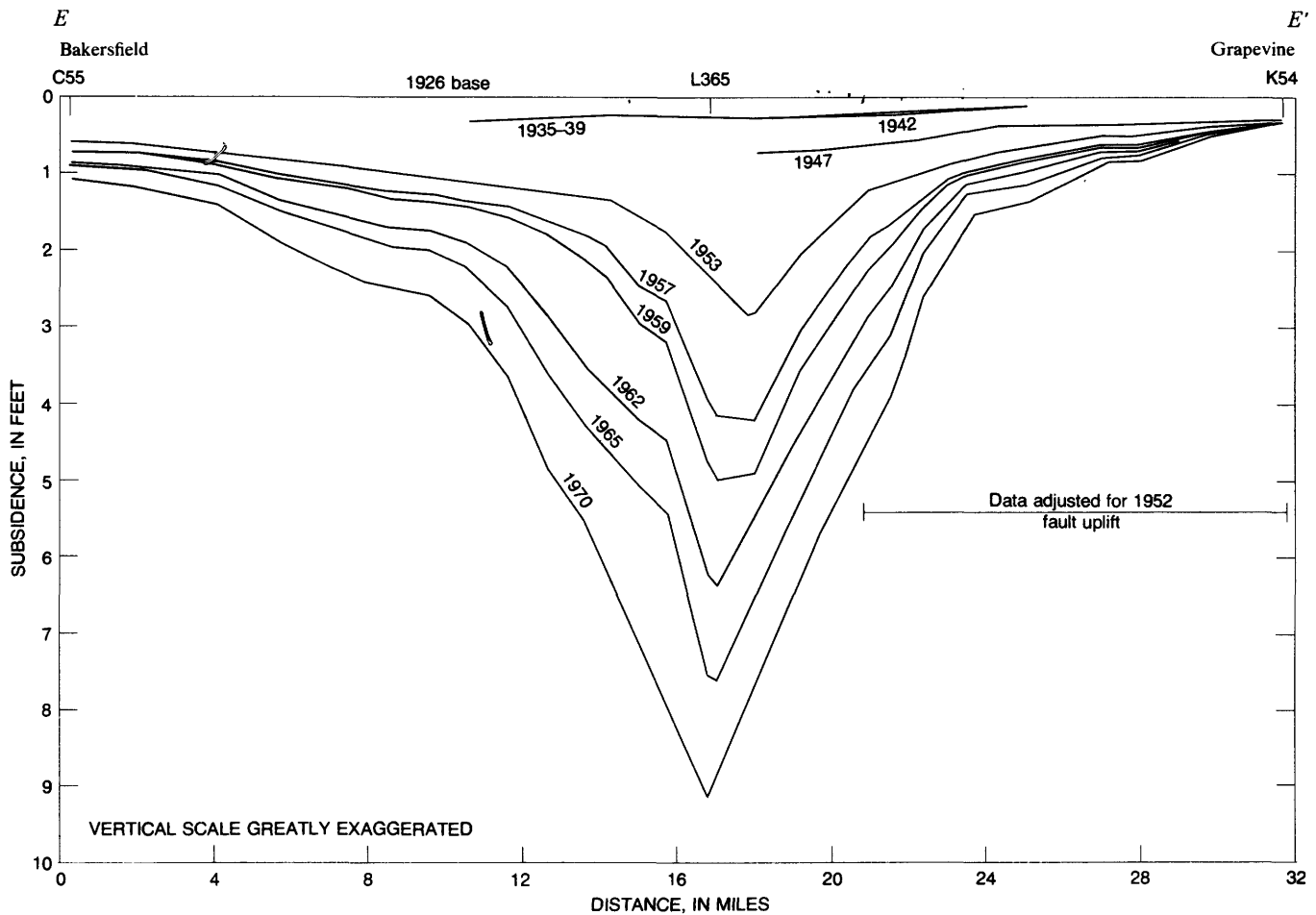


FIGURE 40.—Profiles of land subsidence E-E' along U.S. Highway 99, Bakersfield to Grapevine, 1926-70.

The subsidence/pumpage ratio was computed for all unit areas enclosed within or crossed by the 0.2-foot line of equal subsidence for the 1962-64 period (shown in figure 43). The method of computation was the same as has been described for the Los Banos-Kettleman City area. The ratio map so obtained (fig. 43) is remarkably similar in shape to the longer term subsidence maps for the area. The ratio, which is the proportion of water pumped in the 3 years that was derived from compaction of the ground-water reservoir, ranges from 0.01 (1 percent) at several points around the perimeter of the subsiding area to more than 40 percent in the area of maximum subsidence.

The subsidence/pumpage ratios of figure 43 are a rough indication of the recharge characteristics of the ground-water reservoir. Where recharge is adequate, little or no long-term water-level decline or associated subsidence occur and subsidence/pumpage ratios are small, even though pumping may have been substantial. In the central part of the subsiding area, however,

water levels have declined rapidly in response to pumping, and as much as 40 percent of the water is mined from the compressible beds.

#### ANALYSIS OF STRESSES CAUSING SUBSIDENCE

Increase in effective stress (grain-to-grain load) is the cause of compaction of sediments. Change in stress can be examined in terms of total, fluid, and effective stresses, the classical method, or solely in terms of effective stresses. There are advantages to each approach. The idealized pressure diagram of figure 44 utilizes the classical method to illustrate the stresses that cause subsidence (Poland and Davis, 1969, p. 194). The withdrawal of water from wells reduces the head in the aquifers tapped and increases the effective stress borne by the aquifer matrix. In 1925, Terzaghi introduced the theory of effective stress,

$$p = p' + u_w$$

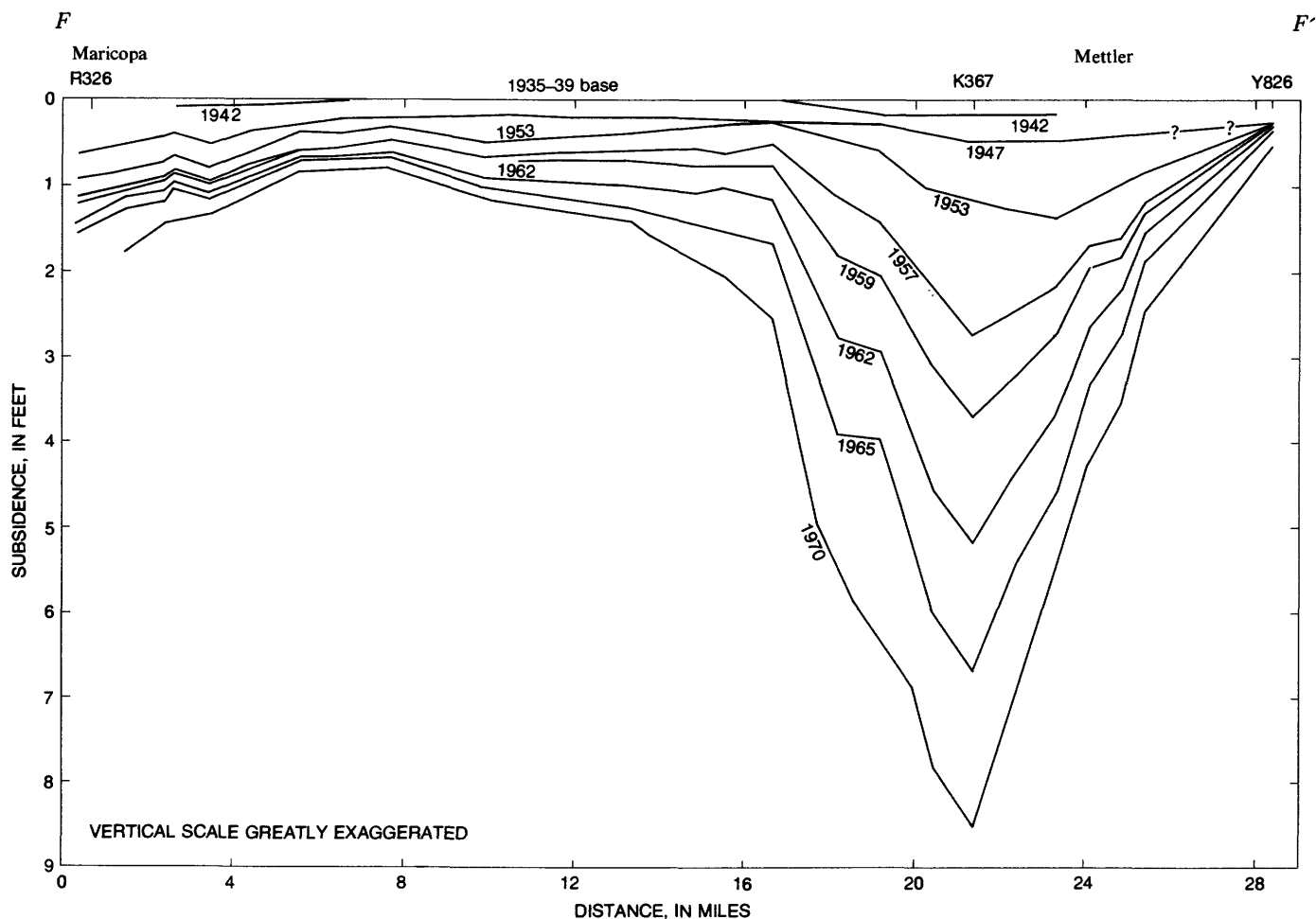


FIGURE 41.—Profiles of land subsidence F-F' along the Maricopa Road, Maricopa to Mettler, 1935-39 to 1970.

where

$p'$  = effective stress (effective overburden pressure or grain-to-grain load),

$p$  = total stress (geostatic pressure), and

$u_w$  = pore pressure (fluid pressure or neutral stress).

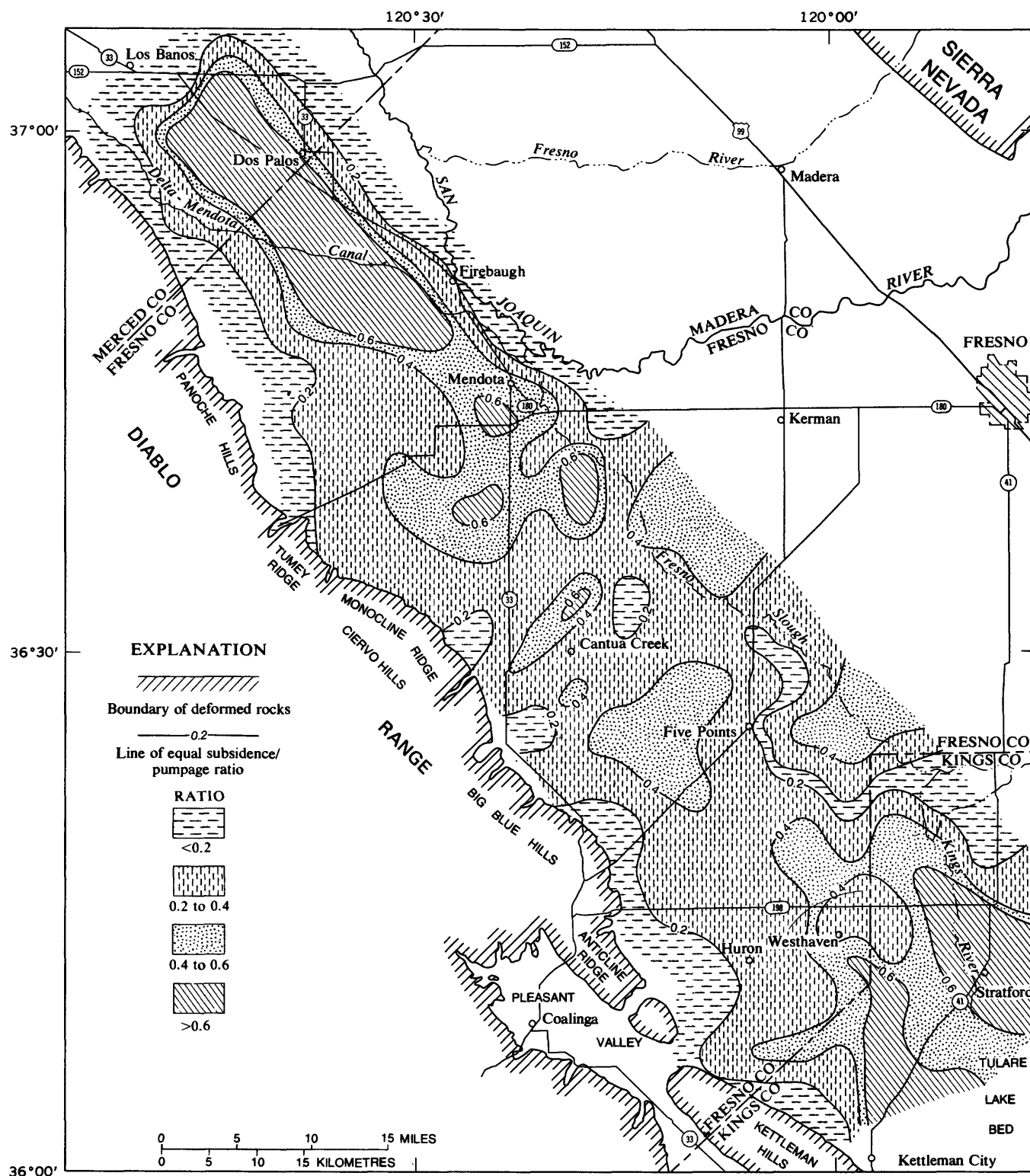
The lowering of artesian head in a confined aquifer system, for example, from depth  $z_1$  to  $z_3$  in figure 44, does not change the geostatic pressure appreciably. Therefore, the increase in effective stress in the confined aquifers is equal to the decrease in fluid pressure. The compaction in these is immediate and is chiefly recoverable if fluid pressure is restored, but usually it is small.

On the other hand, in the aquitards (fine-grained interbeds) and confining beds, which have low vertical permeability and high specific storage under virgin stressing, the vertical escape of water and the adjustment of pore pressures is slow and time dependent. Hence, in these fine-grained beds the stress increase applied by the head decline in the confined aquifers

becomes effective only as rapidly as pore pressures decay toward equilibrium with those in adjacent aquifers. (See dashed pore-pressure lines of fig. 44, where  $m_t$  represents the excess pore pressure at time  $t$ .) Attainment of pore-pressure equilibrium (dotted lines) may take months or years; the time varies directly as the specific storage and the square of the draining thickness and inversely as the vertical hydraulic conductivity of the aquitard or the confining bed.

Although not illustrated in figure 44, it is readily apparent that increase of fluid pressure from a steady-state condition decreases effective stress and causes expansion of the pressurized sediments (as in subsidence control and underground waste disposal). Fluid pressure cannot exceed geostatic pressures without causing uplift of the overburden.

The stress relations of figure 44 serve to illustrate the principle of effective stress, but do not emphasize the hydrodynamic cause of compaction. Actually, the downward hydraulic gradient developed across the confining bed by the head decline induces downward movement of water through the pores that exerts a viscous drag on the clay particles. The stress so exerted on the particles



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

FIGURE 42.—Proportion of pumpage derived from water of compaction, 1963-66, in the Los Banos-Kettleman City area.

in the direction of flow is a seepage stress. We have found it quantitatively convenient in treating complex aquifer systems to compute effective stresses and stress

changes in terms of gravitational and seepage stresses, which are algebraically additive. The following brief discussion is largely summarized from a paper by Lof-



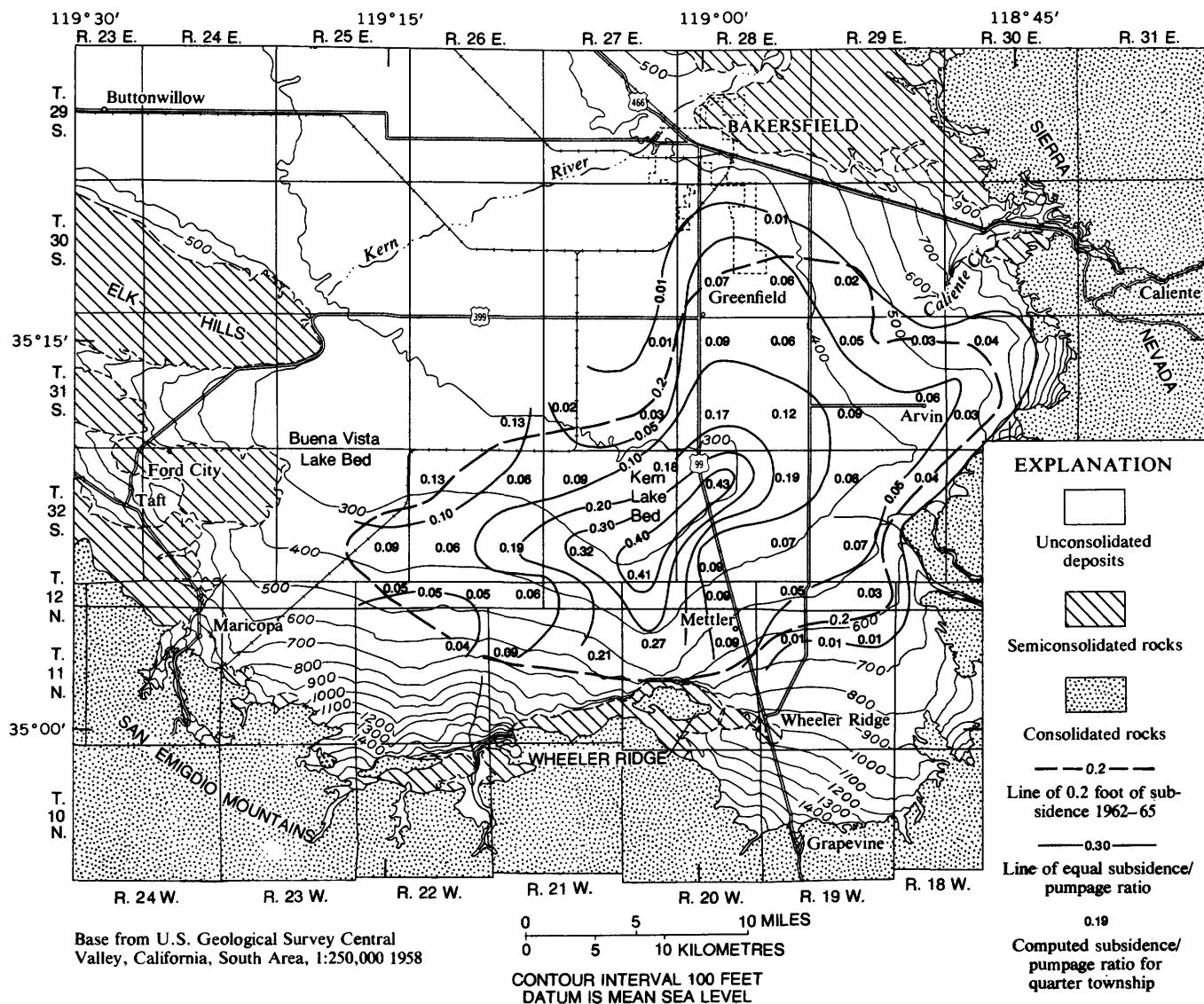


FIGURE 43.—Proportion of pumpage derived from water of compaction, 1962-65, in the Arvin-Maricopa area.

gren (1968) on the analysis of stresses causing land subsidence and also in part from Bull and Poland (1975).

Diagram A of figure 45 illustrates part of a confined aquifer system containing an aquitard, overlain by a confining bed and an unconfined aquifer. The water table and the potentiometric surface of the confined system are initially at the same depth; hence, fluid pressure at all depths is hydrostatic. If we assume an average porosity,  $n$ , of 40 percent, an average specific gravity,  $G$ , of 2.70 for the grains, an average specific retention,  $r_s$ , of 0.20, and let the unit weight of water be unity, then the effective unit weight of moist deposits above the water table,  $\gamma_m$ , equals 1.8 feet of water per foot of thickness:

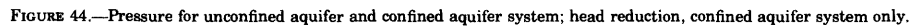
$$\gamma_m = [G(1-n) + r_s]\gamma_w \text{ or } [2.7(1-0.4) + 0.20]1 = 1.8$$

Also, the effective submerged, or buoyant, weight of saturated deposits,  $\gamma_b$ , equals 1 foot of water per foot of thickness:

$$\gamma_b = (1-n)(G-1)\gamma_w \text{ or } (1-0.4)(2.7-1)1 = 1.0$$

If these gravitational stresses are expressed in feet of water (1 ft of water = 0.433 lb in  $^{-2}$ , they can be added directly to hydraulic stresses.

Vectors to the right of diagram A (fig. 45) represent the two components of effective gravitational stress at three depths. At the 400-foot depth, for example, the stress due to the unsaturated deposits,  $s$ , equals 200 feet of thickness times 1.8, or 360 feet of water; the stress due to the buoyant weight of submerged deposits,  $b$ , equals  $200 \times 1.0$ , or 200 feet of water. The sum of  $s+b$ , or 560 feet of water, is the grain-to-grain stress at this plane of reference. The effective stress of the saturated



If the potentiometric surface of the confined aquifer system is drawn down 100 feet as in diagram *B*, gravitational stresses remain as in *A* because the water table is unchanged. However, a downward hydraulic gradient is developed across the confining bed, which induces downward movement of water through the pores and exerts a viscous drag on the grains. The force transferred to the grains at any depth is measured by the head loss to that depth. The stress so exerted on the grains in the direction of flow is called a seepage stress. This third effective stress component, represented by vector *J*, is algebraically additive to the gravitational stresses and is transmitted downward through the confined aquifer system. The solid vectors to the right of diagram *B* indicate the net change in effective stress at the base of the confining bed and below, from the hydrostatic condition of diagram *A*. Because the water table is unchanged, the net change is the change in seepage stress, which is equal to the decrease in fluid (neutral) pressure represented by line *C-F* (base of aquiclude).

If the potentiometric surface of the confined aquifer system remains constant and the water table is lowered or raised, both gravitational and seepage stresses change, but with opposite sign (not illustrated in fig. 45, but see Lofgren and Klausning, 1969, fig. 52). For example, if the water table is lowered and the parameters are as assumed earlier, the change in gravitational stress is +0.8 foot of water per foot of lowering; however, the unit

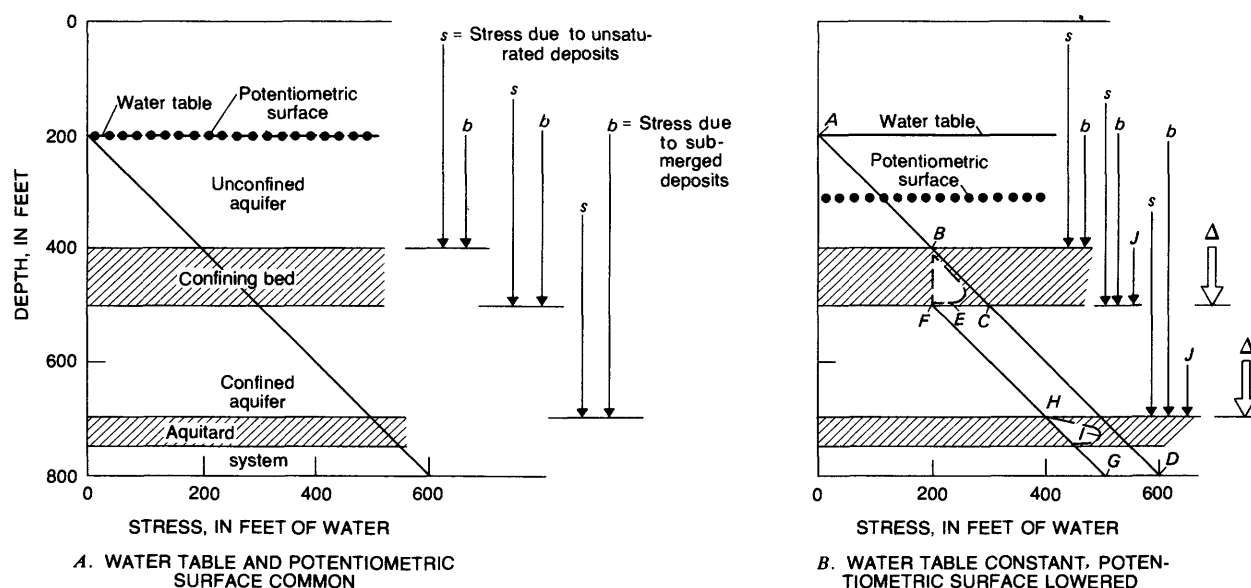


FIGURE 45.—Effective stress for a confined aquifer system overlain by an unconfined aquifer.

change in seepage stress (differential between water table and potentiometric surface of confined system) is  $-1.0$  foot, and so the net unit change in applied stress in the confined system is  $-0.2$  foot of water. Conversely, if the water table is raised, the net change in applied stress is  $+0.2$  foot per foot of rise.

In summary, water-level fluctuations change effective stresses in the following two ways:

1. A rise of the water table provides buoyant support for the grains in the zone of the change, and a decline removes the buoyant support; these changes in gravitational stress are transmitted downward to all underlying deposits.
2. A change in position of either the water table or the artesian head, or both, may induce vertical hydraulic gradients across confining or semiconfining beds and thereby produce a seepage stress. This stress is algebraically additive to the gravitational stress that is transmitted downward to all underlying deposits. A change in effective stress results if preexisting seepage stresses are altered in direction or magnitude.

The change in applied stress within a confined aquifer system, due to changes in both the water table and the artesian head, may be summarized concisely (Poland and others, 1972, p. 6) as

$$\Delta p_a = -(\Delta h_c - \Delta h_u Y_s),$$

where  $p_a$  is the applied stress expressed in feet of water,  $h_c$  is the head (assumed uniform in the confined aquifer system),  $h_u$  is the head in the overlying unconfined aquifer, and  $Y_s$  is the average specific yield (expressed as a decimal fraction) in the interval of water-table fluctuation.

In the San Joaquin Valley, the areas in which subsi-

ence has been appreciable coincide generally with the areas in which ground water is withdrawn chiefly from confined aquifer systems (figs. 1, 4; also Poland and Davis, 1969, fig. 32). Furthermore, the great increases in stress applied to the sediments in the ground-water reservoir by the intensive mining of ground water have developed chiefly as increased seepage stresses on the confined aquifer systems.

#### METHODS FOR STOPPING OR ALLEVIATING SUBSIDENCE

Studies of land subsidence in California and in other parts of the world furnish conclusive evidence that decrease in artesian head increases effective stress, causing compaction of sediments and correlative land subsidence (Poland and Davis, 1969). Conversely, increase in artesian head decreases effective stress and slows or stops land subsidence. In a compacting confined system, if fluid pressures in the aquifers are increased, the rate of subsidence will decrease; if fluid pressures in the aquifers are increased sufficiently to eliminate all excess pore pressures in the aquitards, subsidence will stop.

If artesian head declines for several years, causing compaction, and subsequently the head fluctuates seasonally with about the same maximum stress application (depth to water) each year, compaction will continue, but the annual rate of net compaction will gradually decrease until hydraulic equilibrium is reached—until pore pressures in the fine-grained beds attain steady state with pressures in adjacent aquifers. Compaction (and subsidence) will then stop. (Parameters determining the time required to reach equilibrium are on page 40.) If the artesian head in the system then recovers to a higher level, it can subsequently be drawn

down to the prior maximum effective-stress level without inducing appreciable compaction and subsidence. Effects of secondary consolidation, due to internal processes that continue after pore pressures reach steady state, are not considered in this discussion.

Remedial action to raise water levels can be accomplished by reducing ground-water pumpage or increasing recharge, or both. In an area that has been intensively developed agriculturally by overdraft of the ground-water supply, reduction of pumping does not occur until pumping lifts or well yields become uneconomic, water quality becomes unusable, an adjudication of water rights is reached through legal procedures, or until water is imported.

As of 1972, surface water was being imported into all three principal subsiding areas in the San Joaquin Valley (fig. 3). These imports now constitute a large part of the applied irrigation water in each area and have replaced much of the ground-water withdrawal of prior years. Therefore, a brief summary of the quantity of imports to each of the subsiding areas follows.

Imports to the northern part of the Los Banos-Kettleman City area began in 1951 when the Bureau of Reclamation completed the Delta-Mendota Canal. Supplemental water from that canal has been used only in the northern part of the area (north of the midline of T. 14 S. (fig. 4). Surface-water deliveries from the Sacramento-San Joaquin Delta through the joint-use reach of the California Aqueduct to the San Luis service area of the Bureau of Reclamation (for location, see Bull and Poland, 1975, fig. 40) began in 1967 (table 3). This service area occupies most of the Los Banos-Kettleman city area west of Fresno Slough and, as of 1967, utilized 930,000 acre-feet of ground-water pumpage—about 90 percent of the total ground-water pumpage in the area (Mitten, 1972). Imports to the service area through the 104-mile Federal-State joint-use reach of the California Aqueduct (fig. 46) increased from 19,000 acre-feet in 1967 to 650,000 acre-feet in 1971. Of this 1971 total, 450,000 acre-feet was used on cropland downslope from the aqueduct, and 200,000 acre-feet was used upslope. Deliveries through 1971 were most extensive north of T. 17S., but by December 1971 water was being delivered throughout the aqueduct joint-use reach to Kettleman City, although no distribution laterals had been completed south of T. 19 S. These importations have had a very significant effect on water levels because several hundred irrigation wells have been shut down. The artesian head for the lower zone rose about 60 feet from December 1967 to December 1971 and slowed subsidence rates substantially during that period. (See figs. 12, 16.) Deliveries in 1972 rose to 865,000 acre-feet, 93 percent of the estimated ground-water pumpage from the San Luis service area in 1967.

Surface-water imports into the Tulare-Wasco area

from the Friant-Kern Canal of the Bureau of Reclamation began in 1949 and since the early 1950's have served as a supplemental irrigation supply to irrigation districts throughout the area (fig. 47). Cumulative imports to yearend 1972 were 15.5 million acre-feet. (See table 4.) As noted earlier (Lofgren and Klausing, 1969, fig. 14, table 3), Friant-Kern Canal deliveries, on the average, represent roughly 80 percent of the total surface-water inflow to the Tulare-Wasco area and have had a marked effect on both the ground-water pumpage and subsidence rates through the years.

Imports into the Arvin-Maricopa area since 1962, from the Friant-Kern Canal and the California Aqueduct, are shown in figure 48. Deliveries to the Rosedale-Rio Bravo Water Storage District, released

TABLE 3.—Surface-water deliveries through the joint-use reach of the California Aqueduct to the Los Banos-Kettleman City area, 1967-72  
[In thousand acre-feet per calendar year; data from U.S. Bureau of Reclamation. Deliveries are to San Luis service area and include water pumped from Mendota Pool by Westlands Water District]

Year	Total deliveries	Part from Mendota Pool included in total
1967	19	18
1968	209	26
1969	306	15
1970	478	15
1971	650	23
1972	865	23

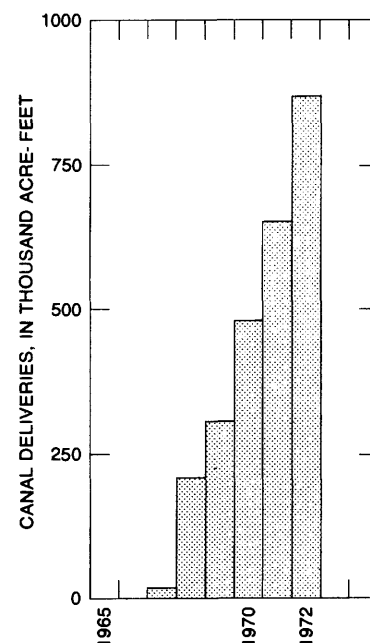


FIGURE 46.—Surface-water imports from the joint-use reach of the California Aqueduct to the Los Banos-Kettleman City area, 1967-72. (Imports include water from Mendota Pool but exclude deliveries from Delta-Mendota Canal; data from U.S. Bureau of Reclamation.)

into the Kern River channel from the Friant-Kern Canal, began in 1962 and undoubtedly have affected subsequent water levels on the north margin of the subsidence area. Deliveries from the Friant-Kern Canal to the Arvin-Edison Water Storage District on the eastern and southern part of the area south of the Kern River began in 1966 and have since been a major source of water supply. Then in 1971, deliveries from the California Aqueduct replaced much of the ground-water pumping around the south and west margins of the area. In 1971 the combined importation from the Friant-Kern Canal and California Aqueduct was 250,000 acre-feet (table 5), or about 40 percent of the annual pumpage of ground water from the subsiding area from 1962 through 1964 (Lofgren, 1975, table 6). In 1972, a year of low precipitation and runoff in California, the combined importation decreased to 247,500 acre-feet, but import-

ation through the California Aqueduct increased 85 percent from 1971. Total imports from 1962 through 1972 equaled 1,036,000 acre-feet (table 5).

The importation of surface water to replace mining of ground water has two effects, not necessarily entirely beneficial, with respect to subsidence alleviation. The immediate effect is to reduce or eliminate pumping of ground water in the area of surface-water delivery, causing the artesian head to rise in the zones experiencing reduced pumping. This effect is wholly beneficial because it reduces seepage stresses and hence effective stresses. The second effect of importation is to increase recharge because any imported water that seeps through the soil zone and reaches the water table, whether from stream channels, canals, ditches, or field irrigation is a net increase to the ground-water supply. This increase tends to raise the water table. If the recharge is accomplished in deposits in hydraulic continuity with a compacting confined system, such as the recharge (intake) area for that system, then buildup of the water table will be transmitted to the confined system as a pressure increase. This pressure increase will

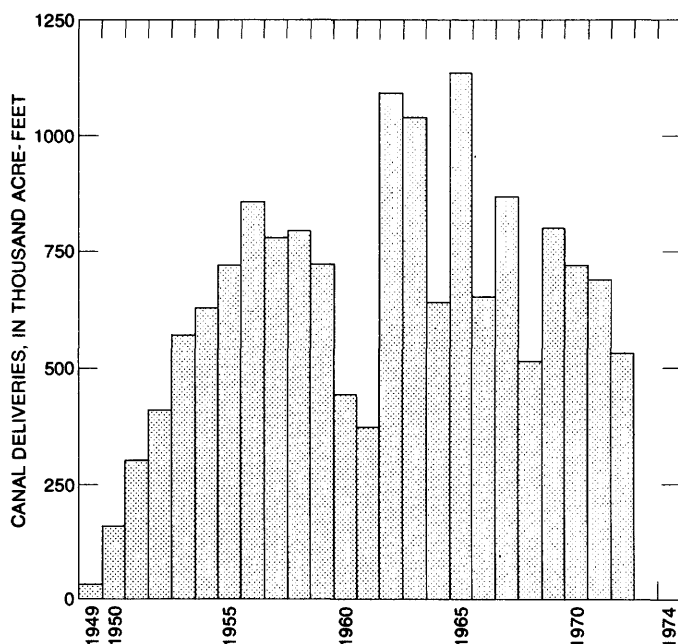


FIGURE 47.—Surface-water deliveries from the Friant-Kern Canal to irrigation districts in the Tulare-Wasco area, 1949-72. (Data in thousand acre-feet per calendar year, from U.S. Bureau of Reclamation.)

TABLE 4.—Summary of surface-water deliveries from the Friant-Kern Canal to irrigation districts in the Tulare-Wasco area, 1949-72

[In thousand acre-feet per calendar year; data from U.S. Bureau of Reclamation. Imports through 1964 given by district in Lofgren and Klausing, 1969, table 3]

Year	Delivery	Year	Delivery	Year	Delivery
1949	31	1957	788	1965	1,137
1950	163	1958	800	1966	660
1951	304	1959	724	1967	870
1952	412	1960	441	1968	519
1953	573	1961	374	1969	809
1954	627	1962	1,096	1970	722
1955	724	1963	1,042	1971	693
1956	868	1964	638	1972	533
			Total	15,548	

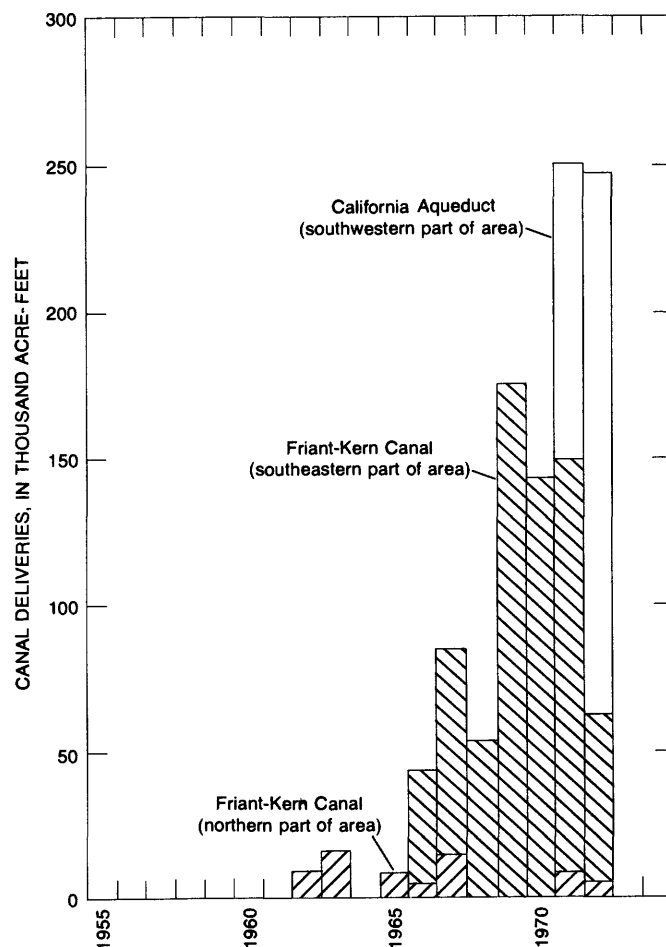


FIGURE 48.—Surface-water imports to the Arvin-Maricopa area, 1962-72.

TABLE 5.—Surface-water imports from the Friant-Kern Canal and the California Aqueduct to the Arvin-Maricopa area, 1962–72  
[Deliveries, in thousand acre-feet]

Year	Friant-Kern Canal	California Aqueduct <sup>1</sup>	Combined
1962	9.8	-----	9.8
1963	15.9	-----	15.9
1964	-----	-----	-----
1965	8.8	-----	8.8
1966	43.7	-----	43.7
1967	85.5	-----	85.5
1968	54.6	-----	54.6
1969	176.8	-----	176.8
1970	143.0	-----	143.0
1971	149.5	100.9	250.4
1972	62.5	185.0	247.5
Total	-----	-----	1,036.0

<sup>1</sup>South of Buena Vista Pumping Plant.

be beneficial in decreasing effective stress on the confined system. Also, if recharge can be accomplished by injection through wells directly in the confined system, the pressure buildup will be directly beneficial.

If, however, the recharge from the imported water percolates down to a water table in unconfined or semiconfined deposits overlying a compacting confined aquifer system, as occurs in most of the principal subsidizing areas in the San Joaquin Valley, any buildup of the overlying water table will be nonbeneficial with respect to the confined system. The water-table rise will have the net effect of increasing stress applied to the confined system by 0.2 foot per foot of rise. (See page 44.)

Thus, in much of the area now being supplied with imported water, the net change in effective stress on the confined aquifers is the result of two opposing components, a recovery of artesian head in the confined system due to the decrease in pumping and a rise of an overlying but hydraulically separate water table due to recharge by imported water moving down through the unsaturated zone. Because the recovery of artesian head decreases the effective stress 1 foot per foot of head rise, whereas the water-table rise increases the effective stress only 0.2 foot per foot of water-table rise (for the parameters assumed earlier), each 1 foot of artesian head rise offsets 5 feet of water-table rise. Furthermore, the recovery of artesian head is very substantial as shown by several of the graphs (figs. 8–11, 23, and several of the computer plots), but the rise in water table (not shown) is small.

In the Los Banos–Kettleman City area, for example, the hydrograph for well 16/15–34N4 (fig. 61A; for location, see fig. 50) shows artesian-head recovery of about 80 feet from mid-1968 to the end of 1970, whereas the water table in well 16/15–34N5 (fig. 61A) rose only 2 feet in the 2½ years. Hence, at this site, the effective stress on the confined aquifer system decreased by about 80 feet during the 2½-year period. The general recovery of artesian head in 1969 through 1971 produced a drama-

tic decrease in the rate of subsidence. (See figures 12, 16.)

In the Tulare-Wasco area, recovery of artesian head northeast of Delano has been as much as 230 feet since 1950 (fig. 23). At the same site, the rise in the water table has been about 90 feet. Thus, the effective stress on the confined aquifers decreased about 210 feet in the 20 years. Even though 12 feet of subsidence occurred in this general area from 1926–54 (Lofgren and Klausing, 1969, fig. 43) and shows as a 12-foot subsidence "hole" on the long-term subsidence map of 1926–70 (fig. 27), subsidence from 1962 to 1970 was negligible (figs. 23, 24).

## MEASUREMENT OF COMPACTION

Two principal objectives of the cooperative program with the California Department of Water Resources on land-subsidence studies, and essential elements of the Federal program on mechanics of aquifer systems, are to determine the depth interval(s) in which compaction is occurring and to measure the magnitude and the time distribution of the compaction where possible. Such information, together with periodic measurement of land subsidence as determined by spirit-level surveys to surface bench marks, is essential to determining the cause of subsidence and for monitoring the magnitude and the change in rate of subsidence. Also, when coupled with measurement of water-level or head change in the stressed aquifer systems, these data supply the parameters required for stress-compaction or stress-strain analysis.

As an initial step in developing techniques for measuring compaction, the Geological Survey installed the first equipment to record compaction in well 19/17–35N1, 16 miles northwest of Kettleman City in 1955. The equipment constituted a heavy weight lowered to the bottom of the well (2,030 ft below land surface) on an attached cable that was counterweighted at the land surface to maintain constant tension. Compaction was measured continuously by a recorder mounted over the casing and attached to the downhole cable. Both the equipment and the record of compaction to the autumn of 1960, when the cable failed because of corrosion, have been described by Lofgren (1961, p. B49–B51 and figs. 24.1, 24.2; also see Bull and Poland, 1975, fig. 11). In 4.8 years, measured compaction within the 2,030-foot-depth interval was 3.8 feet, or 82 percent of land-surface subsidence of 4.6 feet in the same period.

Because of the success of the first installation, in 1958 the Survey began installing a large number of compaction recorders (extensometers) in selected wells in the valley. Companion water-level recorders also were installed wherever possible to measure the change in applied stress. By the end of 1961, 18 extensometers were operating, and by 1969 there were 31. Of these, 22

were in the Los Banos-Kettleman City area, 6 in the Tulare-Wasco area, and 3 in the Arvin-Maricopa area. Water levels were being measured in 21 of these wells and in 4 supplementary wells. Bull (1975, table 1) gave supplementary information for the 22 wells in the Los Banos-Kettleman City area. Several improvements in measuring equipment have been made since the first installation in 1955. Figure 49 is a diagram of the recording compaction gage and illustrates the general type of equipment used in the later installations.

Figure 50 shows the location of the 31 sites where water-level changes and compaction of the water-bearing deposits are currently being measured. Table 6 summarizes the net annual compaction rate (in feet per year) at each of the 31 sites through 1970 and also gives compaction in 8 additional depth intervals defined by multiple-depth installations. For example, at 12/12-16H, wells H2, 3, and 4 are respectively 1,000, 350, and 500 feet deep. The extensometer in well H2 records total compaction from land surface to the 1,000-foot depth, and the extensometer in H4 measures the compaction from land surface to the 500-foot depth. By subtracting the compaction in H4 from that in H2, the compaction of the 500-1,000-foot-depth interval is calculated. Water-

level and compaction data from these sites are plotted and interpreted by computer and are monitoring the characteristics and changes of the aquifer system at these selected locations.

The maximum recorded compaction of 10.85 feet from September 1958 through 1970 occurred at well 16/15-34N1, which is 2,000 feet deep and is adjacent to the California Aqueduct in the joint-use reach in western Fresno County.

Four wells in the Tulare-Wasco area showed negative compaction in certain years. For example, the record for well 24/26-34F1 shows negative compaction in the 4 years 1962, 1965, 1967, and 1969. In other words, the extensometer registered net expansion of the measured interval (0-1, 510 ft) during each of those 4 years. Figure 72 shows depth to water (A), change in applied stress (B), measured compaction (C), and a stress-compaction plot (D) for this well. Inspection of graph B indicates that in each of these 4 years the applied stress at yearend was less than at the beginning. Evidently the elastic expansion due to the net decrease in stress was larger than any continuing compaction of the central parts of the thicker aquitards. Hence the aquifer system showed net expansion for each of these years. By 1967, the stress change being applied was wholly in the elastic range. In the 4 years 1967-70, the net expansion of the aquifer system was 0.012 foot.

## INTERRELATIONS OF WATER-LEVEL CHANGE, COMPACTION, AND SUBSIDENCE

### EXAMPLES OF STRESS-STRAIN GRAPHS

Field measurements of compaction and correlative change in water level serve as continuous monitors of subsidence and indicators of the response of the system to change in applied stress. They also can be utilized to construct stress-strain curves from which, under certain favorable conditions, one can derive storage and compressibility parameters of the aquifer system, as demonstrated by Riley (1969).

Two examples will serve to illustrate the stress-strain relations obtained from the measuring sites in the San Joaquin Valley and the significance of these curves. Figure 51 depicts the stress-strain relations at a site where compaction of the aquifer system has continued uninterrupted since 1958 and there has been no net expansion of the measured interval at any time. The other, figure 52, shows stress-strain relations since 1967 at a site where aquifer-system response has been in the elastic range of stressing (expanding when the stress is decreased) when the depth to water has been less than about 180 feet.

At site 16/15-34N, on the west side of the valley 18 miles south of Mendota (fig. 50), compaction is recorded in three adjacent wells, 503, 703, and 2,000 feet deep.

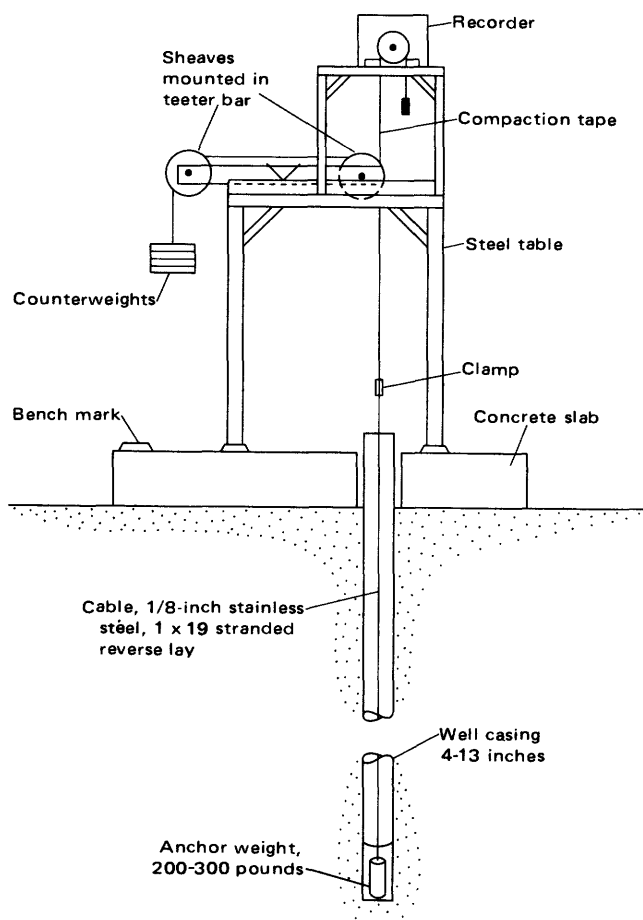


FIGURE 49.—Recording compaction gage.

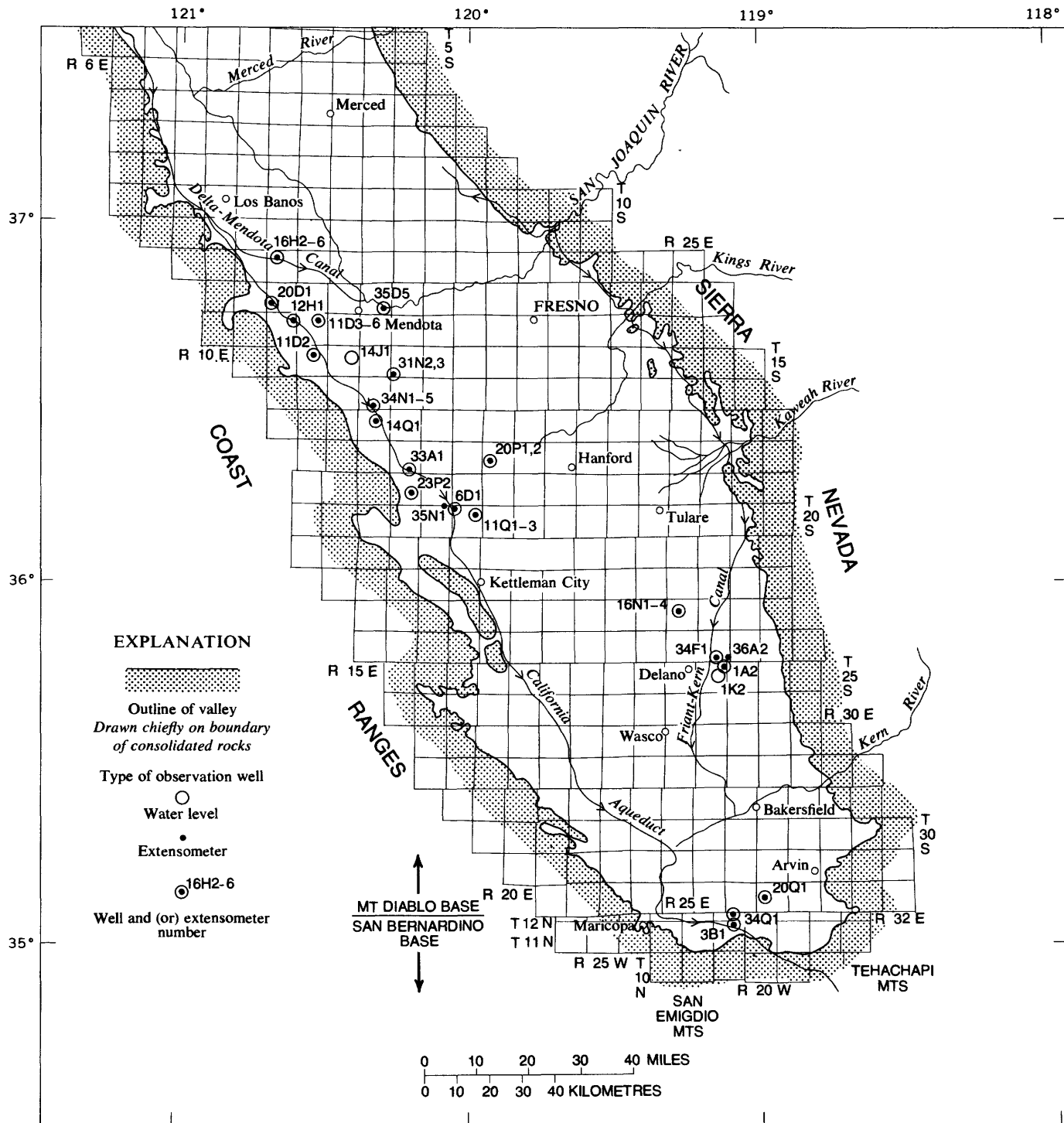


FIGURE 50.—Water-level and compaction measuring sites.

The record from the multiple-depth installation indicates the magnitude and rate of compaction, not only within the well depths but also within the depth intervals between well bottoms. Figure 51 is a plot of compaction for the depth interval 703–2,000 feet below land

surface versus the change in applied stress in this interval, as represented by change in water level in well 16/15–34N4 (fig. 61A, B). The interval compacted 7.9 feet from 1958 through 1970 (table 6; fig. 61F). The horizontal distance between the vertical lines drawn at



TABLE 6.—Annual compaction rates at compaction-measuring sites, San Joaquin Valley

[In order to arrive at consistent sums, the amount of annual compaction is shown to a thousandth of a foot; however, many of the measured yearly rates are not accurate to less than a few hundredths of a foot]

Well number	Anchor depth when installed (ft.)	Depth interval (ft.)	Start of record <sup>1</sup>	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Total measured compaction (ft.)
<b>Los Banos-Kettleman City area</b>																	
12/12-16H3	350	0- 350	5/19/58	0.052	0.053	-0.004	0.013	0.036	0.005	0.008	0.007	0.002	0.004	0.002	0	0.002	0.180
16H4	500	350- 500	5/19/58	.032	.087	.019	.002	.008	.003	.011	.013	.011	.013	.015	.008	.007	.229
16H2	1,000	500-1,000	5/19/58	.211	.302	.293	.325	.158	.187	.173	.066	.125	.105	.075	.060	.060	2.140
16H2	1,000	0-1,000	5/19/58	.295	.442	.308	.340	.202	.195	.192	.086	.138	.122	.092	.068	.069	2.549
13/12-20D1	681	0- 681	10/10/61				.077	.340	.215	.119	.182	.120	.094	.074	.056	.032	1.309
13/15-35D5	440	0- 440	5/13/66									-.022	.014	.022	.006	.034	.054
14/12-12H1	913	0- 913	1/10/65								.414	.336	.239	.139	.097	.164	1.389
14/13-11D4	780	0- 780	1/1/61				.310	.196	.222	.199	.108	.194	.160	.071	.001	.013	1.474
11D6	1,358	780-1,358	5/25/61				.354	.462	.259	.400	.322	.279	.326	.157	.073	.078	2.710
11D6	1,358	0-1,358	5/25/61				.480	.658	.481	.599	.430	.473	.486	.228	.074	.091	4.000
15/13-11D2	958	0- 958	1/11/65								.204	.154	.126	.099	.060	.047	.690
15/16-31N3	596	0- 596	3/23/67										.088	.120	.092	.032	.332
16/15-34N3	503	0- 503	9/25/58	.010	.118	.093	.087	.138	.082	.096	.082	.085	.090	.101	.130	.112	1.224
34N2	703	503- 703	9/25/58	.094	.232	.123	.191	.167	.172	.174	.104	.104	.122	.118	.046	.077	1.724
34N1	2,000	703-2,000	9/25/58	.286	.857	.717	.867	.697	.710	.829	.634	.614	.604	.573	.312	.202	7.902
34N1	2,000	0-2,000	9/25/58	.390	1.207	.933	1.145	1.002	.964	1.099	.820	.803	.816	.792	.488	.391	10.850
34N4	1,096	0-1,096	8/16/60			.232	.661	.648	.416								1.957
16/15-34N4 <sup>3</sup>	900	0- 900	9/15/64								.358	.320	.340	.334	.233	.210	1.795
17/15-14Q1	2,315	0-2,315	11/4/69												.079	.478	.557
18/16-33A1	1,029	0-1,029	3/10/65								.128	.210	.186	.124	.034	.094	.776
18/19-20P2	578	0- 578	3/24/67									.026	.070	.036	.065		.197
19/16-23P2	2,200	0-2,200	1/2/60			.508	.660	.553	.378	.424	.259	.552	.355	.328	.201	.192	4.410
20/18-6D1	867	0- 867	1/11/65								.273	.267	.280	.179	.090	.121	1.210
11Q1	710	0- 710	7/24/64								.115	.259	.240	.225	.224	.149	1.357
11Q2 <sup>3</sup>	845	0- 845	2/27/63						.230	.330	.300	.330	.290	.280	.220	.190	2.170
11Q2	845	710- 845	7/24/64							.025	.041	.090	.065	.056	.071	.045	.393
11Q3	1,930	845-1,930	2/27/63						.261	.212	.357	.240	.199	.259	.207	.160	1.895
11Q3	1,930	0-1,930	1/1/63						.611	.542	.657	.570	.489	.539	.427	.350	4.185
<b>Tulare-Wasco area</b>																	
23/25-16N4	250	0- 250	6/24/59		0.005	0.024	0.024	0.008	0.007	0.022	0.009	0.001	0	0.003	-0.002	0	0.101
16N3	430	250- 430	6/24/59		.055	.100	.062	.120	.042	.080	.048	.085	.003	.057	.005	.033	.690
16N1	760	430- 760	6/24/59		.184	.433	.473	.051	.056	.253	.131	.225	.063	.160	.036	.100	2.165
16N1	760	0- 760	4/18/58	0.454	.482	.557	.559	.179	.105	.355	.188	.311	.066	.220	.039	.133	3.648
24/26-34F1	1,510	0-1,510	1/21/59		.242	.100	.111	-.051	.018	.063	-.025	.068	-.031	.038	-.057	.038	.514
36A2	2,200	0-2,200	5/12/59		.059	.342	.333	.059	.096	.329	.062	.145	-.045	.168	-.060	.143	1.631
25/26-1A2	892	0- 892	4/6/59		.058	.061	.059	-.013	-.004	.050	-.003	.096	-.012	.018	-.001	.014	.323
<b>Arvin-Maricopa area</b>																	
32/28-20Q1	970	0- 970	4/11/63						0.192	0.365	0.178	0.255	0.219	0.124	0.124	0.095	1.552
12N/21W-34Q1	810	0- 810	6/2/60			0.207	0.326	0.271	.209	.186	.266	.197	.130	.014	.186	.153	2.145
11N/21W-3B1		810-1,480	4/12/63						.188	.261	.135	.229	.184	.344	.152	.149	1.642
3B1	1,480	0-1,480	4/12/63						.326	.447	.401	.426	.314	.358	.338	.302	2.912

<sup>1</sup>Date when stabilized installation began giving acceptable record.

<sup>2</sup>Compaction to June 11, 1963.

<sup>3</sup>Compaction based on protrusion of 4-inch casing.

the end of each calendar year indicates the yearly magnitude of compaction. The decrease in applied stress beginning late in 1968, reflecting the recovery in artesian head due to surface-water imports and reduction in ground-water withdrawal, has had a notable effect on the rate of compaction: 0.2 foot in 1970 compared with 0.87 foot in 1961. (Also see table 6.)

The stress-compaction plot has moved consistently to the right throughout the period graphed, indicating that the compaction recorder has not registered net expansion at any time. Even during times of rapid decrease in applied stress (rapid increase in head), such as late in 1961 and 1962 and even during the 80-foot decrease in stress since August 1968, the rate of elastic expansion of the aquifers and of the outer parts of the aquitards has not been sufficient at any time to exceed the rate of continuing compaction of the central parts of the aquitards. However, at least three times in 1969-70 during periods of decrease in applied stress, the stress-

compaction curve has been essentially vertical, indicating that the elastic expansion was about equal to the continuing compaction during those intervals of head increase. This suggests that pore pressures in the aquifers are approaching pore pressures in the central parts of the thicker aquitards. Under these transient conditions, one cannot derive either the elastic or the virgin parameters of storage and compressibility.

In contrast to figure 51, the stress-strain relations shown in figure 52 have been largely in the elastic range of stress application since the start of the record in 1967. Well 18/19-20P2, 17 miles west of Hanford (fig. 50), is 578 feet deep. Depth to water is plotted increasing upward, representing increasing stress. Change in depth to water represents change in effective stress in the aquifers in this confined aquifer system, which is 347 feet thick, from 231 to 578 feet below the land surface. It is assumed that the water table and pore pressures in thin aquifers above the 231-foot depth are not affected

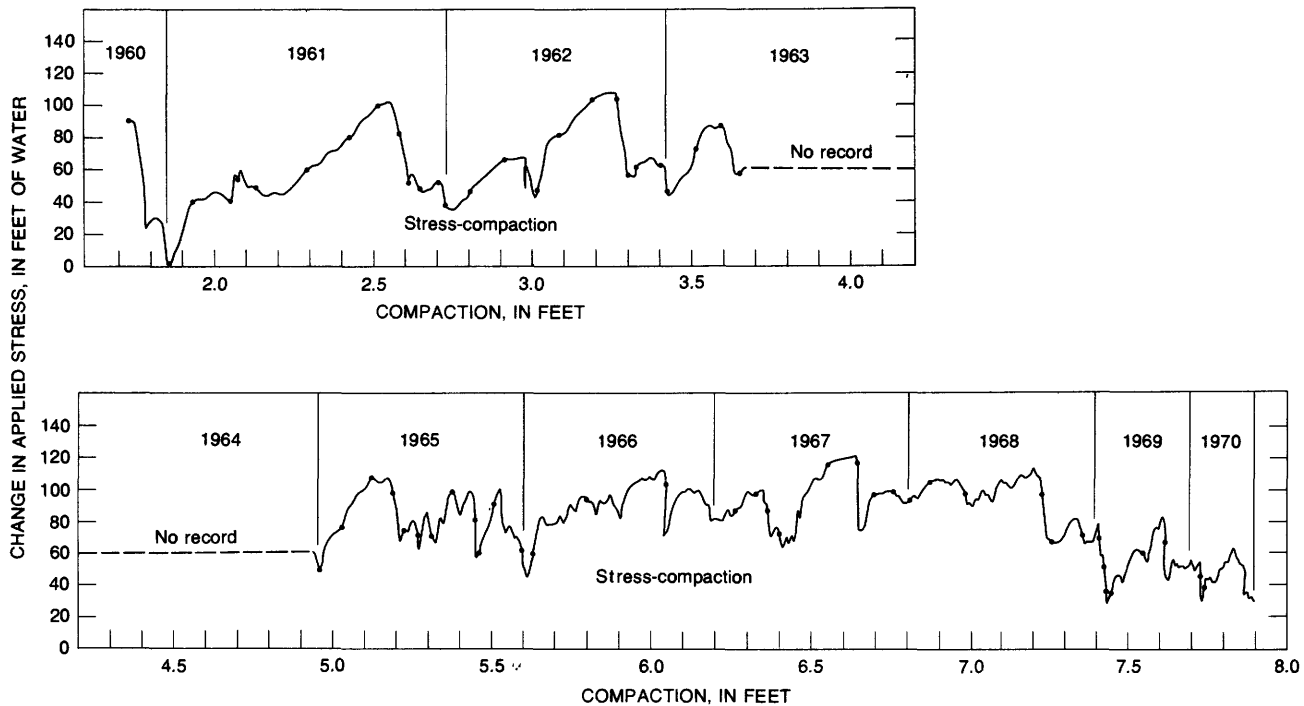


FIGURE 51.—Stress change versus compaction at 16/15-34N (for the depth interval 703-2,000 ft.

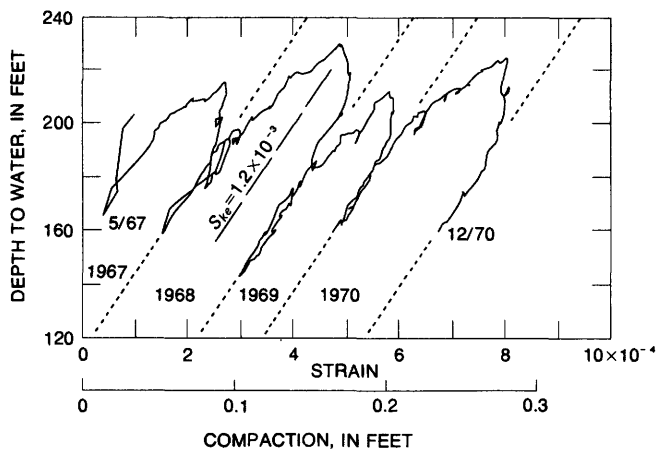


FIGURE 52.—Stress change, compaction, and strain, well 18/19-20P2.

by the irrigation withdrawals and remain constant. The yearly fluctuation of water level caused by the seasonal irrigation demand and the permanent compaction that occurs each summer when the depth to water is greatest produces a series of stress-strain loops. The lower parts of the descending segments of the irrigation-year loops for the three winters 1967-68 to 1969-70 are approximately parallel straight lines (the four dotted lines are drawn parallel), indicating that when the depth to water is less than about 180 feet, the response (expansion or compaction) of the system is essentially elastic in both aquifers and aquitards.

The heavy dashed line in the 1968 loop (drawn paral-

lel to the dotted lines) represents the average slope of the straight-line segments in the elastic range of stress. The reciprocal of the slope of the line is the component of the storage coefficient attributable to elastic deformation of the aquifer-system skeleton,  $S_{ke}$ , and equals  $1.2 \times 10^{-3}$ . The component of average specific storage due to elastic deformation,  $S_{ske}$ , equals  $S_{ke}/347$  feet or  $3.4 \times 10^{-6} \text{ ft}^{-1}$ . The average elastic compressibility of the skeleton,  $\beta_k$ , is

$$S_{ske} = 3.4 \times 10^{-6} \text{ ft}^{-1} / 0.433 \text{ lb in}^{-2} \text{ ft}^{-1} = 8 \times 10^{-6} \text{ lb in}^{-2}$$

where  $\gamma_w$  is the unit weight of water. In consistent units, however, when stresses are expressed in feet of water and  $\gamma_w = 1$ ,  $\beta_k = S_{ske} = 3.4 \times 10^{-6} \text{ ft}^{-1}$ . Thus, at this site, the value of the elastic storage parameters can be closely approximated through use of the stress-strain plot after only 2-3 years of record. Because maximum seasonal stresses increased only slightly during this period of record, the inelastic response characteristics of the aquifer system to significant increased stresses cannot be calculated from this record.

#### COMPUTER PLOTS OF FIELD RECORDS

The records of compaction and of depth to water in the extensometer wells or in nearby observation wells have been computerized on a daily basis, and computer plots of these records through 1970 are included as figures 53-78 at the end of this report. Graphs of subsidence of a

surface bench mark located at the measuring site, determined by periodic instrumental surveys to a stable bench mark, are also included for all or part of the period of compaction measurement. Table 8, also at the end of this report, supplies pertinent notes on the individual graphs. Site locations are shown in figure 50.

With respect to the objectives of the cooperative study of land subsidence, the primary purpose of including these records is to show graphically the measured compaction and the subsidence at specific sites, and, so far as possible, the change in effective stress in the pertinent aquifers at these sites, as indicated by the hydrographs. Because of confining beds and multiple-aquifer-aquitard systems, it is difficult to obtain water-level measurements that one can be confident represent the mean stress and stress change for the interval in which compaction is being measured. At each of several sites, one to three additional observation wells would be needed to define the magnitude of head change, if any, in aquifers 100–200 feet below the water table. However, funds for exploring the variation in head with depth have been limited.

Change in applied stress and stress-compaction or stress-strain relationships are plotted for 14 of the 26 figures. In these figures, compaction equals the change in thickness of the compacting interval, and strain refers to the unit change in thickness or the compaction divided by the thickness of the compacting interval. Of the 14 relationships included, 7 are in the Los Banos–Kettleman City area, 5 are in the Tulare–Wasco area, and 2 are in the Arvin–Maricopa area. Change in applied stress was plotted for each site where the measurements of depth to water were considered to define, at least approximately, the change in applied stress on the aquifer-system thickness interval being measured by the extensometer.

At sites where both the water table and the artesian head were measured, as at 16/15–34N (fig. 61) and 23/25–16N (figs. 70, 71), the computer program made use of the equation cited on page 44 to determine the change in applied stress. At sites where changes in the water table were not known or were assumed to be 0, the plot of change in applied stress is identical in direction and magnitude to the change in artesian head (plotted as depth to water) because (1) both are expressed in feet of water and (2) the change in stress in the confined system is solely a change in seepage stress, with magnitude equal to the change in vertical distance between the water table and the artesian head. (See p. 43; fig. 45.)

Stress-compaction plots are included for six wells in which the measured water-level change is considered to be representative for the compacting zone being measured but where the thickness of the compacting zone is not known. For example in well 15/16–31N3 (fig. 60),

the extensometer measures change in thickness between the land surface and the anchor at a depth of 596 feet. Inspection of the electric log (not shown) suggests that the deposits to a depth of 320 feet below land surface probably are not experiencing as much change in stress as is indicated by the hydrograph and may not be experiencing any change in stress. The hydrograph does represent change in applied stress in the depth interval 320–596 feet, and the compacting interval is at least 276 feet thick. At least one additional observation well would be required, however, to resolve the question of whether any compaction is occurring above the 320-foot depth. If it is, at least two additional wells would be required to define magnitudes of change in stress.

The stress-compaction plot for 16/15–34N (fig. 61H) is an exception because the thickness of the compacting zone is known (1,297 ft), and hence a stress-strain plot could have been made.

Stress-strain plots are included for seven wells in which the measured water-level change is considered to represent change in applied stress throughout the compacting zone being measured and where the thickness of the compacting zone is known. For example, at site 23/25–16N (fig. 70), the extensometers in wells N3 and N1 measure change in thickness between the land surface and the anchors at depths of 430 and 760 feet, respectively. The deposits between depths of 430 and 760 feet are 330 feet thick and are affected by the stress change defined by the hydrographs for wells N3 and N4. Therefore, on the stress-strain plot for this site and depth interval (fig. 70E), the strain has been computed as measured compaction divided by 330 feet of thickness.

Elastic storage parameters are given in table 7 for five sites, based on the stress-compaction or stress-strain plots for the respective sites. All these plots have hysteresis loops developed during the elastic response range of stress change. The storage parameters are computed following the example given on page 50 for site 18/19–20P2. In table 7, the first two sets of parameters are for principal parts of the upper zone in the Los Banos–Kettleman City area; the other three are for sites in the Tulare–Wasco area. At well 15/16–31N3, 596 feet deep, the thickness of the compacting interval is at least 276 feet. If any compaction is occurring at a shallower depth than 320 feet, the average specific storage component,  $S_{ske}$ , would be reduced accordingly.

At site 23/25–16N, the storage coefficient component of the aquifer system skeleton,  $S_{ke}$ , for the bottom interval 330 feet thick about equals that for the overlying interval 100 feet thick, and for the two intervals together,  $S_{ke} = 1.3 \times 10^{-3}$ . Thus, the average specific storage component for the 100-foot interval,  $7 \times 10^{-6} \text{ ft}^{-1}$ , is four times as large as that for the 330-foot interval.

TABLE 7.—*Tentative elastic storage parameters*  
[Numbers in parentheses are provisional]

Fig. No.	Well or site No.	Storage coefficient component, $S_{ke}$ (dimensionless)	Thickness of compacting interval	Average specific storage component, $S_{ske}$	Remarks
			(ft)	(ft <sup>-1</sup> )	
60	15/16-3N3	$1.06 \times 10^{-3}$	(276)	$(3.8 \times 10^{-6})$	Upper zone.
64	18/19-20P2	$1.2 \times 10^{-3}$	347	$3.4 \times 10^{-6}$	Do.
70	23/25-16N	$0.64 \times 10^{-3}$	330	$1.9 \times 10^{-6}$	Interval 430-760 ft.
71	-----do	$0.7 \times 10^{-3}$	100	$7.0 \times 10^{-6}$	Interval 330-430 ft.
	Sum for site 16N	$1.3 \times 10^{-3}$	430		Interval 330-760 ft.
72	24/26-34F1	$2.5 \times 10^{-3}$	(1,310)	$(1.9 \times 10^{-6})$	
74	25/26-1A2	$(0.6 \times 10^{-3})$	-----	-----	May still be transient value.

<sup>1</sup>When stress is expressed in feet of water and unit weight of water=1, the numerical value on the average compressibility (ft<sup>-1</sup>) of the compacting interval equals the average specific storage component.

Riley (1969, p. 427) used the stress-compaction plot for a 405-foot thickness at Pixley (the 355-760 ft-depth zone) to obtain  $S_{ke}$  which he found to be  $1.15 \times 10^{-3}$ . The component of the storage coefficient for the depth interval 330-355, which Riley did not include in his estimate, is  $7 \times 10^{-6} \text{ft}^{-1} \times 25 \text{ feet}$  or  $0.18 \times 10^{-3}$ . Adding this element to Riley's  $1.15 \times 10^{-3}$  gives  $1.3 \pm \times 10^{-3}$ , which is the sum of the two components of the storage coefficient given for 23/25-16N in table 7. In short, the elastic storage parameters in table 8 are consistent with Riley's (1969).

The rising artesian head in the aquifers of the lower zone in the Los Banos-Kettleman City area is rapidly reducing the pore-pressure differential between aquifers and aquitards, and hence the graphs showing a large rise in head from 1968 through 1970 also show a very marked decrease in rate of compaction. As the artesian head continues to recover, the pore pressures in the aquifers at some sites are (1973) approaching values equal to the pore pressures in the central parts of the thicker aquitards. When the aquifer pressures exceed the aquitard central pore pressures, the response of the system will be wholly in the elastic range. At that time, elastic parameters can be derived from stress compaction plots for the lower zone—the main confined aquifer system. The required head recovery will be greatest where the aquitards are thickest, all other factors being equal.

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**FIGURES 53–78 AND TABLE 8**

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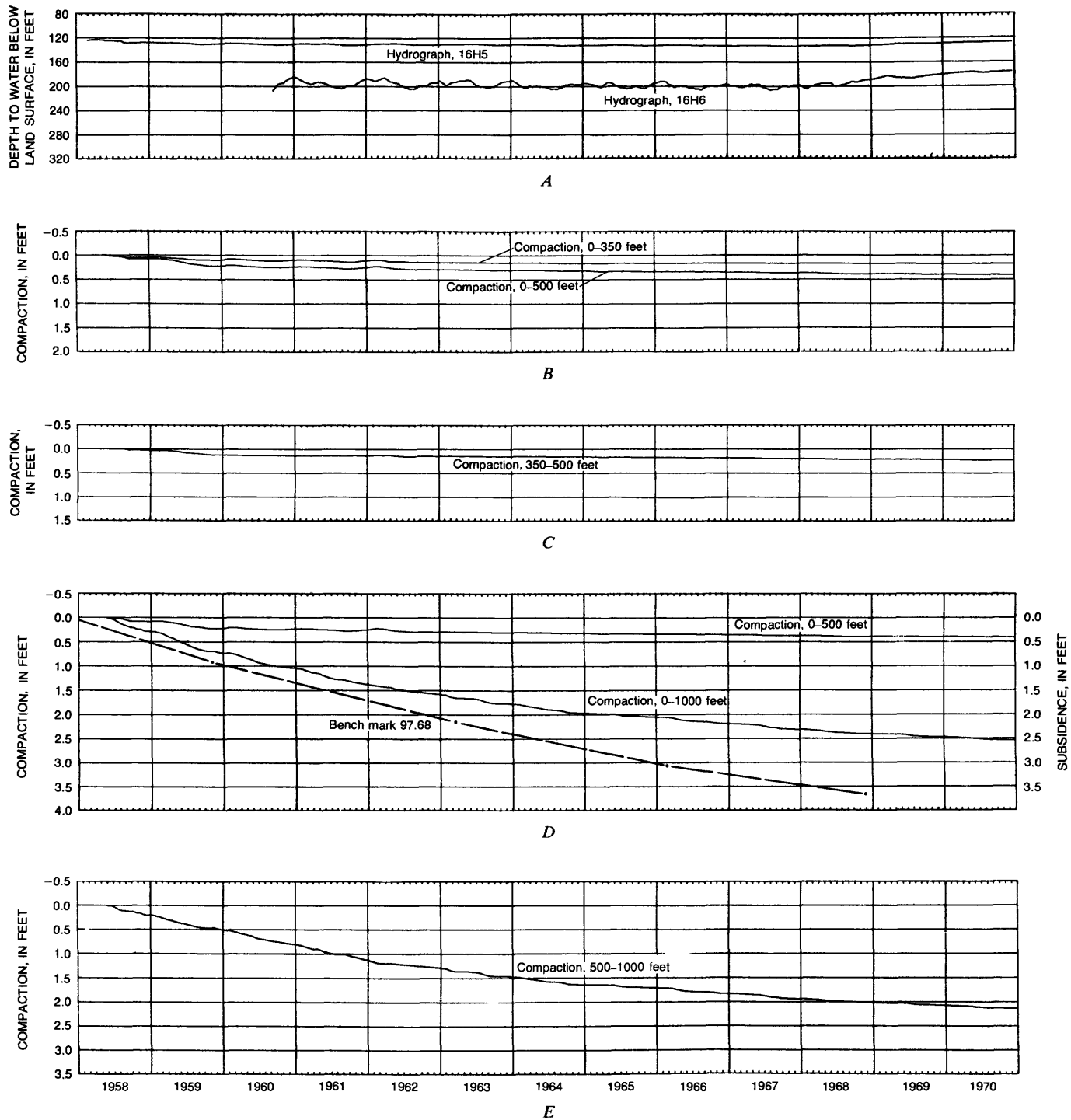


FIGURE 53.—Hydrographs, compaction, and subsidence, 12/12-16H. A, Hydrographs of wells 12/12-16H5, perforated 670-712 feet, and 12/12-16H6, perforated 770-909 feet. B, Compaction to 350-foot depth in well 12/12-16H3 and compaction to 500-foot depth in well 12/12-16H4. C, Compaction in 350-500-foot-depth interval. D, Compaction to 500-foot depth in well 12/12-16H4, compaction to 1,000-foot depth in well 12/12-16H2, and subsidence of bench mark 97.68(USBR), 330 feet south-southeast of well 12/12-16H2. E, Compaction in 500-1,000-foot-depth interval.

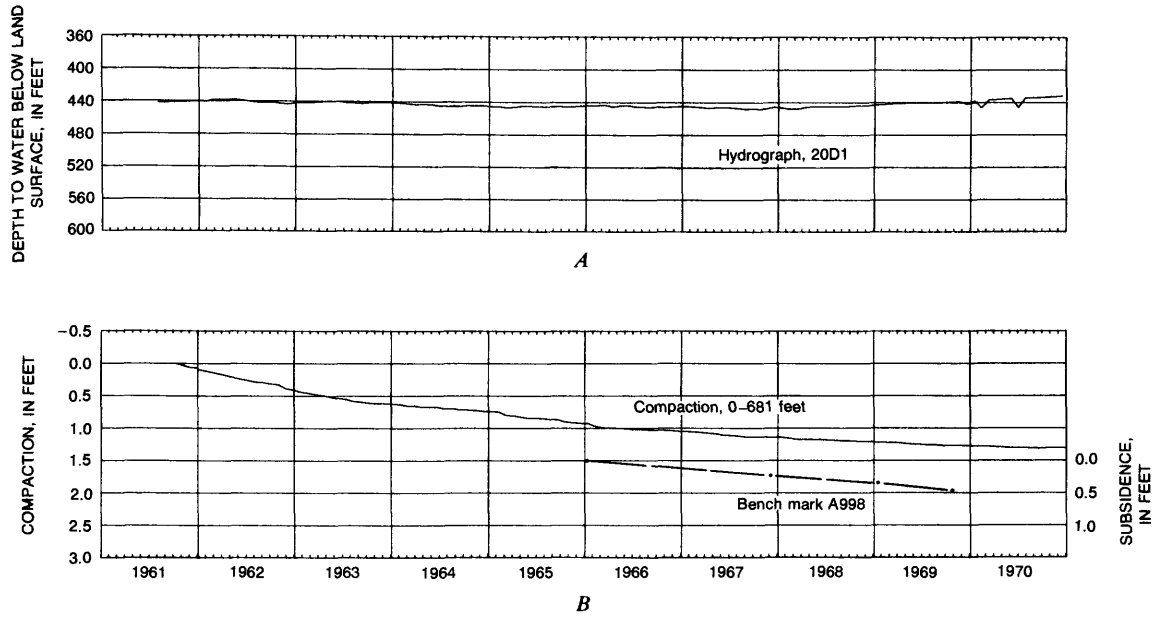


FIGURE 54.—Hydrograph, compaction, and subsidence, 13/12-20D1. A, Hydrograph of well 13/12-20D1, perforated 425-665 feet. B, Compaction to 681-foot depth and subsidence of bench mark A998 at well 13/12-20D1.

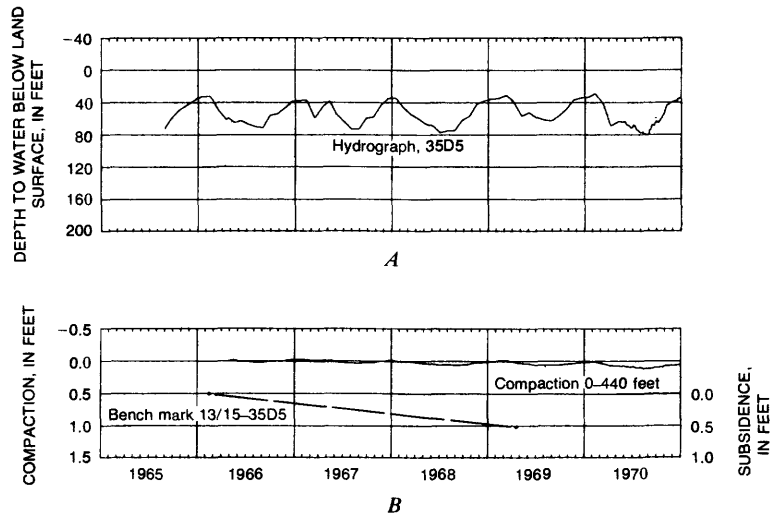


FIGURE 55.—Hydrograph, compaction, and subsidence, 13/15-35D5. A, Hydrograph of well 13/15-35D5, perforated 373-433 feet. B, Compaction to 440-foot depth and subsidence of bench mark 13/15-35D5 at well 13/15-35D5.



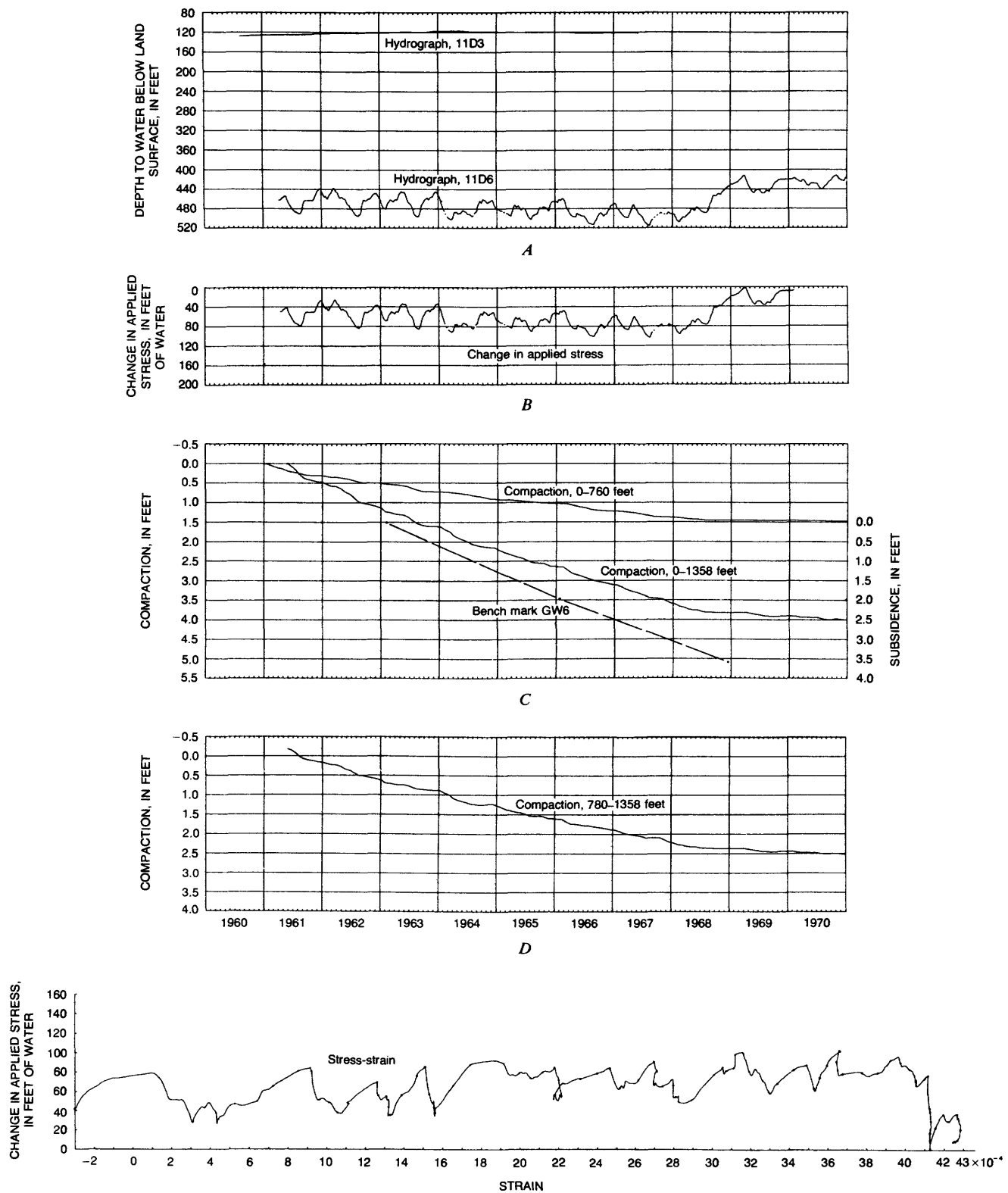


FIGURE 56.—Hydrographs, change in applied stress, compaction, subsidence, and stress-strain relationship, 14/13-11D. A, Hydrographs of wells 14/13-11D3 (water table), perforated 180-240 feet, and 14/13-11D6 (lower zone), perforated 1,133-1,196 feet. B, Change in applied stress. C, Compaction to 780-foot depth in well 14/13-11D4, compaction to 1,358-foot depth in well 14/13-11D6, and subsidence of bench mark GW6 at well 14/13-11D6. D, Compaction in 780-1,358-foot-depth interval. E, Stress change versus strain (578-ft thickness).

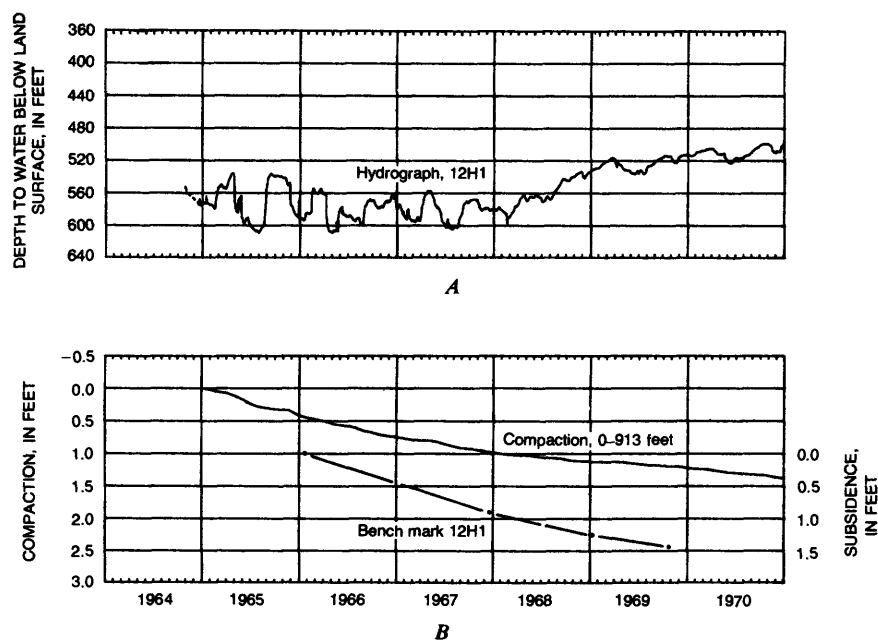


FIGURE 57.—Hydrograph, compaction, and subsidence, 14/12-12H1. A, Hydrograph of well 14/12-12H1, perforated 740-936 feet. B, Compaction to 913-foot depth and subsidence of bench mark 12H1 at well 14/12-12H1.

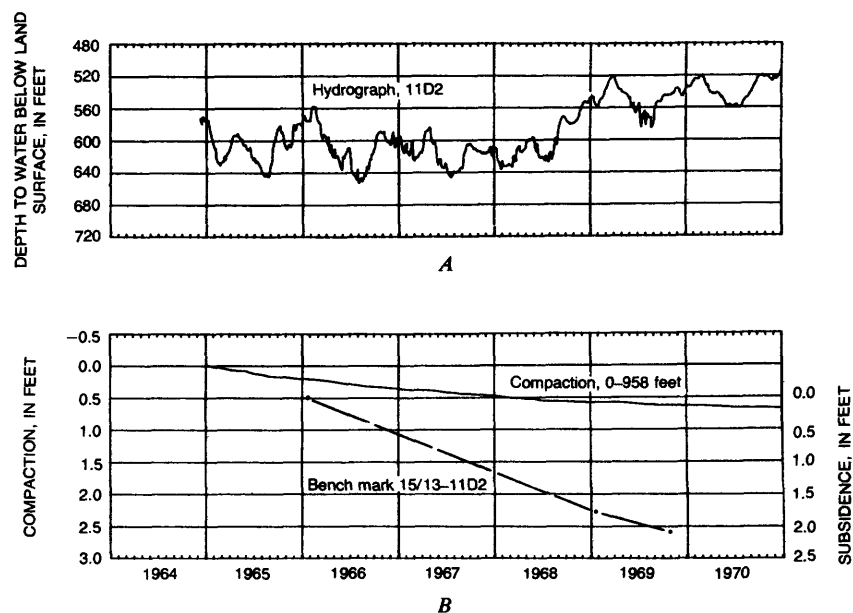


FIGURE 58.—Hydrograph, compaction, and bench-mark subsidence, 15/13-11D2. A, Hydrograph of well 15/13-11D2, perforated 900-960 feet. B, Compaction to 958-foot depth and subsidence of bench mark 15/13-11D2 at well 15/13-11D2.

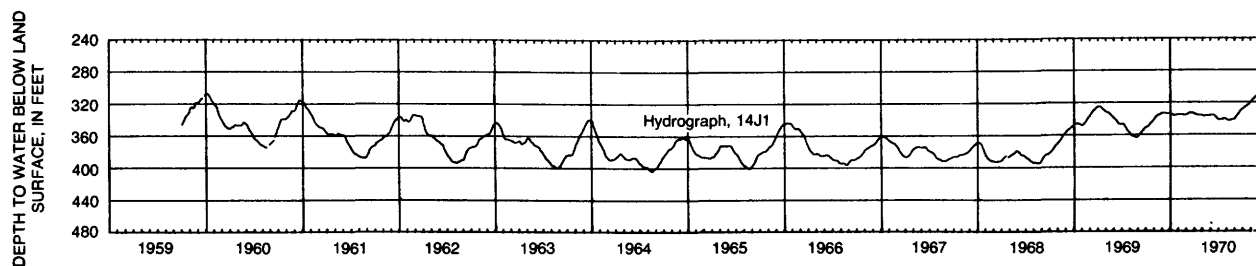


FIGURE 59.—Hydrograph of well 15/14-14J1, depth 1,010 feet.

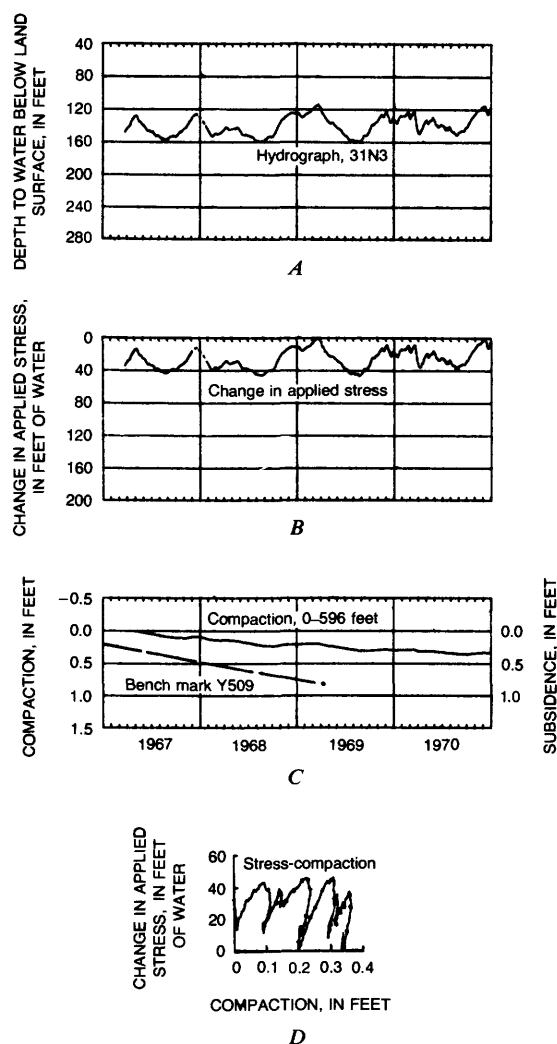


FIGURE 60.—Hydrograph, change in applied stress, compaction, subsidence, and stress-compaction relationship, 15/16-31N3. *A*, Hydrograph of well 15/16-31N3, perforated 497-537 feet, upper zone. *B*, Change in applied stress, water table assumed constant. *C*, Compaction to 596-foot depth at well 15/16-31N3 and subsidence of bench mark Y509, 220 feet north of 15/16-31N3. *D*, Stress change versus compaction of deposits above 596-foot depth.

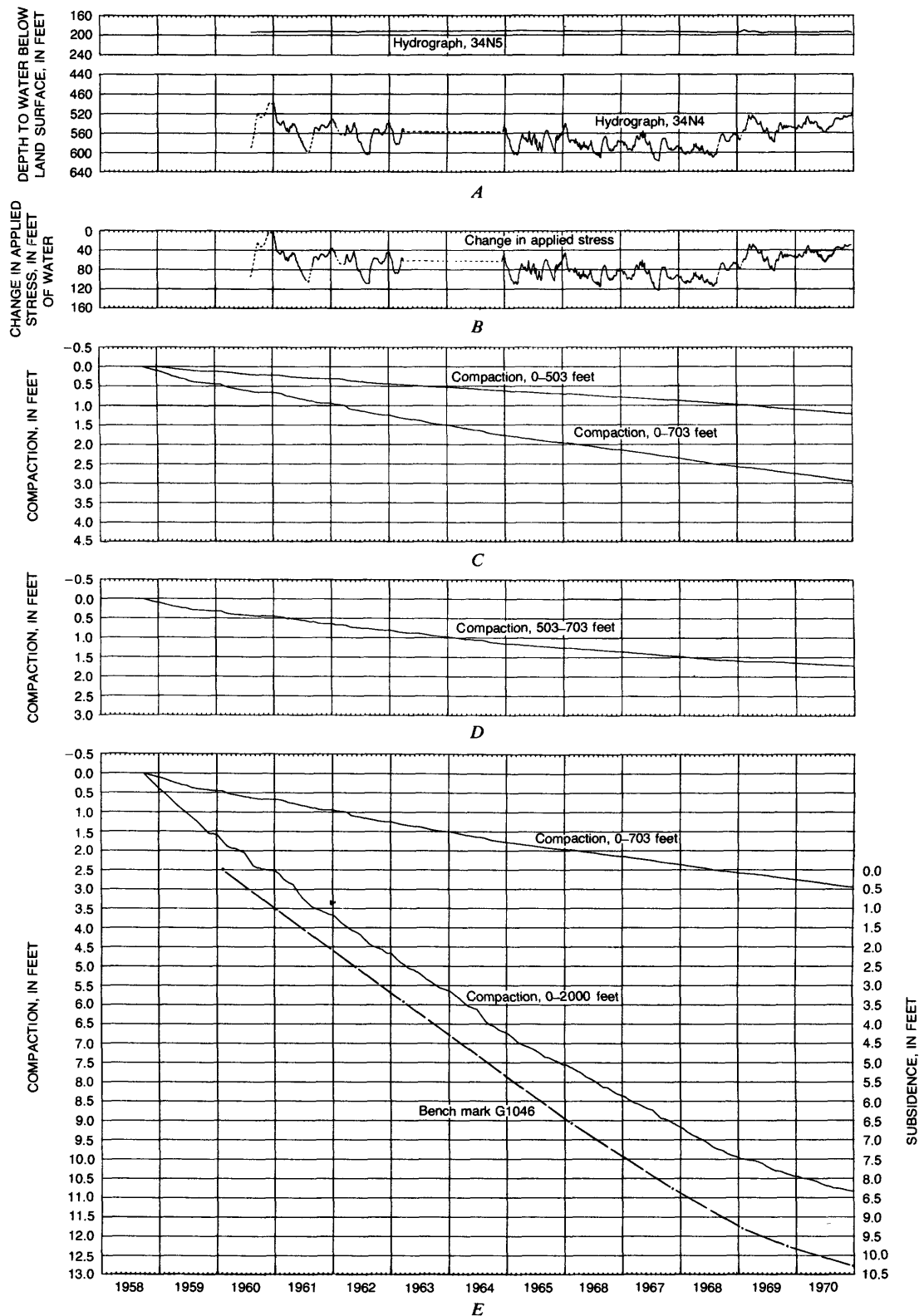


FIGURE 61.—Hydrographs, change in applied stress, compaction, subsidence, casing separation, and stress-compaction relationship, 16/15-34N. A, Hydrographs of wells 16/15-34N5 (water table), perforated 240-300 feet and 16/15-34N4 (lower zone), perforated 1,052-1,112 feet. B, Change in applied stress. C, Compaction to 503-foot depth in well 16/15-34N3 and to 703-foot depth in well 16/15-34N2. D, Compaction in 503-703-foot-depth interval. E, Compaction to 703-foot depth in well 16/15-34N2, to 2,000-foot depth in well 16/15-34N1, and subsidence of bench mark G1046 at well 16/15-34N3. F, Compaction in 703-2,000-foot-depth interval. G, Compaction to 1,096-foot depth and casing separation (compaction to 900-foot depth) in well 16/15-34N4. H, Stress change versus compaction of deposits in the 703-2,000-foot-depth interval. Figure continued on following page.

## STUDIES OF LAND SUBSIDENCE

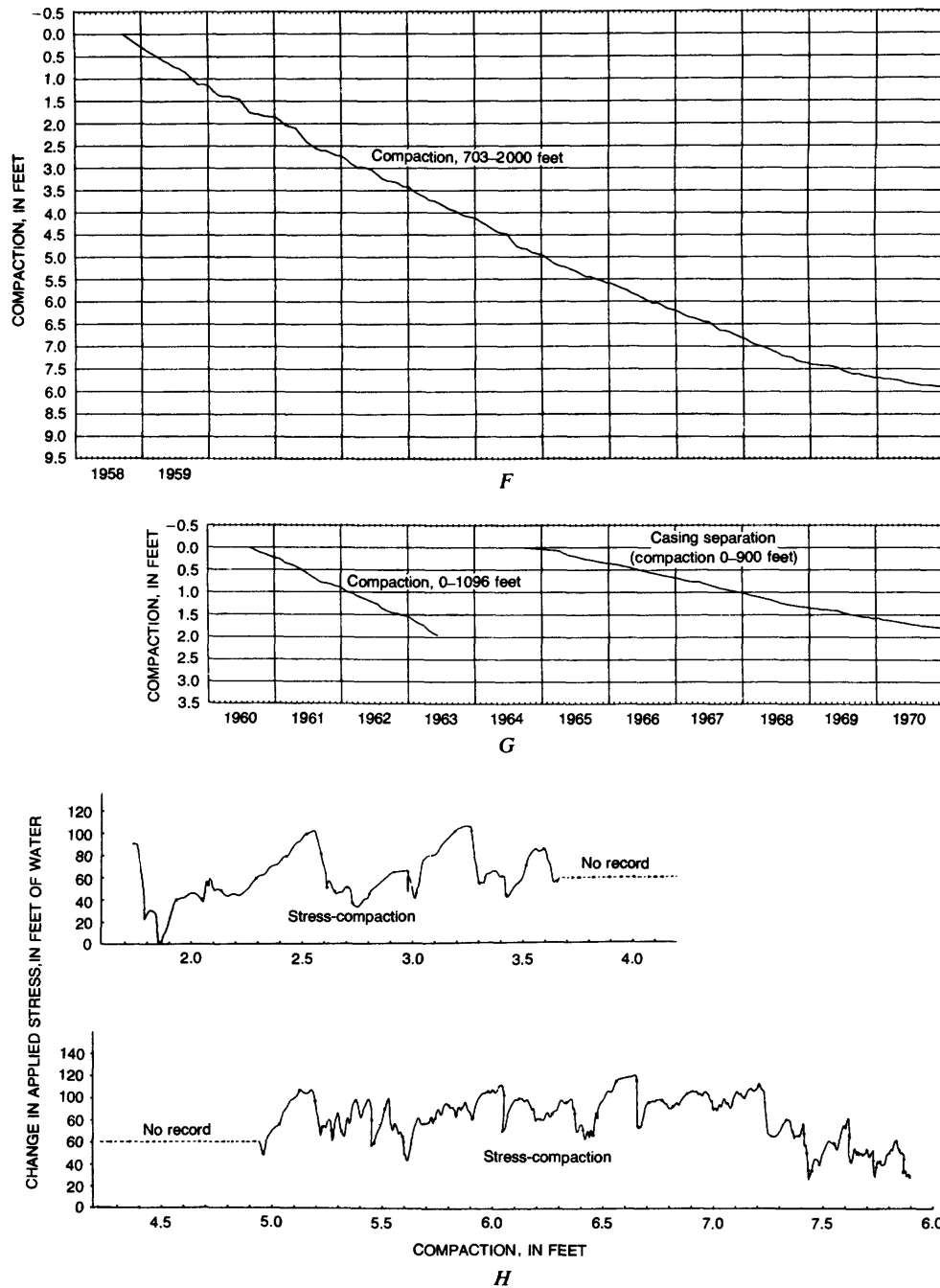


FIGURE 61.—Continued.

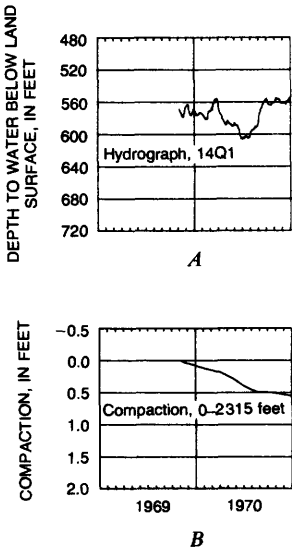


FIGURE 62.—Hydrograph and compaction, 17/15-14Q1. A, Hydrograph of well 17/15-14Q1, perforated 1,064-1,094 feet. B, Compaction to 2,315-foot depth in well 17/15-14Q1.

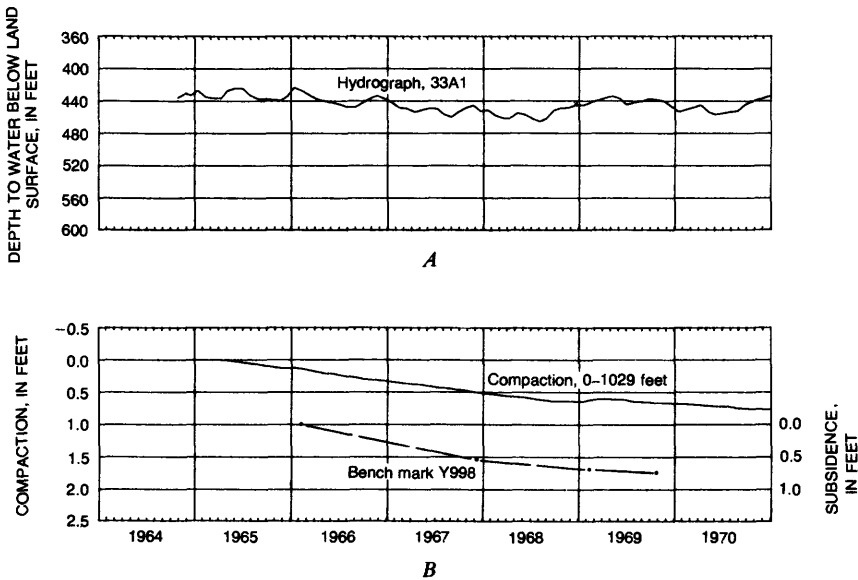


FIGURE 63.—Hydrograph, compaction, and subsidence, 18/16-33A1. A, Hydrograph of well 18/16-33A1, perforated 858-1,070 feet. B, Compaction to 1,029-foot depth and subsidence of bench mark Y998 at well 18/16-33A1.

## STUDIES OF LAND SUBSIDENCE

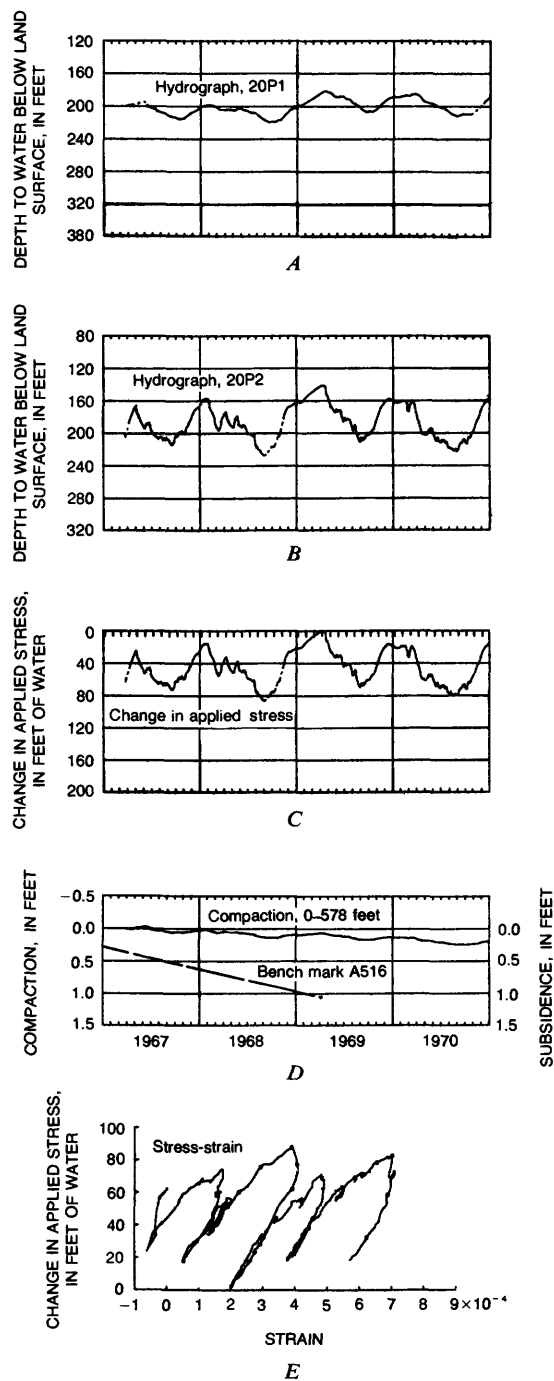


FIGURE 64.—Hydrographs, change in applied stress, compaction, subsidence, and stress-strain relationship, 18/19-20P. *A*, Hydrograph of well 18/19-20P1 (lower zone), perforated 647-687 feet. *B*, Hydrograph of well 18/19-20P2 (upper zone), perforated 497-537 feet. *C*, Change in applied stress (upper zone), water table assumed constant. *D*, Compaction to 578-foot depth at well 18/19-20P2 and subsidence of bench mark A516, one-half mile west. *E*, Stress change versus strain (347-ft thickness).

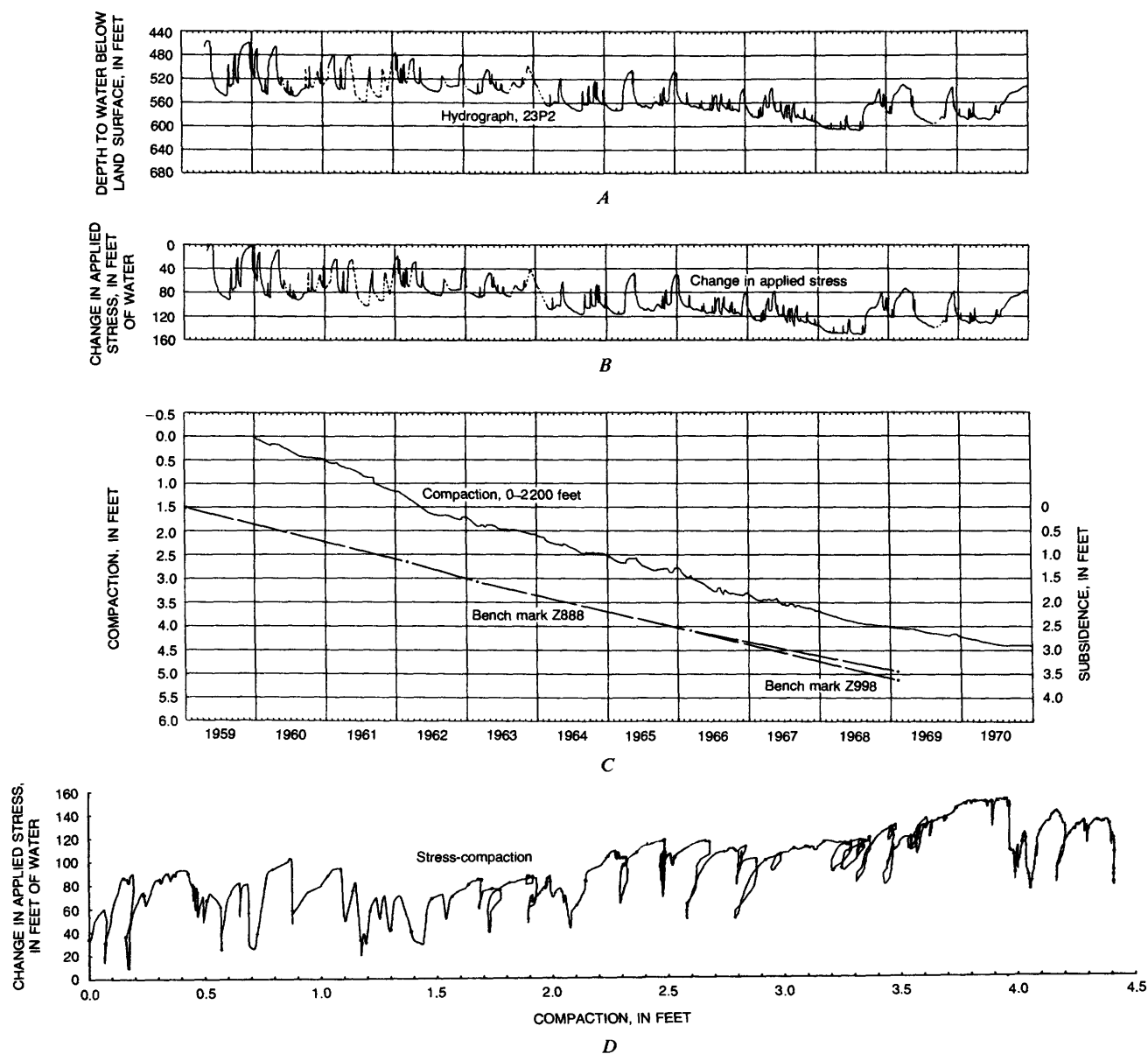


FIGURE 65.—Hydrograph, change in applied stress, compaction, subsidence, and stress-compaction relationship, 19/16-23P2. A, Hydrograph of well 19/16-23P2. B, Change in applied stress, water table assumed constant. C, Compaction to 2,200-foot depth at well 19/16-23P2 and subsidence of bench marks Z888, 575 feet south-southwest, and Z998 at well 19/16-23P2. D, Stress change versus compaction of deposits above 2,200-foot depth.



## STUDIES OF LAND SUBSIDENCE

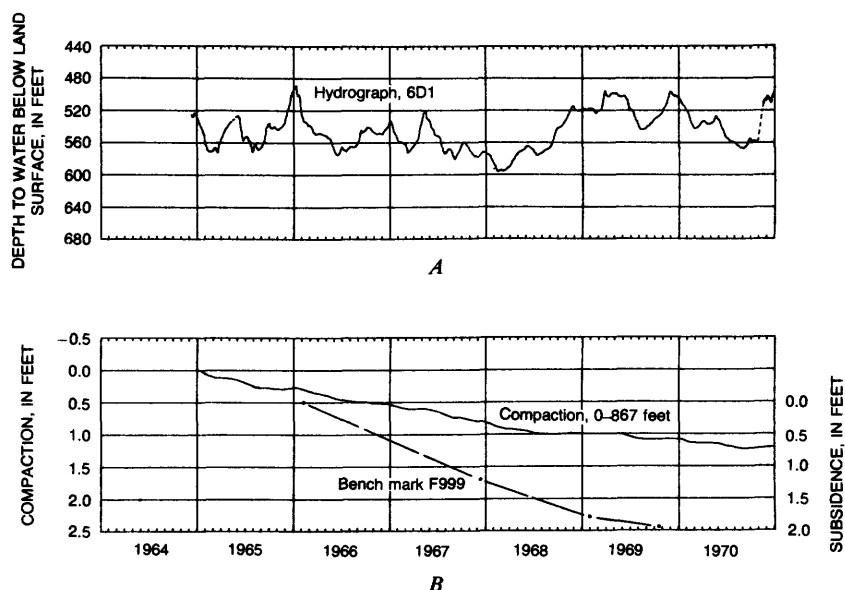


FIGURE 66.—Hydrograph, compaction, and subsidence, 20/18-6D1. A, Hydrograph of well 20/18-6D1, perforated 716-736, 760-835, and 851-872 feet. B, Compaction to 867-foot depth and subsidence of bench mark F999 at well 20/18-6D1.

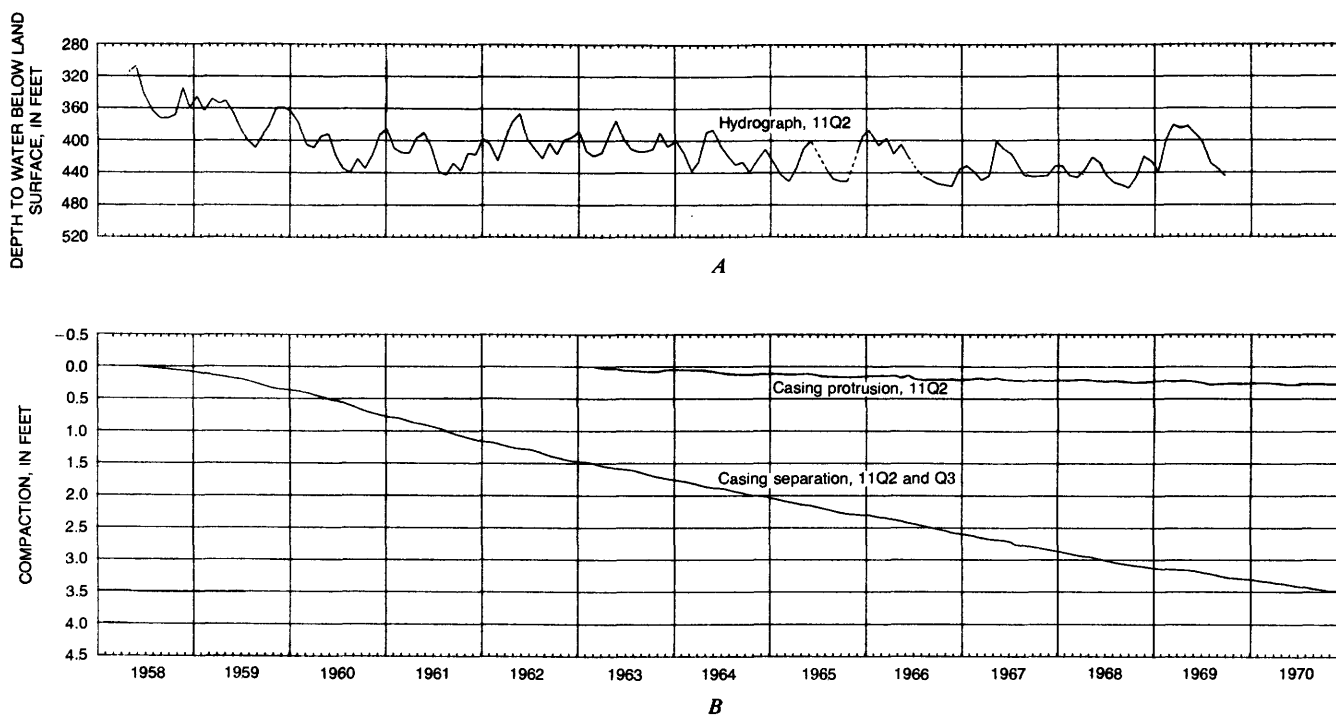


FIGURE 67.—Hydrograph, casing protrusion, and casing separation, 20/18-11Q2 and 20/18-11Q3. A, Hydrograph of well 20/18-11Q2, perforated 755-805 feet. B, Casing protrusion (protrusion of the 11-in. casing, 11Q2, above the land surface) and casing separation (vertical separation between the 11-in. casing, 11Q2, and the 4-in. casing, 11Q3).

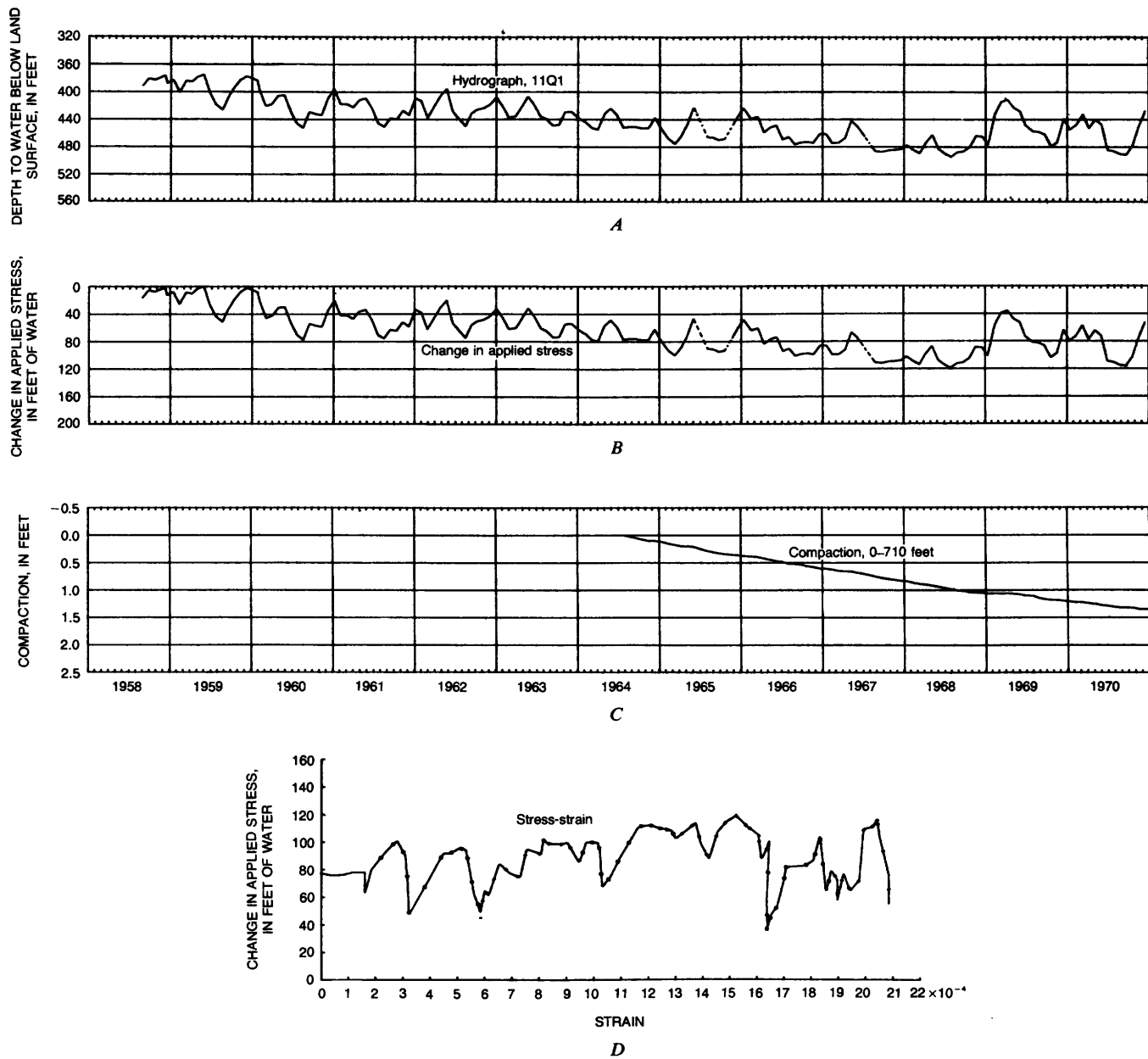


FIGURE 68.—Hydrograph, change in applied stress, compaction, and stress-strain relationship, 20/18-11Q1. A, Hydrograph of well 20/18-11Q1, perforated 650-710 feet. B, Change in applied stress, water table assumed constant. C, Compaction to 710-foot depth at well 20/18-11Q1. D, Stress change versus strain (650-ft thickness).

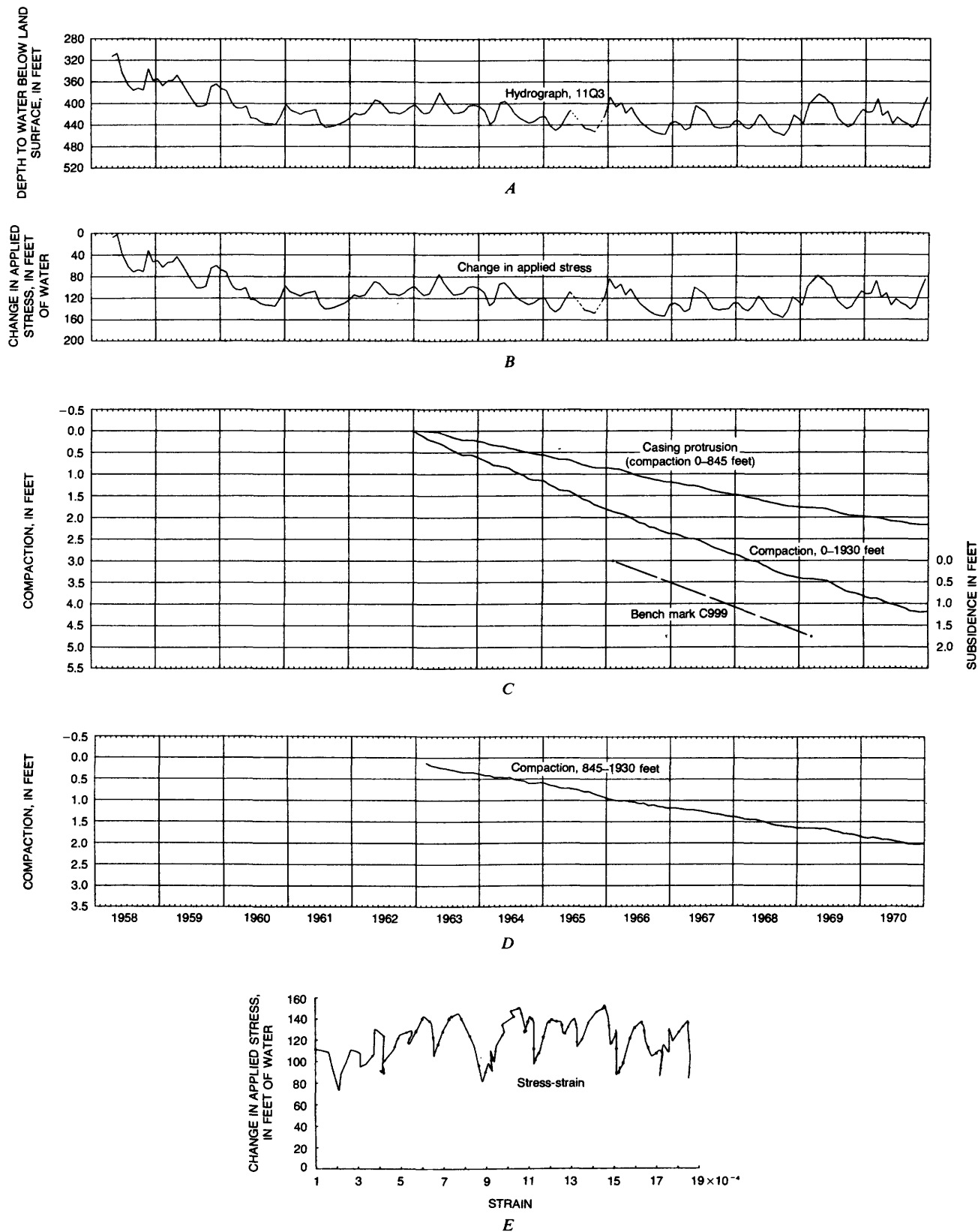


FIGURE 69.—Hydrograph, change in applied stress, compaction, subsidence, and stress-strain relationship, 20/18-11Q3. A, Hydrograph of well 20/18-11Q3, perforated 1,885-1,925 feet. B, Change in applied stress, water table assumed constant. C, Casing protrusion (compaction to 845-ft depth), compaction to 1,930-foot depth, and subsidence of bench mark C999 at well 20/18-11Q3. D, Compaction in 845-1,930-ft depth interval. E, Stress change versus strain (1,085-ft thickness).

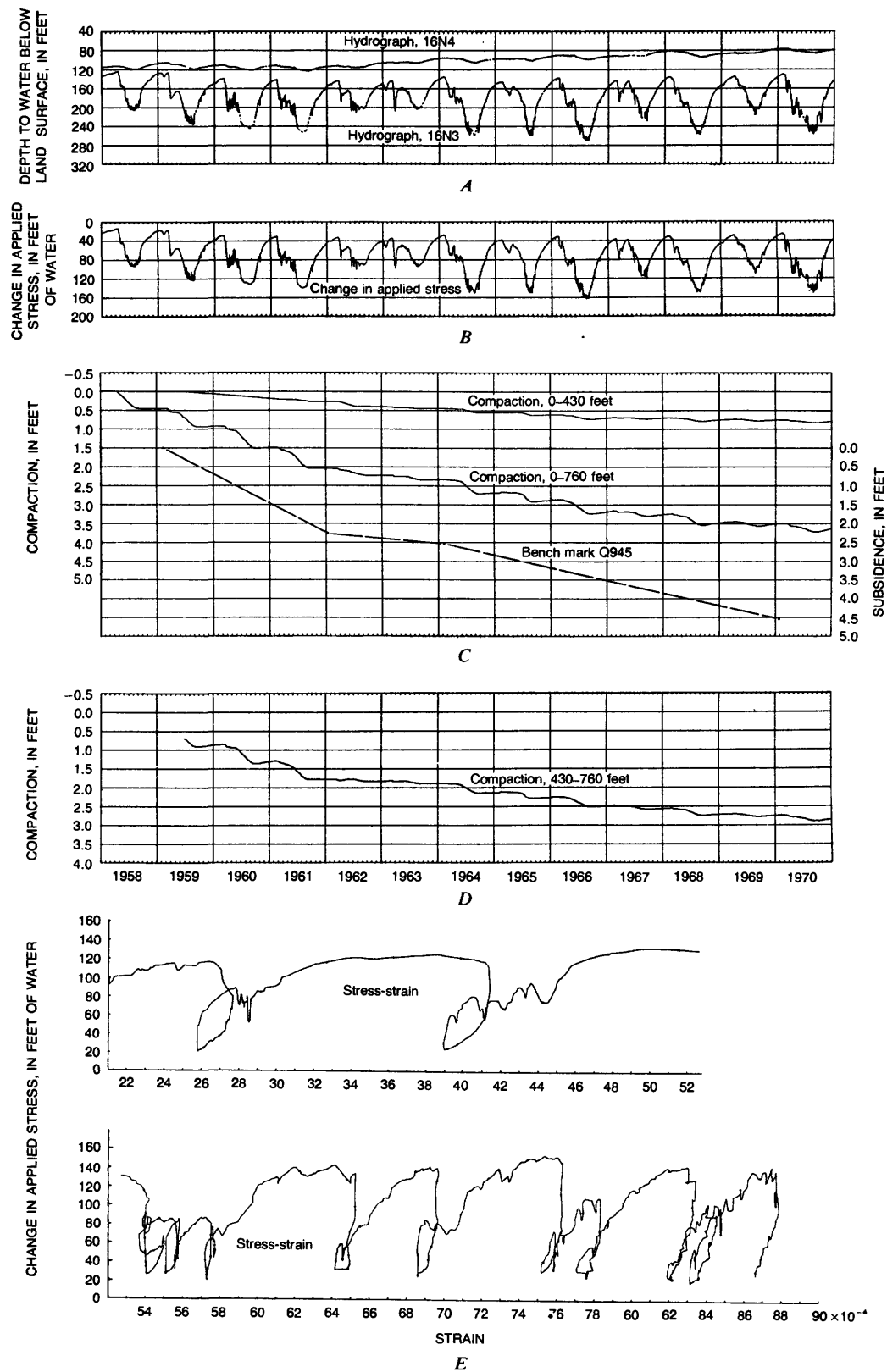


FIGURE 70.—Hydrographs, change in applied stress, compaction, subsidence, and stress-strain relationship, 23/25-16N. A, Hydrographs of wells 23/25-16N4, perforated 200-240 feet, and 23/25-16N3, perforated 360-420 feet. B, Change in applied stress. C, Compaction to 430-foot depth in well 23/25-16N3 and to 760-foot depth in well 23/25-16N1 and subsidence of bench mark Q945 at well 23/25-16N1. D, Compaction in 430-760-foot-depth interval. E, Stress change versus strain (330-ft thickness).

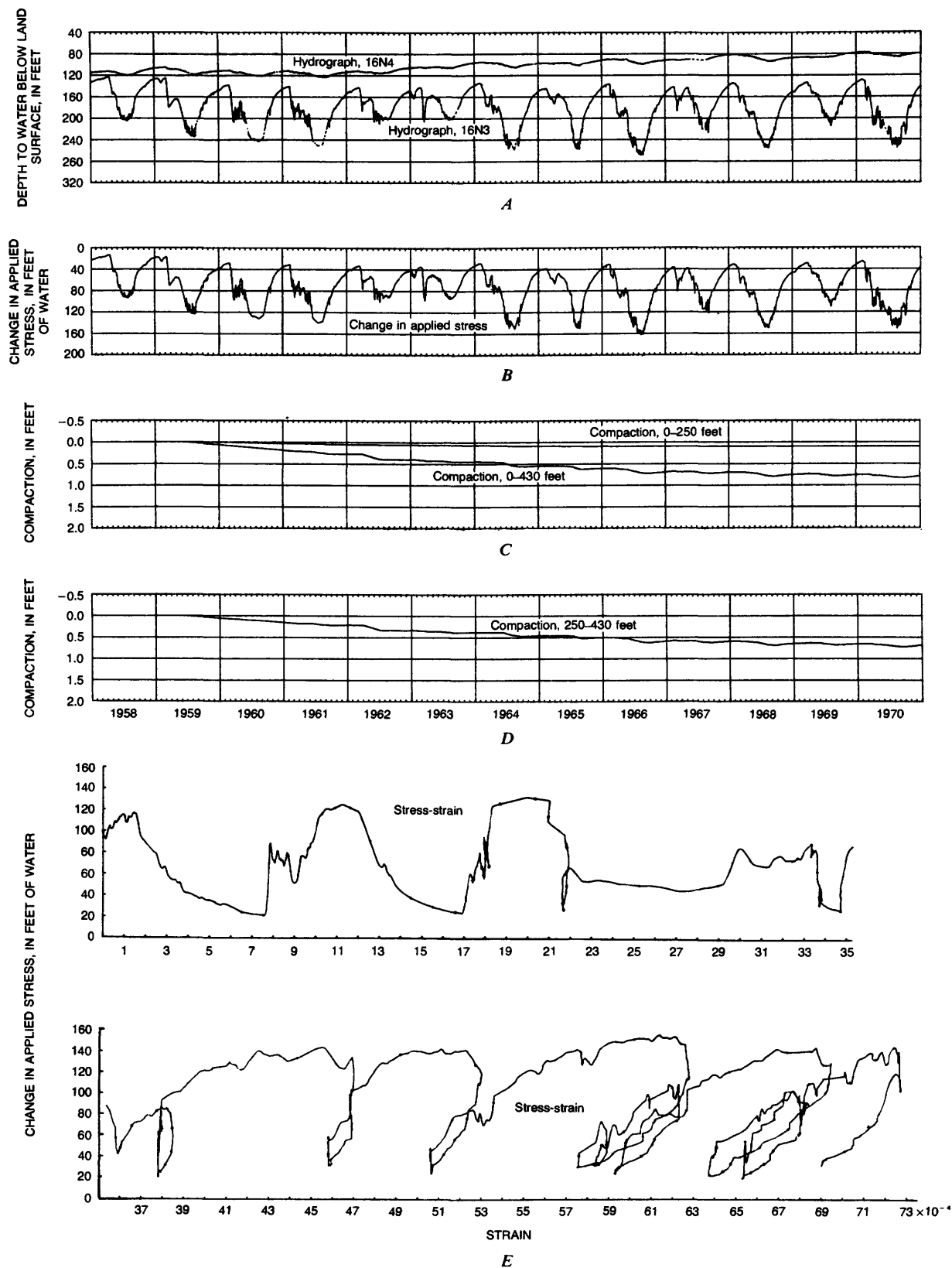


FIGURE 71.—Hydrographs, change in applied stress, compaction, and stress-strain relationship, 23/25-16N3 and N4. A, Hydrographs of wells 23/25-16N4, perforated 200–240 feet, and 23/25-16N3, perforated 360–420 feet. B, Change in applied stress. C, Compaction to 250-foot depth in 23/25-16N4 and to 430-foot depth in 23/25-16N3. D, Compaction in 250–430-foot-depth interval. E, Stress change versus strain (100-ft thickness).

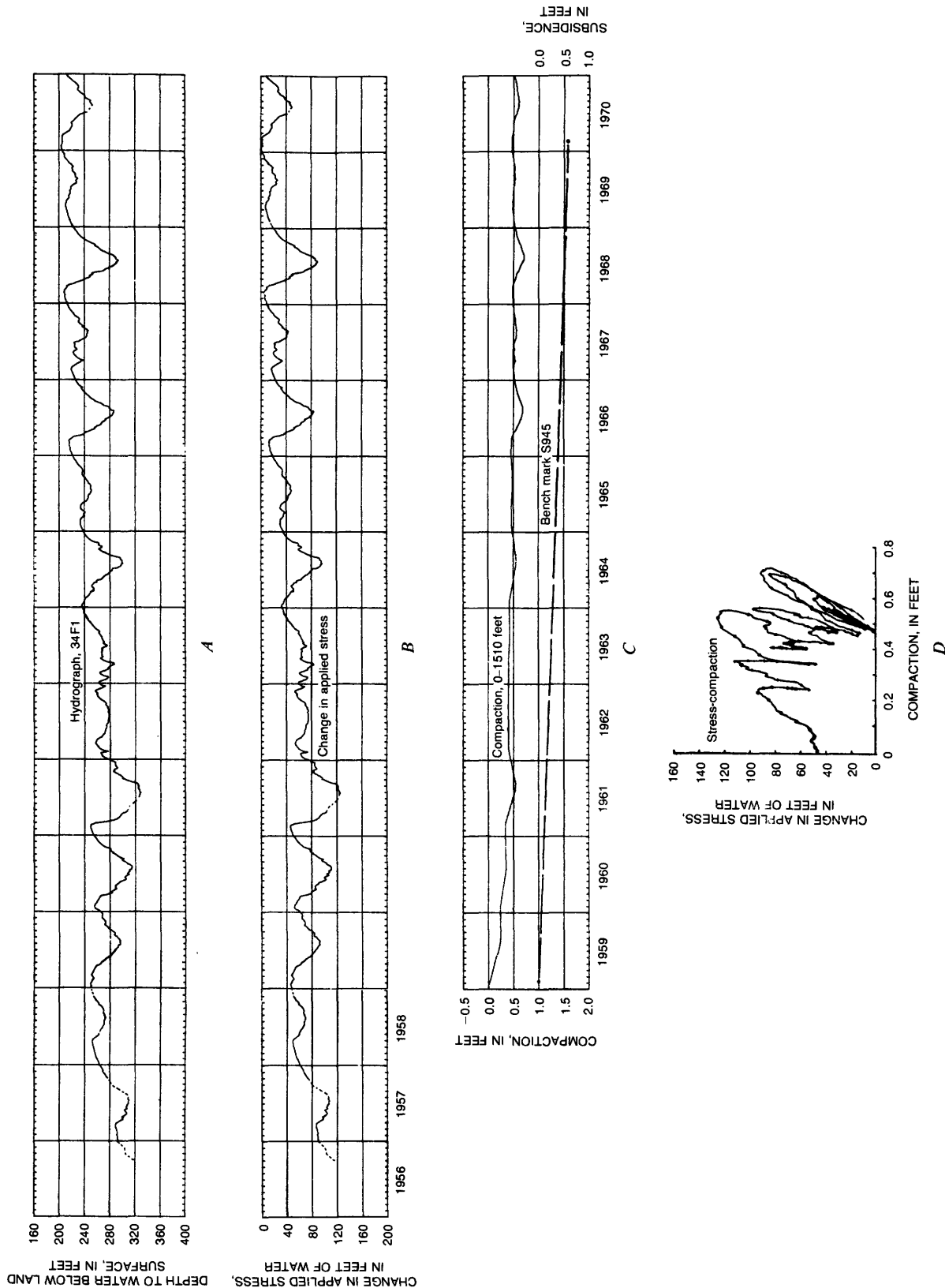


FIGURE 72.—Hydrograph, change in applied stress, compaction, subsidence, and stress-compaction relationship, 24/26-34F1. A, Hydrograph of well 24/26-34F1, perforated 400-1,522 feet. B, Change in applied stress, water table assumed constant. C, Compaction to 1,510-foot depth and subsidence of bench mark S945 at well 24/26-34F1. D, Stress change versus compaction of deposits above 1,510-foot depth.

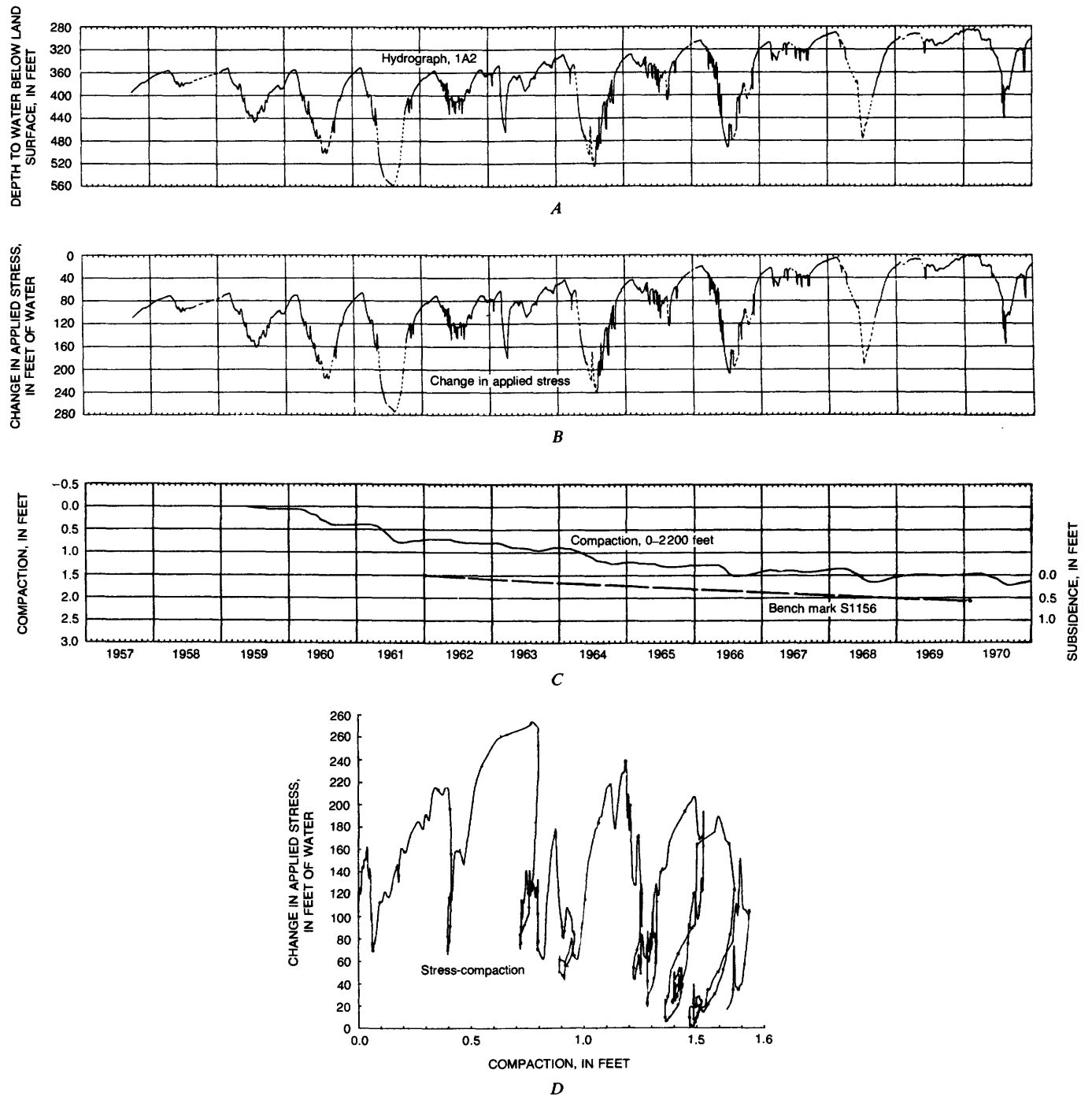


FIGURE 73.—Hydrograph and change in applied stress at well 25/26-1A2 and compaction, subsidence, and stress-compaction relationship at well 24/26-36A2. A, Hydrograph of well 25/26-1A2, perforated 200-600 feet. B, Change in applied stress, water table assumed constant. C, Compaction to 2,200-foot depth at well 24/26-36A2 and subsidence of bench mark S1156, 265 feet east-southeast. D, Stress change versus compaction of deposits above 2,200-foot depth.

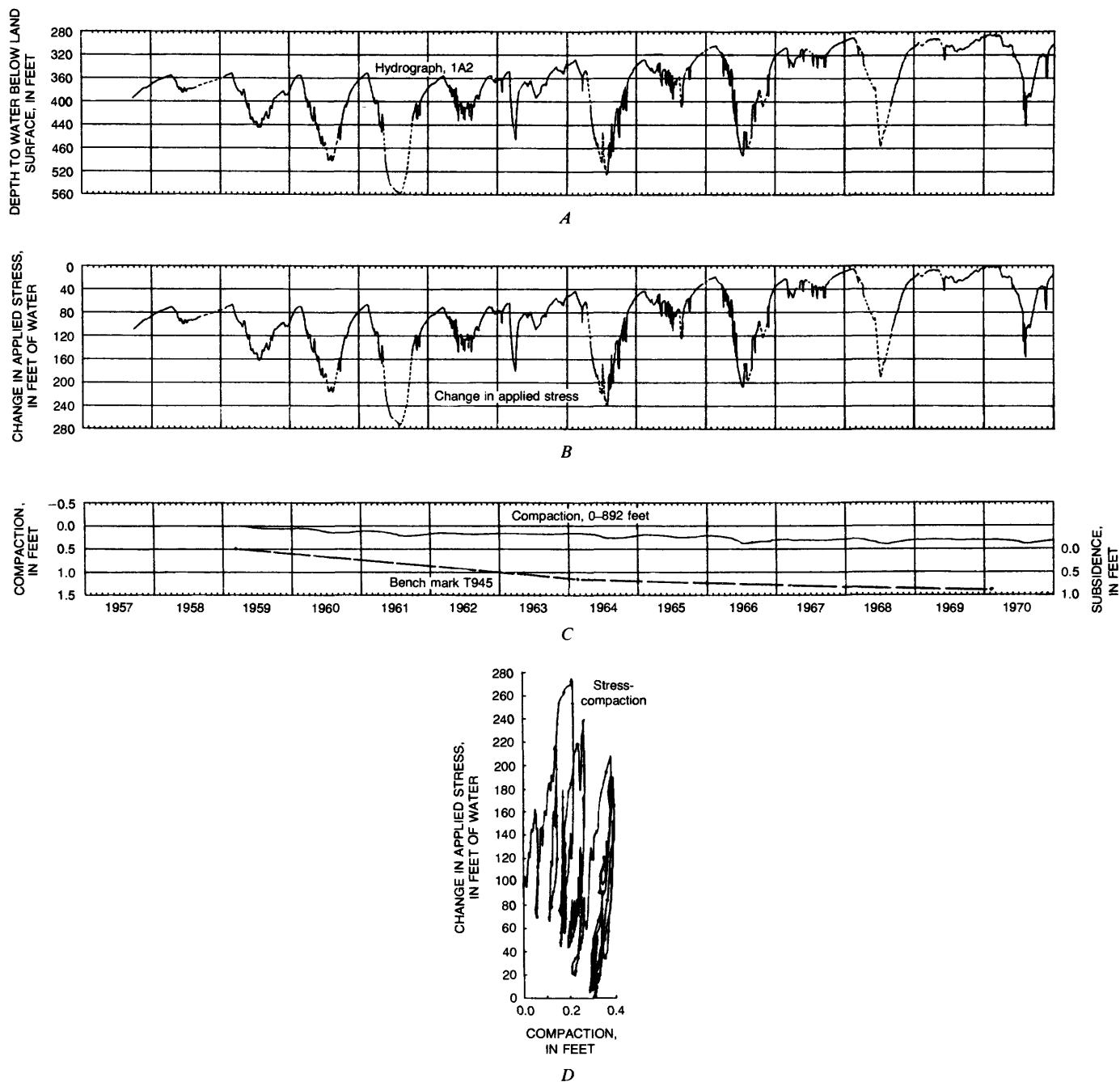


FIGURE 74.—Hydrograph, change in applied stress, compaction, and stress-compaction relationship, 25/26-1A2. *A*, Hydrograph of well 25/26-1A2, perforated 200-600 feet. *B*, Change in applied stress, water table assumed constant. *C*, Compaction to 892-foot depth and subsidence of bench mark T945 at well 25/26-1A2. *D*, Stress change versus compaction of deposits above 892-foot depth.



STUDIES OF LAND SUBSIDENCE

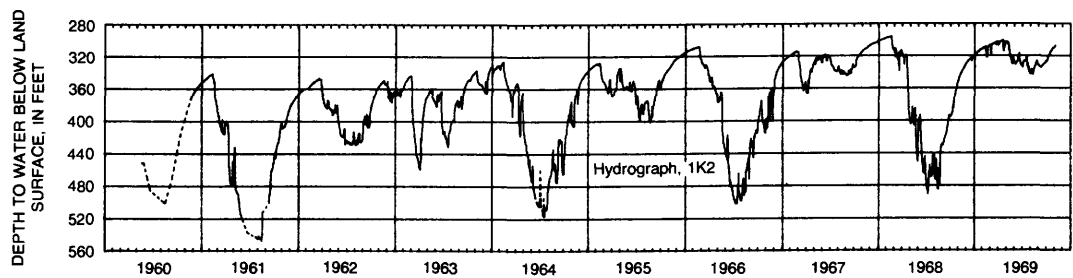


FIGURE 75.—Hydrograph of well 25/26-1K2, perforated 1,000-2,200 feet.

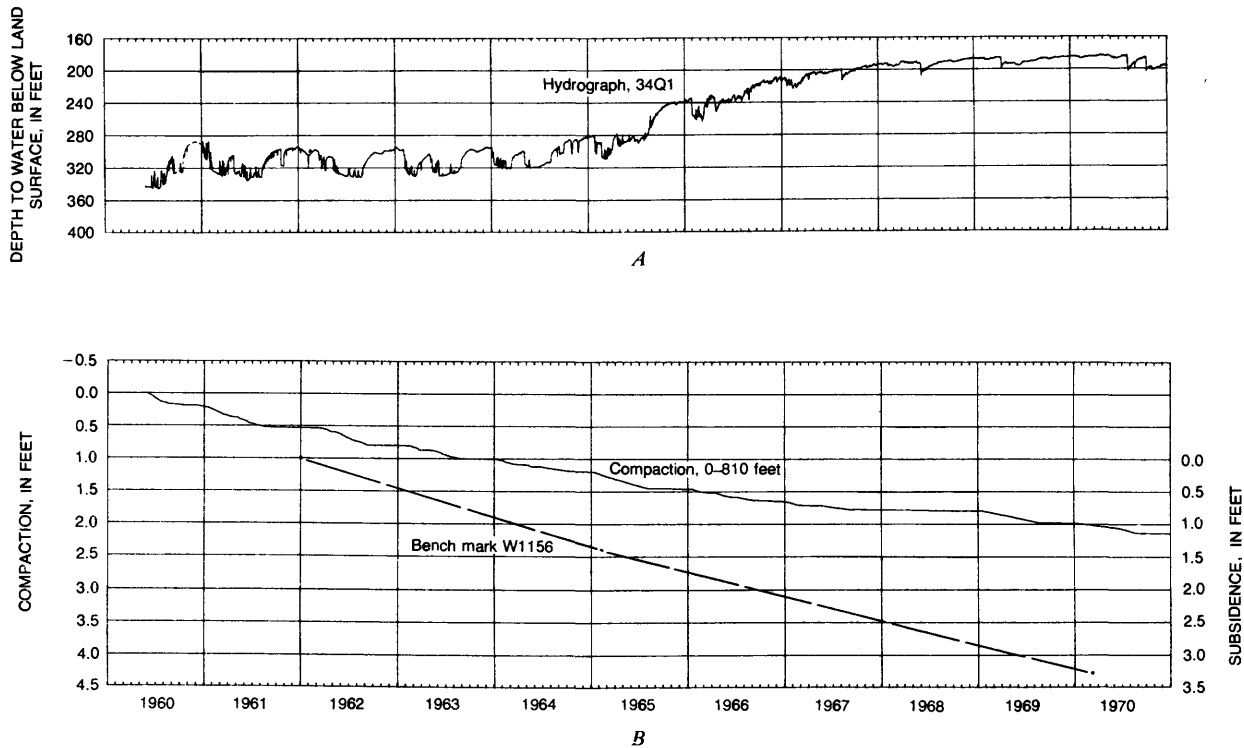


FIGURE 76.—Hydrograph, compaction, and subsidence, 12N/21W-34Q1. A, Hydrograph of well 12N/21W-34Q1, perforated 400-800 feet. B, Compaction to 810-foot depth and subsidence of bench mark W1156 at well 12N/21W-34Q1.

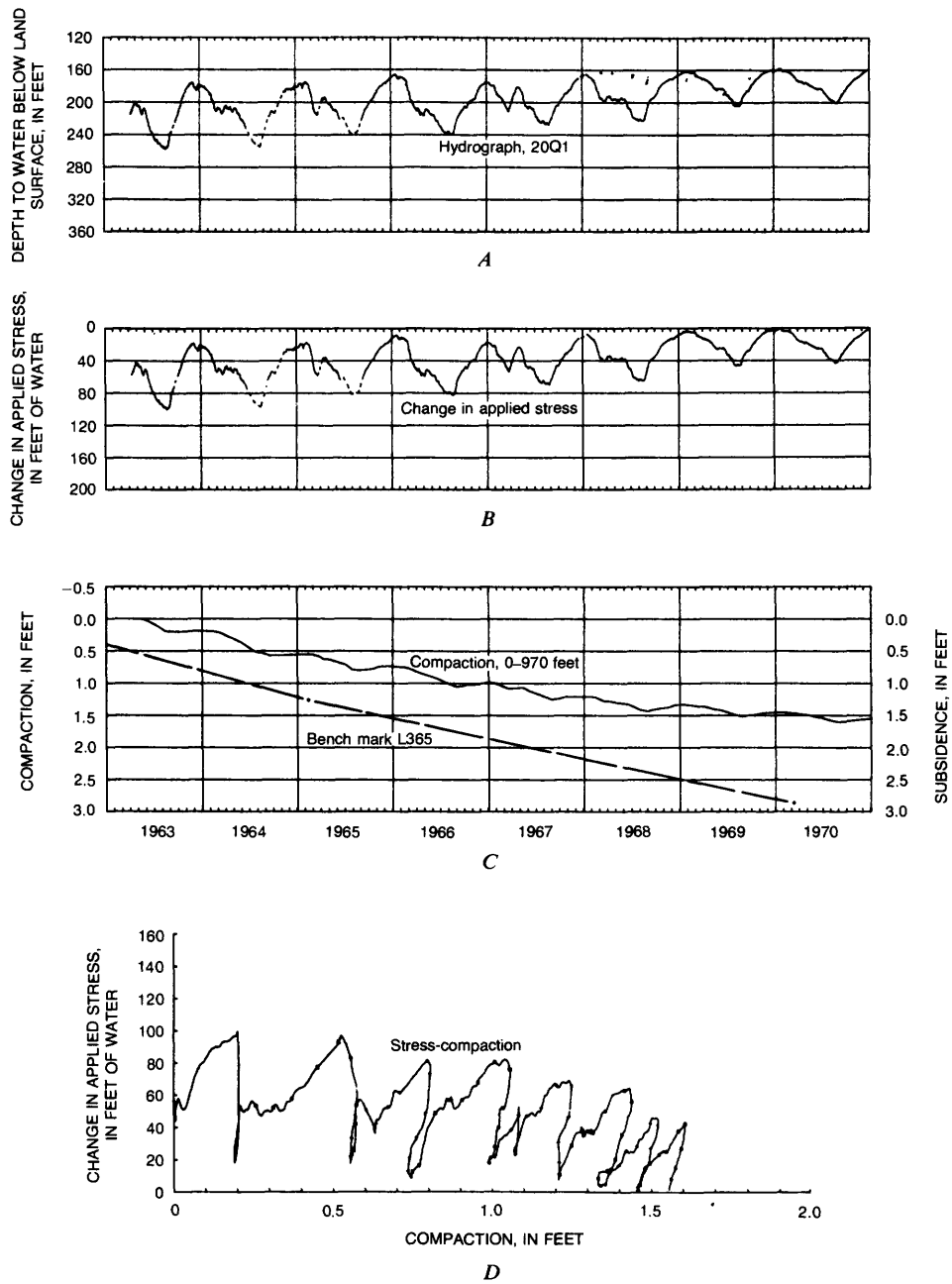


FIGURE 77.—Hydrograph, change in applied stress, compaction, subsidence, and stress-compaction relationship, 32/28-20Q1. A, Hydrograph of well 32/28-20Q1. B, Change in applied stress, water table assumed constant. C, Compaction to 970-foot depth at well 32/28-20Q1 and subsidence at bench mark L365, 1 mile north on State Highway 99. D, Stress change versus compaction of deposits above 970-foot depth.

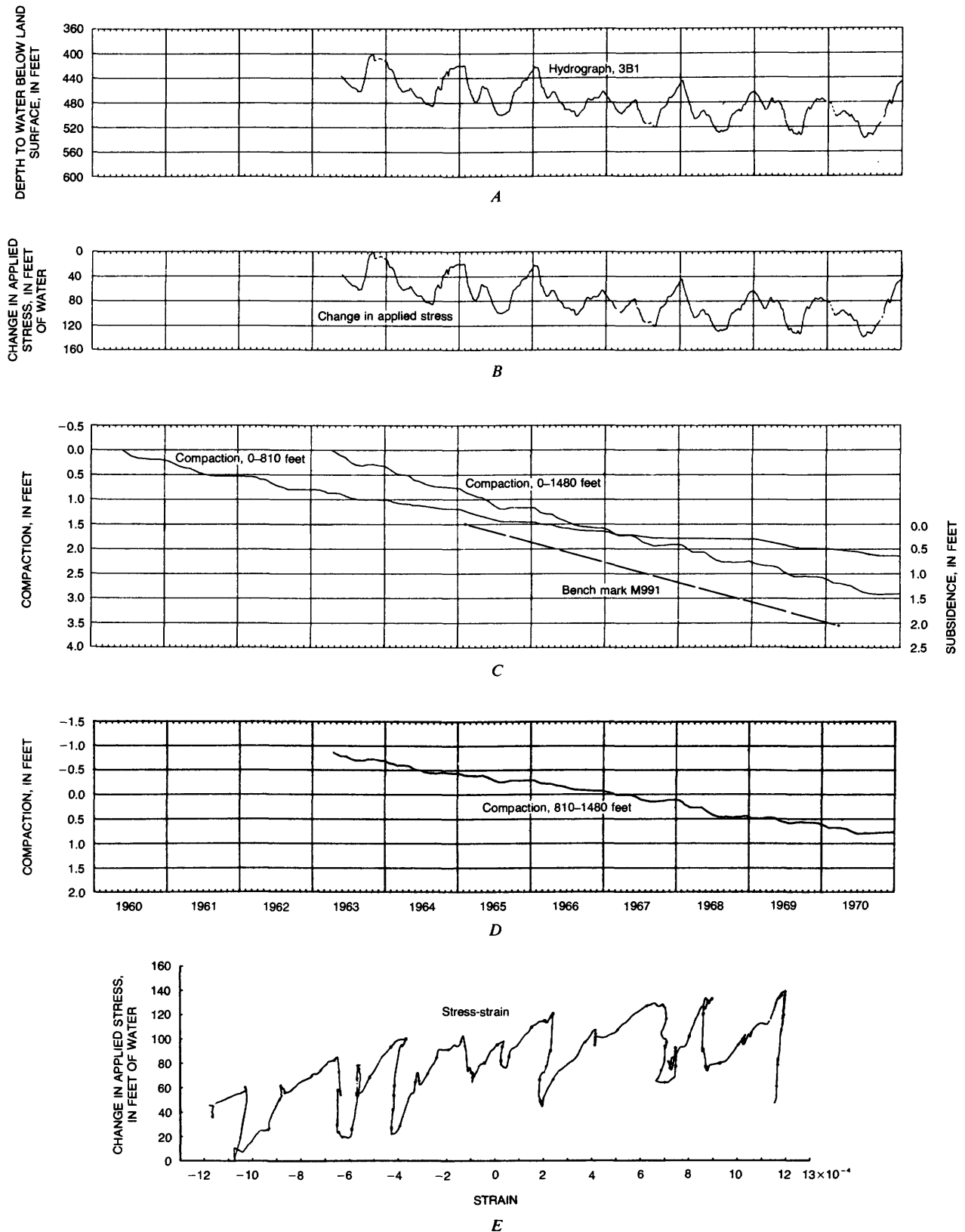


FIGURE 78.—Hydrograph, change in applied stress, compaction, subsidence, and stress-strain relationship, 11N/21W-3B1. A, Hydrograph of well 11N/21W-3B1, perforated 1,037–1,237 feet. B, Change in applied stress, water table assumed constant. C, Compaction to 810-foot depth at well 12N/21W-34Q1 and to 1,480-foot depth at well 11N/21W-3B1 and subsidence of bench mark M991 at well 11N/21W-3B1. D, Compaction in 810–1,480-foot-depth interval. E, Stress change versus strain (670-ft thickness).

TABLE 8.—Notes on wells or sites for which records are included in figures 53–78

[For location of well or site, see fig. 50]

Fig. No.	Well or site No.	Number of compaction plots	Number of hydrographs	Stress-compaction or stress-strain plot made	Remarks
<b>Los Banos-Kettleman City area</b>					
53	12/12-16H	5	2		Complex head relations, lower zone.
54	13/12-20D1	1	1		Primarily observation well, lower zone; compaction measurement includes only part of lower zone.
55	13/15-35D5	1	1		Compaction, upper zone; hydrograph not representative for all stress-change interval. Well is east of Fresno Slough.
56	14/13-11D	3	2	Stress-strain	Compaction for interval 578 ft thick in lower zone.
57	14/12-12H1	1	1		Primarily observation well, lower zone; compaction measurement includes only part of lower zone.
58	15/13-11D2	1	1		Primarily observation well, lower zone; compaction measurement includes only part of lower zone.
59	15/14-14J1	---	1		Representative for the lower zone.
60	15/16-31N3	1	1	Stress-compaction	Compaction and hydrograph, upper zone.
61	16/15-34N	6	2	do	Compaction for interval 1,297 ft thick in lower zone.
62	17/15-14Q1	1	1		Deepest compaction anchor, 2,315 ft below land surface.
63	18/16-33A1	1	1		Primarily observation well, lower zone; compaction measurement includes only part of lower zone.
64	18/19-20P	1	2	Stress-strain	Compaction and water level, upper zone.
65	19/16-23P2	1	1	Stress-compaction	Compaction to depth of 2,200 ft.
66	20/18-6D1	1	1		Primarily observation well, lower zone; compaction measurement includes only part of lower zone.
67	20/18-11Q2	1	1		Casing-separation plot; hydrograph for top of lower zone.
68	20/18-11Q1	1	1	Stress-strain	Compaction and hydrograph, upper zone.
69	20/18-11Q3	1	1	Stress-strain	For most of lower zone; hydrograph for lower part of lower zone.
<b>Tulare-Wasco area</b>					
70	23/25-16N	3	2	Stress-strain	Confined system, compaction in 430–760-ft-depth interval.
71	Do	3	2	do	Confined system, assumed all compaction in 250–430-ft-depth interval occurred in 330–430-ft depth.
72	24/26-34F1	1	1	Stress-compaction	Compaction to 1,510 ft.
73	24/26-36A2	1	---	do	Assumed that hydrograph for 1A2 represents stress change in compacting zone of 36A2.
73	25/26-1A2	---	1		
74	Do	1	1	Stress-compaction	Compaction measured to depth of 892 ft. Perforated 1,000–2,200 ft.
75	25/26-1K2	---	1		Perforated 1,000–2,200 ft.

## STUDIES OF LAND SUBSIDENCE

TABLE 8.—Notes on wells or sites for which records are included in figures 56-78—Continued

Fig. No.	Well or site No.	Number of compaction plots	Number of hydrographs	Stress-compaction or stress-strain plot made	Remarks
<b>Arvin-Maricopa area</b>					
76	12N/21W-34Q1 -----	1	1	-----	Well 810 ft deep.
77	32/28-20Q1 -----	1	1	Stress-compaction	Well 970 ft deep.
78	11N/21W-3B1 -----	2	1	Stress-strain	Well 1,480 ft deep, but strain computed for 670-ft thickness.



