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LAND SUBSIDENCE DUE TO GROUND-WATER WITHDRAWAL

ARVIN-MARICOPA AREA, CALIFORNIA

By Ben E. Lofgren

Prepared in cooperation with the

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ABSTRACT

The Arvin-Maricopa area is the southernmost of three principal areas of widespread subsidence in the San Joaquin Valley. As of 1970, 700 square miles of irrigable land, roughly 60 percent of the area, has subsided due to the intensive pumping of ground water. Maximum subsidence exceeds 9 feet, and the total volume of subsidence (1926-70) is about 1 million acre-feet. Subsidence results from the compaction of water-yielding deposits as intergranular stresses are increased by water-level declines. Also, scattered local areas are affected by the hydrocompaction of moisture-deficient surficial deposits and by subsidence due to the extraction of oil-field fluids.

The use of ground water in the Arvin-Maricopa area greatly increased during the late forties and fifties. This resulted in the accelerated decline of water levels and accompanying land subsidence in the central part of the area. Significantly, this was a period of below-normal precipitation and severely deficient ground-water recharge. From 1947 through 1966 above-normal runoff occurred in only 3 years, and a runoff deficiency of 2,500,000 acre-feet accumulated for the Kern River. With the return of normal precipitation and the importation of surface water from the Friant-Kern Canal and the California Aqueduct, the ground-water supply could easily change from one of shortage to one of excess. Quite possibly, the ground-water levels of the late sixties could be the lowest of all time--past and future.

The subsidence/pumpage ratio is a measure of the proportion of the ground-water pumpage represented by mined "water-of-compaction." For the period 1962-65 this ratio varied from a few percent around the perimeter of the subsidence area to more than 40 percent in the area of maximum subsidence. When contoured, these ratios clearly define areas where surface-water imports would have the most significant effect in alleviating subsidence.

The subsidence/head decline ratio is a rough approximation of the compressive response of the aquifer system to changes in stress related to water-level declines, and is one of the most effective tools in estimating future subsidence. In the Arvin-Maricopa area this ratio varied from 3.2×10^{-3} to 5.06×10^{-2} for the period 1957-65.

As in other subsidence areas of the San Joaquin Valley, subsidence will continue in the Arvin-Maricopa area as long as declining water levels continue to cause increased effective stresses, and stop as soon as excess pore pressures in the aquitards are dissipated. Beginning in the mid-sixties, significant quantities of canal water were imported into the Arvin-Maricopa area, with the dual effect of increasing recharge to the ground-water reservoir and reducing ground-water pumpage. Imports were greatly increased to the southeastern part of the area in 1969 and to the southwestern part of the area in 1971. As of the end of 1970, water levels in key observation wells showed a definite decrease in downward trend and compaction recorders at two sites indicated an abrupt flattening of the subsidence trend. By 1972, measured compaction at Lakeview was less than one-quarter the rate of three years earlier.

INTRODUCTION

The Subsidence Problem

One-half of the entire San Joaquin Valley is currently (1972) affected by land subsidence caused by man's exploitation of the natural resources. About 4,300 square miles have subsided more than 1 foot, and maximum subsidence exceeds 28 feet. This subsidence is of great economic and environmental significance, and has been studied in detail by various agencies for about 15 years. Results from these studies not only provide answers to some of the management problems of the San Joaquin Valley, but are applicable to subsidence problems in other areas.

Four quite unrelated processes are causing land subsidence in the San Joaquin Valley due to man's activities. Although each of these results in a net lowering of the land surface, they are different in their causes and effects, and must be differentiated to be properly understood. In descending order of areal extent, these processes are: (1) subsidence caused by the intensive pumping of ground water, (2) subsidence due to the collapse of moisture-deficient deposits when water is first applied--a process known as hydrocompaction, (3) lowering of the land surface due to the oxidation of organic soils, principally in the delta area of the Sacramento and San Joaquin Rivers, and (4) local subsidence caused by the extraction of fluids from producing zones in several oil fields. Collectively, these processes have produced major changes of the land surface, have necessitated significant changes in land use, caused extensive damage to thousands of deep well casings and to many large structures, and have involved millions of dollars in remedial design and construction costs. In addition, tectonic adjustments--principally slow uplift of some of the mountain areas and very slow settlement of the valley floor--are recognized in the southern and western parts of the valley.

The Arvin-Maricopa area, in which three of the above types of subsidence occur, is the southern of three principal areas of widespread subsidence in the San Joaquin Valley. As of 1970, roughly 700 square miles of irrigable land were affected by subsidence, and the maximum subsidence rate exceeded 0.5 foot per year. Maximum subsidence approached 9 feet, and the total volume of subsidence was more than 1,060,000 acre-feet. Most of this subsidence is due to the overdraft of ground water, representing a one-time "mining" of the ground-water resource and a permanent decrease in the storage capacity of the area. Subsidence due to hydrocompaction is also prevalent, particularly on the southern and western margins of the area. Oil-field subsidence is presently of secondary significance, although during earlier periods of heavy production it may have been more extensive. Certainly, an understanding of the magnitude and extent of subsidence that is occurring, and the natural and manmade processes that are causing it, is essential for the successful management of this highly productive ground-water basin and for most efficient construction and maintenance of canals and other large engineering structures in the area.

Location and General Features

The Arvin-Maricopa area comprises 1,140 square miles of relatively flat alluvial plain in the extreme southern end of the San Joaquin Valley and the south-central part of Kern County, Calif. (fig. 1). It is bounded

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Figure 1 near here.

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on three sides by mountainous terrain and opens northwestward into the main part of the San Joaquin Valley. It includes the usually dry Buena Vista and Kern Lake beds and the coalescing alluvial fans that slope valleyward from the Sierra Nevada foothills on the east, the Tehachapi and San Emigdio Mountains on the south and the Coast Ranges on the west.

Kern River, entering the area at Bakersfield, is the principal source of surface water and, in an average year, probably represents about 90 percent of the total natural streamflow into the area. In the early days, the natural and artificial distributaries of Kern River covered the northwestern half of the Arvin-Maricopa area and were the principal source of recharge to the ground-water basin. Many changes have occurred, however, since farming began. Gradual changes in the hydrologic regime have occurred throughout the basin and, since the completion of the Isabella Dam in 1954, the flow of Kern River has been closely regulated to supply irrigation needs. Further changes to the hydrologic regime will undoubtedly result from the importation of large quantities of canal water into the area. Delivery from the Friant-Kern Canal (fig. 3) began in 1962, and delivery to the western part of the area from the California Aqueduct began in 1971.

Bakersfield, with a 1970 population of 69,515, is the principal social and commercial center, with a half dozen smaller communities scattered in the area. Most of the Arvin-Maricopa area is intensely farmed and irrigation demands are great. Ground-water pumpage from an estimated 2,300 irrigation wells (1965), ranging in depth from 300 to more than 1,500 feet, supplies as much as two-thirds of the total irrigation requirements. Alfalfa, cotton, potatoes, deciduous fruits, grapes, grains, and beef cattle, are the principal agricultural products.

The production of oil and gas has been a major industry in the area since the turn of the century. Thousands of active wells in more than a dozen fields make this one of the important petroleum centers of the State. At the west edge of the Arvin-Maricopa area, the Midway-Sunset oil field has joined the exclusive "billion-barrel club," and the Elk Hills oil field, considered to be the third largest in the United States, has an estimated billion barrels in reserve. Some subsidence attributed to the extraction of oil and gas has been observed over several of the producing fields.

Purpose and Scope of the Investigation

In July 1956, after several planning meetings by an interagency committee of various concerned Federal and State agencies, an intensive investigation of land subsidence in the San Joaquin Valley was begun. The objectives of this cooperative investigation were:

1. To obtain vertical control on the land surface adequate to define the extent, rate, and magnitude of subsidence.
2. To determine causes of the subsidence and the relative magnitude attributable to the different causes; also, the depth range within which compaction is occurring.
3. To furnish criteria for estimating the rates and amounts of subsidence that might occur under assumed hydrologic change; to determine whether any part of the subsidence is reversible and, if so, to what extent; and to suggest methods for decreasing or stopping subsidence.

Subsidence studies in the San Joaquin Valley by the Geological Survey have continued since 1956, in financial cooperation with the California Department of Water Resources. At first, the cooperative investigation encompassed two principal areas of subsidence, the Los Banos-Kettleman City area (2,000 square miles), chiefly in western Fresno County, and the Tulare-Wasco area (1,200 square miles) in Tulare and Kern Counties. The investigation was later expanded to include the Arvin-Maricopa area which is the subject of this report..

Detailed studies of the geology and ground-water features of parts of the Arvin-Maricopa area have been completed by the Geological Survey (Wood and Dale, 1959 and 1964; Dale, French, and Gordon, 1966; Croft, 1969). These studies serve as background information for this subsidence investigation. No attempt is made here to restate general geologic and hydrologic findings of these earlier reports. For further details on the geology and hydrology of the region, the reader is referred to these earlier Survey publications and to various other studies referenced throughout this report.

This report is one of a series describing the results and conclusions of subsidence studies by the Geological Survey in the San Joaquin Valley. Areal studies of the effects of ground-water pumping in the Tulare-Wasco area (Lofgren and Klausing, 1969) and the Los Banos-Kettleman City area (Bull and Miller, 1972; Bull, 1972; Bull and Poland, 1972) cover the principal subsidence areas of Fresno, Tulare, and northern Kern Counties, and are similar in scope to this report. Also, clay-mineral analyses of core samples from the San Joaquin Valley and interpretive studies related to the compaction of fine-grained sediments by Meade (1964, 1967, and 1968) are of direct interest. Bull (1964) made a detailed study of hydrocompaction (near-surface subsidence) in western Fresno County, which is similar to the hydrocompaction in this area.

The purpose of this report is to describe the pertinent geologic and hydrologic features of the Arvin-Maricopa ground-water reservoir; to present the historic change of water levels and the resulting effective-stress increases that caused most of the subsidence; to describe the various types of land subsidence; to report on field measurements of aquifer-system compaction and relate this to subsidence; to furnish criteria for estimating future subsidence under assumed hydrologic change; to determine what part of the subsidence is reversible; to suggest methods for decreasing or alleviating the subsidence; and to anticipate the effects of imported canal water on subsidence trends.

This is largely an interpretive report, based on data collected over many years by many organizations. No geologic mapping or well measuring programs were included in the study. Compaction and water-level recorders were installed in 1959 in three unused irrigation wells and one shallow bored hole. In 1963, a 1,480-foot observation well was drilled near the center of maximum subsidence, and recorders were installed to measure compaction and water-level change to the depth of most of the irrigation wells in the area. These recorders have been maintained to the present (1972), and have provided definitive data on the direct relationship between water-level changes and compaction.

It is not intended that this report be considered as final. Rather, it interprets the results of the investigation through 1970, and draws general conclusions based on the information then available. Undoubtedly, major changes in the hydrologic regime of the ground-water basin, due to large imports of canal water beginning in 1967, will have a significant effect on the trend of subsidence throughout the area. It is suggested that water-level and compaction recorders be maintained and that subsidence be monitored as long as it continues in the area. Surveillance of subsidence and hydrologic changes is essential for the long-term management of the ground-water reservoir, and will contribute to the understanding of the causes and effects of land subsidence. Since this report was written, significant changes have occurred in the area, due largely to the recent importation of large quantities of canal water. Several of the graphs have been updated to include data through 1972.

Well-Numbering System

The well-numbering system used in California by the Geological Survey and by the State shows the locations of wells according to the rectangular system for the subdivision of public lands. For example, in well 31/29-36D1, which is 1 mile south of Arvin, the first two segments of the number designate the township (T. 31 S) and the range (R. 29 E.); the third gives the section (sec. 36); and the letter indicates the 40-acre subdivision of the section, as shown in figure 2.

Figure 2 near here.

Within each 40-acre tract, the wells are numbered serially, as indicated by the final digit of the number. Thus, well 31/29-36D1 is the first well to be listed in the NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 36, T. 31 S., R. 29 E. As most of the San Joaquin Valley is in the southeast quadrant of the Mount Diablo base line and meridian, the letters S and E after the township and range may be omitted. The area south of the eighth standard parallel (Copus Road-David Road), however, is referred to the San Bernardino base line and meridian. Wells in that area are distinguished by use of the letters N and W after the township and range, respectively, as for example, well 11N/19W-30N1 at Wheeler Ridge.

Physical or hydrologic features, other than wells, are described by use of a similar location number but without the final digit. For example, an oil well in the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 4, T. 30 S., R. 29 E., near Edison, may be described as being in 30/29-4H.

Acknowledgments

Many agencies, organizations, and individuals contributed information and assistance during this investigation. Most of the water-level measurements used were made by the U.S. Bureau of Reclamation, California Department of Water Resources, and Kern County. Leveling data used extensively throughout this report for computing all land subsidence and tectonic deformation were by the U.S. Coast and Geodetic Survey, in financial cooperation with the California Department of Water Resources. Areas of known hydrocompaction were delineated early in the investigation by the California Department of Water Resources. Computations of pumpage were made by the Geological Survey from power data supplied by the San Joaquin Division of the Pacific Gas and Electric Co. The Standard Oil Company of California, Kern County Land Company, and Bidart Brothers gave permission to install compaction recorders on their property. Acknowledgment is extended to all these agencies, and to the many residents and company representatives who furnished basic data and assistance during this study.

This study has been under the general direction of J. F. Poland, research hydrologist in charge of subsidence studies. R. L. Ireland assisted in the installation of water-level and compaction recorders and, with R. G. Pugh, has had responsibility for their maintenance and for the plotting and filing of records. M. G. Croft prepared the electric-log sections from which figures 4, 5, and 7 were adapted.

GEOLOGIC SETTING

The San Joaquin Valley--the southern two thirds of the Central Valley of California--is an elongated southeasterly trending structural trough between the westward tilted Sierra Nevada and the rising Coast Ranges. Although part of the same structural basin, the extreme southern end of the valley is different from the rest of the valley in several aspects (Repenning, 1960, p. 49). It does not have the westward-tilted floor or the folded and somewhat faulted western margin characteristic of the valley to the north. Also, the tectonically active Tehachapi Mountains which form the southern closure of the valley, are an unusual transverse structural feature.

Continued downwarping of a westward-trending structural trough through the central part of the Arvin-Maricopa area resulted in the accumulation of about 28,000 feet of Cenozoic deposits (de Laveaga, 1952, p. 103).

More than 15,000 feet of continental deposits, consisting of successive layers of lacustrine and deltaic sand, silt, and clay, interfingered with thick alluvial sequences from the surrounding mountains, overlie a sequence of marine rocks. Abundant organic material in the extensive marine beds is the source of the widespread oil and gas production in this part of the valley. The upper few thousand feet of this continental sequence forms the ground-water reservoir in the Arvin-Maricopa area, one of the major ground-water basins of California. The base of fresh water in this ground-water reservoir ranges from sea level to 4,400 feet below sea level, but is at least 2,000 feet below sea level in most of the Arvin-Maricopa area as defined in figure 1 (Page, 1971, pl. 1).

Most of the present topography of the Arvin-Maricopa area has formed during Quaternary time, and horizontal and vertical tectonism is continuing in the region. Mountains continue to rise, and tectonic downwarping of the structural trough probably is continuing. Measurements indicate this to be one of the most tectonically active regions of the Nation. Superimposed on this highly complex geologic environment are the manmade processes that cause land subsidence. Though geologically trivial, the environmental changes wrought by these processes are significant in the perspective of man.

The broad floor of the southern end of the San Joaquin Valley is an almost level plain, 300 to 400 feet above sea level (fig. 3), and has persisted as a shallow basin of interior drainage through much of Quaternary time. Occasionally, pluvial lakes have occupied the lowest depression in the basin; Kern and Buena Vista Lakes are the historic remnants. Steep alluvial fans projecting northward into the depositional basin from the structurally complex Tehachapi and San Emigdio Mountains are composed principally of granitic and sedimentary detritus. Fans from the Sierra Nevada on the east are dominantly granitic in character. Fans from the Coast Ranges on the west are largely derived from marine sediments.

Kern River (fig. 3), the principal source of detritus in the south end of the valley, has built a long, gentle alluvial fan forming a topographic barrier across the valley to the edge of Elk Hills. This persistent depositional feature has isolated the southern end of the valley, both topographically and hydrologically, from the rest of the valley.

In 1952, the U.S. Bureau of Reclamation drilled nine core holes in the Arvin-Maricopa area to determine the nature of the water-bearing deposits of the basin. A tenth core hole was drilled in 1963 by the Geological Survey, in cooperation with the California Department of Water Resources. Pertinent details of the cored intervals in these holes are tabulated below.

Table 1.--Core holes in the Arvin-Maricopa area

[Location of core holes shown in figure 3]

Core hole	Year drilled	Depth (feet)	Drilled by	Cored interval (feet)
29/25-12M1	1952	1,250	USBR 1/	10 per hundred.
29/27-34N1	1952	800	do.	10 per hundred.
30/24-4C1	1952	800	do.	50-60, 100-109 150-160, 210-496, 500-780.
30/26-22P1	1952	794	do.	10 per fifty.
30/28-10N1	1952	1,199	do.	0-790, 10 per hundred.
31/25-27F1	1952	1,000	do.	10 per hundred, except continuous 200-800.
32/28-30D1	1952	1,460	do.	10 per fifty.
32/29-19H2	1952	1,000	do.	10 per fifty.
11N/19W-7R2	1952	1,100	do.	Irregularly.
11N/21W-3B1	1963	1,500	USGS, DWR 2/	335-339, 392.5-404, 530-543, 660-666, 685-696, 830-836, 1,146-1,155, 1,455-1,460.

1/ U.S. Bureau of Reclamation

2/ U.S. Geological Survey and California Department of Water Resources.

Figure 3 shows the location of the 10 core holes listed in table 1

Figure 3 near here.

and 3 geologic sections that transect the basin. The electric logs (fig. 4) and the geologists' logs (tables 2 and 3) of two of the core holes

Figure 4 near here.

31/25-27F1 on Buena Vista Lake bed, and 32/28-30D1 southeast of Kern Lake bed, give detailed descriptions of the nature of the deposits at those locations. These logs were obtained by the Bureau of Reclamation at the time of drilling.

Table 2.--Descriptive log of core hole 31/25-27F1

[Modified from U.S. Bureau of Reclamation]

Depth (feet)	Lithologic Description
0- 40	Clay, sandy; blue.
40- 50	Silt, clayey, interbedded with silt and sandy silt; dark greenish-gray; loose to friable; very poorly sorted.
50- 90	Sand, fine to coarse; blue, with clay streaks.
90-100	Silt, sandy, very fine, coarse sand, silty clay and very fine to medium sand; grayish-olive; plastic to friable; well sorted to poorly sorted.
100-140	Sand, silty, blue, and sandy clay.
140-150	Clay and sand; dark greenish-gray to olive-brown; plastic to friable; massive; moderately well sorted.
150-200	Sand, fine, blue, and silty sand.
200-310.8	Sand, fine to coarse; dark greenish-gray; loose to friable; massive; moderately well sorted; scattered clayey and silty lenses.
310.8-326	Sand, interbedded with silt and clay; greenish-gray; plastic to loose; poorly sorted. Woody fragments and shell fragments 315-318 feet.

Table 2.--Descriptive log of core hole 31/25-27F1--Continued

Depth (feet)	Lithologic description
326 -338.5	Clay; dark greenish-gray; plastic; well sorted; contains shell fragments.
338.5-369.5	Sand, silt; dark greenish-gray; loose to friable; massive; poorly sorted; calcareous nodules.
369.5-391.0	Sand, fine to coarse; dark greenish-gray; loose; massive; poorly sorted; arkosic.
391.0-563.2	Sand and clay, fine to medium, interbedded; dark greenish-gray; plastic to friable; massive; poorly sorted to very poorly sorted; considerable silt throughout.
563.2-614.0	Sand, fine to coarse; greenish-gray; loose; massive; moderately well sorted; micaceous.
614.0-660.0	Clay silty; dark greenish-gray; friable; massive; moderately well sorted.
660.0-679.0	Sand, very fine to coarse; dark greenish-gray; loose to friable; massive; poorly sorted.
679.0-800	Clay, silty, sandy clay, and clayey sand, interbedded; greenish-gray to 722.5; below 722.5 alternates with shades of moderate yellowish-brown; plastic to firm; massive; very poorly sorted. Ash bed(?) at 717.5. Siliceous shale fragments 722.5-800.0. Variably calcareous below 714.5.

Table 2.--Descriptive log of core hole 31/25-27F1--Continued

Depth (feet)	Lithologic description
800 - 900	Clay, silty, and clay; dark greenish-orange, plastic; massive; moderately well sorted to well sorted; siliceous shale fragments and soft calcareous layers.
910 - 990	Clay, silty, and clay, sandy, brown, and coarse sand.
990 -1,000	Sand, very coarse; greenish-gray to pale olive; loose; massive; poorly sorted.

Table 3.--Descriptive log of core hole 32/28-30D1

[Modified from U.S. Bureau of Reclamation]

Depth (feet)	Lithologic description
0- 40	Clay, silty, brown; silt, blue, and coarse sand with some fine gravel.
40- 50	Sand, coarse; dark greenish-gray; loose; massive; very poorly sorted.
50- 90	Sand, medium to coarse, with streaks of silty clay; blue.
90-100	Clay, interbedded with silt, fine sand, and medium to very coarse sand; dark greenish-gray; loose to plastic; massive; poorly sorted to very poorly sorted.
100-140	Sand, fine to medium, interbedded with silt and clay; dark greenish-gray to pale olive; loose; horizontally bedded; poorly sorted.
140-150	Clay, interbedded with silt and fine to medium sand, dark greenish-gray to pale olive; loose; horizontally bedded; poorly sorted .
150-190	Sand, fine to coarse, with thin seams of silty clay and silty sand with thin streaks of silty clay.

Table 3.--Descriptive log of core hole 32/28-30D1--Continued

Depth (feet)	Lithologic description
190-200	Sand and clay; dark greenish-gray; loose to plastic; massive; very poorly sorted.
200-240	Sand, silty, with silty clay seams and fine to coarse sand with clay streaks.
240-250	Sand, fine to medium, and silty fine sand; dark greenish-gray to pale olive; loose; massive; poorly sorted.
250-290	Sand, fine to coarse, with clay streaks; brown.
290-300	Sand, fine, clay and fine to medium sand; moderate yellowish-brown to pale olive; loose to plastic; massive; poorly sorted.
300-340	Sand, with clay streaks and scattered gravel and sand; brown.
340-350	Clay, silty, interbedded with very fine sand and medium sand; pale olive to moderate yellowish-brown; plastic to loose; bedded to massive; poorly sorted.
350-390	Sand, brown, with silty clay streaks and silty clay; blue.
390-400	Clay, silty; dark greenish-gray; firable to firm; massive; poorly sorted.

Table 3.--Descriptive log of core hole 32/28-30D1--Continued

Depth (feet)	Lithologic description
400-440	Clay, silty, blue, with sand streaks and silty sand, brown.
440-450	Silt, clayey, sandy; moderate yellowish-brown with dark greenish-gray mottling; firable; massive; very poorly sorted.
450-490	Clay, silty, and medium to coarse sand with clay streaks; brown.
490-496	Silt, clay, and fine sand, interbedded; moderate yellowish-brown to pale olive; loose to plastic; horizontally bedded; very poorly sorted.
496-540	Clay, sandy, with streaks of sand; brown.
540-550	Sand, silty, fine, interbedded with silt and clay; moderate yellowish-brown; friable to plastic; horizontal bedding; very poorly sorted.
550-590	Sand and sandy clay; brown.
590-600	Sand, silty, fine to medium, and fine to very coarse sand; moderate yellowish-brown to pale olive; bedded; friable to loose; very poorly sorted.

Table 3.--Descriptive log of core hole 32/28-30D1--Continued

Depth (feet)	Lithologic description
600-640	Sand with scattered gravel, sandy clay with streaks of sand, and silty sand with streaks of sand; brown.
640-650	Sand, silty, fine to medium; silty clay and silty sand; fine to medium; moderate yellowish-brown; loose to plastic, massive, poorly sorted.
650-690	Sand and clay, interbedded.
690-700	Silt, sandy, and coarse sand; moderate yellowish-brown; friable to loose; massive, very poorly sorted.
700-740	Sand, silty, with streaks of clay; brown.
740-750	Sand, fine, silty; moderate yellowish-brown; friable, bedded; very poorly sorted.
750-790	Sand, with streaks of clay; brown.
790-795	Sand, coarse, and clay and sandy silt interbedded; moderate yellowish-brown to pale olive; loose to friable; massive; poorly sorted.
795-840	Clay, sandy, with streaks of sand.
840-850	Clay, silt, and silty very fine sand; dark grayish-brown; loose to friable; horizontally bedded; poorly sorted.

Table 3.--Descriptive log of core hole 32/28-30D1--Continued

Depth (feet)	Lithologic description
850- 890	Silt, blue, and silty clay with streaks of sand.
890- 900	Clay, silty, interbedded with silt, sandy silt, and very coarse sand; moderate yellowish-brown; plastic to loose; massive; very poorly sorted.
900- 940	Sand and clay, interbedded; brown.
940- 950	Sand, silty, interbedded with silt and sandy silt; moderate yellowish-brown; loose to friable; horizontally bedded; very poorly sorted.
950- 990	Sand, interbedded with silty sand and clay; brown.
990-1,000	Sand, silty, fine; grayish-olive; loose to friable; massive; poorly sorted.
1,000-1,040	Sand, silty, with clay streaks; brown.
1,040-1,050	Clay, sand, and silt; interbedded; poorly sorted; plastic to friable; moderate yellow-brown to pale olive.
1,050-1,090	Clay, silty, with sand lenses; brown to blue.
1,090-1,100	Clay, silty and silt, sandy; interbedded; poorly sorted; friable; moderate yellow-brown.

Table 3.--Descriptive log of core hole 32/28-30D1--Continued

Depth (feet)	Lithologic description
1,100-1,140	Clay, silty and sandy, and sand, silty; brown.
1,140-1,150	Sand, fine; loose to friable; massive; moderately well sorted; moderate yellow-brown.
1,150-1,190	Sand, silty, fine; brown and gray.
1,190-1,200	Sand, fine to coarse; well to poorly sorted; lo moderate yellow-brown.
1,200-1,240	Sand, silty, with streaks of clay; brown.
1,240-1,250	Sand, silt, and clay; interbedded; poorly sorted; massive to bedded; moderate yellow-brown.
1,250-1,290	Sand, and sand, clayey; brown.
1,290-1,300	Sand, fine; moderately well sorted; loose; moderate yellow-brown.
1,300-1,340	Sand, with clay streaks; brown.
1,340-1,350	Sand, fine and clay, silty; interbedded, loose to plastic; moderately well sorted; dark yellow to brown.

Table 3.--Descriptive log of core hole 32/28-30D1--Continued

Depth (feet)	Lithologic description
1,350-1,390	Sand, silty, fine, with streaks of clay and silty clay.
1,390-1,400	Clay, sandy, and sand, fine; very poorly to moderately sorted; plastic to loose; grayish olive-green.
1,400-1,460	Sand, and clay, silty; blue.

Figure 4A shows the electric log of core hole 11N/21W-3B1 (table 1)

Figure 4A near here.

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at Lakeview, and the depths of seven selected core samples that were tested for consolidation characteristics in the laboratory. As shown, the samples ranged in depth from 335 to 1,459 feet below the land surface, and were all described as sandy clay by the sampling geologist. These samples were selected as the most representative of the fine-grained beds of the cored interval. Most of the deposits of the cored interval were considerably coarser grained.

Figure 4B shows the consolidation test curves of the seven selected

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Figure 4B near here.

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samples from core hole 11N/21W-3B1, as determined in the Sausalito testing laboratory of the U.S. Corps of Engineers in early 1964. In accordance with standard practice, void-ratio determinations were made for 11 load increments between 1.39 psi (pounds per square inch) and 1,455.5 psi of applied stress, during both the loading and rebound limbs of the loading cycle. The arrow on each curve of figure 4B indicates the approximate in situ effective stress on the sample at the time of coring. In addition to the consolidation-test data, the results of the following tests for each of the seven samples are available for review in the Survey's project file: sieve and hydrometer analysis, Atterberg limits, specific gravity, and field dry unit weight.

Geologic section A-A' (fig. 5) shows the nature of the deposits along

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Figure 5 near here.

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a radial of the Kern River fan from south of Elk Hills to north of Bakersfield. (For location, see fig. 3.) Extensive sands, presumably from the Sierra Nevada, dominate the section. Even in the central trough of the basin beneath Buena Vista Lake bed (note descriptive log of 31/25-27F1) sands predominate above about the 614-foot depth. Two pluvial clays are recognized in the thick alluvial sequence: The upper A clay (Croft, 1969) which underlies Kern and Buena Vista Lake beds at shallow depth, and the lower E clay (Croft, 1969) which is an effective confining bed throughout much of the Arvin-Maricopa area. The structure and extent of these clays, as defined by Croft, are shown in figures 3 and 7, respectively. The depths and thicknesses of these clays are shown in geologic section B-B', (fig. 6). Croft postulates (1969, p. 18-19) that the E clay is continuous

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Figure 6 near here.

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through the narrows of Buena Vista slough (fig. 7) with the Pleistocene Corcoran Clay Member of the Tulare Formation that underlies most of the San Joaquin Valley to the north.

The configuration of the structure contours on the base of the E clay (fig. 7) suggests considerable tectonic deformation in the basin

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Figure 7 near here.

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trough since the deposition of this Pleistocene clay, apparently a differential settlement of the trough and uplift of Elk Hills. The indicated downwarping of the E clay in the vicinity of Kern Lake bed suggests continued tectonic settlement in this area. This may account for part of the topographic reentrant immediately north of Wheeler Ridge. Page (1971) mapped the depth and configuration of the base of fresh water in this part of the valley. He delineated a deep fresh-water hole south of Bakersfield (fig. 7A), extending more than 4,700 feet below the land surface,

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Figure 7A near here.

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which suggests a downwarping of the Quaternary unconsolidated deposits.

Geologic section C-C' (fig. 8) shows the nature of the alluvial

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Figure 8 near here.

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deposits from Kern River near Bakersfield to Wheeler Ridge. At well 30/28-16K in south Bakersfield, the interbedded sequence of sand, silt, and clay is seen to continue uninterrupted to depths over 3,000 feet. The coarse fan deposits comprising the bajada on the north flank of Wheeler Ridge, shown on this section, contrast sharply with the fine-grained beds that underlie Buena Vista Lake bed shown in figure 6. A lithologic description of the deposits to a depth of 1,000 feet (31/25-27F1) beneath Buena Vista Lake bed and to a depth of 1,460 feet (32/28-30D1), 4 miles northwest of Mettler near the center of maximum subsidence, is given in tables 2 and 3 respectively. Electric logs of core holes at these two locations are shown in figure 4.

If the valley floor is assumed to have been as uniform and flat at the time the pluvial E clay was deposited as the present topography is--that is, about 200 feet of relief--as much as 600 feet of differential tectonic settlement is indicated since the E clay was deposited (fig. 6). The Corcoran Clay Member of the Tulare Formation, which Croft postulates to be correlative with his E clay of this southern area, is at least 600,000 years old (Miller, Green, and Davis, 1971, p. E24). Thus, an average rate of differential tectonic subsidence of about 0.001 foot per year is suggested. Elk Hills apparently has been rising during this same period, as evidenced by the upwarping of the E clay on its northeastern flank. About 900 feet of Quaternary deposits have accumulated near the east edge of Buena Vista Lake bed since the E clay was deposited (fig. 6), suggesting an average rate of basin deposition in this area of 0.0015 foot per year.

Three radiocarbon dates (determinations by the Geological Survey) are the basis for estimating the average rate of sedimentation in the basin trough during the last 31,000 years. A radiocarbon date (W-1505) of 9,040±300 years B.P. was obtained for wood within the upper stratum of the A clay in 32S/26E-10N (for location, see fig. 3) at a depth of 38 feet (Croft, 1968, p. B155). Also, a date (W-1504) of 17,130±350 years B.P. (Croft, 1968, p. B155) was obtained for wood found in sand at a depth of 74 feet in well 32S/26E-16F. These dates suggest an average depositional rate of about 0.0043 foot per year, or 1 foot in 230 years, between Buena Vista and Kern Lake beds (fig. 1) during the last 17,000 years. A radiocarbon date (W-2336, Meyer Rubin, oral commun., Oct. 1969) of 31,000± 1,000 years B.P. was obtained during the progress of this investigation for a fibrous wood sample collected by Neal Crawford of the California Department of Water Resources at a depth of 62 feet at 29S/23E-35K near Buena Vista Slough. This date suggests an average depositional rate of about 0.002 foot per year, or 1 foot in 500 years, at this location during the past 31,000 years.

Hydrologic Units

As discussed earlier, unconsolidated continental deposits have accumulated to great depth in the downwarped structural trough that underlies the Arvin-Maricopa area. These deposits consist of heterogeneous alluvial sequences of silt, sand, and gravel transported into the valley trough from the surrounding mountains, interbedded with fine-grained lacustrine sediments deposited in pluvial lakes that periodically occupied the central part of the trough. The saturated fresh-water beds of this sequence, as diverse as the contributing source areas, comprise the extensive aquifer systems of this highly productive ground-water basin. The maximum depth to the base of fresh ground water in this basin is about 4,700 feet, in T. 31 S. and T. 32 S., R. 28 E.; the minimum depth is about 300 feet, along Buena Vista slough on the flank of Elk Hills (fig. 7A).

Only two of the more persistent lacustrine clays in the depositional sequence are identified in the geologic sections of figures 5, 6, and 8. These are the shallow A clay (fig. 3) and the deeper E clay (fig. 7A), as delineated and described by Croft (1972). Other intermediate clay layers appear in the sections, and locally one or another of these intermediate clays is the dominant confining bed in the depositional sequence. Regionally, however, the E clay is the most extensive and effective barrier to vertical movement of ground water.

Ground water is generally thought of as occurring under either unconfined (water table) or confined (artesian) conditions. In the Arvin-Maricopa area, however, as in most ground-water basins, this clear-cut distinction does not exist. Few wells pump from an unconfined water body; most water-level data indicate increased confinedment with depth and several distinct confining beds of local extent.

For purposes of this interpretive study, the hydraulically and geologically complex Arvin-Maricopa ground-water basin is arbitrarily subdivided into the two following gross productive hydrologic units:

(1) A semiconfined aquifer system that overlies the principal confining layer in the central part of the area and extends to the full depth of the fresh-water-bearing deposits beyond the lip of the confining layer, and

(2) a confined aquifer system that underlies the principal confining layer, and extends down to the base of the fresh ground water (fig. 7A). Only the upper few hundred feet of this confined system has been penetrated by wells and affected by pumping.

Although this simplified two-layer system may not conform locally with actual conditions, regionally it is not unreasonable. This assumption provides a simplified model to which gross parameters can be assigned and from which conceptual interpretations can be made. As defined above, the semiconfined aquifer system underlies all of the Arvin-Maricopa area and comprises the entire ground-water basin except that portion in the central part of the trough effectively overlain by confining clays. In this study, the E clay, wherever present (fig. 7), is assumed to separate the confined aquifer system below from the semiconfined aquifer system above. Beyond the lateral limits of the E clay (fig. 7), the semiconfined aquifer system is assumed to extend downward from the usually indefinite water table to the full depth of the producing water wells.

Below the extensive confining E clay, the confined aquifer system is assumed to extend downward to the base of the fresh water. Laterally, the confined aquifers are continuous with the semiconfined aquifers of coalescing alluvial fans, and much of the recharge to the confined system comes as lateral movement from the semiconfined aquifers.

The vertical hydraulic conductivity and lateral extent of the E clay are not well defined (fig. 7), and other interpretations may be placed on the extent and nature of the confining beds. These factors are of little significance, however, in computing changes in effective stress that cause subsidence. No attempt has been made herein to verify or modify Croft's (1972) geologic interpretations.

Many of the casing of the productive irrigation wells are perforated indiscriminately and thus the wells may withdraw water from several aquifers. Both the semiconfined and confined water levels have all been depressed by the accelerated pumping of the past several decades. Pressure declines in the various beds have been irregular, however, both areally and with depth. Also, most of the observation wells being measured by various water agencies are active or unused irrigation wells; therefore, few of the hydrographs available for this study are representative of any particular depth zone. Most of the hydrographs are a composite of water levels in several zones, and are difficult to interpret in terms of hydrologic changes. It is significant that, even with the several hundred observation wells currently being measured, the principal limitation in this interpretive subsidence investigation has been the inadequacy of water-level records to define hydraulic changes that have occurred in the principal compacting zones.

Tectonic Adjustments

Evidence indicates that the structural downwarping of the valley trough that persisted during the accumulation of 28,000 feet of Cenozoic deposits (de Laveaga, 1952, p. 103) is continuing. Active movement along the Kern Front and Buena Vista faults (Manning, 1968, p. 133) in the foothills north of Bakersfield and north of Taft, respectively, give evidence of modern tectonism.

As noted earlier, tectonic differential downwarping of the structural trough has averaged about 0.001 foot per year during the past 600,000 years. During this same period, the accumulation of deposits in the trough has averaged 0.0015 to 0.004 foot per year of increased thickness. Both of these processes tend to change the elevation of the land surface in the valley trough; their magnitude is slight, however, compared to manmade subsidence rates of as much as 0.4 foot per year. Of much greater concern in this study is tectonic uplift occurring in the surrounding mountains, particularly in the Tehachapi Mountains south of Grapevine, which indirectly affects subsidence data in the valley. Analysis of regional leveling data indicates that the mountain block south of the White Wolf fault (fig. 3) is gradually rising. Periodic releveling surveys since 1953 have been tied to an assumed-stable reference bench mark on the mountain block. Thus bench-mark elevations used in this subsidence study have a built-in component of apparent subsidence that is not real.

Figure 9 shows the vertical movement of bench mark M54 (for location,

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Figure 9 near here.

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see fig. 32), 2 miles north-northwest of Grapevine, for the period 1926-62 (Lofgren, 1966, fig. 4), based on adjusted elevations of the U.S. Coast and Geodetic Survey. The marked uplift that occurred between the 1947 and 1953 levelings (graph A) is attributed to the severe Arvin-Tehachapi earthquake of July 1952. An apparent subsidence trend that preceded 1947 and has continued since 1953 also is clearly shown. Graph B is an interpretation of the vertical movement of bench mark M54. The movement has been resolved into two components: (1) a general downward trend that resulted in about 0.45 foot of subsidence (relative to the assumed unchanging datum), and (2) a vertical uplift of 1.77 feet apparently directly related to the 1952 earthquake. In this graphical analysis, the slope of the interpolated curve from 1947 to 1953 is constructed as an average slope between earlier and later parts of the curve. It is noteworthy that the apparent subsidence trend was not interrupted or changed by the 1952 earthquake which caused 1.8 feet of uplift at this location. Interestingly, all the surveys after 1953, and probably the 1947 survey, were tied to assumed-stable bench marks south of M54. The apparent gradual subsidence at M54 is more likely a gradual rise of the reference bench mark. Unfortunately, bench mark M54 was disturbed before the leveling of 1965; however, at nearby bench marks, this same regional trend continues.

Figure 10 (Lofgren, 1966, fig. 5) shows the intrepreted two components

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Figure 10 near here.

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of vertical movement of bench marks P54 and 370+20.10, just south of the trace of the White Wolf fault. (See fig. 12A.) Bench mark P54 was last surveyed, and 370+20.10 first surveyed, in 1953. The data indicate about 0.96 foot of apparent subsidence from 1926 to 1962, and an uplift of 1.61 feet that is attributed to the 1952 earthquake. By this method of graphical analysis the tectonic uplift attributed to the 1952 earthquake was computed for each bench mark along U.S. Highway 99 from Mettler to Gorman that was leveled prior to and after the 1952 earthquake (fig. 11).

Figurell near here.

The up-arching of the mountain block south of the fault between Mettler and Gorman, resulted in a maximum tectonic uplift of 2 feet, 2-4 miles south of the fault (fig. 11). A short distance north of the White Wolf fault, however, the effect of the 1952 earthquake is not discernible in bench-mark plots. The subsidence north of the fault, earlier attributed to tectonic adjustment (Whitten, 1955), is directly related to the accelerated decline of ground-water levels which began in the late 1930's (Lofgren, 1963). It is significant that the maximum computed tectonic uplift along U.S. 99 occurred at bench marks nearest the earthquake epicenter, 2-4 miles south of the White Wolf fault trace; also, that the amount of uplift decreased abruptly to the north and to the south.

Figure 12A (Lofgren, 1966, fig. 8) shows the measured vertical

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Figure 12 near here.

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displacement in the Grapevine area, 1953-62. The map (A) shows the amount of subsidence that occurred from 1953 to 1962, based on releveling of bench marks along U.S. Highway 99 and throughout the contoured area. Changes in altitude of all available bench marks, based on published 1953 leveling data and tentatively adjusted 1962 data, were used in constructing this map. As shown, the 0.1- and 0.2-foot lines of equal subsidence pass through the deformed rocks of Wheeler Ridge. Also, the 0.5- and 1.0-foot lines of equal subsidence apparently cross the trace of the White Wolf fault without interruption.

Graph (B) in figure 12 shows the measured subsidence along U.S. Highway 99 during the 6 years following the 1952 earthquake. During this period, as much as 2.5 feet of subsidence caused by water-level decline occurred north of the White Wolf fault. Also, differential subsidence occurred along the line of bench marks south of the fault trace. As shown, no subsidence was indicated at bench mark D367, in the mountains 2 miles south of Grapevine, but relative subsidence occurred both north and south of this axis of flexure. It is noteworthy that this axis is about 6 miles south of the area of maximum uplift during the 1952 earthquake.

Figure 12C shows the vertical displacement of bench marks along U.S. Highway 99 that occurred during the 3-year period 1959-62. Bench mark H537, which was the starting reference bench mark for the 1962 leveling, was first leveled in 1957 and was considered stable for the 1959 and 1962 surveys. Leveling data show no change in altitude of bench mark D367 from 1953, when first leveled, to 1962. The nontectonic subsidence caused by water-level decline extended south about to the trace of the White Wolf fault, and possibly beyond it. In the heavily pumped area north of the White Wolf fault, it continued at a maximum annual rate of about 0.5 foot per year. South of the fault, subsidence during the 3-year period decreased from 0.15 foot near the fault to zero at bench mark H537. Although the observed subsidence south from bench mark 422+24.04 about to U824 may, in part, be due to water-level decline, the tectonic subsidence occurring on the Wheeler Ridge mountain mass to the west was of the same order of magnitude, suggesting that the subsidence between the cited bench marks south of the fault was largely, if not wholly, tectonic.

In order to determine vertical crustal movement in the region, a releveling from the tidal bench mark at San Pedro (Los Angeles County) was completed in 1964 by the Coast and Geodetic Survey. This indicated a net tectonic rise at Lebec (fig. 12) of 0.55 foot (0.168m) since 1953 (Small, 1965, p. 9). To verify this, a releveling of the same line in 1965 indicated a rise of 0.82 foot (0.250m) since 1953 (Small, 1965, p. 9). Associated with this tectonic rise, horizontal movements in the vicinity of Wheeler Ridge were on the order of 4.5 feet (1.5 meters) during the period 1932 to 1963 (Meade, 1965, p. 16). These surveys indicate a continually rising mountain block, with tectonic uplift of 0.05 to 0.07 foot per year at Lebec. Local leveling in 1965 and 1966 by the Coast and Geodetic Survey indicated that tectonic uplift of the mountain block continued through 1966.

Tectonic uplift of this magnitude apparently is affecting several of the bedrock reference bench marks south of the White Wolf fault which have been considered stable ties in the subsidence leveling surveys. Corresponding instability is evident in the Coast Ranges west of the study area, and to a lesser extent in the Sierra Nevada to the northeast. In an area as tectonically active as this, it is difficult to find stable bench marks from which to tie leveling surveys. Most of the leveling data used in this interpretive investigation are based on adjustment procedures which assumed stability in the surrounding mountains. Actually, these bench marks were rising, probably about 0.06 foot per year in the Tehachapis, possibly half that amount in the Coast Ranges west of Bakersfield, and only slightly in the Sierra Nevada 30 miles northeast of Bakersfield. Thus, all bench marks in the Arvin-Maricopa subsidence area have a component of apparent subsidence which is not real. This component ranges from about 0.05 foot per year in the southeastern part to about half that rate in the northwestern part of the area.

Figure 13 shows the apparent subsidence trend of four widely separated

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Figure 13 near here.

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bench marks in the valley, all outside the area of measurable subsidence due to water-level decline. All these bench marks trend downward, at from 0.023 to 0.031 foot per year. This is not tectonic subsidence but rather, apparent subsidence that results from the continuing tectonic uplift of reference bench marks assumed to be stable. This apparent subsidence is about 20 times the rate of the actual tectonic downwarping of the valley floor discussed earlier. Both of these tectonic influences, one apparent subsidence and one real, complicate the leveling data for all bench marks in the study area. The magnitude of the complication is variable and indeterminate from one bench mark to another, and fortunately is relatively small in terms of elevation changes caused by compaction processes. Therefore, tectonic changes in the leveling data are disregarded in the subsidence maps and profiles of this study. For a more exacting analysis of subsidence rates, however, these influences would necessarily be considered.

HYDROLOGIC SETTING

The southern end of the San Joaquin Valley is essentially a closed basin of interior drainage. Except during excessively wet periods, almost all the precipitation that falls within its tributary watershed remains in the basin until lost by evapotranspiration. Evaporation rates far exceed the normal precipitation, and even the beds of ephemeral Buena Vista and Kern Lakes are dry most years. Precipitation is the ultimate source of all surface runoff in the area, and the discharge of streams fluctuates widely in response to changes in precipitation. Surface streams are the principal source of recharge to the ground-water basin. Although the available recharge varies greatly from one year to the next, water levels show a delayed response to changes in streamflow and precipitation because the ground-water reservoir is large.

Seasonal precipitation varies greatly throughout the watershed area, influenced largely by elevation and location (Wood and Dale, 1964, p. 12). Of principal concern in this study, however, are the long-term climatic changes that affect the area as a whole. As shown in figure 14, the

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Figure 14 near here.

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seasonal precipitation (July 1 to June 30) at Bakersfield has ranged from 11.61 inches in 1940-41 to 2.21 inches in 1933-34, with a mean of 5.94 inches for the 66 years 1890-1957. Well defined climatic dry and wet periods are shown by the cumulative departures from mean precipitation (upper graph, fig. 14). As shown, the latest period of deficient precipitation continued from 1945-46 through 1965-66, which coincides with the period of increased ground-water pumpage and also intense land subsidence in the Arvin-Maricopa area. During this 21-year period, above normal precipitation occurred in only 4 years, and only 2 of these were significantly above normal. A net deficiency (below the 1890-1957 mean of 5.94 inches) of 15.80 inches resulted during this 21-year period, representing $2\frac{1}{2}$ years of normal precipitation or 15 percent of the total precipitation. This suggests that at least part of the pumping overdraft discussed later may relate to deficient recharge.

Kern River, entering the valley from the high Sierra Nevada near Bakersfield, represents possibly 90 percent of the total stream inflow to the Arvin-Maricopa area. Smaller streams, largely ephemeral around the margin of the valley, contribute possibly 10 percent of the natural inflow. Although the total runoff from these perimeter streams is small, their effect on the recharge characteristics of the basin and the local areas of overdraft is significant.

Figure 15 shows the discharge of Kern River as measured near

Figure 15 near here.

Bakersfield since 1894. During this 73-year period, the discharge had varied from 160 to 1,950 thousand acre-feet per year, and averaged about 650 thousand acre-feet per year. Three periods of deficient runoff are indicated by the cumulative departure graph (fig. 15C), the latest from 1947 to 1966, inclusive. Above-normal runoff occurred in only 3 years of this 20-year drought, and an accumulated runoff deficit of about 2,500,000 acre-feet resulted. This period of deficient runoff coincides with the period of ground-water overdraft and closely relates to the land subsidence considered in this investigation.

Not all the natural stream inflow to the Arvin-Maricopa area remains within the area. For many years, canal diversions from the Kern River have exported some water to the north. For purposes of this study, these canal exports are assumed to approximate the unmeasured inflow of the secondary perimeter streams, and the net surface inflow is assumed to equal the annual discharge of Kern River prior to 1966. Beginning in 1962, surface-water imports from the Friant-Kern Canal began on asmall scale in the northern part of the Arvin-Maricopa area (fig. 15A). Then, with the completion of canals by the Arvin-Edison Water Storage District in 1965, significant quantities of water from the Friant-Kern Canal has been imported to the southeastern part of the area. This was followed by large imports of surface water from the California Aqueduct, largely to the southwestern part of the area, beginning in 1971. These imports have completely modified the hydrologic regime of the Arvin-Maricopa area. Whereas in 1960 there were no canal imports and the discharge of Kern River approximated the entire inflow to the area, in 1971, canal imports exceeded 250,000 acre-feet and represented about 35 percent of the total inflow to the area. Direct precipitation on the valley floor averages less than 6 inches per year, and is largely lost to the atmosphere before it percolates below the root zone.

Figure 16 shows the pattern of early distributaries of Kern River;

Figure 16 near here.

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historically, most of the surface flow continued southward and southwestward to Kern and Buena Vista Lakes and westward to the valley trough near Buttonwillow. At the turn of the century, Buena Vista and Kern Lakes were connected by sloughs and much of the bottom area was surrounded by extensive marshes. During wet periods, when Buena Vista Lake was deeper than about 13 feet, water overflowed northward through Buena Vista slough into Tulare Lake basin. In 1905-6, water-table contours were close to the topographic contours and artesian wells flowed throughout much of the central part of the basin (fig. 16) indicating that the ground-water reservoir was full to overflowing. At that time, water-table contours indicated westward and southwestward hydraulic gradient of about 10 feet per mile down the Kern fan toward the valley trough. Kern Lake, before it finally dried up due to river diversions, was highly mineralized (unpublished notes indicate more than 3,000 ppm dissolved solids, March 24, 1880) and not suitable for agricultural use. Lands around the margins of Kern and Buena Vista Lakes became excessively alkaline, and even today the belt of low productivity alkaline soils bordering these lake beds is a significant feature of the area.

Many hydrologic changes have occurred since 1905-6. Intensive farming now covers much of the valley floor, and maximum agricultural use is made of all surface water. Stream and canal losses have been reduced to a minimum. Following the construction of Isabella Dam on the upper Kern River in 1954, most of the inflow to the area became regulated for maximum consumptive use and minimum ground-water recharge. These changes have had a marked effect on the hydrologic regime of the basin. The Kern River channel below U.S. Highway 99 now is dry most years, except for a few months during spring runoff. Buena Vista and Kern Lakes seldom are flooded, and once-common swamps and marshes are mostly gone. Through the years, hundreds of irrigation wells have been drilled throughout the valley, both as supplemental supply in areas of insufficient surface water and as full supply in about 20 percent of the area where no surface water is available (Wood and Dale, 1964, pl. 9). Ground-water levels have declined throughout the basin, and heads in the semiconfined and confined aquifers are considerably below the land surface.

One of the consequences of the extensive ground-water overdraft, principally since about 1945, is the widespread land subsidence that is the subject of this report. Subsidence is caused by the extraction of interstitial pore water from the fine-grained beds of the aquifer system. Locally, a significant part of the ground water pumped is derived not from changes in renewable storage in the usual fashion, but rather is mined from the interstices of the aquifer system as water of compaction. As much as 40 percent of the total pumpage in the central part of the subsidence area represents water of compaction. When subsidence is stopped by natural or artificial repressuring of the aquifer system, this water of compaction will no longer be available as a source of supply.

As noted earlier, the rapid exploitation of the Arvin-Maricopa ground-water basin has occurred during a period of extended surface-water deficiency. What the trend of water levels might be during periods of normal or excessive runoff is an interesting consideration. This, together with the significant importation of surface water from the Friant-Kern Canal and the California Aqueduct, could easily change the basin ground-water supply from one of shortage to one of excess, as suggested by Manning (1967, p. 1525). Quite possibly, ground-water levels of the late sixties will define the all time low--past, present, and future.

GROUND WATER

Precipitation in the tributary watershed was the ultimate source of most ground-water recharge prior to 1966. In general, ground water moves radially through the perimeter fans toward the axis of the valley trough, in much the same direction and gradient as the streamlaid deposits themsleves. Thus, under the natural regime, ground water percolates from recharge areas of little confinedment, through regions of increasing confinement, and passes either over or under the lip of the principal confining layer which separates the semiconfined-aquifer system above from the confined aquifer system below. Under each of these conditions--unconfined, semiconfined, and confined--ground water moves in the direction of maximum hydraulic gradient; that is, from recharge areas of high heads to discharge areas of low heads.

Prior to intensive development, natural discharge from the ground-water reservoir was principally by upward percolation from the confined and semiconfined aquifers to the land surface and by extensive draft by phreatophytes. Some subsurface underflow undoubtedly left the basin to the north, but the quantity was probably small. Since the fifties, however, pumpage has exceeded replenishment most years, water levels in the deeper aquifers have declined, and little natural discharge occurs. In the area of Buena Vista Lake and Kern Lake beds, however, the shallow water levels above the confining clays have undergone little change. Locally, these shallow levels have actually risen as development has progressed, due to the downward percolation of excess irrigation water. During the past several decades, pumpage represents almost the entire discharge from the ground-water reservoir.

Assuming a surface area of 600 square miles (about half the total area), a cumulative saturated thickness of 1,000 feet, and an effective porosity (specific yield) of only 20 percent, the Arvin-Maricopa ground-water basin has more than 70 million acre-feet of usable fresh water in storage. This is 100 times the storage capacity of Isabella Reservoir, and equal to about 110 years of average runoff of Kern River. Only a small part of this ground-water storage capacity can be depleted, however, without causing major changes in the reservoir system. The extensive subsidence in the basin is directly related to the depletion that has occurred since pumping began.

Water-level Changes

Subsidence is caused by changes in the effective stress applied to the compressible aquifer system; these changes, in turn, are caused by water-level fluctuations. Of particular interest in this subsidence study, therefore, are the long-term water-level changes that have caused significant stress changes.

In 1905-6, the Arvin-Maricopa ground-water reservoir was full to overflowing (fig. 16). The water table was shallow in the central part of the area and artesian wells flowed throughout about 200 square miles, comprising the lower part of Kern River fan and Buena Vista and Kern Lake beds. When inventoried in 1905 (Mendenhall, Dole, and Stabler, 1916, p. 291), 112 flowing wells were examined in Kern County, with a total discharge of 70-75 cfs (cubic feet per second). Also, 25 pumping wells were visited with a combined yield of slightly over 100 cfs. The average depth to ground water in these wells was about 10 feet. Little development had occurred in the southern and eastern parts of the area.

Significant development had occurred by 1920. Extensive farms covered the areas where surface streams were available, and a belt of newly opened farmland in what later became the areas of Arvin and Edison depended solely on ground water for irrigation (fig. 17). The concentric

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Figure 17 near here.

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array of water-level contours down Kern River fan, indicating a ground-water gradient of 5-10 feet per mile toward Kern and Buena Vista Lake beds, demonstrates the dominant role of Kern River in recharging the ground-water basin. Little development had occurred south of Kern and Buena Vista Lake beds, even though these bottom areas by 1920 were dry most of the time. Water levels were less than 20 feet deep (fig. 18) in much of the farmed area,

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Figure 18 near here.

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and many drainage systems had been constructed to lower the water table sufficiently for farming. The last of the flowing wells had finally stopped flowing, indicating a definite loss in artesian head even though the ground-water reservoir apparently was still full.

Figure 19 shows the amount of lowering of the water table that

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Figure 19 near here.

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occurred from 1921 to 1944 in the north central part of the Arvin-Maricopa area, as mapped by the California Division of Water Resources (Calif. Div. Water Resources, 1944). As yet, there had been little ground-water development south and east of the contoured area (fig. 19), and little information as to water-level changes in this outlying area was available. Over most of the Kern River fan area, water levels had declined less than 10 feet during this 23-year period. In the Arvin-Edison area, east of the sustained surface-water supply, water levels had declined from 25 to more than 75 feet. Also, northwest of Bakersfield declines locally exceeded 25 feet. Along the margins of Buena Vista and Kern Lake beds, water levels had changed very little or, in a few locations, even risen during this period of development.

After 1946, the use of ground water expanded rapidly throughout the Arvin-Maricopa area. Within a few years, most of the productive land had been put under cultivation and many new and deeper wells had been drilled. The distribution graphs of figure 20, based on a field

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Figure 20 near here.

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inventory by Wood and Dale (1964, p. 5), show the year completed and depth of irrigation wells in eight townships in the area of maximum subsidence, as of 1958. Most of the wells in these townships were drilled after 1946; in general, wells in the central part of the basin are shallower than those on the steep fans north of the San Emigdio and Tehachapi Mountains.

Most casings of the older irrigation wells were perforated through a considerable depth range, and early pumping caused more or less uniform declines in all wells. With the accelerated use of ground water following World War II, however, distinct head differences developed between wells of different depths. Many of the later wells were selectively perforated in particular aquifers; also, fine-grained aquitards became effective separators between aquifers of different head. During the late forties and early fifties, large head declines occurred in all the deeper aquifers in the central part of the ground-water basin, but declines varied greatly both areally and with depth. Attempting to map head changes in semiconfined or confined aquifers was filled with complexities. Because most of the several hundred observation wells being measured register composite water levels of several different zones, there is little basis for differentiating water-level changes in the confined aquifers from those of the various semiconfined aquifers.

Figure 20A, modified from a change map of the Bureau of Reclamation,

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Figure 20A following here.

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shows the generalized change in water levels in deep wells from the seasonal high (late winter) of 1951 to the seasonal high of 1956. No control is shown for the southwest quadrant of the ground-water basin. In general, the shaded area of head declines from 30 feet to more than 110 feet during the 5-year period roughly coincides with the area of most active subsidence (fig. 44). Water levels declined less than 30 feet throughout most of the area recharged by Kern River.

During a detailed study of ground-water conditions in 1958 (Wood and Dale, 1964), hundreds of wells were measured in the Arvin-Maricopa area. Because of the complexity of the ground-water basin and the irregularity of the depressed water levels, however, basinwide water-level maps were not drawn for either the deep- or shallow-aquifer systems. Rather, the basin was subdivided into seven subareas, and representative hydrographs and hydrologic characteristics of each of these subareas were considered separately.

Figure 21 shows the general depth to water in wells tapping the main

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Figure 21 near here.

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producing zone as of December 1958 (Wood and Dale, 1964, pl. 7). This is representative of the aquifers tapped by most producing wells, and shallow water levels or water levels much deeper than the majority were disregarded. Significantly, 1958 was a very wet year (fig. 14), and water levels were higher and pumping stresses less that year than in most years of record. The depth to water in the principal producing aquifers of the ground-water reservoir, as of December 1958 (fig. 21), fist a rather orderly pattern skirting the central part of the basin, ranging from less than 100 feet below the land surface northward from Kern and Buena Vista Lake beds to more than 500 feet below the land surface on the southern margin of the valley. Interestingly, the depth lines of figure 21 roughly follow the configuration of the topographic contours, suggesting a relatively flat potentiometric surface of not over 150-foot relief throughout the basin. Undoubtedly, during the summer months of maximum pumping drawdown, water levels were much more erratic and diverse than as shown in figure 21.

Figure 21A shows the change in water level in the unconfined- and

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Figure 21A near here.

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shallow semiconfined-aquifer system from spring 1957 to spring 1965, as computed from annual water-level maps of the California Department of Water Resources. Water-level declines southwest of Bakersfield reflect the greatly reduced recharge on the Kern River fan since the completion of Isabella Reservoir in 1954. Little decline occurred in a narrow belt extending from Bakersfield south to Greenfield, and to Kern and Buena Vista Lake beds. This apparently is due in part to recharge from Caliente Creek north of Arvin. As much as 30 feet of rise occurred in a small area on the southeast margin of Kern Lake bed. Because of insufficient water-level control, no definition of water-level change has been made for the southwestern third of the basin. It is presumed that shallow water levels along the north slope of Wheeler Ridge drop off to merge with the deeper levels as on the eastern margin of the ground-water basin.

Figure 21B is an attempt to depict head changes in the confined and

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Figure 21B near here.

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deep semiconfined aquifer from the autumn of 1957 to that of 1965. Lines of equal water-level decline are based on comparable water-level measurements of selected wells that were measured both years; spot values are from hydrographs in figures 23-31. In general, the shaded area of water-level declines exceeding 50 feet during the 8-year interval roughly coincides with the area of active subsidence (fig. 47). Because of the wide diversity of water levels, 1957-65 head changes were not computed for the uncontoured western part of the basin.

Figure 22 shows the trend of representative hydrographs outside the

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Figure 22 near here.

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principal subsidence area. At each of the wells shown, a long-term water-level decline was observed; the rate of decline ranges from 2 to 12 feet per year. Maximum declines were southeast of Mettler (11N/19W-7R1), where 180 feet of change occurred from 1953 to 1967, and in northern Bakersfield (29/28-20B1), where water levels declined about 160 feet before reversing the downward trend in 1965. At three locations, multiple hydrographs give an indication of differences in the rate of head decline with depth. In Bakersfield (30/28-10N1, N3, N4), for example, the hydrographs of three piezometers of different depths are available since 1952. At this location, the heads in the two deep zones have declined more than 100 feet while the water level in the shallow zone has declined only 35 feet during the 15 years of record. Three miles west of Bakersfield (29/27-34N1, N2, and N4), the water level in the shallow zone has declined more rapidly than that of the deep zone, and in 1967 was only slightly higher than the deeper water level. Eight miles southwest of Bakersfield (30/26-22P1, P3), however, hydrographs for deep and shallow zones remained close together during 45 feet of head decline in 15 years of record.

It is significant that the heads in deep aquifers in all parts of the basin have declined as a result of the accelerated pumping and the reduced recharge of the past several decades. The declines within the principal subsidence area (figs. 23-31), however, have been generally greater than in the outlying area.

Figures 23-31 illustrate the declining trend in water level in 31 wells

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Figures 23-31 near here.

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and piezometers in the Arvin-Maricopa subsidence area for the respective periods of available record. These hydrographs were selected from more than a hundred observation wells currently being measured by various water agencies. For the most part, they are representative of water levels in the confined aquifer system and the closely related deep aquifers of the semiconfined system. Also included are graphs showing the subsidence of bench marks near many of these observation wells; these graphs will be considered later in the discussion "Relation of subsidence to water-level change." The subsidence graphs are based on published elevations by the Coast and Geodetic Survey, and scales have been arbitrarily selected to make each graph roughly parallel its accompanying hydrograph. Locations of wells and bench marks within the subsidence area for which graphs are included in this report are shown in figure 32.

Figure 32 near here.

Effective stresses in a compacting aquifer system are generally greatest, and subsidence most rapid, during periods of maximum water-level decline. Changes in seasonal low-water levels are therefore usually more significant in relation to compaction and subsidence than are changes in seasonal high levels. The discussion of water-level trends that follows relates to seasonal low levels where possible, and generally to static levels, rather than pumping levels, unless so designated.

The long-term hydrographs of four wells 815-850 feet deep tapping the confined aquifer system on the northern margin of Kern Lake bed are shown in figure 23. These hydrographs are believed to be representative of the deeper producing aquifers, and indicate a long-term decline during the period of record. Artesian pressures that were above the land surface in 1905 (fig. 16) and about at land surface in the late forties, were more than 150 feet below the land surface in the mid-sixties. Included with the hydrograph of well 32S/28E-6E1 (bottom graph, fig. 23) are the summer pumping low-water levels, which are as much as 75 feet below the corresponding static levels.

Hydrographs of four wells tapping the confined aquifer system north of Kern Lake bed at various depths between 300 and 815 feet are shown in figure 24. As shown, the water-level decline in these wells on the southern toe of Kern River fan is much less than that in wells on the east margin of the subsidence area (fig. 25), where little natural recharge is available.

The water-level trends of deep wells tapping the semiconfined to confined aquifers on the north flank of the San Emigdio Mountains where the southern extent of the confining E clay is poorly defined (fig. 6), are shown in figures 26-30. At all depths throughout this area, water levels have declined since the first records, in response to the accelerated pumping of ground water. Several of the hydrographs show a decrease in the rate of decline during the mid-sixties, a relationship discussed later.

Figure 30 shows the hydrographs of three piezometers at 32S/28E-30D1 in the center of the subsidence area. The two deepest piezometers, completed by the U.S. Bureau of Reclamation in 1952, indicate the water-level trend at two depths in the confined aquifer system. Although the hydrographs of these deep piezometers cross in 1962, these graphs both indicate an increased fluctuation in piezometric head and a long-term decline of water level in an area that once had flowing wells year around. The upper hydrograph is considered representative of the semiconfined zone above the principal confining clay.

SUBSIDENCE OF THE LAND SURFACE

Widespread subsidence was first recognized in the Arvin-Maricopa area in 1953, following the destructive 1952 Arvin-Tehachapi earthquake. Bench marks along U.S. Highway 99 and Maricopa Road that had remained at relatively constant elevations during earlier surveys in 1926-27, 1935-39, 1942, and 1947 gave evidence of a broad area of subsidence in the valley when resurveyed by the U.S. Coast and Geodetic Survey in 1953. Because the Tehachapi Mountain area south of the White Wolf fault (figs. 3 and 12) was upwarped during the 1952 tectonic activity. Whitten (1955) ascribed the downwarp in the valley alluvium north of the fault to this same readjustment. However, an analysis of subsequent bench-mark releveling in 1957, 1959, and 1962 in relation to earlier leveling (Lofgren, 1963) indicated that the subsidence in the valley was not due to the 1952 earthquake but, instead, was related to the extensive decline of ground-water levels that began about 1940 and continued through 1971.

As of spring 1965, 455 square miles, or about 40 percent of the Arvin-Maricopa area, was affected by subsidence caused by declining water levels. Maximum subsidence was about 8 feet, and maximum rates approached 0.5 foot per year. This subsidence occurred in the central part of the area where ground-water levels had declined the most. By 1970, maximum subsidence exceeded 9 feet and 700 square miles had been affected by subsidence. The total volume of subsidence from 1926 to 1970 was about 1.06 million acre-feet. Subsidence due to water-level decline is discussed in detail later in the report.

In addition to subsidence caused by water-level decline, and the apparent tectonic subsidence discussed earlier, two other types of land subsidence are recognized in the Arvin-Maricopa area. These are: (1) subsidence caused by the hydrocompaction of moisture-deficient alluvial deposits, principally on the southwestern margin of the area, and (2) subsidence resulting from the extraction of oil and gas from scattered fields. Although these two types of subsidence are of secondary importance in this study, they are discussed briefly later under separate headings. First, however, the extent and frequency of leveling control, which is the basis for determining the rate and extent of all subsidence in the area, is considered.

Leveling Data Available

The earliest precise leveling by the U.S. Coast and Geodetic Survey in the Arvin-Maricopa area was in 1926-27 (fig. 33), when north-south

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Figure 33 near here.

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and east-west lines of bench marks through Bakersfield were surveyed. Subsequent surveys along these and other lines were run as shown in figure 33. In 1957, as a result of coordinated efforts of an Inter-Agency Committee (Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958) concerned with problems of land subsidence in the San Joaquin Valley, an extensive network of bench marks was established throughout the area of suspected subsidence. This network included the lines of earlier leveling and tied to the regional network of the valley. Releveling of the subsidence network in 1959, 1962, 1965, and 1970 (fig. 33) provided most of the data for subsidence maps and profiles in this report. Figure 34 shows the network of leveling control and the

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Figure 34 near here.

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location of the subsidence profiles discussed later.

Most of the leveling in the Arvin-Maricopa area by the Coast and Geodetic Survey was done during the winter months when ground-water levels were high and subsidence rates at a minimum. Thus, many of the problems related to maintaining leveling accuracy in an area of active subsidence (Lofgren, 1969, p. B50) have been avoided. The inaccuracies introduced by continued tectonic uplift of reference bedrock bench marks, however, are of real concern in this part of the valley. Because of these complications, first- and second-order surveys were considered of roughly equal accuracy in this investigation, and no elevations were reported closer than the nearest hundredth of a foot.

The Arvin-Maricopa area falls within four 30-minute quadrangles, as designated by the Coast and Geodetic Survey (fig. 34). Chronologic tabulations of adjusted elevations of bench marks, listed by line of leveling and number in each quadrangle, adjusted and published by the Coast and Geodetic Survey, are the basis for the subsidence maps, profiles, and graphs in this report. From these tabulations, the amount of subsidence that occurred at each bench mark between successive surveys is computed as the difference between successive elevations. No attempt has been made to adjust out the apparent tectonic subsidence that affects all bench marks in the area.

Subsidence Due to Hydrocompaction

Extensive areas in the San Joaquin Valley are subject to "near-surface" subsidence when the surficial soils are wet for the first time (Lofgren, 1960, p. 1053; Bull, 1964). Subsidence is due to collapse of the soil structure of certain moisture-deficient deposits when their dry strength is lost by wetting, a process referred to as hydrocompaction (Lofgren, 1969, p. 273). These areas are on the arid western and southern margins of the valley where natural rainfall has not penetrated below the root zone of the sparse vegetation.

Numerous evidences of hydrocompaction are observed in the Arvin-Maricopa area, particularly in a large area south of Buena Vista Lake bed (fig. 35). Extensive settling and cracking occur around ditches and ponds,

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Figure 35 near here.

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and highly irregular, undulating topography has developed in some irrigated areas. Some of the most intense hydrocompaction has occurred in the vicinity of water-disposal sumps east of Maricopa (Manning, 1968, p. 137). About 20 miles of the California Aqueduct traverses hydrocompactible deposits in the Arvin-Maricopa area and 20 million dollars was spent in preconsolidation ponding of the aqueduct alinement before construction began (Lucas, 1968, p. A-7).

Figure 35 shows the areas known to be susceptible to hydrocompaction in the Arvin-Maricopa area, as determined largely by field mapping by the California Department of Water Resources (1964, pl. 2) in 1958-59. Susceptible deposits occur principally on the gentle bajada that flanks the San Emigdio Mountains and Wheeler Ridge and in isolated patches south of Wheeler Ridge and northeast of Taft. Only on the north flank of Wheeler Ridge do the hydrocompactible fan deposits overlap the deep water-bearing deposits that are subsiding due to excessive pumping (fig. 35).

As much as 6 to 15 feet of local subsidence has resulted from the initial wetting of hydrocompactible deposits. Even though the hydrocompaction is a one-time process and occurs as soon as the deposits become wet, the subsidence of the land surface may continue for months or years at a given location as the downward percolation of infiltrating water continues and deeper deposits become wet.

Figure 36 shows the settlement and cracking that occurred around

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Figure 36 near here.

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one of the 8-foot infiltration tanks operated by the California Department of Water Resources (1964) prior to the construction of the California Aqueduct. This tank was about 4 miles northeast of Maricopa (fig. 35), and is typical of the several dozen tanks located along the aqueduct alinement in areas of suspected hydrocompaction. Water was supplied to the infiltration tank from a nearby storage reservoir. Staff gages attached to bench marks set in the deposits at various depths below the tank were used to measure subsidence resulting from the hydrocompaction. More than 10 feet of subsidence was measured at some of the test sites, and hydrocompactible deposits frequently extended to depths greater than 100 feet.

Deposits susceptible to hydrocompaction are characteristically derived from short, steep, stream-drainage systems, with relatively small watershed areas. Loose, low-density deposits, having high porosity and poor sorting, are typical of these subsiding areas. These deposits, in successive layers, were desiccated and baked on the alluvial-fan surface by evapotranspiration and intense heat before they were buried by the next layer of alluvial debris. Thereby, thick sequences of low-moisture, low-density deposits, baked hard like adobe, were accumulated. When water first wets these deposits, breaking down their high dry strength, collapse of the granular structure results in immediate compaction. Experience suggests that these hydrocompactible deposits compact on wetting to roughly the same density they would have attained under the usual process of progressive compaction as additional overburden load is added. Hydrocompactible deposits in the San Joaquin Valley are characteristically related to debris flows (Calif. Dept. Water Resources, 1960). Invariably, the deposits occur above the prehistoric water table, and in areas where natural rainfall never penetrates below the root zone of the thirsty vegetation.

Figure 37 shows infiltation ponds north of Wheeler Ridge used by

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Figure 37 near here.

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the California Department of Water Resources to preconsolidate the alluvial deposits prior to the construction of the California Aqueduct. About 24 miles of aqueduct alinement were preconsolidated in this manner in the Arvin-Maricopa area. Typically, these ponds were maintained for about 6 months of infiltration.

Subsidence due to hydrocompaction is a one-time process. Once the deposits become wet, they compact to a density determined by the overburden load. Subsidence of the land surface continues only until all susceptible deposits at depth become wet. Severe differential settlements frequently develop in areas of hydrocompaction. After adequate preconsolidation, however, these deposits are amenable to the same structural stresses and construction practices as other alluvial deposits.

No attempt is made herein to summarize the results of measurements and tests of the process and problems of hydrocompaction in the Arvin-Maricopa area by the California Department of Water Resources. A tremendous amount of detailed field and laboratory data was collected during and prior to the construction of the California Aqueduct. In this area, measurements by the Geological Survey were restricted to two localities, (1) at the Lakeview compaction-recorder site (fig. 58, compaction record) where slight equipment settlement occurred during the first year, but no compaction has been measured to a depth of 105 feet since 1962, and (2) at the Wheeler Ridge tiltmeter site (Riley, 1970, fig. 5) where significant hydrocompaction occurred below a depth of 150 feet during a brief period of wetting.

Subsidence due to the Extraction of Oil and Gas

Land subsidence caused by the extraction of oil and gas has been reported in numerous areas (Poland and Davis, 1969; Yerkes and Castle, 1969; Castle, Yerkes, and Riley, 1969). This type of subsidence is recognized in a few localities in the Arvin-Maricopa area, and would probably be found in more oil fields if detailed leveling control spanning the entire field production history were available.

Figure 38, taken from maps of the California Division of Oil and Gas

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Figure 38 near here.

(1960, p. 10-11), shows the locations of the oil and gas fields of the Arvin-Maricopa area and their relation to the area of principal subsidence caused by the excessive pumping of ground water. These two types of subsidence overlap in only three areas. The magnitude of subsidence caused by oil and gas extractions is shown for a specific period between repeated levelings by the U.S. Coast and Geodetic Survey. In general, the subsidence attributed to oil-field extractions was computed as the amount bench marks in the field subsided more than bench marks immediately outside the field. Along the survey line west of Bakersfield (fig. 38), for example, bench marks in the Fruitvale oil field, 2 miles west of Bakersfield, subsided 0.14 foot more than other bench marks along the line; this differential is attributed to the extraction of oil-field fluids between 1953 when leveling was first available, and 1965. During the same 1953-65 period, 0.03 foot of differential subsidence occurred in the Greeley field 10 miles west of Bakersfield. East of Bakersfield, about 0.3 foot of differential subsidence occurred in the Edison field between 1926 and 1965. Here, the extensive subsidence caused by ground-water pumping is difficult to separate from the effects of oil-field extractions even though one is occurring principally in the upper 1,000 feet of alluvial deposits and the other, several thousand feet below in the consolidated marine sediments.

Of particular interest is the subsidence that occurred in the Midway-Sunset field between McKittrick and Maricopa (fig. 39). Here, about 1.4 feet of subsidence on the north end of the field and 1.6 feet on the south end of the field was measured between 1935 and 1965. East of Maricopa, 0.6 foot of differential subsidence occurred during this same 30-year period. From these values, an idea of the relative magnitude of subsidence that is occurring over the various oil fields is obtained. It must be realized, however, that these data do not span the period of maximum oil and gas withdrawal. In the Midway-Sunset field, for example, first production was in 1894 and peak production was in 1914. Only a very small part of the total production, and probably only a small part of the total subsidence, occurred during the period of available leveling control. Also, since only a few points in the field were near bench-mark control, the point of maximum subsidence in the field probably is not indicated by these data.

Figure 39 shows a series of subsidence profiles across the Midway-

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Figure 39 near here.

Sunset oil field between 1934-35 and 1965. The upper sketch shows the location of bench marks along Highway 33 through the field. The lower graphs show the differential changes in elevation of these bench marks since they were first leveled in 1934-35. From these plots, the amount of subsidence between successive levelings since 1935 can be seen. Of particular interest is the sharp termination of subsidence at the north end of the field. The fact that no subsidence is registered northwest of the field from 1935 to 1965 suggests that tectonic adjustments are not involved in the data, and the entire subsidence is due to oil-field extractions. Maximum subsidence during the 30-year period was just north of Maricopa; however, some of the subsidence may be due to tectonic adjustments. Within the field, only the amount of subsidence that exceeds the settlement outside the field is attributed to oil and gas production.

In general, oil-field subsidence is of little concern in this investigation of subsidence caused by the pumping of ground water--the two types of subsidence usually do not overlap, and the rates on the valley floor are of a different order of magnitude. No attempt has been made in this report to subtract the apparent effect of oil and gas withdrawals from the total subsidence in computing the subsidence attributed to ground-water pumping.

SUBSIDENCE DUE TO WATER-LEVEL DECLINE

About 700 square miles of agricultural land south of Bakersfield is affected by subsidence caused by the excessive pumping of ground water. This represents about 60 percent of the Arvin-Maricopa area. Subsidence has occurred so uniformly and over such a broad area that few residents realize that it has happened. Maximum subsidence since pumping began is about 9 feet and local subsidence rates have exceeded 0.5 foot per year.

Figure 35 shows the extent of the area of subsidence (more than 0.5 foot) due to water-level decline and its relation to areas of hydrocompaction. Figure 38 shows the extent of subsidence due to water-level decline and its relationship to areas of subsidence due to oil and gas extraction. In general, the area affected by subsidence due to water-level decline does not overlap areas of hydrocompaction or oil-field extractions except in a few localities. The principal areas where more than one type of subsidence are active are in the Edison oil field southeast of Bakersfield (fig. 38) and north of Wheeler Ridge (fig. 35).

Subsidence due to water-level decline is attributed to the compaction of the unconsolidated water-bearing deposits that comprise the ground-water reservoir. The subsidence is caused by an increase in effective stress in the unconsolidated deposits resulting from ground-water overdraft. In the chapters that follow, the extent and magnitude of the subsidence, an analysis of the stresses causing the subsidence, and hydrogeologic parameters of the ground-water reservoir, are presented.

The magnitude, extent, and rate of the principal subsidence in the Arvin-Maricopa area, as defined principally by releveling of bench marks, are shown by a series of profiles, maps, and graphs (figs. 40-52). These figures illustrate the great variation in the amount of subsidence, both areally and with time, that has occurred during the period of leveling control. One of the objectives of this study is to related the subsidence to the geologic and hydrologic conditions that account for this great variation.

Subsidence Profiles

Subsidence profiles along two lines of bench marks through the Arvin-Maricopa area show the magnitude and extent of subsidence that has occurred since the earliest leveling control. Each profile is based on the change in elevation of the various bench marks along the line for the respective dates shown. The earliest leveling along each line is used as a base, and is shown as a horizontal straight line. Published elevations for these bench marks by the Coast and Geodetic Survey have been used exclusively. No corrections in the data were made for regional tectonic adjustments, except for the subtraction of tectonic uplift that occurred during the 1952 earthquake near Grapevine (figs. 40 and 11). No bench-

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Figure 40 near here.

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mark data that appeared to be significantly affected by hydrocompaction or by oil-field subsidence were used in preparing these profiles, maps, and graphs. As stated earlier, the inaccuracies introduced by other types of subsidence are small and not readily determinable. Only the apparent tectonic subsidence, introduced into the data by holding stable a rising reference bench mark south of Grapevine is large enough to be of concern in this study.

As shown in figure 40, the entire reach along U.S. Highway 99 from Bakersfield on the north to Grapevine on the south has been affected by subsidence since 1926. Data for the southern bench marks (south from Bench mark S824) were adjusted as discussed earlier (figs. 9 and 10), to eliminate the tectonic uplift that occurred during the 1952 Arvin-Tehachapi earthquake (Lofgren, 1966). Maximum subsidence throughout the period of leveling along this highway occurred about midway between Bakersfield and Grapevine at bench mark 766+42.65, where declining water levels caused 9.1 feet of settlement during the 44 years from 1926 to 1970. At this location, the rate of subsidence was not uniform throughout this period, as illustrated in figure 41. At bench mark T54(reset), 15 miles

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Figure 41 near here.

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south of Bakersfield and just north of the center of maximum subsidence (fig. 40), the subsidence rate varied from 0.02 foot per year from 1926 to 1935-39 to 0.41 foot per year from 1959-62. At this location and elsewhere along U.S. Highway 99, the subsidence rate increased from 1940 to 1960 in response to an accelerated use of ground water.

A rough measure of the magnitude of the apparent tectonic subsidence introduced in all the leveling data (fig. 41) by the tectonic uplift of the reference bench mark is the apparent subsidence of bench marks outside the area of heavy pumping. At Grapevine (bench mark K54) and in the Bakersfield area, where little subsidence due to pumping is sus ected, bench marks show considerable apparent subsidence (see also fig. 13).

The amount of subsidence along Maricopa Road, from Maricopa to Mettler, between successive levelings from 1935-39 to 1970 is shown in figure 42. In general, less subsidence has occurred along this line

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Figure 42 near here.

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than along U.S. Highway 99 (fig. 40); however, the maximum local subsidence along the two lines is not far different. Here also, the rate of subsidence increased markedly with the expansion of ground-water development. Figure 43 shows the subsidence rate at bench mark K367,

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Figure 43 near here.

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4 miles west of Mettler in the area of maximum subsidence (fig. 42). At this location, the rate of subsidence had a tenfold increase from 0.05 foot per year from 1935-39 to 1942 to 0.50 foot per year from 1957 to 1959. From 1959 through 1965 the rate remained about 0.5 foot per year, then dropped to 0.38 foot per year through 1970. Apparently, little subsidence occurred prior to 1935-39, as indicated by the asymptotic curvature of the subsidence graph.

Subsidence Maps

As shown in figure 33, the level net laid out in 1957 to monitor subsidence in the central part of the Arvin-Maricopa area subsequently was releveled completely four times, in 1959, 1962, 1965, and 1970. These relevelings are the basis for five of the six subsidence maps that follow; the sixth incorporates the leveling of these four periods and the approximated subsidence that preceded 1957, as determined from earlier leveling. In the preparation of these maps, published adjusted elevations by the Coast and Geodetic Survey were used without further adjustment, except for the subtraction of tectonic uplift of bench marks south of Mettler during the 1952 Arvin-Tehachapi earthquake (figs. 9 and 10). No bench marks were used for control that appeared to have been significantly influenced by either hydrocompaction of oil-field subsidence.

Figure 44 shows the magnitude and areal extent of subsidence that

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Figure 44 near here.

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occurred in the Arvin-Maricopa area between January-February 1957 and February-April 1959. Subsidence was greatest south of Kern Lake bed, where more than 1 foot of settlement took place in the 2-year period. The effects of heavy ground-water overdraft are clearly shown by the lines of equal subsidence, as also are the effects of recharge from Kern River and Caliente Creek in the Kern River fan area and the reentrant north of Arvin. The close contours on the north flank of Wheeler Ridge, although poorly controlled, reflect the concentration of pumping west of Mettler, the lack of ground-water recharge in this part of the valley, and to some extent the high compressibility of the alluvial deposits, as is discussed later. Of particular interest is the subsidence of Kern Lake bed, an area of little farming and little ground-water pumping. Subsidence here is undoubtedly caused by pressure declines in the deeper zones due to deep pumping to the south and east.

Planimetry of figure 44 indicates that about 72,000 acre-feet of subsidence occurred in the Arvin-Maricopa area in the 2-year 1957-59 period, for an average rate of 36,000 acre-feet per year. This represents an equivalent volume of interstitial pore water extracted from the fine-grained deposits of the aquifer system; a permanent "mining" that cannot be restored.

Figure 45 shows the subsidence that resulted between February-April

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Figure 45 near here.

1959 and December 1961-January 1962 from continued ground-water overdraft. During this time interval the subsiding area was considerably larger than during the previous period, expanding considerably onto the Kern River fan and into the Edison area. Significantly, this was a period of deficient precipitation (fig. 14) and severely deficient runoff of Kern River (fig. 15). These deficiencies had a marked effect on both the pumping pattern and the amount of ground-water recharge in these areas. During thsi 3-year period the maximum rate of subsidence averaged about 0.5 foot per year, and the effects of deep pumping continued to migrate northwestward under Kern Lake bed. At the north edge of Kern Lake bed, the average rate of subsidence doubled, increasing from 0.1 foot per year in 1957-59 to 0.2 foot per year in 1959-62.

About 172,000 acre-feet of subsidence occurred during the 1959-62 period, for an average annual rate of 57,300 acre-feet per year. This rate is 58 percent higher than during the prior period, and relates to the marked precipitation deficiency and consequent increased ground-water withdrawals.

Figure 46 shows the magnitude and extent of subsidence in the 3 years

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Figure 46 near here.

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from December 1961-January 1962 to March 1965, a period of moderately deficient runoff (fig. 15). A much smaller area was affected by subsidence during this period than during the previous one, the difference being largely in the areas of recharge from Kern River and Caliente Creek. The annual subsidence rate in the area of maximum subsidence exceeded 0.53 foot per year for the 1962-65 period.

The total volume of subsidence during the 1962-65 period (fig. 46) was about 143,000 acre-feet, or about 47,700 acre-feet per year. Ground-water pumpage in the subsiding area (table 4B) during this 3-year period was about 1,780,000 acre-feet (Ogilbee and Rose, 1969). Thus, subsidence, or water of compaction, represents about 8 percent of the total ground water pumped. This compares with about 10 percent for the Tulare-Wasco area for the 1950-62 period (Lofgren, 1969, p. B98).

Figure 47 is a composite of figures 44-46, showing the total amount

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Figure 47 near here.

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of subsidence from January-February 1957 to March 1965. Approximately 350 square miles experienced greater than 0.5 foot of subsidence during this 8-year period, and maximum subsidence exceeded 4.0 feet. Deficient rainfall (fig. 14) persisted through all but 2 years of this period. During the period, the pumping pattern did not change significantly and the configuration of the subsidence contours in figure 47 is similar to that on previous maps (figs. 44-46).

Figure 47A shows the magnitude and extent of subsidence between

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Figure 47A near here.

March 1965 and January-May 1970, a period of about normal precipitation. The subsidence in the 5-year period was a maximum of 2.2 feet, and a small center of 0.4 foot enclosed the town of Arvin. About 530 square miles are within the 0.2-foot contour and 114 square miles are within the 1.0-foot contour.

The average annual rate of subsidence for the 1965-70 period is shown in figure 48. The subsidence rate in the area of maximum subsidence

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Figure 48 near here.

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probably is greater than 0.4 foot per year; however, there is no bench-mark control in this area.

From the time the bench-mark network was established in 1957 to 1970, subsidence exceeded 6 feet at the center 4 miles north of Wheeler Ridge (fig. 48A). About 430 square miles of irrigable land, extending from Bakersfield south to Wheeler Ridge and from Buena Vista Lake bed east of Arvin, subsided more than 0.5 foot during the 13 years. The volume of subsidence during this period, obtained by planimetry of figure 48A, is 584,000 acre-feet.

Figure 48A near here.

Leveling control along U.S. Highway 99 began in 1926, and along Maricopa Road in 1935-39 (fig. 33). Subsequent leveling along these lines is shown in the subsidence profiles of figures 40 and 42. These profile lines traverse the subsidence area in two directions and give reasonable definition of the magnitude and extent of the subsidence that preceded the 1957 leveling. Using these profiles as control for the period prior to 1957 and figure 48A for the 1957-70 period, a subsidence map for the 1926-70 period is obtained. Thus, figure 49 is believed to be a

Figure 49 near here.

reasonable representation of the subsidence that occurred during the 44 years from 1926 to spring 1970. Maximum subsidence during this period exceeded 9 feet (fig. 40) and about 455 square miles are within the 1-foot subsidence contour.

Figure 50 shows the relation of magnitude to area of subsidence

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Figure 50 near here.

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for the 1926-70 period, based on the planimetry of the areas within the respective subsidence contours of figure 49. As shown, approximately 315,000 acres (490 sq mi). or about 43 percent of the entire Arvin-Maricopa area, had subsided more than 1 foot by 1970. Sixty-six thousand acres (103 sq mi), or about 9 percent of the total area had subsided more than 5 feet, and a small area subsided over 9 feet. The total area affected by subsidence, though poorly defined, appears to be about 450,000 acres (703 sq mi) or about 62 percent of the total Arvin-Maricopa area (1,140 sq mi). The area under the curve of figure 50 represents the volume of subsidence, which is about 1.06 million acre-feet for the 44-year 1926-70 period.

Volume of Subsidence

In order to approximate the volumetric rate of subsidence prior to 1957, the assumption is made that the volume of subsidence for each time interval prior to 1957 varied directly as the respective areas under the 1926-57 profiles along U.S. Highway 99 (fig. 40). On this basis, the pre-1957 subsidence computed as the difference between figures 47 and 49 is broken down into three intervals as shown in table 4.

Table 4 (p. 118) near here.

Table 4 summarizes the total subsidence and volumetric rate of subsidence for seven periods between 1926 and 1970, approximated as described above, for the three periods prior to 1957, and planimetered from the subsidence maps (figs. 44-47A) for the four periods since 1957.

Table 4.--Total subsidence and subsidence rates for the Arvin-Maricopa area, 1926-70.

[Based on planimetry of maps of figs. 44-49.]

	Volume of subsidence (acre-ft)	Cumulative volume of subsidence (acre-ft)	Average subsidence rate (acre-ft per yr)
1926-47	84,000	84,000	4,000
1947-53	207,000	291,000	34,500
1953-57	142,000	433,000	35,500
1957-59	72,000	505,000	36,000
1959-62	172,000	677,000	57,300
1962-65	143,000	820,000	47,700
1965-70	240,000	1,060,000	48,000

The average rate of subsidence for the seven periods of control are shown by the histogram of figure 51. The dashed curve is an estimated

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Figure 51 near here.

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probable rate obtained by rounding of the histogram. It is significant that the rate of subsidence increased rapidly prior to 1947 and remained relatively constant from 1947 to 1959. The high rate of subsidence from 1959 to 1962 apparently is directly related to the rainfall deficiency of that period.

The cumulative volume of subsidence for the Arvin-Maricopa subsidence area, based on the data of table 4 is shown in figure 52,

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Figure 52 near here.

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and was about 1.06 million acre-feet in 1970 (fig. 50). Plotted points on the graph show the cumulative volume of subsidence as of the dates when control was available, and the dashed connecting line indicates the estimated rate of cumulative increase between the controlled points.

As stated earlier, subsidence results from the xtraction of interstitial pore water in the fine-grained beds of the aquifer system; a one-time "mining" of the water of compaction. Thus, 1.06 million acre-feet of interstitial water was pumped from the ground-water basin by 1970. This represents about 1 1/2 years of normal runoff of Kern River (fig. 15), and nearly the amount of ground water pumped in an average year (1962-66 average) from the Arvin-Maricopa ground-water area. This one-time source of water supply not only produces permanent changes in the aquifer system and permanent lowering of the land surface, but also gives a misleading impression of the usable storage capacity of the ground-water basin. Because it is available during the early stages of ground-water development, this water of compaction is apt to be considered as part of the permanent water supply. When subsidence is stopped, and the ground-water basin is "managed" to prevent continued water-level decline, this source of water will no longer be available.

Subsidence-Pumpage Relationship

Subsidence of the land surface results from the compaction of fine-grained water-bearing deposits, and is a measure of the "water of compaction" that is permanently mined from the ground-water reservoir. This is a one-time source of water to wells, and in parts of the Arvin-Maricopa area, represents a significant percentage of the total pumpage.

Table 4A gives the estimated ground-water pumpage for agricultural

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Table 4A (p. 122 of ms.) near here.

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use in the Arvin-Maricopa area (all townships of figure 46 within the valley) for 5 years (1962-66), based on electrical power data (Ogilbee and Rose, 1969). Table 4B lists by township the estimated ground-water pumpage for the 3 years 1962-64 for only that part of the valley in which pumping produced significant subsidence during the 1962-64 period (fig. 46 spans the same 3-year period). Calculations were made on a quarter-township basis, and included all quarter townships within or crossed by the 0.2-foot subsidence line of figure 46. Since pumping effects and subsidence extend beyond the 0.2-foot subsidence, line, the pumpage values of table 4B relate to the same part of the valley as the subsidence value listed in table 4.

Table 4A.--Estimated ground-water pumpage for agricultural use in the Arvin-Maricopa area for 5 years, 1962-66, based on electrical power data.

[For agricultural year April 1-March 30.

Data from Ogilbee and Rose, 1969.]

Year	Approximate number of irrigation wells 1/	Pumpage, in thousand acre-feet
1962	2,316	1,185.7
1963	2,409	1,111.8
1964	2,399	1,095.0
1965	2,326	1,034.2
1966	2,131	1,112.7
Subtotal 1962-64		3,392.5
Total 1962-66		5,539.4

1/ Listed as number of tests in Ogilbee and Rose tabulations.

The volume of subsidence for the 3-year 1962-65 period was 143,000 acre-feet (table 4), which was about 8 percent of the 1,781,400 acre-feet (table 4B) of total pumpage in the subsidence area, and 4 percent of the

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Table 4B (p. 124 of ms.) near here.

3,392,500 acre-ftte (table 4A) of pumpage in the Arvin-Maricopa area for the same 3-year period. The relationship between subsidence and pumpage, however, varied greatly throughout the Arvin-Maricopa area.

Table 4B.--Estimated ground-water pumpage for agricultural use in the Arvin-Maricopa subsidence area, 1962-64, based on electrical power data

[For agricultural year April 1-March 30. Data from Ogilbee and Rose, 1969.]

Township/ range	Number of quadrants of township included	Pumpage, in thousand acre-feet	Township/ range	Number of quadrants of township included	Pumpage, in thousand acre-feet
30/28	3	89.9	12N/22W	2	22.9
30/29	2	138.1	12N/21W	2	64.3
31/26	1	7.8	12N/20W	2	47.2
31/27	3	156.6	12N/19W	2	49.8
31/28	4	138.0	12N/18W	1	21.6
31/29	4	208.2			
31/30	2	62.7	11N/22W	1	27.2
			11N/21W	2	49.3
32/25	1	16.1	11N/20W	2	71.7
32/26	4	83.1	11N/19W	2	106.5
32/27	4	86.3			
32/28	4	180.6	Total		1,781.4
32/29	3	153.5			

Using ground-water pumpage computed from electrical power data, converted to acre-feet per acre or feet of water, and subsidence averaged from figure 46, the subsidence/pumpage ratio was computed for each quarter-township in the Arvin-Maricopa subsidence area. This gives the proportion of the total ground-water pumpage that is derived from "water of compaction" of the aquifer systems for the 1962-65 period. As shown in figure 53, this percentage of mined "water of compaction" varied from

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Figure 53 near here.

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a few percent around the perimeter of the subsidence area to more than 40 percent in the area of maximum subsidence. The effects of recharge from the Kern River, Caliente Creek, and various smaller streams are clearly demonstrated by small subsidence/pumpage ratios and by reentrants in the outer contours of the ratio map. Thus, where there is adequate recharge, little or no long-term water-level decline and associated subsidence occurs even though there has been considerable pumping. In the interior part of the subsidence area, however, water levels decline at a rapid rate, and as much as 40 percent of the total pumpage is mined from the compressible beds of the aquifer systems as permanent compaction occurs.

The subsidence/pumpage ratios of figure 53 are a rough measure of the recharge characteristics of the ground-water basin. These are of prime significance in the consideration of importing surface water to alleviate subsidence. The importation of surface water will affect subsidence rates in two ways:

(1) By supplying some of the irrigation demands, less ground water will be pumped, and

(2) through planned or incidental deep percolation, the ground-water reservoir will be partially recharged and water levels will tend to rise.

If recharge water were spread on the surface within the subsidence area, it would tend to recharge the water table and not the deep confined aquifers. This would tend to increase effective stresses in the deep zones and thereby aggravate subsidence. Also, if spreading were accomplished in the perimeter areas, using natural stream channels to get the water underground, recharge would first affect subsidence rates in the perimeter areas, and interior areas of maximum subsidence would be the last affected. Probably the most effective method of reducing subsidence in the interior area of maximum subsidence is to use imported surface water to supply irrigation demands and thereby stop pumping of ground water. Even in the center of maximum subsidence, more than half the current pumpage is derived each year from recharge. Therefore, water levels should recover and subsidence should decrease rapidly soon after pumping is discontinued. It appears that if pumpage in the area of maximum subsidence were reduced to about half the present rate, water levels would stabilize at about their present low levels and subsidence would eventaully stop.

Analysis of Hydraulic Stresses Causing Subsidence

Land subsidence in areas of intense water-level declines is attributed to the compaction of the subsurface water-yielding deposits. Compaction results from an increase in effective loading stress on the deposits, caused by the water-level change.

Depending on the nature of the deposits, compaction may be (1) largely elastic, independent of time, and reversible, or (2) principally nonelastic resulting from a rearrangement of the granular structure, causing a permanent volume decrease and density increase of the deposits. In general, if the deposits are coarse sand and gravel, the compaction will be small and largely elastic and reversible, whereas if they contain fine-grained interbeds, or even small amounts of clay, the compaction will be much greater and chiefly inelastic and permanent. In either case, one-dimensional compression of the deposits occurs which results in subsidence of the land surface.

As described by Lofgren (1968, p. B219-B225), effective stresses in an aquifer system are changed in two principal ways: (1) water-table fluctuations change the buoyant support of the grains in the zone of the change, and (2) a change of water table or of artesian head, or both, may induce vertical hydraulic gradients and seepage stresses in the deposits; the stress changes are additive in their effect with gravitational stresses, and generally are the principal cause of compaction of the compressible deposits.

According to the Terzaghi theory of consolidation (Terzaghi and Peck, 1948, p. 233), compaction results from the slow escape of pore water from the stressed deposits, accompanied by a gradual transfer of stress from the pore water to the granular structure of the deposits. When an increment of loading stress is applied to a compressible aquitard, the entire stress increase first is borne by the interstitial water. No increase in grain-to-grain stress can occur until drainage from the aquitard begins. A steep hydraulic gradient develops at the surface of the aquitard, causing rapid drainage from the pores near the surface. Then, as the excess pressure in the aquitard gradually dissipates, the intergranular stress increases and the void ratio decreases. This slow process always is in a more advanced state near the aquitard surface and at a less advanced state near its center. A slow-draining aquitard may take months or years to adjust to an increase in applied stress, whereas a coarse-grained aquifer may adjust in only minutes.

Types of Stresses

Three different types of stresses are involved in the compaction of an aquifer system. These stresses are closely interrelated, yet of such different nature, that a clear distinction is of utmost importance. The first of these is a gravitational stress, caused by the effective weight of overlying deposits, which is transmitted downward through the grain-to-grain contacts in the deposits. The second, a hydrostatic stress equal to the hydraulic head times the unit weight of water, is transmitted downward through the water. The third is a dynamic seepage stress exerted of the grains by the viscous drag of vertically moving interstitial water. The first and third are additive in their effect and together comprise the grain-to-grain stress which effectively changes the void ratio and mechanical properties of the deposit; it is commonly known as the "effective stress." The second type of stress, although it tends to compress each individual grain, has virtually no tendency to change the void ratio of the deposit and is referred to as a "neutral stress."

Relation of Change in Effective Stress to Water-Level Fluctuation

Water-level fluctuations change effective stresses in the following two ways:

1. A rise of the water table increases the buoyant support of grains in the zone of the change, and a decline decreases 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.

First, consider the stress change caused by a change in the water table. The dry unit weight of deposits above the water table, $\gamma_{\underline{d}}$, may be expressed

$$\gamma_{\underline{d}} = (1 - n)\,\underline{G} \cdot \gamma_{\underline{w}} \qquad (1)$$

where

$\underline{n}$ = porosity

$\underline{G}$ = specific gravity

$\gamma_{\underline{w}}$ = unit weight of water.

Correspondingly, the buoyant (submerged) unit weight, γ', of the deposits below the water table equals

$$\gamma' = (1 - \underline{n})\,(\underline{G} - 1)\,\gamma_{\underline{w}} \qquad (2)$$

The change in effective weight of the deposits from dry to buoyant in the zone of water-table decline, therefore, equals

$$\Delta\underline{p}' = (1 - \underline{n})\,(\underline{G} - 1)\,\gamma_{w} - (1 - \underline{n})\,\underline{G} \cdot \gamma_{\underline{w}} = -\,(1 - \underline{n})\,\gamma_{\underline{w}} \qquad (3)$$

Thus, the change in effective weight equals the weight of the displaced water, and is not influenced by the specific gravity of the deposits.

If, as usually occurs in nature, the deposits above the water table are moist, rather than dry, the moist unit weight of these deposits, γ_m. equals

$$\gamma_m = (1 - n) G \cdot \gamma_w + y \cdot \gamma_w \tag{4}$$

where

y = specific retention, or volume of contained water.

The change in effective weight of the deposits $\Delta p'$, from moist to buoyant in the zone of water-table change, therefore, equals

$$\Delta p' = - (1 - y_s) \gamma_w \tag{5}$$

where

$y_s = n - y$ - specific yield.

Assuming a porosity, n, of 40 percent, a specific retention, y of 20 percent, an average specific gravity of 2.70, and expressing γ_w as 1 foot of water, the effective stress due to the weight of moist deposits above the water table equals 1.8 feet of water per foot of thickness. Similarly, the effective stress due to the buoyant weight of deposits below the water table equals 1.0 foot of water per foot of thickness. The change in effective stress from moist to buoyant conditions equals -0.8 foot of water per foot of water-table change.

Gravitational stress changes, as described above, are borne by the grain-to-grain contacts of the deposit, and are transmitted downward through the water-bearing deposits to basement.

Under simple hydrostatic conditions for a confined aquifer system, the hydraulic heads for the aquifers above and below the confining layer stand at the same elevation; therefore, no seepage occurs through the confining layer. If the artesian head in a confined aquifer system is drawn down or the overlying water table is raised, however, the downward hydraulic gradient developed across the confining layer (aquiclude) induces downward seepage. The loss of hydraulic head through the aquiclude represents the energy expended in moving the water through the pore passages. As head is dissipated by viscous flow through the confining layer, force is transferred from the water to the granular skeleton of the deposit by viscous drag. The force transferred to the grains is exerted in the direction of flow. The seepage stress (force per unit area) is algebraically additive with the gravitational stresses that tend to compact the deposits.

As commonly used, the term "seepage force" refers to the energy transfer that occurs within the body through which the seepage takes place. As defined by Scott (1963, p. 96, equation 4-20), the seepage force, $\underline{f}$, exerted on the grains can be represented by the expression

$$\underline{f} = \underline{h} \cdot \gamma_{\underline{w}} \cdot \underline{A},$$

in which $\underline{h}$ is equal to the head loss across an incremental thickness, and $\underline{A}$ is equal to the cross-sectional area.

Within an aquiclude that is compacting under the stress of downward seepage, the hydraulic gradient, and therefore the seepage force per unit thickness, varies from a minimum at the upper surface to a maximum at the lower surface until steady-state conditions are reached. The loading effect of the incremental seepage force developed through each unit volume vertically through the aquiclude is additive downward. Thus, the net effect of these incremental units of seepage force at any horizontal plane in the structure of the aquiclude is equal to the summation of the incremental forces above that point. Although the distribution of these forces within the aquiclude may be indeterminate, the total seepage force accumulated through the aquiclude is equal to the total head differential, $\underline{H}$, across it. Thus, at the base of the aquiclude, the total seepage force, $\underline{F}$, may be expressed as

$$\underline{F} = \underline{H} \cdot \gamma_{\underline{w}} \cdot \underline{A},$$

and the seepage force per unit area, $\underline{J}$, hereafter referred to as the seepage stress, is

$$\underline{J} = \frac{\underline{F}}{\underline{A}} = \underline{H} \cdot \gamma_{\underline{w}} \; .$$

This seepage stress is transmitted downward through the intergranular structure of the aquifer system below the aquiclude. If stress and force are expressed as equivalent head of water, and $\gamma_{\underline{w}} = 1$, then from the above expression, the seepage force per unit area, $\underline{J}$, is simply

$$\underline{J} = \underline{H} \text{ (feet of water)} \qquad (6)$$

Thus, regardless of porosity or specific gravity of the deposits, or the vertical hydraulic conductivity of the aquiclude, the seepage force applied to the intergranular structure of the aquifer system equals the hydraulic head differential across the aquiclude. A downward seepage force causes an effective-stress increase, and an upward seepage force an effective-stress decrease in the confined aquifer system.

Summary

In considering the stresses that cause subsidence, consideration must be given to two different hydraulic regimes, (1) unconfined (water-table) conditions in which no vertical hydraulic gradients exist, and (2) confined (artesian) conditions, in which vertical gradients exist and result in seepage stresses that usually represent the major component of effective-stress change. Generally, a ground-water reservoir reacts as an unconfined system, if no significant vertical head differentials occur within it under ordinary pumping stress. A ground-water basin includes one or more confined aquifer systems if vertical head differentials within the basin are significant.

Unconfined (water-table conditions.--Under natural conditions, the unconsolidated deposits of an unconfined aquifer system generally are in equilibrium with their overburden load. A change in loading stress, however, causes the compressible beds of the system to deform.

A water-table change causes an effective-stress change throughout the aquifer system. The stress change equals the change in buoyant weight of the deposits in the zone of the water-table change. Assuming an effective porosity of 20 percent in this zone, the change in effective stress $\Delta p'$ (equation 5, above), equals 0.8 foot (0.34 psi) for each foot of water-table change. The stress increases for a water-table decline, and decreases for a water-table rise. The stress change affects all deposits in the unconfined system below the new water level--immediately in the coarse-grained beds that usually dominate a truly unconfined system, and with a time delay within the slow-draining interbeds. The compaction or expansion that occurs in this unconfined aquifer system is independent of stress/strain changes that might occur at greater depth.

Where field values of porosity and specific retention are known, these are used in computing changes in effective stress. Where field determinations of these parameters are not available, a specific retention of 20 percent is probably a reasonable approximation of actual values in the subsidence areas of the San Joaquin Valley.

Confined (artesian) conditions.--If the overlying water table and the artesian head in a confined aquifer system remain at equal elevation, the system behaves as an unconfined system. If, however, head differentials develop, either across the confining aquiclude or across interbedded, aquitards, two components of stress change in the confined system must be considered. The first is a gravitational stress change that occurs at the water table (equation 5, above) and is transmitted to the skeleton of the confined system. The second is a net seepage force equal to the head differential between the overlying water table and the confined zone. A change in either the water table or the artesian head, or both, may cause a change in the seepage component of effective stress (equation 6, above). This seepage component is algebraically additive with gravitational stress change in effective stress.

For an assumed specific yield of 0.2 in the zone of water-table lowering, regardless of the porosity, hydraulic conductivity, or specific gravity of the deposits of the confined aquifer system or the confining aquiclude, the following changes in applied stress result in the confined aquifer system:

(a) A water-table rise of 1 foot in the overlying unconfined aquifer will cause a 0.2-foot increase in applied stress, whereas a water-table decline of 1 foot will cause a 0.2-foot decrease in applied stress.

(b) A pressure decline of 1 foot in the confined aquifer system will cause a 1-foot increase in applied stress and a 1-foot rise will cause a 1-foot decrease in applied stress.

Changes in effective stress produce immediate deformation of the coarse-grained beds of a confined aquifer system. Within fine-grained interbeds, however, externally applied stresses become effective only as rapidly as water can be squeezed out by compaction. The time delay for adjustment of excess pore pressures within the slow-draining beds results in continued subsidence weeks and months after a given water-level change occurs.

Relation of Subsidence to Water-Level Change

Subsidence of the land surface at a point 8 miles west of Mettler is shown in figure 54 by a change in the elevation of bench mark LS2

Figure 54 near here.

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between 1942 and 1947 and by subsequent changes in the elevation of bench mark J824, which replaced LS2 in 1947. (For location, see fig. 32.) The subsidence at this location began during the period 1942-47 and has been continuous since 1947; it has been accelerating between each releveling since 1953. Also shown in figure 54 is a hydrograph for well 11N/21W-14D2, which is about 1 mile southeast of the bench-mark location. The water level in the well declined about 270 feet between 1949 and 1962, and probably had been declining for several before 1949. As shown, the relationship between subsidence and water-level decline has varied greatly during the period of available record. Water levels were falling rapidly between 1947 and 1953, while virtually no subsidence was observed. From 1957 to 1962, the subsidence at bench mark J824 was at a rate of about 1 foot for each 120 feet of water-level decline in well 11N/21W-14D2.

The relation of subsidence to water-level decline 2 miles west of Mettler is shown in figure 55. Subsidence at bench mark A303 was first

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Figure 55 near here.

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recorded in 1942 and continued at an accelerated rate to 1965 in direct response to the rapid decline of ground-water levels. Water levels at this location fell from less than 20 feet below the land surface in the late 1920's to about 130 feet below the land surface in the summer of 1946, an average rate of about 7 feet per year. During the period 1946-62, the water level in well 11N/20W-9A1 fell from about 130 feet to about 415 feet, an average rate of 18 feet per year. During the period 1947-53, the rate of subsidence at bench mark A303 was 0.16 foot per year and in 1959-62 was 0.30 foot per year. Thus, the ratio of subsidence to water-level decline increased between these two periods from 1:112 to 1:60, repsectively. Since 1961, measured water levels in well 11N/20W-9A1 have been erratic, and suggest possible casing failure in the upper part of the well.

Similar correlations between subsidence and water-level change at 31 locations in the subsidence area are shown in figures 23-31.

The actual change in head in the semiconfined and confined aquifers since ground-water development began in the Arvin-Maricopa area is not clearly defined. Generally, water levels have declined throughout the period of development. Locally, shallow water levels have risen in recent years from earlier depressed conditions, but deeper zones, in general, have maintained a long-term decline through the period of this study. In much of the area, water levels and changes in water level are gradational with depth, and most hydrographs indicate the composite head in several different aquifers. Few hydrographs are representative of specific zones, and none are an accurate measure of changes in the confined aquifer system as a whole.

Because of inadequate water-level control, computation of long-term changes in effective stress is possible at only a few localities. For most of the area, only composite water levels for the principal producing aquifers are available, and little information is available to indicate long-term water-table changes or trends in the less productive artesian aquifers. Head changes in the confined aquifer system are the best control data available, and as they are directly related to changes in effective stress at a given location, they have been used to derive ratios between subsidence and head decline at 29 locations in the subsidence area. These ratios are a rough approximation of the compressive response of the aquifer system under a change in stress related to a given water-level change.

Table 5 gives the computed subsidence to head-decline ratio for 29 locations in the subsidence area for the 8-year interval from 1957 to 1965. These values are based on the long-term head changes indicated by the hydrographs of figures 23-31, 54, and 55, and the measured subsidence of nearby bench marks (for locations, see fig. 32). Since the water level in well 11N/21W-1K1 had attained deeper levels prior to 1957, a subsidence to head-decline ratio was not computed for this location.

Figure 56 shows the areal distribution of the computed subsidence

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Figure 56 near here.

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to head-decline ratios of table 5 and the approximate lines of equal subsidence to head-decline ratio for the Arvin-Maricopa subsidence area for the 8-year period from 1957 to 1965. Significantly, this ratio is smallest in areas of least subsidence (fig. 47), and greatest where subsidence has continued for many years, and where total subsidence is greatest. Two factors undoubtedly influence this relationship: (1) the thickest, most compressible part of the compacting aquifer system should produce the greatest subsidence for a given stress change, and (2) as in most other areas studied, little subsidence occurred until water levels had declined more than 100 feet.

If, as in the northwest corner of T. 32 S., R. 28 E., the subsidence to head-decline ratio is 3.6×10^{-2} --that is, 0.036 foot of subsidence per foot of head decline--future water-level declines probably would cause subsidence at about this same rate. Thus, a map of estimated future subsidence, based on assumed future water-level changes throughout the area, can be computed. In so doing, however, only those declines that exceed previous declines at a location should be considered as producing subsidence.

Table 5.--Relationship between subsidence and head decline at 29 locations, 1957-65

Well (for locations, see fig. 32)	Reference figure	Depth (feet)	Head decline (feet)	Subsidence (feet)	Subsidence / Head-decline ratio
					$\times 10^{-2}$
30S/28E-10N1	31	1,199	45	0.298	0.67
31S/26E-36A1	23	820	40	.775	1.94
31S/27E-2M1	23	815	38	.580	1.53
-10D1	24	300	28	.510	1.82
-15K1	24	509	52	.60	1.15
-24B1	24	713	37	.94	2.54
-30E1	24	815	37	.62	1.67
31S/29E-8J3	25	350	60	.575	.96
32S/27E-18D1	23	859	71	1.31	1.84
32S/28E-6E1	23	820	72	2.52	3.60
-30D1	30	800	79	3.46	4.38
32S/29E-9R1	25	510	95	1.19	1.25
-19H1	25	1,000	59	2.04	3.46
11N/22W-4H1	26	1,008	79	.555	.70
11N/21W-1K1	27	1,200	-	-	-
-4H1	26	1,240	87	1.17	1.35
-7D1 1/	26	2,212	142	.55	.37
-8D1	26	1,158	125	.87	.70

Table 5.--Relationship between subsidence and head decline at 29 locations, 1957-65--Continued

Well (For locations, see fig. 32)	Reference figure	Depth (feet)	Head decline (feet)	Subsidence (feet)	Subsidence / Head-decline ratio
					$\times 10^{-2}$
11N/21W-11N1	27	1,205	123	2.79	2.27
-12E1	27	1,204	50	2.53	5.06
-14D2 2/	54	584	59	.48	.81
11N/20W-5L1	28	1,025	45	1.92	4.27
-7N1	28	1,200	117	2.70	2.31
-8A1	28	1,025	75	3.52	4.70
-9A1	55	1,100	140	2.43	1.74
11N/20W-9K1	28	1,202	133	3.55	2.67
-13G1	29	1,001	85	.275	.32
-17H1	29	1,038	115	3.76	3.27
-24A1	29	1,007	82	.28	.34

1/ 1959-65 data.

2/ 1957-62 data.

As discussed in the chapter, "Analysis of hydraulic stresses causing subsidence," change in the vertical seepage stress is the dominant component of increased effective stress that causes subsidence. At any depth in the aquifer system, the seepage stress equals the hydraulic-head differential between the water table and the pore pressure at that depth, and is conveniently expressed in feet of water.

Figure 56A shows the estimated spring 1965 seepage stresses for

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Figure 56A near here.

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part of the Arvin-Maricopa area, based on water-level maps of the California Department of Water Resources. Shaded areas denote seepage stresses in excess of 60 and 100 feet, respectively, of hydraulic head differential, and have a significant coincidence with the area of maximum subsidence. Realizing that before extensive development, upward seepage stresses prevailed throughout much of the subsidence area, the stresses of figure 56A represent the minimal change since development began and should be correlative with the long-term subsidence of figure 49. Using the 1926-70 subsidence values of figure 49 and the spring 1965 seepage stresses of figure 56A, specific subsidence (subsidence-to-stress ratios) ranges from 6.0×10^{-2} in the center of maximum subsidence to less than 1.0×10^{-2} in the perimeter areas. Throughout the Arvin-Maricopa area, the long-term specific subsidence values are greater than, but with the same general configuration, as the 1957-65 ratios of figure 56.

COMPACTION OF THE WATER-YIELDING DEPOSITS

The amount of compaction at a given location depends on the thickness and compressibility of the deposits, the magnitude of the increase in effective stress, the time of stress application, and possibly the type of stress applied. The range of stress change, grain size, clay mineralogy, and geochemistry of the pore water all affect the compressibility of the deposits. Also, the effective stresses in a confined aquifer system are affected by (1) water-level changes in an overlying unconfined or semiconfined aquifer system and (2) by seepage stresses that may develop within the confined aquifer system.

Compaction-Recorder Installations

Subsidence of the land surface is measured by periodic leveling of a network of bench marks, whereas compaction of the deposits is measured by observing the change in thickness of a particular sequence of the deposits. For any given time interval, subsidence of the land surface should equal the sum of the incremental compaction of all strata between the land surface and the bottom of the compacting section. A special type of installation (Lofgren, 1961, p. B49) is being used to measure the rate and magnitude of compaction in the subsidence areas of the San Joaquin Valley. As shown in figure 57, the assembly consists of a heavy weight

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Figure 57 near here.

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emplaced in the formation below the bottom of a well casing and an attached cable stretched upward in the casing and counterweighted at the land surface to maintain constant tension. A monthly recorder (with battery-driven clock) mounted over the open casing is used to measure directly the amount of cable that rises above the casing as compaction occurs.

The success of this type of recorder installation depends largely on the durability and stretch characteristics of the down-hole cable and the minimization of down-hole friction between the cable and the well casing. The cable must remain at constant length during the period of record. If the length changes, due to temperature changes, fatigue elongation, or untwisting, this change is measured by the recorder and is indistinguishable from the record of actual compaction or expansion. Friction in the system, both in the well casing and in the recording mechanism above the land surface, results in a stepped or interrupted record of compaction. This reduces the accuracy and resolution of the recorded data, especially during reversals in trend. Ball-bearing sheaves have been used in the installation to reduce frictional drag.

During the early phases of the investigation in the San Joaquin Valley, a 1/8-inch, 7 by 7 stranded, preformed, galvanized steel aircraft cable was used. Many of the recorder installations failed after 6-15 months due to cable corrosion. Generally, failure occurred in the interval of water-level fluctuations in the well casings and was most rapid in wells that had excessive falling water. After experimentation with methods to prevent corrosion, a specially manufactured 1/8-inch, stainless steel, 7 by 7 stranded, plastic-coated preformed cable was selected, and installed in several installations in 1959. Further experimentation with an uncoated 1/8-inch, 7 by 7 stranded, preformed stainless steel cable, and an uncoated 1/8-inch, 1 by 19 stranded, preformed stainless steel cable seemed to reduce the down-hole friction of the system. Inasmuch as the 1 by 19 stranded cable has much better performance characteristics than the 7 by 7 cable, all anchored-cable compaction-recorder installations since 1965 have been made with the 1 by 19 cable. All compaction recorders in the Arvin-Maricopa area operate with plastic-coated 7 by 7 cable, except 11N/21W-3B1 which was installed with uncoated 7 by 7 cable.

Compaction recorders have been operated in five wells in the Arvin-Maricopa area during this investigation. Companion water-level recorders have been operated in four of these wells. The period of record of these recorders is given in table 6. Each of the compaction recorders operates with a 1:1 scale; that is, 0.1 foot of compaction of the depth interval registers 0.1 foot of displacement on the recorder chart. This record permits correlation of the measured compaction with fluctuations in artesian pressure in the aquifer system.

Table 6.--Compaction and water-level recorders in the Arvin-Maricopa area.

[Records continue beyond 1969 for all recorders except 35E1. Location of wells shown in figure 34.]

Well	Anchor depth (feet)	Records available (month and year)	
		Compaction	Water-level
32S/28E-20Q1 1/	970	4/63-12/69	4/63-12/69
12N/21W-34Q1 1/	810	6/60-12/69	6/60-12/69
12N/21W-34Q3 2/	105	6/60-12/69	None
12N/21W-35E1 1/	485	6/60-9/69	6/60-10/69
11N/21W-3B1 3/	1,480	4/63-12/69	4/63-12/69

1/ Unused irrigation well.

2/ Drilled test well. Monthly readings only.

3/ Drilled test well. Partial coring.

Measured Compaction of Deposits at Lakeview

Four of the five compaction recorders and three of the four water-level recorders maintained in the Arvin-Maricopa area during this investigation (table 6) are located at Lakeview (fig. 34), 21 miles southwest of Bakersfield. At this site, compaction occurring in four different depth intervals can be monitored with these recorders. Also, the amount of compaction occurring at depths below the deepest anchor can be calculated by comparing the measured compaction with the subsidence of surface bench marks.

Figure 58 shows the measured compaction of the four Lakeview

Figure 58 near here.

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recorders through December 1969, and the subsidence trend of bench marks W1156 (at 12N/21W-34Q3) and M991 (at 11N/21W-3B1) through March 1970. Figure 59 shows the depth relation of these compaction

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Figure 59 near here.

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recorders, and the unit rate of compaction in four depth zones for two 3-year periods of measured compaction.

The shallowest recorder, 12N/21W-34Q3, with anchor set above the water table at a depth of 105 feet, was designed to measure possible hydrocompaction of surficial deposits in the area. Although this recorder is only 3 miles from deposits known to be susceptible to hydrocompaction (fig. 35), only slight settlement was observed through 1962 (fig. 58) and little or no compaction was observed during the following 6 years.

Compaction recorder 12N/21W-35E1 measured the vertical shortening of the deposits to a depth of 485 feet from June 1960 until it was dismantled in September 1969. Throughout this period, the compaction record was stepped due to excessive downhole friction. Only yearend values of compaction have been used in plotting the 12N/21W-35E1 compaction graph of figure 58. These, however, are believed to be a reliable representation of the compaction to the 485-foot depth at the Lakeview location. The rate of compaction of deposits spanned by this 485-foot recorder slowed considerably from June 1960 to January 1963. Since January 1963, to the end of the record in 1969, however, the annual compaction rate remained almost constant at about 0.06 foot per year.

The 810-foot compaction recorder, 12N/21W-34Q1, has given a reliable record of compaction since June 1960, except for a 2-year period of questionable record from August 1967 to August 1969. Beginning in 1966 the rate of compaction in the depth zone spanned by this recorder decreased markedly. Also, a distinct change in the annual pattern of compaction occurred--from a stairstepped seasonal pattern prior to 1965 to a smoothed declining trend since 1965. Undoubtedly, the drilling of additional deep wells in the area and the discontinued pumping of several nearby wells of intermediate depth is responsible for this change in pattern.

Compaction recorder 11N/21W-3B1 was installed to a depth of 1,480 feet in April 1963 in a test well specially drilled as part of this investigation. Few irrigation wells in the vicinity were this deep; thus it was assumed that most of the subsidence would be measured by this recorder. In plotting the graphs of figure 58, the compaction record of 3B1 and the subsidence record of bench mark W1156 were positioned so their projected trends intersect the June 1962 origin of the three shallower recorder graphs. Also, the beginning of the graph of bench mark M991, first leveled in April 1963, was arbitrarily positioned on the graph of bench mark W1156. The difference in the amount of subsidence at these two bench marks (located about 900 feet apart) since 1963 can be measured directly from the graph, and is in accord with the differential shown in the 1962-65 (fig. 46) and 1965-70 (fig. 47A) subsidence maps.

As shown in figure 58, since 1967 the compaction of the deposits to 1,480 feet, as measured by recorder 11N/21W-3B1, has decreased markedly; significantly less than the subsidence rate of bench mark M991 at that site. It is apparent that the amount of compaction occurring below the 1,480-foot recorder anchor is increasing with time. This is undoubtedly due to the pumping effects of deeper new wells in the area, and also, to the delayed effects of the continued pumping of the 1,000 to 1,500-foot wells reaching to increasing depths.

By comparing the compaction record of the four recorders during a common period, the amount of compaction in each of four depth intervals has been determined. Table 7 summarizes the computed compaction and

Table 7 (p. 161 of ms.) near here.

rate of unit compaction in the four depth zones spanned by the Lakeview recorders during two 3-year periods, 1963-65 and 1967-69. As shown, no measurable compaction occurred in the upper 105-foot thickness of alluvial deposits above the water table during these time periods, and about 0.16 foot of compaction (.05 foot per year) occurred in the 105- to 485-foot zone during both periods. The 810-foot and 1,480-foot recorders showed large reductions in measured compaction in the second period compared to the first, the shallower decreasing from 0.22 to 0.11 foot per year (0.66 to 0.33 foot for 3 years) and the deeper from 0.43 to 0.33 foot per year. Almost all of the change, however, occurred in the 485- to 810-foot zone, as shown by the unit compaction rate (table 7) for the two periods. The unit rate of compaction in the 485- to 810-foot zone decreased from 5.1 to 1.7 feet x 10^{-4} per foot per year, whereas the unit rate of compaction in the 810- to 1,480-foot zone increased slightly from 3.2 to 3.3 feet x 10^{-4} per foot per year. These unit compaction rates for the four depth zones are shown graphically in figure 59 for the two 3-year periods.

Table 7.--Measured compaction and computed average unit compaction at Lakeview for four depth zones during two periods of comparable record

Recorder	Anchor depth (feet)	Compaction (ft) 1963-65 (3 years)	Compaction (ft) 1967-69 (3 years)	Depth zone (feet)	Thickness (feet)	Unit compaction (feet x 10^{-4} per foot per year) (1963-65	Unit compaction (feet x 10^{-4} per foot per year) (1967-69)
				0 - 105	105	0	0
12N/21W-34Q3	105	0	0				
				105- 485	380	1.4	1.4
12N/21W-35E1	485	0.16	0.16 1/				
				485- 810	325	5.1	1.7
12N/21W-34Q1	810	0.66	0.33				
				810-1,480	670	3.2	3.3
11N/21W-3B1	1,480	1.30 2/	1.00				

1/ Extrapolated for 1969.

2/ Extrapolated for 1963.

Figure 60 shows the annual rate of compaction to the 1,480-foot

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Figure 60 near here.

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depth at Lakeview from 1963 through 1970, inclusive. As shown, the decrease during the eight years of measurements has been fairly uniform, from about 0.45 to about 0.33 foot per year. It is interesting that all the decrease in compaction occurred in the 485- to 810-foot zone (fig. 58).

Several large irrigation wells drilled to depths greater than 1,480 feet during the 1960's, pumped water from previously untapped deep aquifers. Undoubtedly, this induced compaction in the deep strata. Another impact was the abandonment of several intermediate-depth irrigation wells, including the discontinued pumping in 1966 of well 12N/21W-34Q2, about 100 feet east of 34Q1. Intermediate water levels rose significantly after 1966 in this area (fig. 61) which accounts for the reduced intermediate compaction.

Figure 61 shows the hydrograph of observation well 11N/21W-34Q1,

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Figure 61 near here.

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assumed representative of water-level fluctuations in the lower zone, and 12N/21W-34Q1, assumed representative of fluctuations in an intermediate zone of the producing aquifer system at Lakeview. From these, changes in applied stress in the deposits below 810 feet is obtained (fig. 61), based on the stress concepts developed in the chapter entitled "Analysis of hydraulic stresses causing compaction," and assuming no change in the depth to the water table during the period of record. As shown, the seasonal maximum effective stress in the lower zone (fig. 61C), which matches the hydrograph of 11N/21W-3B1, increased rapidly but at a somewhat decreasing rate through 8 summers of record. This continuing stress increase explains the continuing rapid compaction in the 810- to 1,480-foot zone (table 7). No stress calculations have been made for the 485- to 810-foot zone, however, the rising trend of hydrograph 34Q1 (fig. 61A) indicates a decreasing stress during this 8-year period which accounts for the decreasing compaction in this zone.

Measured Compaction of Deposits 5 miles Northwest of Mettler

Figure 62 shows the measured compaction and water-level fluctuations

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Figure 62 near here.

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in observation well 32S/28E-20Q1 (5 miles northwest of Mettler), and the subsidence trend of bench mark L365 (for location, see fig. 34). Compaction is measured to a depth of 970 feet, and water-level fluctuations are assumed to be representative of the semiconfined and confined aquifers to this same depth.

The water level in well 32S/28E-20E1 rose gradually between 1963 and 1969; both the seasonal lows and highs register an almost continuous rise during the 7-year period. The amplitude of the annual pumping-recharge cycle diminished, however, from about 80 feet in 1963 to about 40 feet in 1969. Artesian heads that were above land surface in 1905 (fig. 16) and had been drawn down more than 260 feet prior to 1963, were obviously recovering during the period of compaction measurement. This had a marked effect on the rate of both compaction and subsidence in this part of the valley. The rate of subsidence at bench mark L365 was about 0.02 foot per year less than at compaction recorder 32S/28E-20Q1 prior to 1965 (fig. 47).

The rate of compaction measured to a depth of 970 feet in well 32S/28E-20Q1 decreased from about 0.30 foot per year in 1963-64 (fig. 63) to 0.09 foot per year in 1970. The subsidence rate decreased

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Figure 63 near here.

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from an average 0.42 foot per year prior to February 1965 to an average 0.33 foot per year after that date. Thus, compaction above the 970-foot anchor accounted for about two-thirds of the subsidence in 1963-64, and one-third of the total subsidence in 1968-69. Even though the compaction rate for the deposits above 970 feet decreased markedly between 1963 and 1970, the amount of compaction occurring below 970 feet, represented by the increase in vertical distance between the compaction and subsidence curves of figure 62, increased significantly during this 8-year period. It is thus apparent that the pumping of deep wells is causing the head in the deep aquifers to continue to decline even though heads in wells as much as 970 feet deep are rising in much of the area.

Conclusions from Compaction Records

At both locations where compaction measurements have been made, at Lakeview 8 miles west of Mettler and at 32S/28E-20Q1, 5 miles northwest of Mettler (fig. 34), there has been a sharp decrease in the rate of compaction in the semiconfined system of intermediate depth from 1963 to 1968. At Lakeview, the rate in the 485-810-foot zone dropped to about 12 percent of its 1963 rate, and at 20Q1 to about one-third of its 1963 rate. This is apparently due to decreased pumpage and rising water levels in these intermediate strata. At Lakeview, the rate of compaction in the strata 810 to 1,480 feet below the land surface has not decreased appreciably since 1965, and the depth of the compacting interval has apparently increased due to the pumping effects of recently drilled deep wells. Similarly, at 20Q1, compaction rates below 970 feet probably continue undiminished, and the effect of deeper pumping probably is affecting deeper horizons than in 1963-64. On the basis of compaction data now available, it appears that the subsidence rate in the area of maximum subsidence has decreased, due largely to decreased pumping of wells of intermediate depth.

Based on a visual inspection of the annual compaction record at both Lakeview and 20Q1, it is apparent that excess pore pressures in the fine-grained, slow-draining aquitards of the intermediate zone are rapidly dissipating. The change from a stairstepped compaction record of no recovery to an oscillating record of largely elastic compaction and expansion, is characteristic of an aquifer system experiencing decreased effective stresses.

PARAMETERS FOR ESTIMATING FUTURE SUBSIDENCE

In areas of large ground-water overdraft, the amount of subsidence, $\underline{S}$, that would result ultimately from a given water-level change can be estimated by the following relationship if adequate data are available:

$$\underline{S} = \beta_{\underline{a}} \cdot \underline{m} \cdot \Delta\underline{p}$$

where

$\beta_{\underline{a}}$ = the average compressibility of the compacting beds

$\underline{m}$ = thickness of the compacting beds, and

$\Delta\underline{p}$ = change in effective stress resulting from water-level change.

Where adequate lithologic, hydrologic, and engineering data are available, the compacting zone can be segmented into lithologic units and an appropriate compressibility, thickness, and stress change applied to each segment. In most basins, however, the knowledge of these subsurface parameters is inadequate to estimate future subsidence by this approach.

As in most ground-water basins, the geohydrology of the Arvin-Maricopa area is highly complex. Few well defined lithologic units have been mapped, and little is known of the gross compressibility of even the best defined beds. Intercalated silt and clay lenses within the aquifer systems create a diverse range of pore pressures in the various beds. An analysis of effective stresses and compaction rates at any location, therefore, is not a simple relationship. Only at Lakeview, where compaction recorders have been maintained and where seven fine-grained cored samples were tested in the laboratory, are compressibility values available.

In areas where sufficient data are available, the most effective method of estimating future subsidence is to calculate the subsidence/head-decline ratio for the period of records, and then project this relationship into the future. This parameter can be derived either on an areal basis from subsidence and water-level change maps or as in this study from hydrographs and bench-mark subsidence graphs for individual locations. The subsidence/head-decline ratio is usable only if water-level trends are representative of the stress change in the compacting beds, and also, if water levels at the end of the period are at their lowest level.

For example, at the northwest corner of T. 32 S., R. 28 E. (fig. 56 and table 5), 2.52 feet of subsidence occurred during 72 feet of water-level decline from 1957 to 1965, for a subsidence to head-decline ratio of 3.5×10^{-2}. This same general relationship probably will apply for future water-level declines. The subsidence to head-decline ratios of figure 56, which in actuality are a rough measure of the gross compressibility times thickness of the compressible deposits (see equation above), is the most direct method of estimating future subsidence from projected water-level changes.

The following general criteria can be applied in relating subsidence to head decline:

1. Where little or no increase in effective stress has occurred, no compaction is expected.
2. Where increased effective stress has caused measurable subsidence, further increases in effective stress will cause continued subsidence.
3. Delayed, or "lag", compaction of slow-draining beds may represent a major part of the ultimate subsidence at a location. Such compaction, and related subsidence, may continue for many months or years after water levels become stabilized at a lower level.

4. In areas where both subsidence and water-level decline have been observed for a sufficiently long period to establish a long-term relationship, the ratio between these two parameters can be projected into the future as far as the projected water-level trend justifies. This relationship does not take into account residual "lag" effects; thus, minimum values of subsidence are determined by this means. Where water levels have declined and then partially recovered, the subsidence to head-decline ratio has little significance until water levels return to their former low levels.

METHODS OF DECREASING OR STOPPING SUBSIDENCE

Inasmuch as the thickness and compressibility of deposits in a subsidence area change only slightly with time, the rate of subsidence is directly related to the change in effective stress that results during ground-water development. Continued increase in effective stress will cause continued subsidence. Subsidence can be slowed, however, by reducing the rate of stress increase or by permitting water levels to stabilize. Subsidence can be stopped altogether by raising water levels sufficiently to eliminate all residual excess pore pressures in the aquitards.

Effective stresses can be reduced, and thereby the subsidence rate slowed or stopped, only if water levels in the producing aquifers of the ground-water basin are raised. Any method used to reduce the continued decline of water levels at a location would tend to reduce subsidence at that location. This might involve reduction of ground-water pumpage, increase in ground-water recharge, spacing withdrawal wells to reduce centers of intense drawdown, or a combination of these three. Frequently, this inovlves economic or legal complications that become the deciding factors.

Several concepts are worthy of consideration in the management of the Arvin-Maricopa ground-water basin to decrease or stop subsidence.

1. About 48,000 acre-feet of subsidence occurred each year from 1965 to 1970. This represents "mined" water, pumped from the ground-water basin. This water of compaction will not be available as a source of water to wells when subsidence stops. This must be offset by increased runoff, surface-water imports, or reduced pumpage if subsidence is to be stopped.
2. The annual runoff deficiency during the 1947-67 drought period (fig. 15) represents about twice the quantity of water mined each year from the ground-water basin. Normal precipitation will undoubtedly reduce the amount of subsidence occurring in the area.
3. The importation of surface water, from the California Aqueduct on the west and the Friant-Kern Canal on the east, is beginning to offset the ground-water overdraft in the Arvin-Maricopa area. However, importation might actually aggravate subsidence in some location. Building up the water table while the deep wells continued to lower the artesian head would tend to increase stresses and accelerate subsidence.

4. Artificial recharge of the ground-water reservoir, by either stream or canal water, can probably be accomplished most effectively along the natural stream channels around the perimeter of the valley. In the extensive central area of rapid subsidence, however, recharging the deep aquifers beneath the confining beds is probably not practical.

5. The subsidence / pumpage ratios of figure 53 are a rough measure of the recharge characteristics of the ground-water basin under the 1962-65 hydrologic regime. It is suggested that the deep aquifers in areas with ratios less than 0.05 can be effectively recharged by increased infiltration along natural stream channels. Areas with ratios greater than 0.05 receive little recharge, either direct or from perimeter infiltration. From 50 to 95 percent of the 1962-65 pumpage in the subsidence area was from natural recharge, thus the deep aquifers would probably repressure rapidly if pumpage were reduced.

6. Downward seepage stress, equal to the head differential between the water table and the artesian head of the deep aquifers, is the principal compacting stress. Both deep and shallow water levels should be monitored, so that shallow levels do not get too high or deep levels too low, and thereby cause continued subsidence.

7. Effective stresses in the confined or semiconfined aquifer systems are changed less when the shallow water table and the artesian heads are lowered together than when the water table is held constant and the confined level is drawn down seasonally by pumping. The rate of compaction of the confined aquifer system can be reduced by planned lowering of shallow water levels to conform with head declines in the confined aquifers.

SUMMARY AND CONCLUSIONS

Four types of subsidence are occurring in the Arvin-Maricopa area. They are:

1. Tectonic subsidence, in which the valley trough is sinking with respect to the surrounding mountains at a long-term rate of about 0.001 foot per year. This has continued through the past 600,000 years, and is probably continuing. Although this tectonic subsidence of the valley trough is of geologic significance, it is of little concern to the residents of the valley.
2. Subsidence due to hydrocompaction of moisture-deficient alluvial deposits affects extensive areas on the southern and western margins of the Arvin-Maricopa area. Hydrocompaction, a one-time densification that occurs when the susceptible deposits are wetted for the first time, results in extensive cracking and differential settlements of the land surface. Experience has shown that when preconsolidated by surface ponding or by long-term irrigation, these deposits stabilize and are able to support normal overburden loads without further settlement.

3. Subsidence due to the extraction of oil and gas affects a number of local fields in the south end of the valley; the rate, however, is currently too small to be of serious concern for most purposes. Maximum subsidence in the area affected by ground-water pumping is generally less than 0.01 foot per year, and maximum measured subsidence since leveling began is 0.3 foot.
4. Subsidence due to water-level decline is of major concern in the Arvin-Maricopa area, and the principal topic of this report. The remainder of these conclusions relate specifically to subsidence caused by changes in effective stress resulting from water-level declines in the Arvin-Maricopa area.

In addition to the above processes causing subsidence, there is a component of "apparent" subsidence that pervades all leveling data and affects all bench-mark elevations in the valley. By assuming as stable a reference bench mark in the Tehachapi Mountains that appears to have been rising 0.05± foot per year, all bench marks that were rising at a lesser rate appear to have been subsiding when they are adjusted to this reference. In the center of maximum subsidence, this component of "apparent" subsidence is a small part of the total and negligible for most purposes. In the perimeter areas, however, and where exacting interpretations of the data are being made, this "apparent" component becomes significant.

Extensive subsidence caused by ground-water overdraft began about 1930 (fig. 51), and increased to 34,000 acre-feet per year soon after World War II. By 1965, more than 450 square miles were affected by subsidence, maximum subsidence was 8 feet, and the total volume of subsidence was about 800,000 acre-feet. About 48,000 acre-feet of subsidence occurred each year from 1965 to 1970, and by the close of 1970 roughly 1,060,000 acre-feet of subsidence had occurred. Subsidence during this 40-year period of pumping overdraft has occurred so gradually and over such a broad area that it has gone unnoticed to most local residents. Many well casings have been severely damaged by the subsidence, however, and its detrimental and costly effects are of serious concern to surveyors, design and construction engineers, irrigation districts and some landowners.

The direct cause of the subsidence is the change in effective stress in the deposits due to a change in ground-water levels. Water-level changes in subsidence areas may change effective stresses in two different ways: (1) a change in the position of the water table changes the effective stress because of the change in buoyant support of grains in the zone of the change or (2) a change in position of the water table or the artesian head, or both, that induces hydraulic gradients across confining or semiconfining beds produces a seepage stress that is algebraically additive to gravitational stresses.

If the artesian head remains unchanged, a rise in the water table reduces effective stresses in the unconfined parts of the aquifer system but increases the effective stress in the confined parts, due to the increased downward seepage stress. A decline in the water table, on the other hand, increases the effective stresses in the saturated part of the unconfined aquifer system, but decreases the effective stress in the confined beds. A decline in artesian head in a confined aquifer system, however, has no effect on stresses in an overlying unconfined system, but increases the stress in the confined beds.

Specially designed compaction recorders, measuring the vertical shortening of the stratigraphic section to depths as great as 1,480 feet, were operated in five wells during this investigation. Companion water-level records are available for three of these wells. At Lakeview, compaction to the 1,480-foot depth roughly equaled total subsidence for 2 extended periods of comparable record. The rate of compaction in the intermediate zone, above 810 feet, decreased significantly after 1962 in response to more than 100 feet of rise in water level in this intermediate zone. The long-term water-level decline and compaction continued after 1962 in the deposits below 810 feet. Five miles northwest of Mettler, also, a marked rise in water levels resulted in a reduction in compaction rate in the intermediate depth zone (less than 970-foot depth) during 6 years of record.

Roughly 48,000 acre-feet of ground water was "mined" (water of compaction) from the ground-water basin each year from 1965 to 1970. This water will not be available to wells after subsidence is stopped in the area. An additional source of water, sufficient to offset this mined water of compaction, will be required if subsidence is stopped while still supplying the 1965-70 irrigation demands. This additional water may come from either increased natural streamflow or canal importation.

Based on the findings of this and other investigations in the San Joaquin Valley (Lofgren, 1969), the following criteria may be applied to anticipate the amount of subsidence that will occur under assumed hydrologic change:

1. Subsidence is directly related to changes in ground-water levels, Therefore, little subsidence would be expected if little change in ground-water level had occurred.
2. In areas where subsidence has occurred in response to increased effective stress (water-level change), future stress increases will cause roughly proportional subsidence, provided the time intervals are comparable.

3. Ratios of subsidence to head decline, established during periods of continuing subsidence and water-level decline, are the best parameters for estimating the subsidence that would occur if water levels in the principal aquifer system were lowered below historic minimum levels. Subsidence to head-decline ratios in the Arvin-Maricopa area range from about 0.32×10^{-2} foot of subsidence per foot of head decline in perimeter areas where little subsidence has occurred to more than 4.0×10^{-2} feet of subsidence per foot of head decline where subsidence has been the greatest. Where the water-level trend has been reversed, however, and effective stresses have been decreased sufficiently to stop subsidence, little future subsidence would be anticipated unless prior maximum effective stresses were exceeded.

4. Because of the slow drainage from the thicker less permeable beds in an aquifer system, subsidence may continue long after maximum effective stresses have been imposed on the permeable beds (aquifers).

It has been clearly demonstrated in the service area of the Friant-Kern Canal that subsidence can be effectively stopped by raising ground-water levels sufficiently high to eliminate all excess pore pressures in the aquitards. Also, it is concluded that if water levels are held at a constant low level, subsidence will stop after all lag, or residual, compaction has been accomplished. This might require several decades, however. As long as excess pore pressures exist in any of the compactible beds, drainage from these beds will occur and subsidence will continue. If pumping were to stop completely, water levels would rise rapidly, resulting in a cessation of subsidence.

No method is known for stopping subsidence other than that of raising the head in the aquifers sufficiently to eliminate the excess pore pressures in the aquitards. This method can be effected either by decreasing pumpage, increasing recharge, or both. If neither is practicable, however, under favorable circumstances, subsidence rates may be substantially reduced by redistirbuting the total pumpage in time and in space so as to reduce local seasonal head declines and minimize the development of seepage stresses (hydraulic gradients) across confining beds within the ground-water reservoir.

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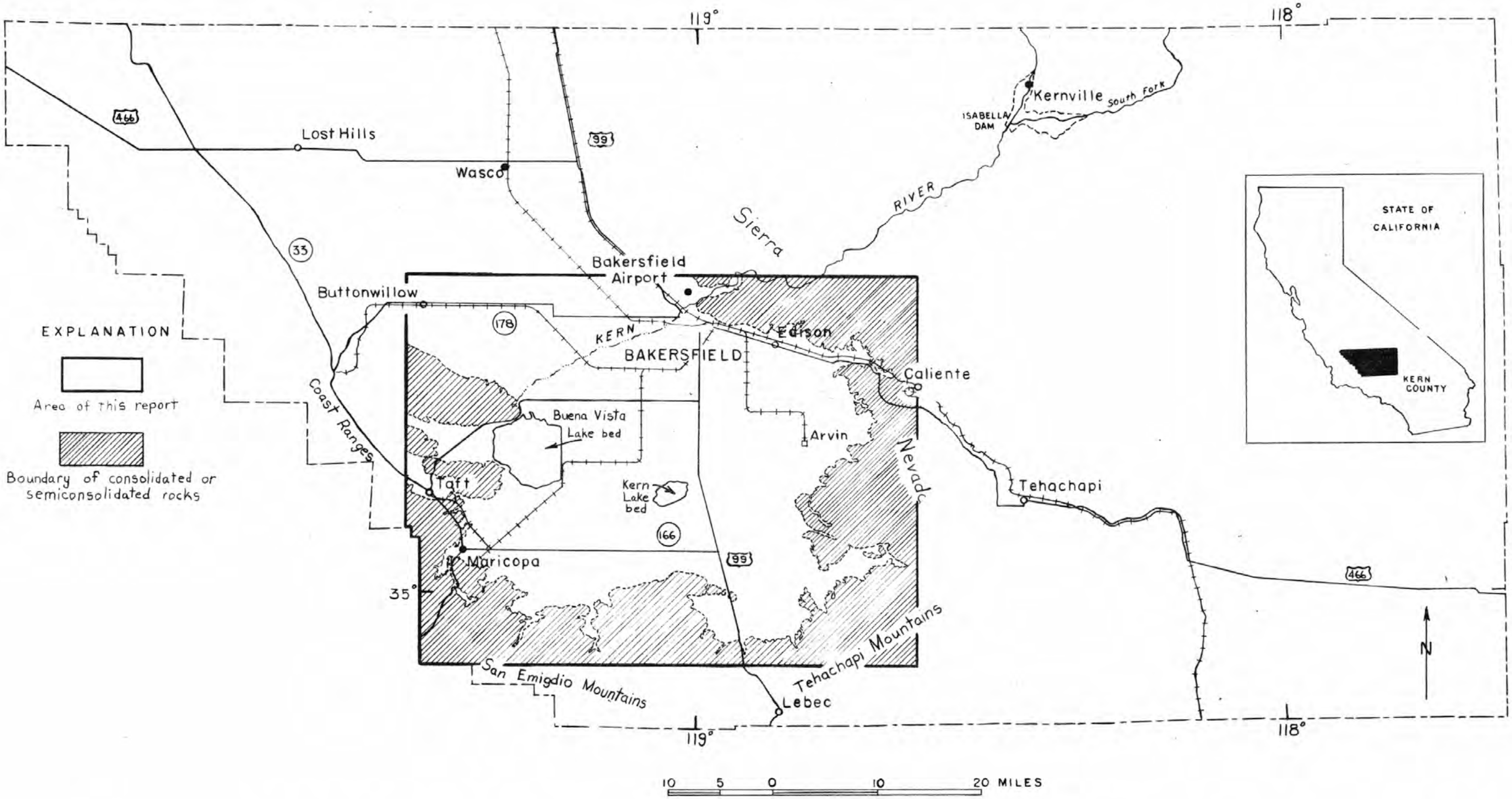


FIGURE 1.—INDEX MAP OF KERN COUNTY, CALIF., SHOWING LOCATION OF THE ARVIN—MARICOPA AREA.

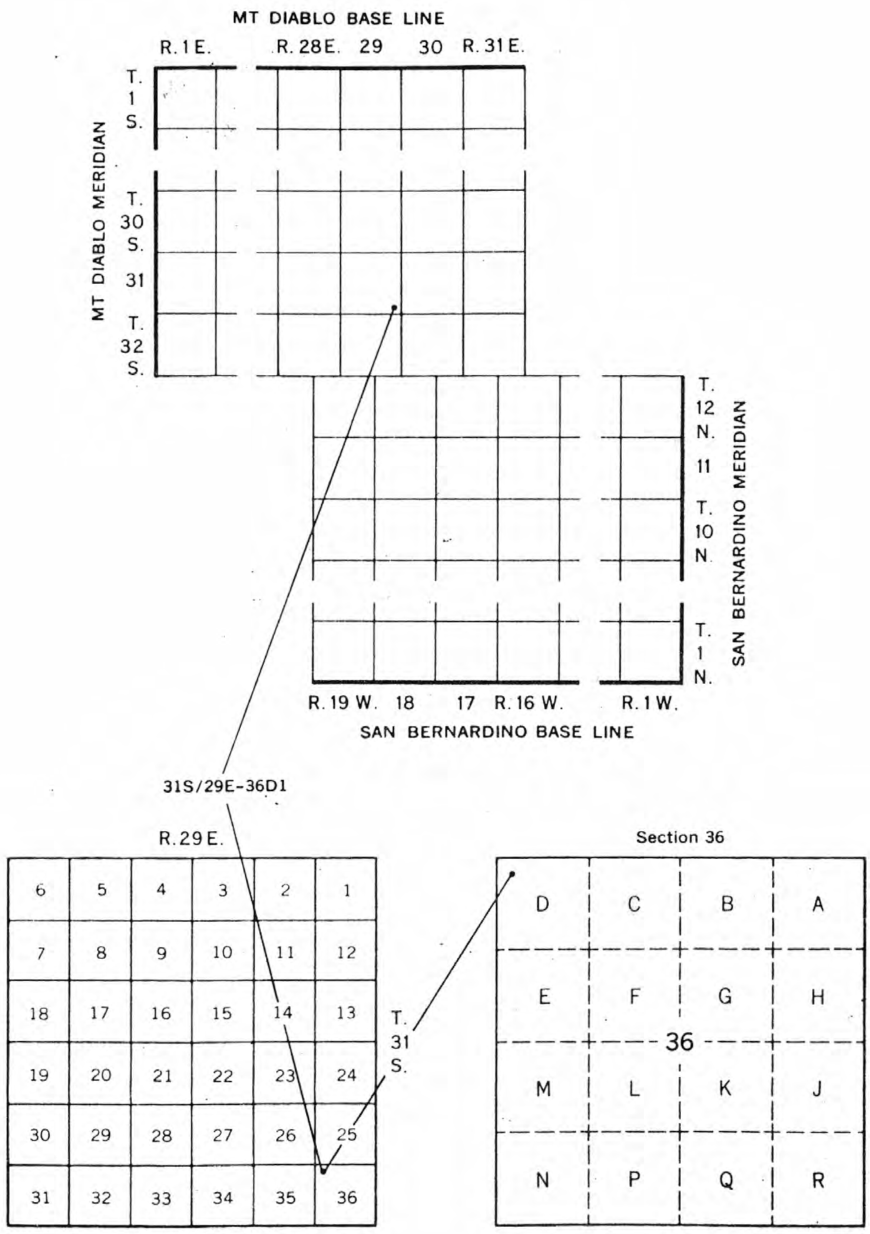


Figure 2.--Well numbering system.

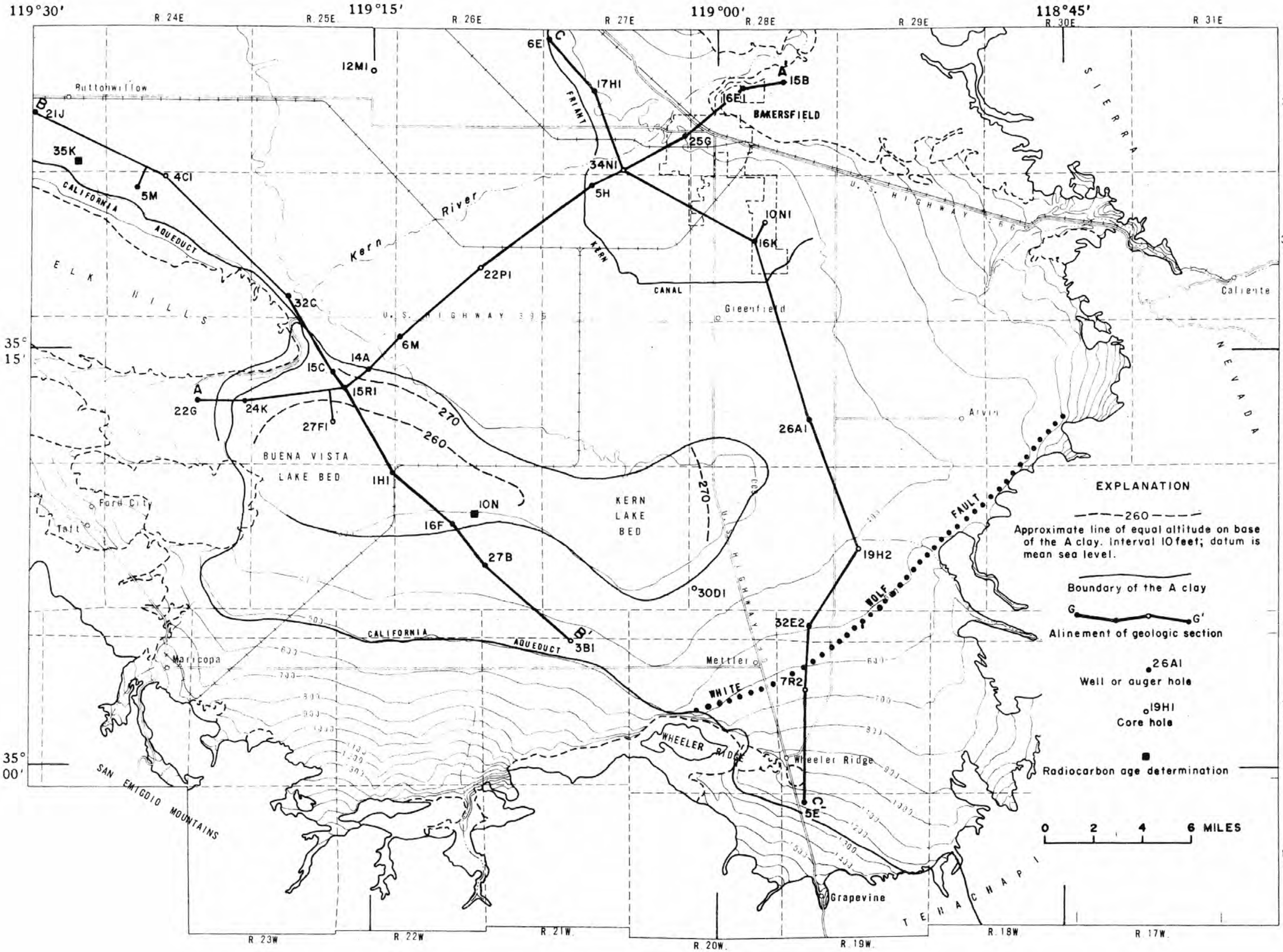
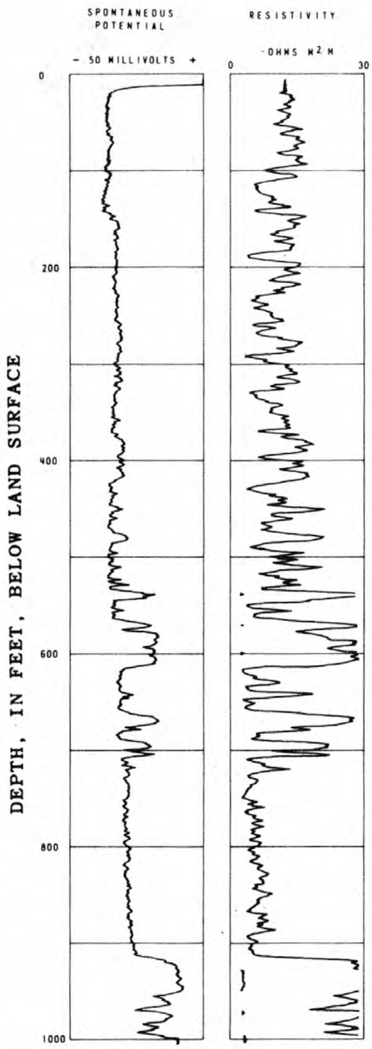
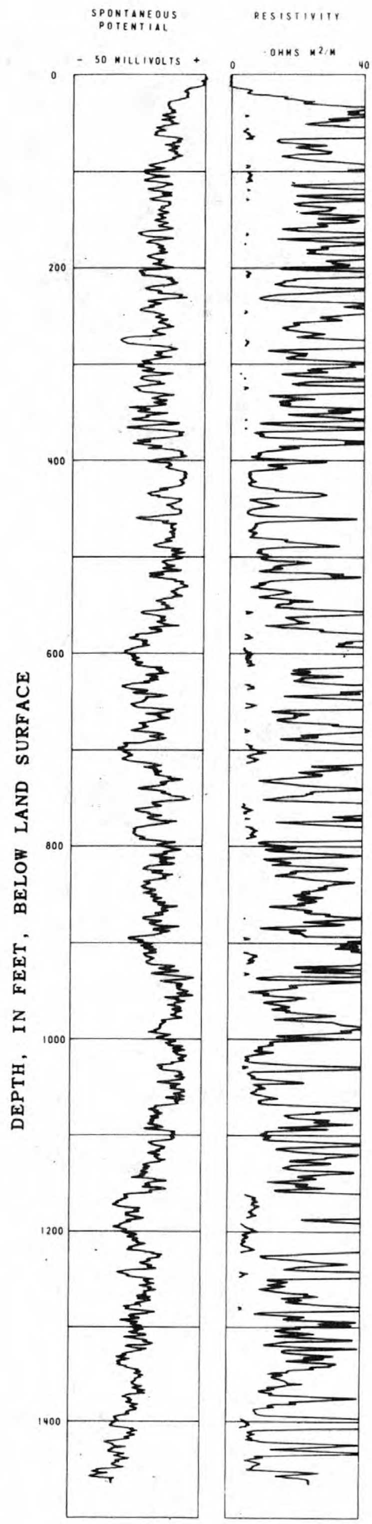


FIGURE 3.—LOCATION OF SECTIONS AND CORE HOLES, AND STRUCTURE AND EXTENT OF THE A CLAY.



A. Core hole 31/25-27F1



B. Core hole 32/28-30D1

FIGURE 4.—Electric logs of two core holes on Buena Vista Lake bed and southeast of Kern Lake bed.

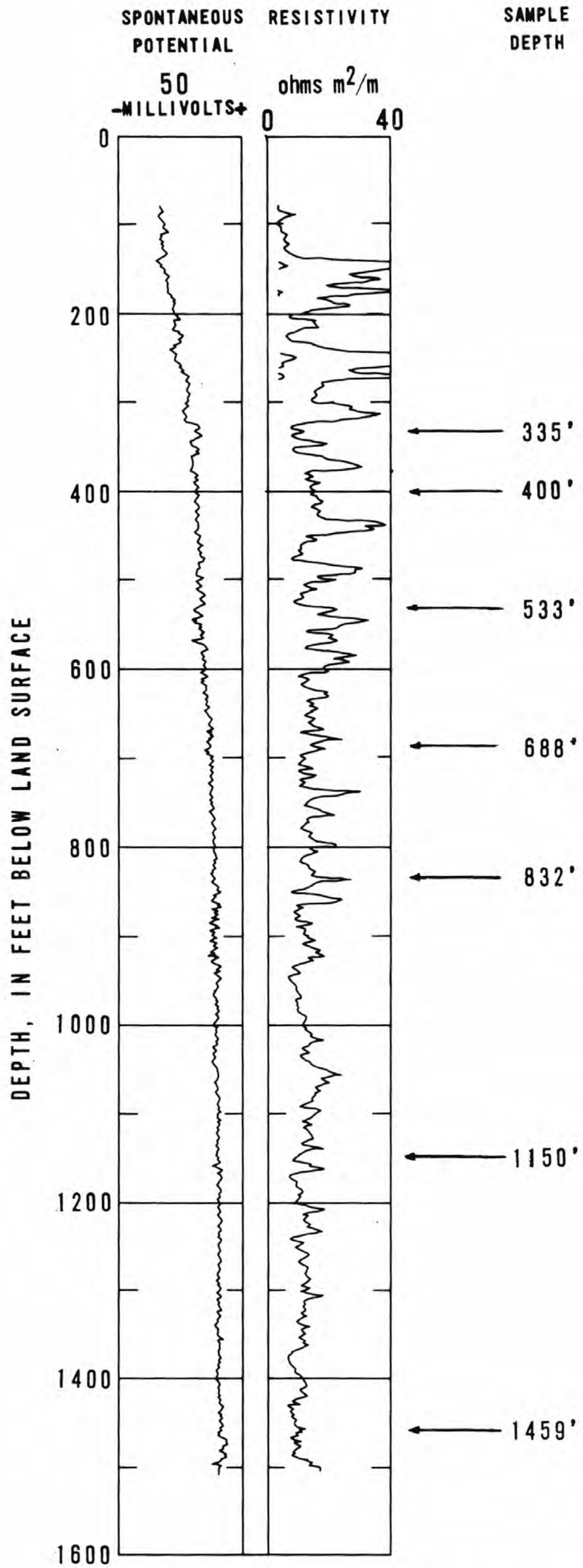
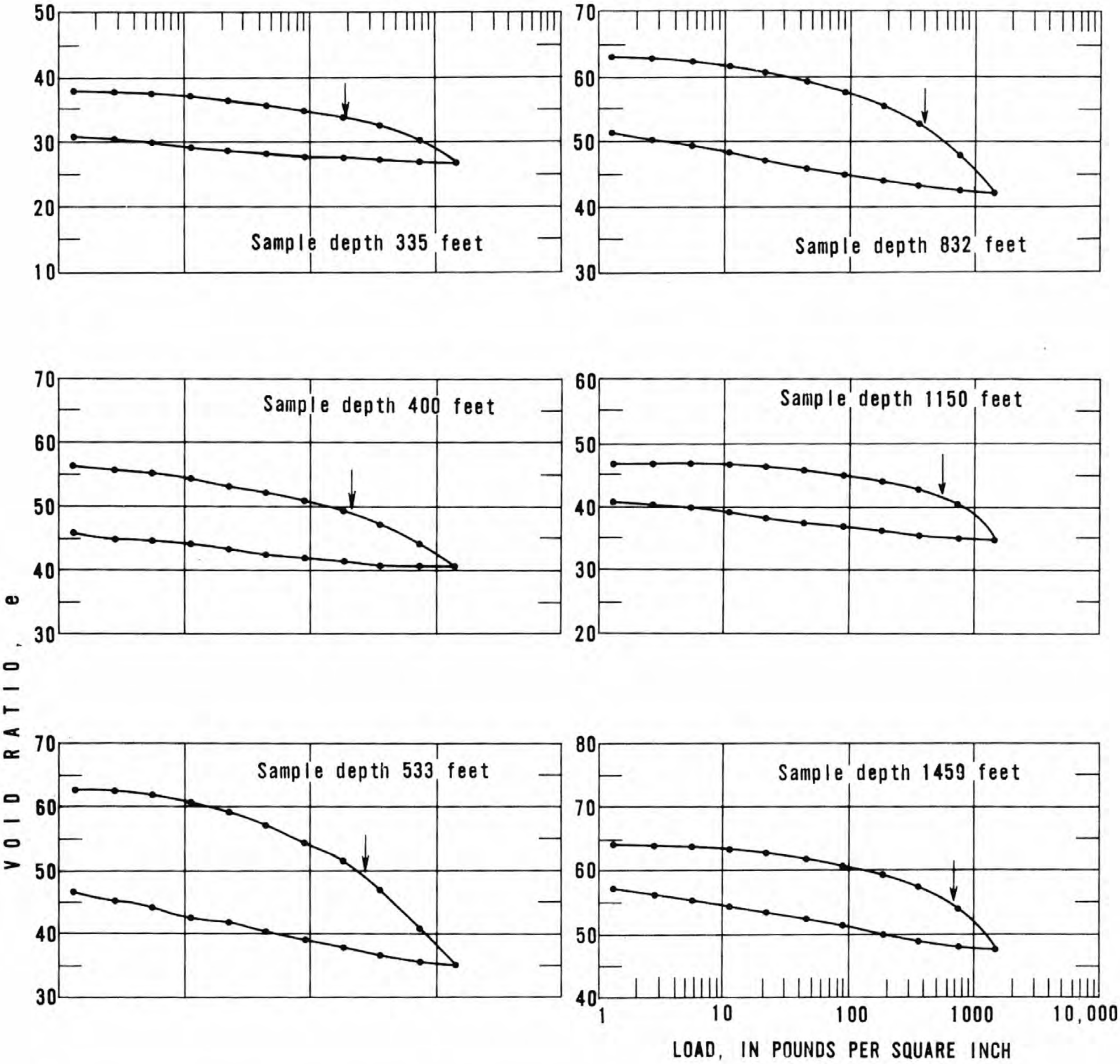


FIGURE 4A.--Electric log of corehole 11N/21W-3B1 at Lakeview and depth of cored samples tested in the consolidometer.



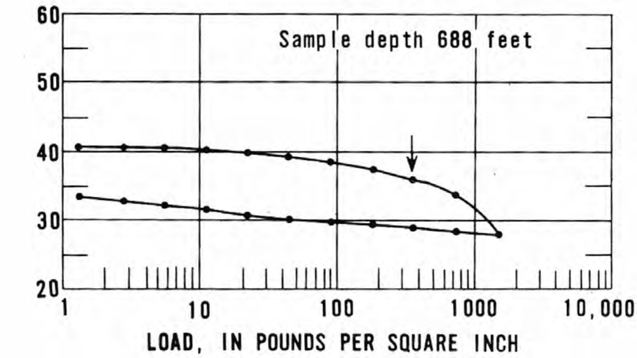


FIGURE 4B.--Consolidation-test curves for selected core samples from core-hole 11N/21W-3B1, at Lakeview

Arrow indicates approximate insitu effective stress

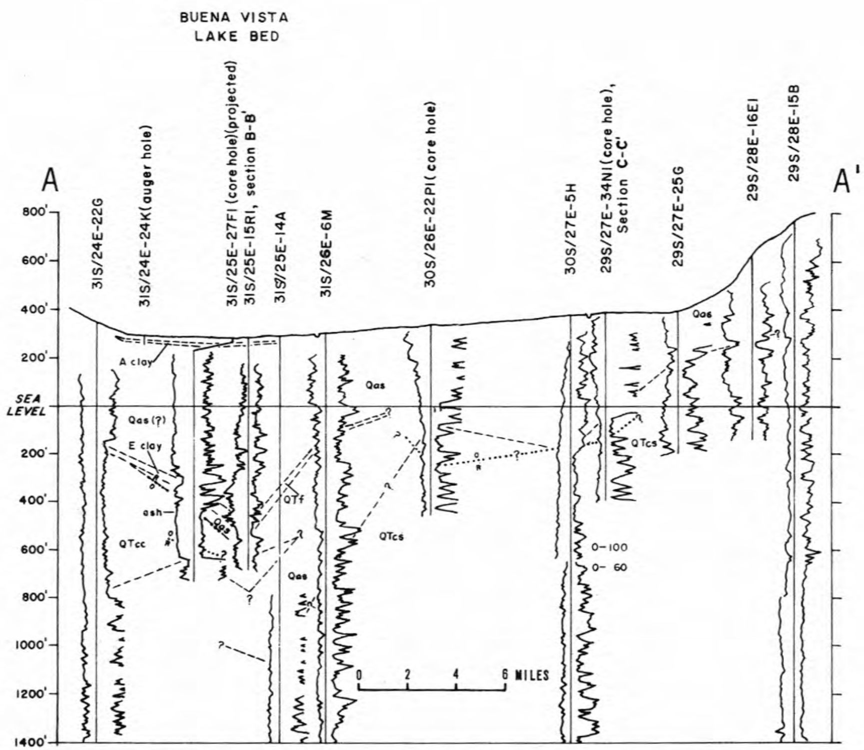


FIGURE 5.—GEOLOGIC SECTION A–A', ALINED RADIALLY UP KERN RIVER FAN TO BAKERSFIELD.

From Croft, 1972, pl.2. For location see figure 3.

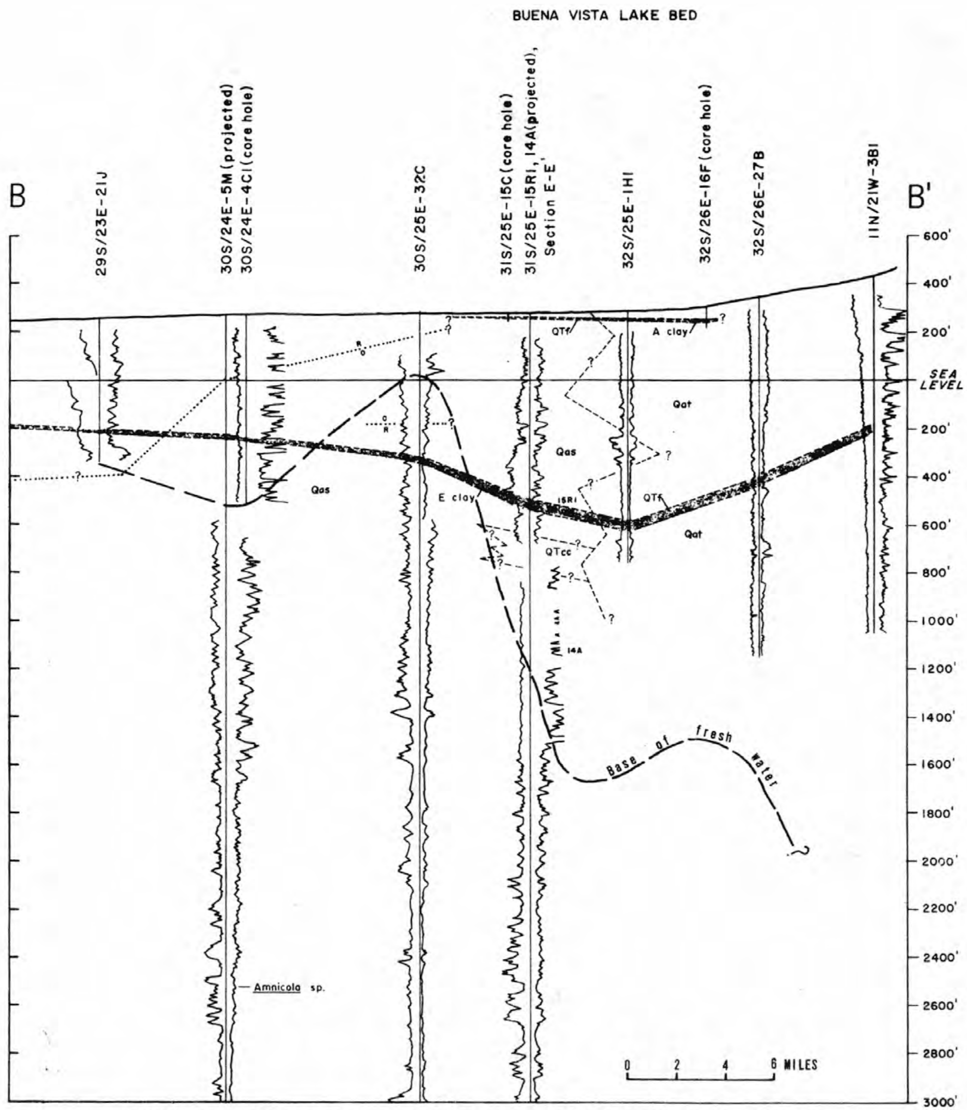


FIGURE 6.— GEOLOGIC SECTION B-B', SOUTHEAST ACROSS BUENA VISTA LAKE BED.

From Croft, 1972, pl.3. For location see figure 3.

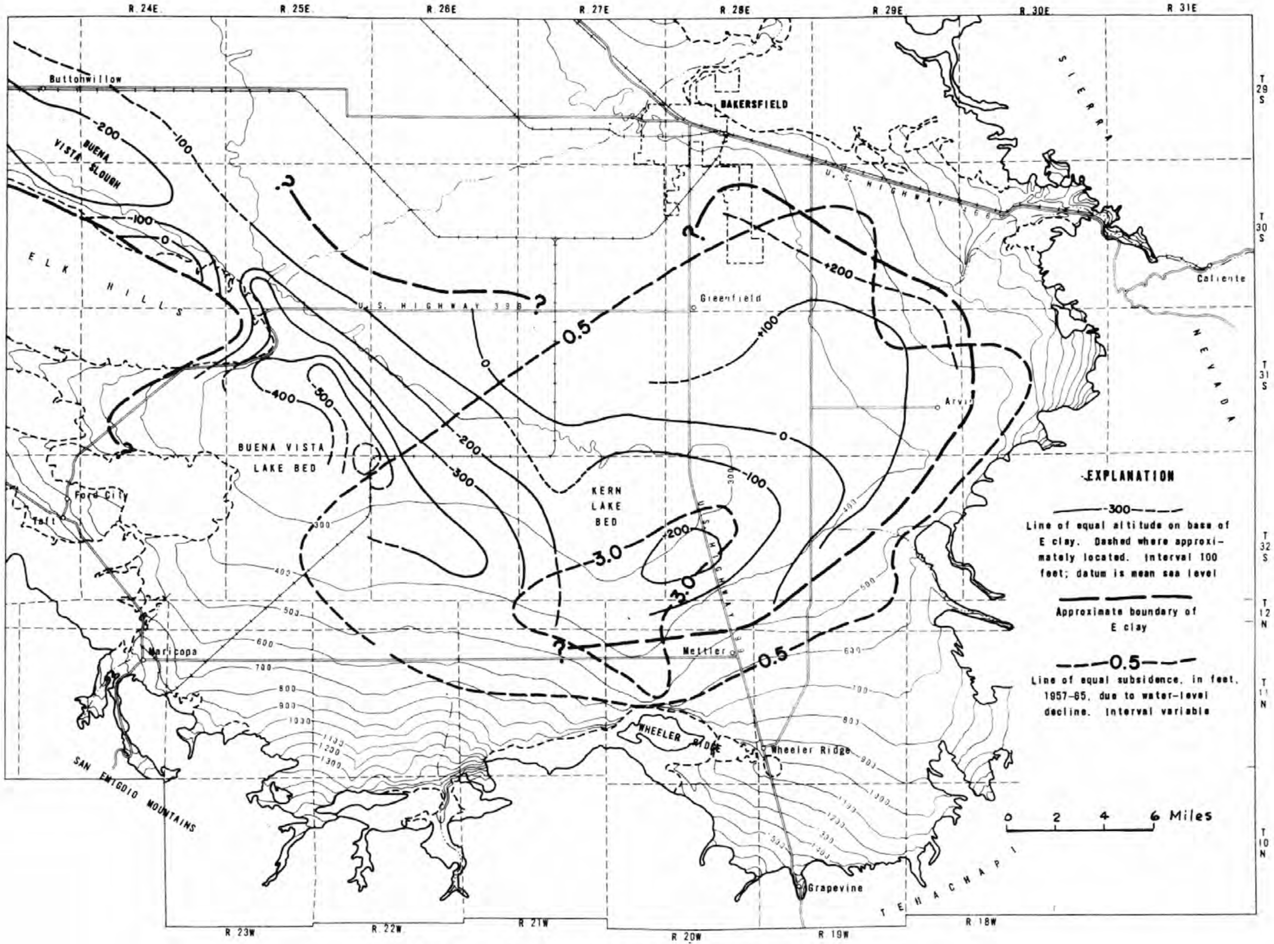


FIGURE 7.—STRUCTURE AND EXTENT OF THE E CLAY.

(Modified from Croft, 1969, pl. 4.)

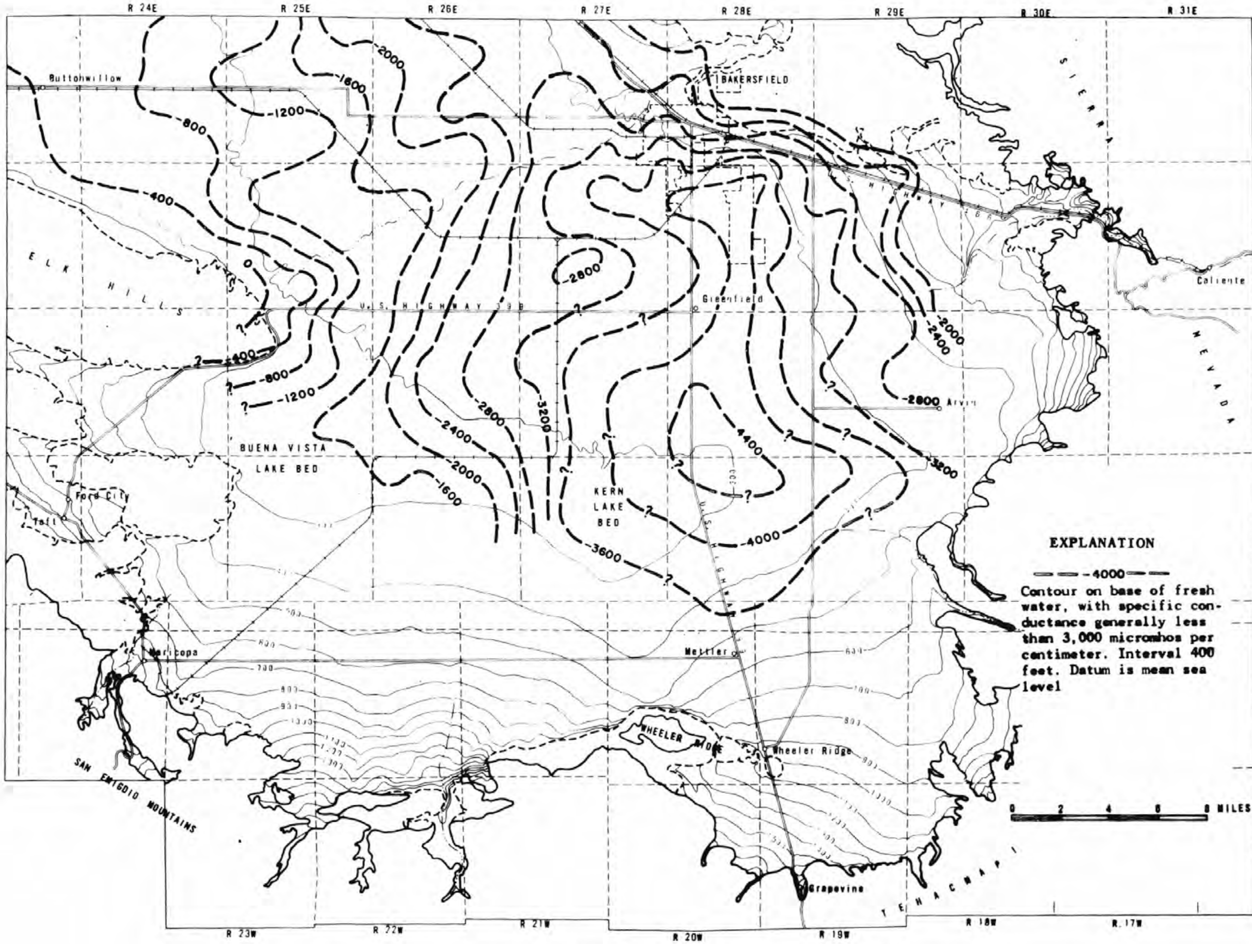


FIGURE 7A.—Base of fresh ground water (approximately 3,000 micromhos).
After Page, 1971, pl. 1

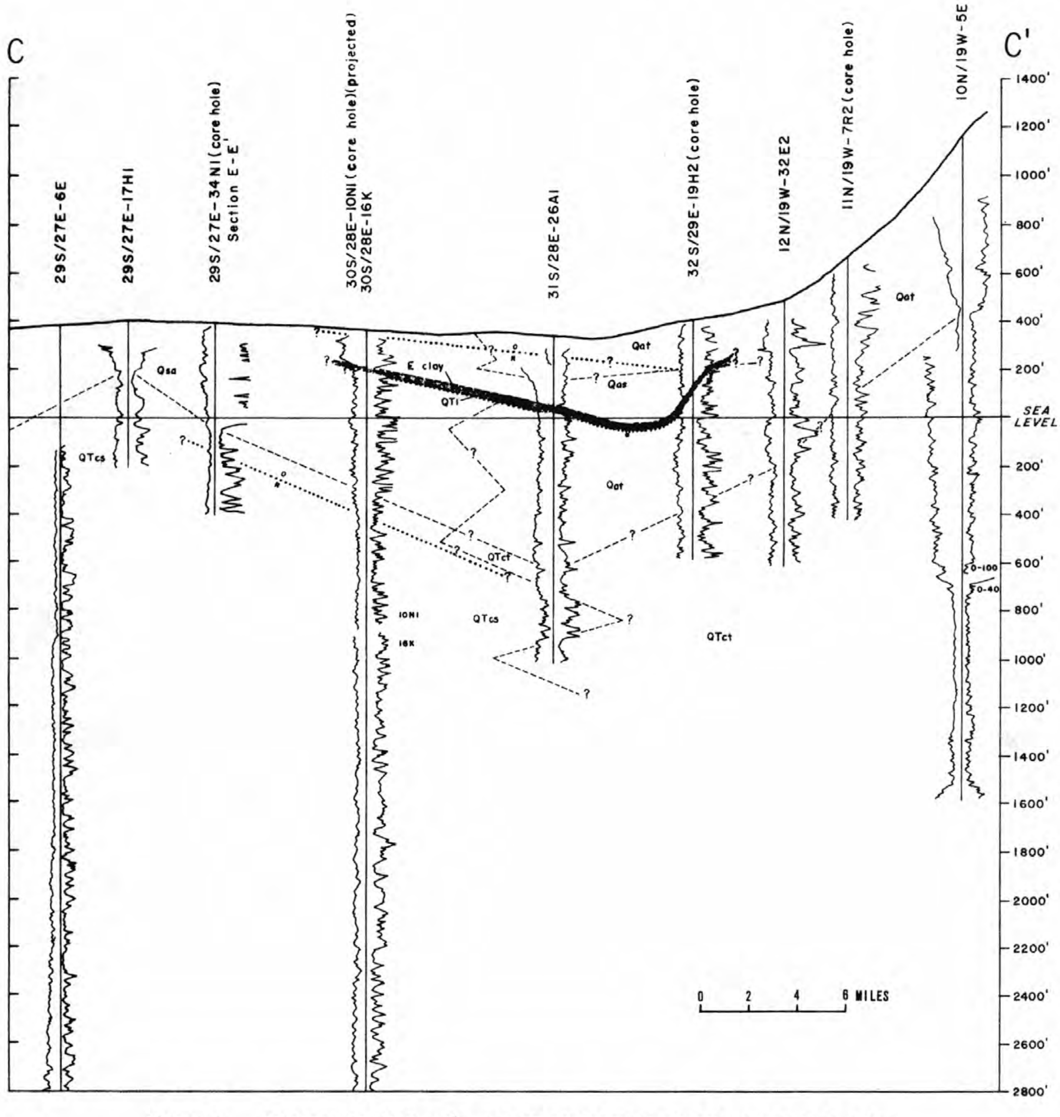


FIGURE 8.—GEOLOGIC SECTION C-C', WEST OF BAKERSFIELD TO EAST OF WHEELER RIDGE.

From Croft, 1972, pl.3. For location see figure 3.

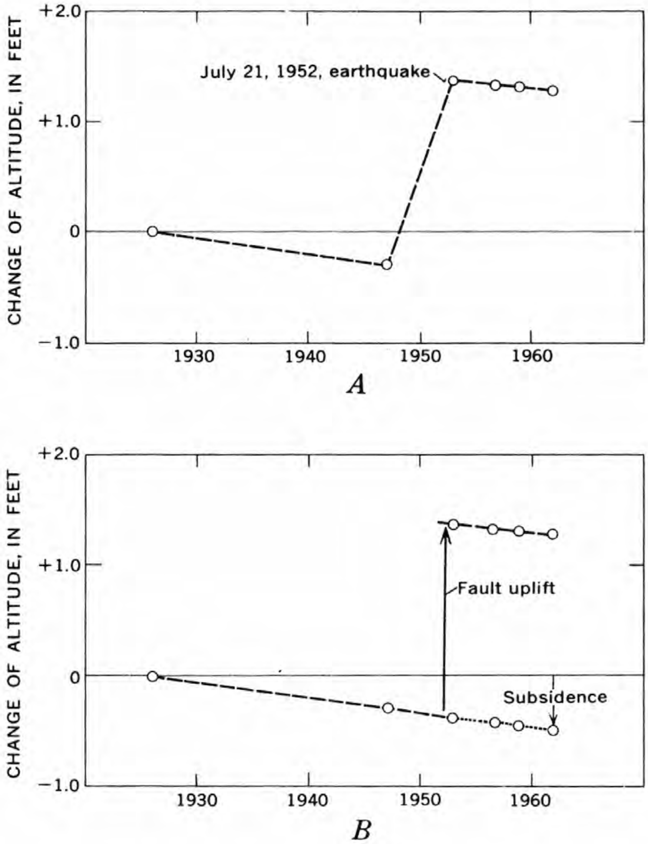


Figure 9.--Vertical movement of bench mark M 54, 2 miles north-northwest of Grapevine, 1926-62. A, direct plot of U.S.Coast and Geodetic Survey data; B, interpretation of movement.

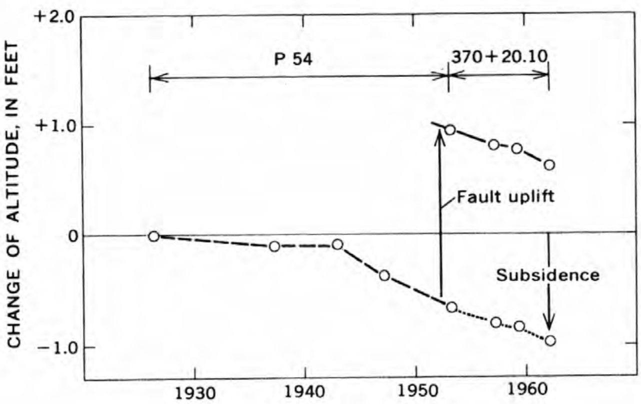


Figure 10.--Vertical movement of bench marks P 54 and nearby 370+20.10, about 7 miles north-northwest of Grapevine, 1926-62.

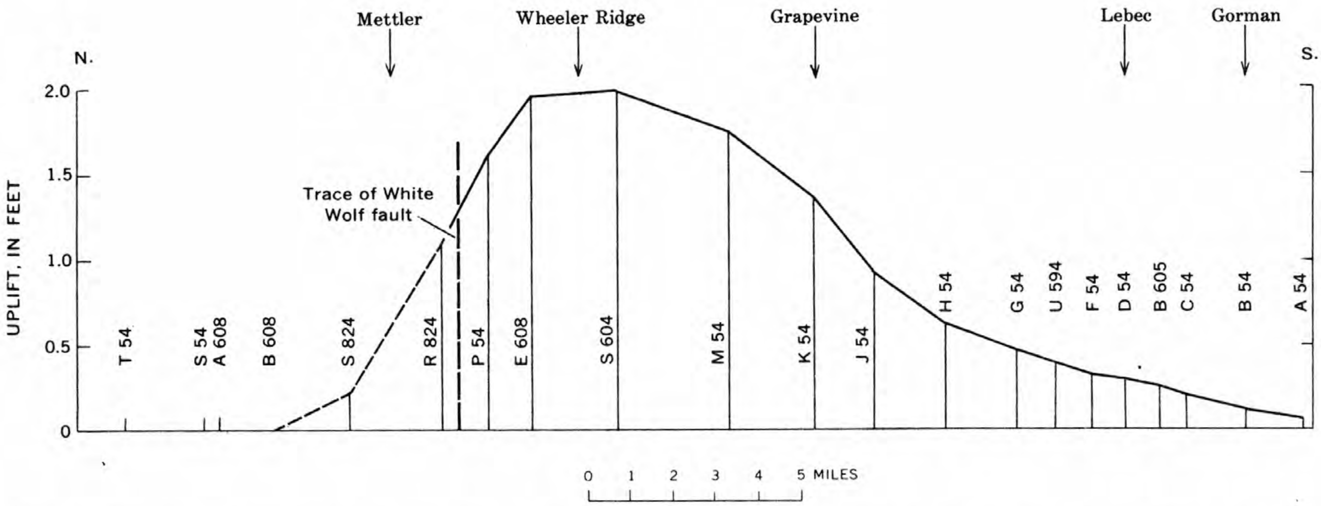


Figure 11.--Tectonic uplift along U.S. Highway 99, between Mettler and Gorman, Calif., that is attributed to the 1952 earthquake. Uplift determined by graphical analysis of data according to method illustrated by figures 9-10. Numbers refer to bench marks (location shown on fig. 12).

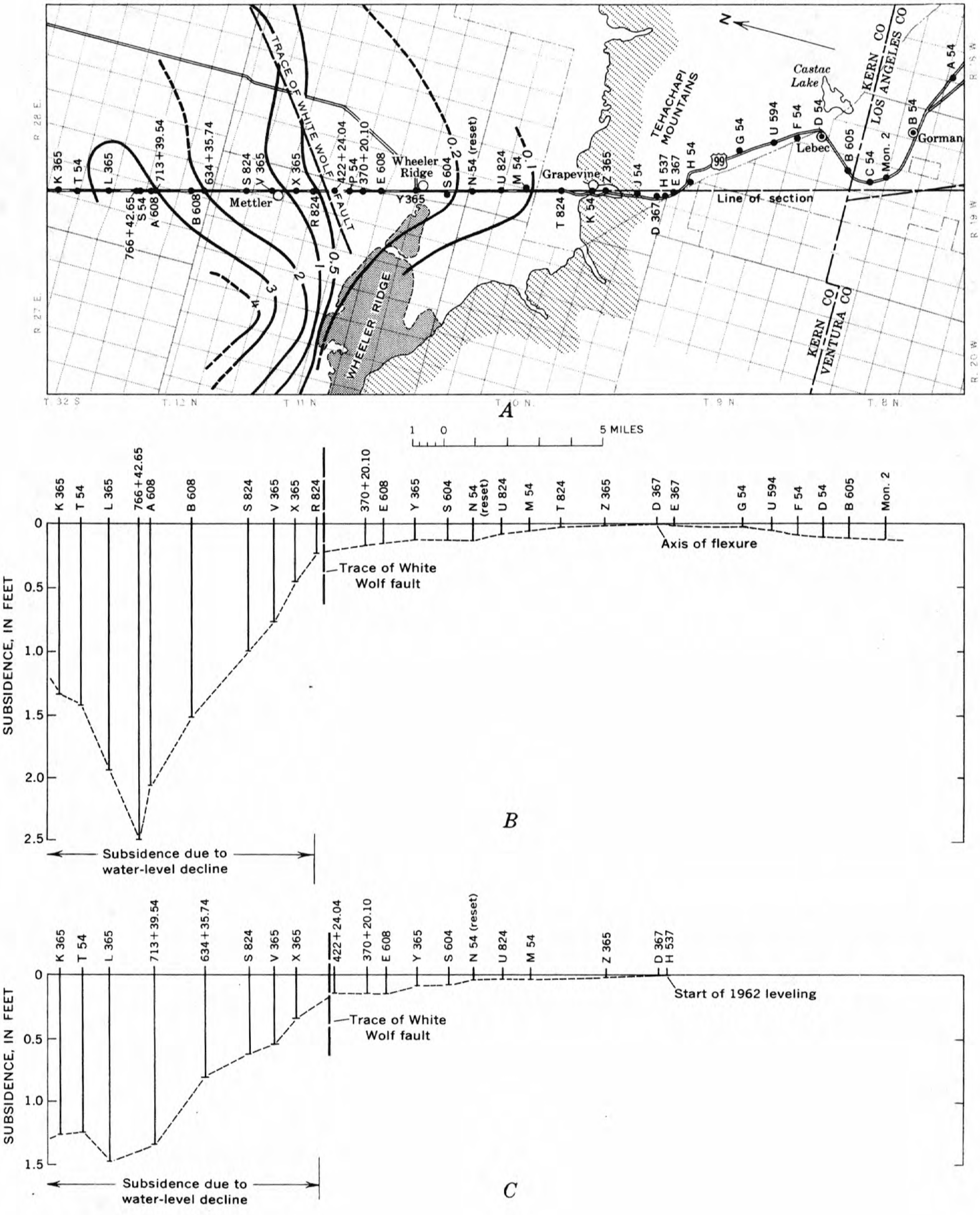


Figure 12.--Vertical movement of bench marks along U.S. Highway 99 in the Grapevine area, 1953-62. A, Lines of equal subsidence, in feet, 1953-62; B, subsidence profile, 1953-59; and C, subsidence profile, 1959-62. The vertical movement of some bench marks in A is shown in figure 11.

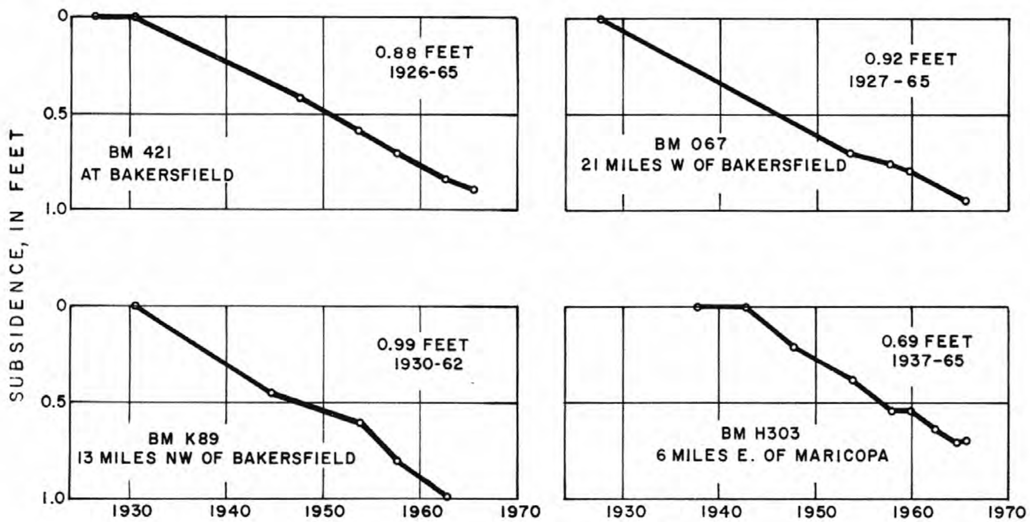


FIGURE 13.—APPARENT SUBSIDENCE OF FOUR BENCH MARKS, RELATED TO DATA-ADJUSTMENT PROCEDURES.

CIRCLES INDICATE TIMES OF LEVELING

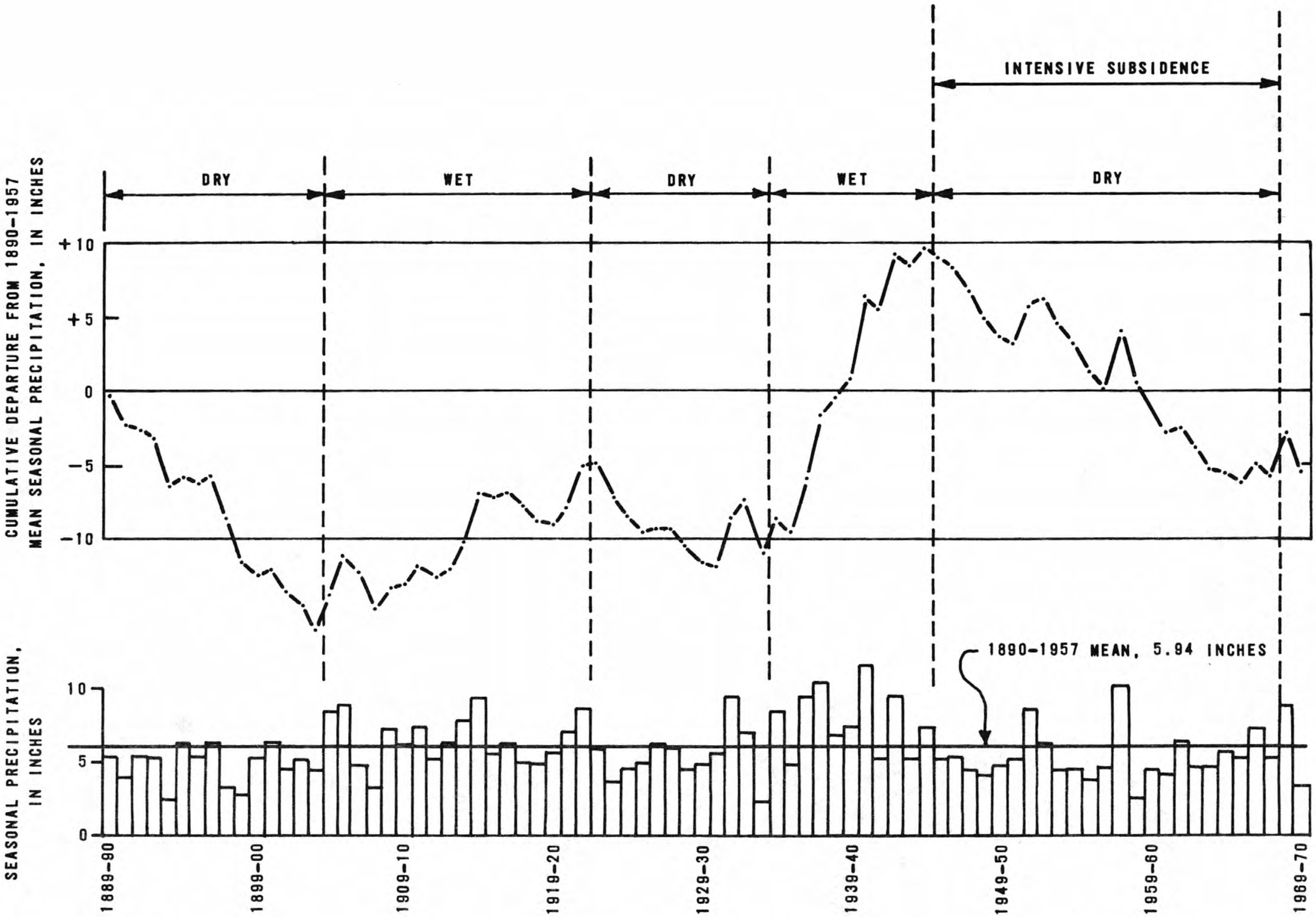
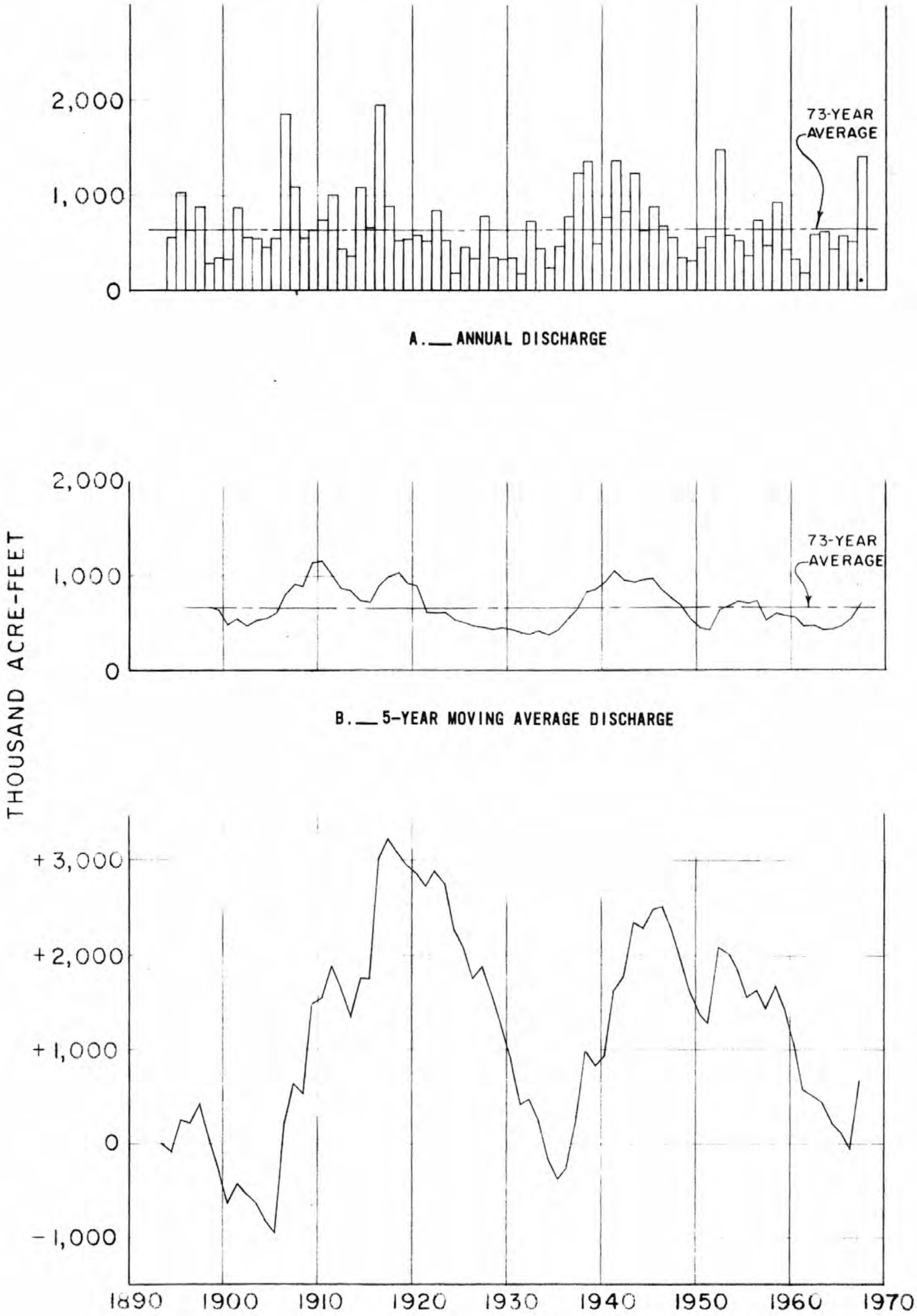


FIGURE 14.—SEASONAL PRECIPITATION AND CUMULATIVE DEPARTURE FROM THE MEAN AT BAKERSFIELD, CALIF., 1889-90 TO 1969-70

(JULY 1–JUNE 30 CLIMATIC YEAR)



C.— CUMULATIVE DEPARTURE FROM 73-YEAR AVERAGE DISCHARGE

FIGURE 15.—DISCHARGE OF KERN RIVER NEAR BAKERSFIELD, 1894-1968.

(FOR WATER YEAR OCTOBER 1 - SEPTEMBER 30)

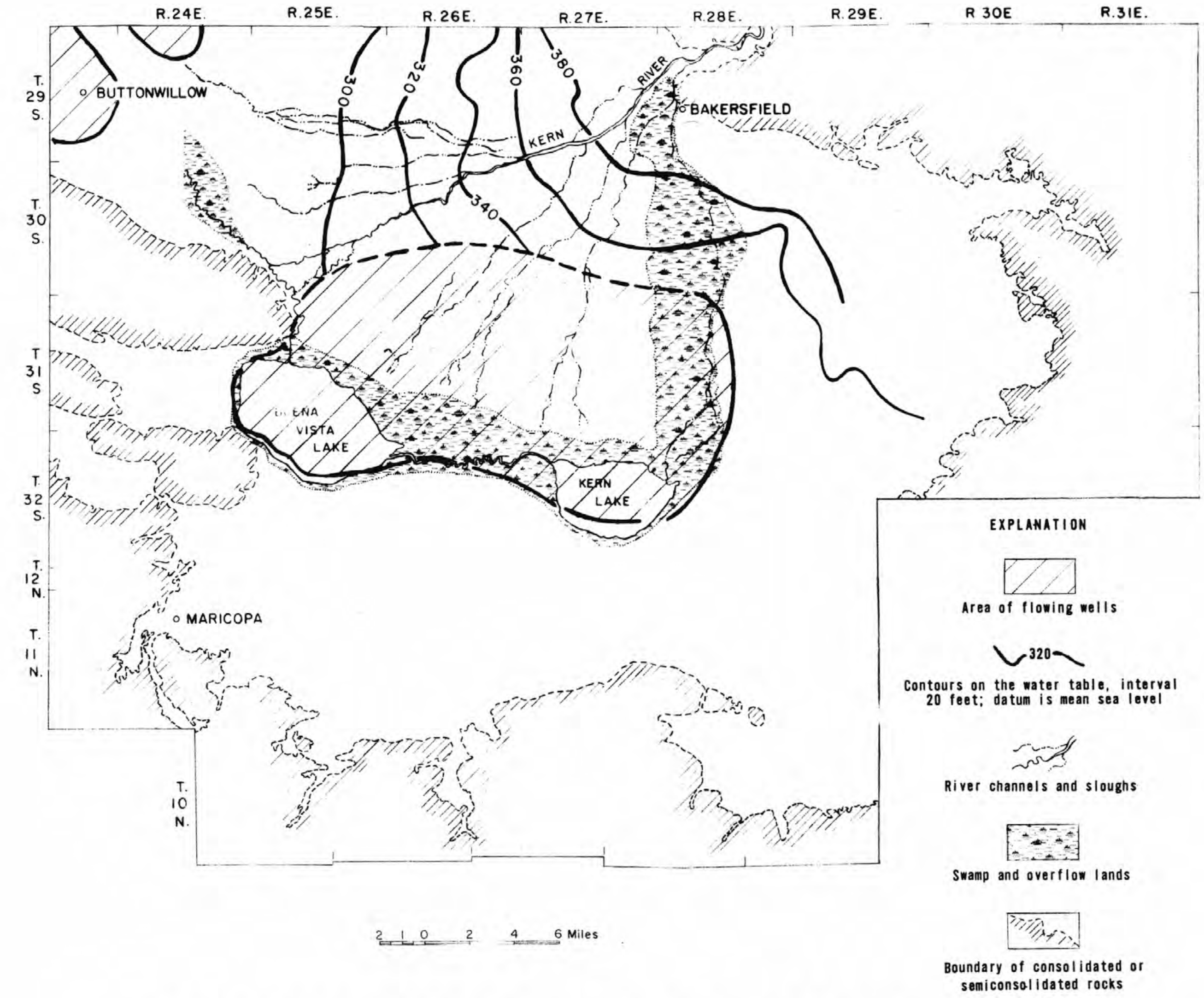


FIGURE 16.—EARLY DISTRIBUTARIES OF KERN RIVER AND EXTENT OF FLOWING WELL AREA IN 1905.

(Modified from Calif. State Eng. Dept., 1886, sheet 4 and Mendenhall, Dole, and Stabler, 1916, pl.1.)

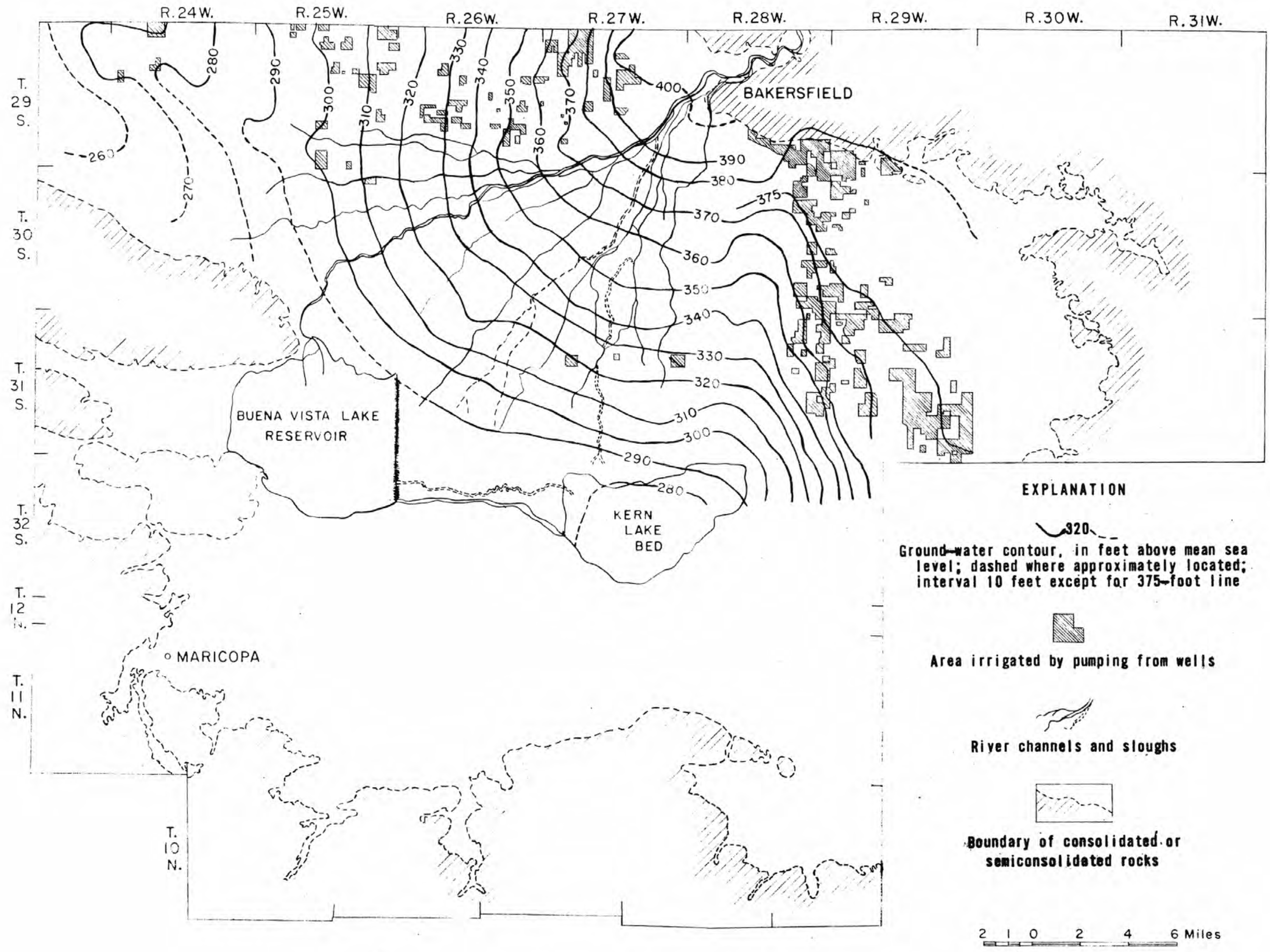


FIGURE 17.—WATER-LEVEL CONTOURS, DECEMBER 1920.

(From California Dept. Eng., 1921, map 2.)

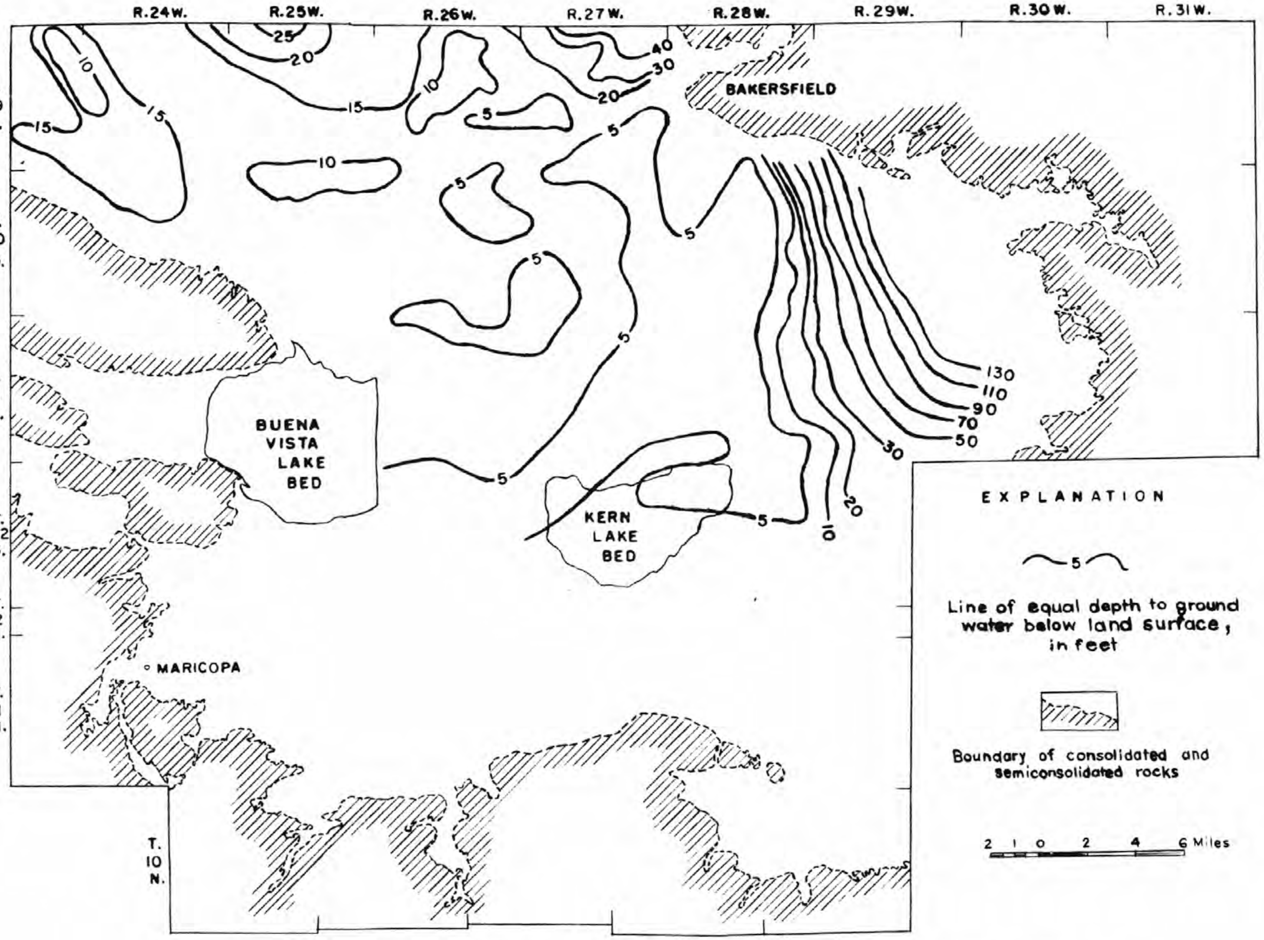


FIGURE 18. — DEPTH TO GROUND WATER, DECEMBER 1920.
(From California Dept. Eng., 1921, map 3)

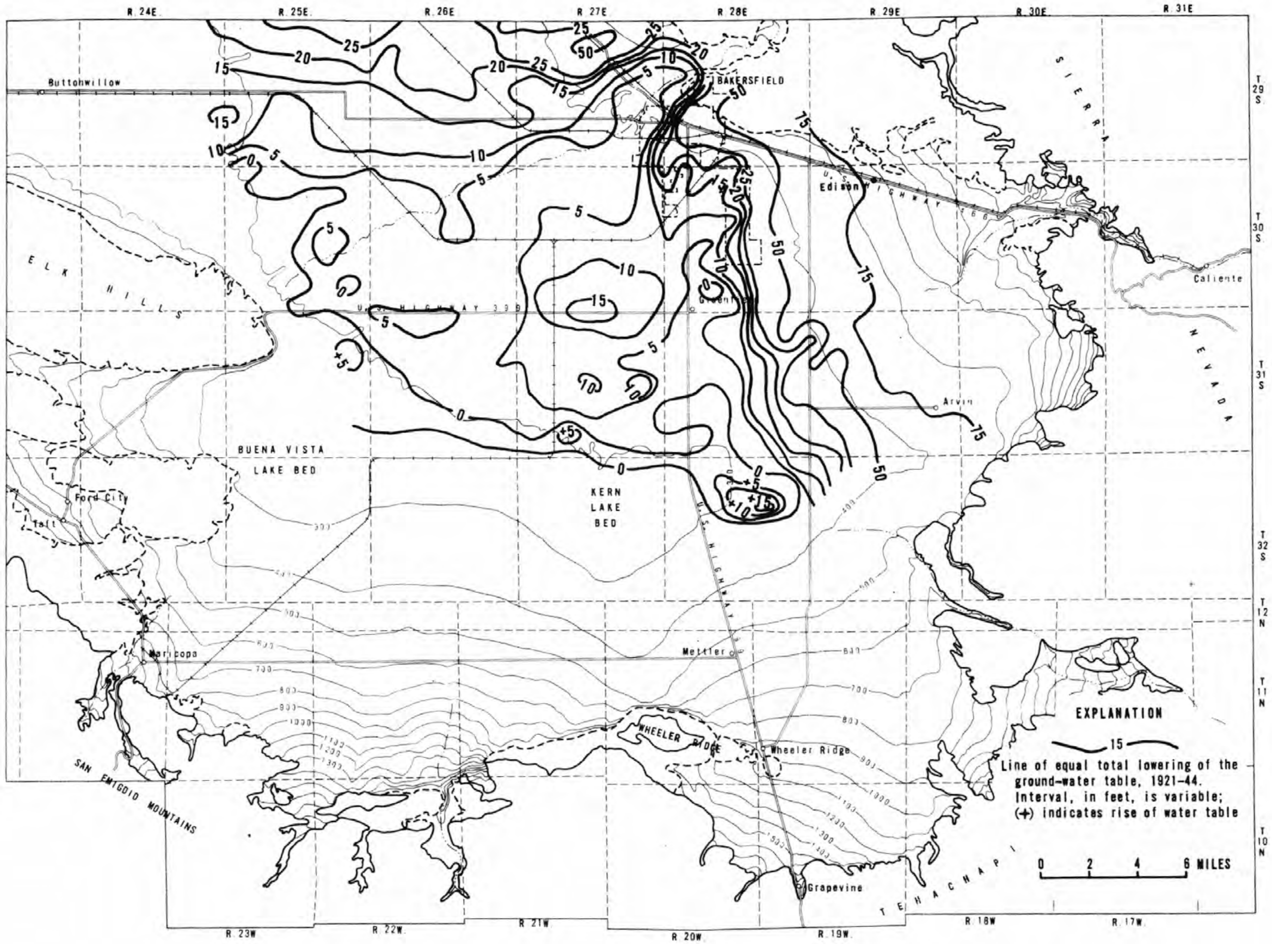


FIGURE 19.—TOTAL LOWERING OF THE GROUND-WATER TABLE, 1921-44.

(From open-file map of Calif. Div. Water Resources)

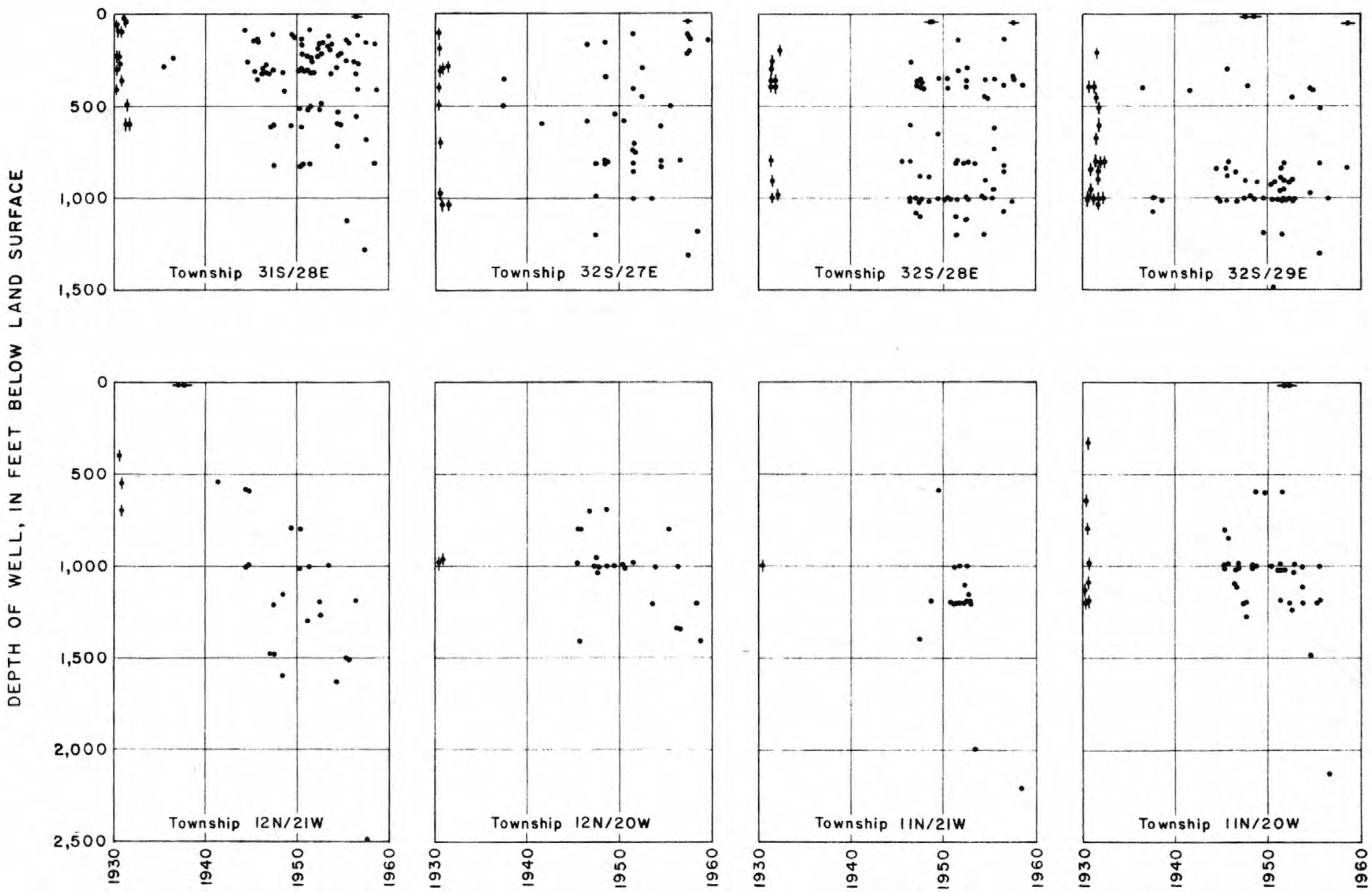


FIGURE 20.—YEAR COMPLETED AND DEPTH OF IRRIGATION WELLS IN EIGHT TOWNSHIPS IN THE CENTER OF MAXIMUM SUBSIDENCE, AS OF 1958. HORIZONTAL BAR (—) DENOTES DEPTH NOT AVAILABLE; VERTICAL BAR (I) DENOTES DRILLING DATE NOT AVAILABLE.

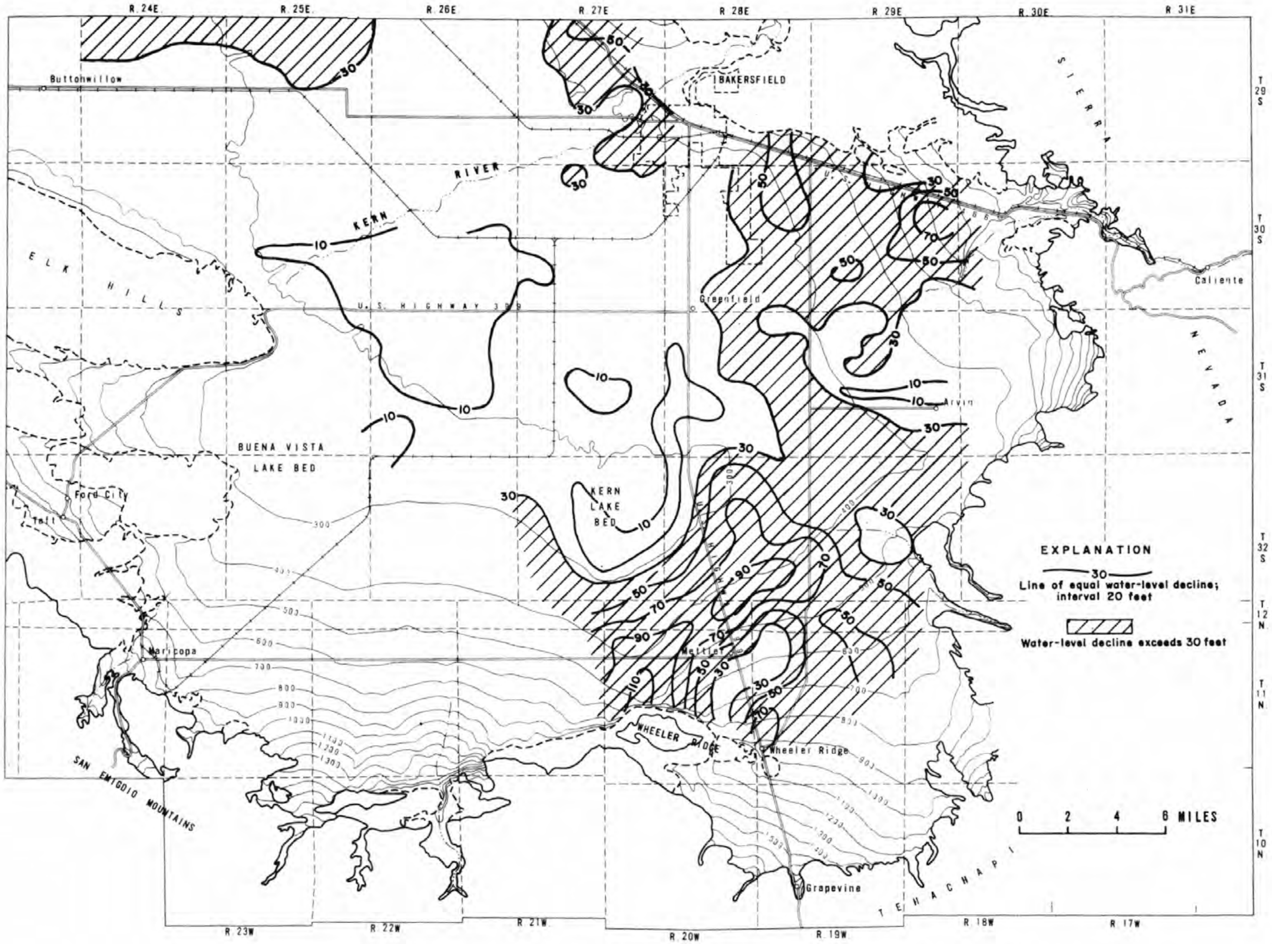


FIGURE 20A.—CHANGE IN WATER LEVEL FROM THE SEASONAL HIGH OF 1951 TO THE SEASONAL HIGH OF 1956.

(Modified from change map of U.S. Bureau of Reclamation), 1957)

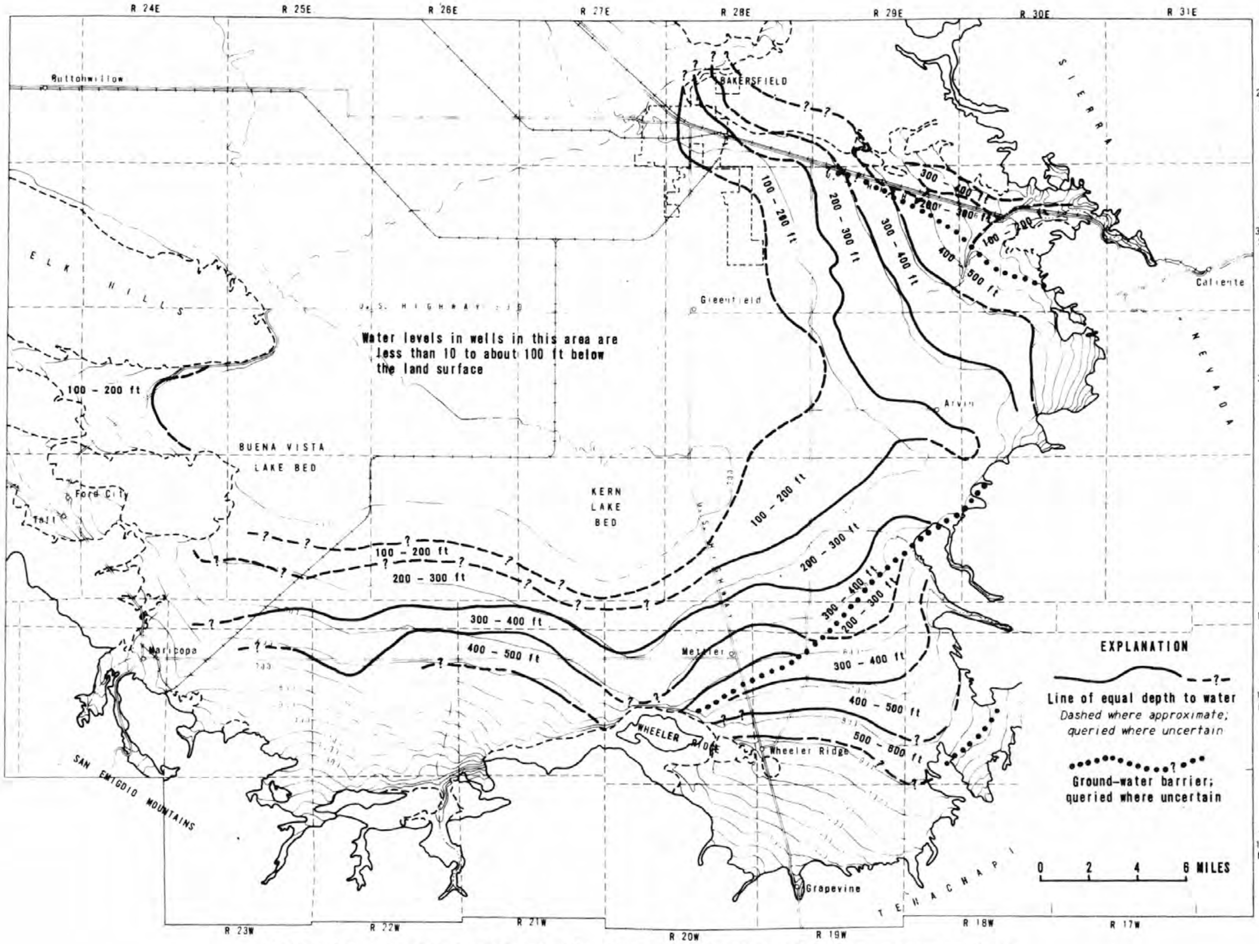


FIGURE 21.—Depth to water in the main ground-water reservoir, December 1958.

From Wood and Dale, 1964, pl.7

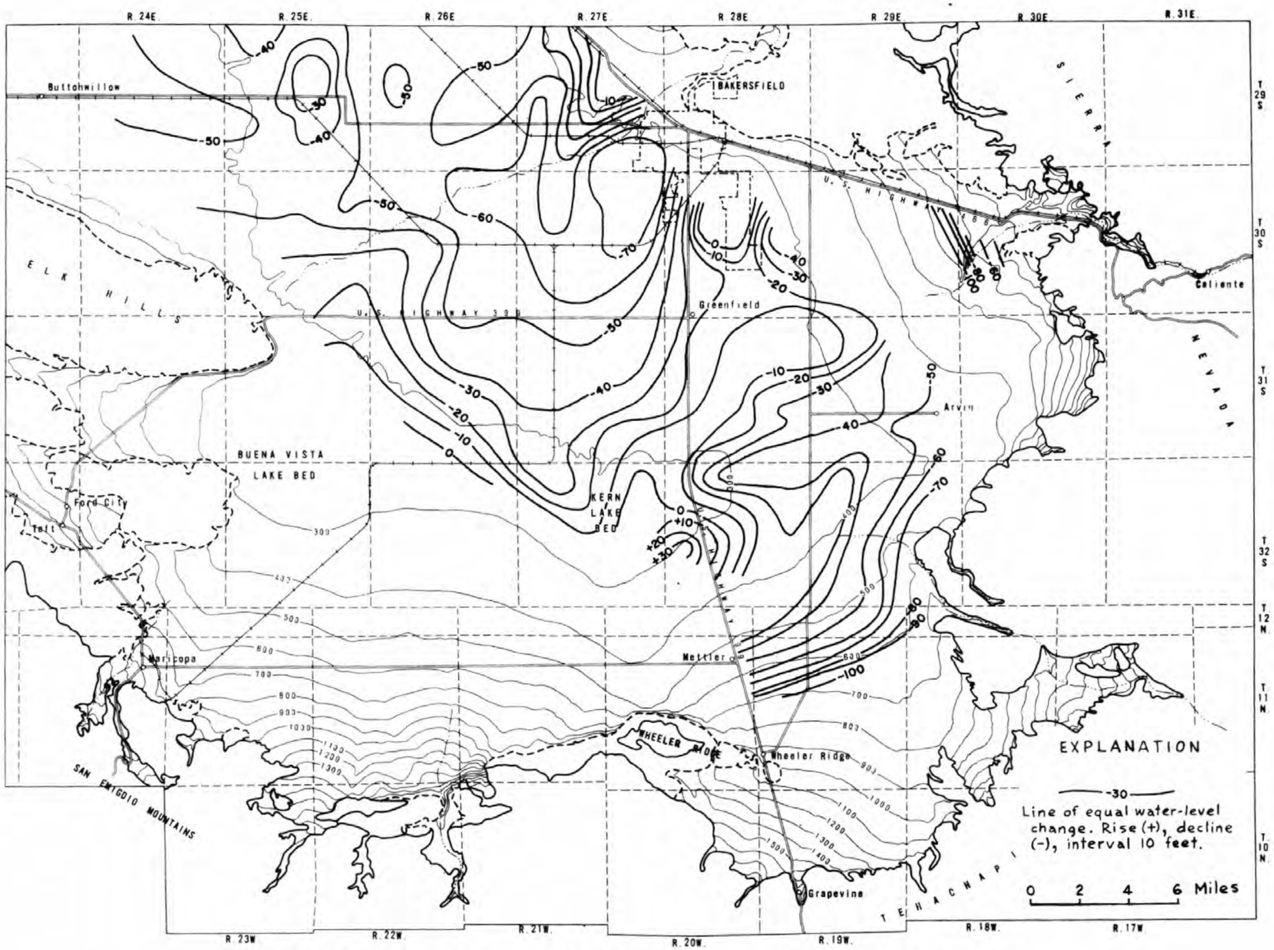


FIGURE 21A.—CHANGE IN WATER LEVEL IN THE UNCONFINED AND SHALLOW SEMICONFINED AQUIFER SYSTEM, 1957-65.

Based on spring water-level maps of the California Department of Water Resources

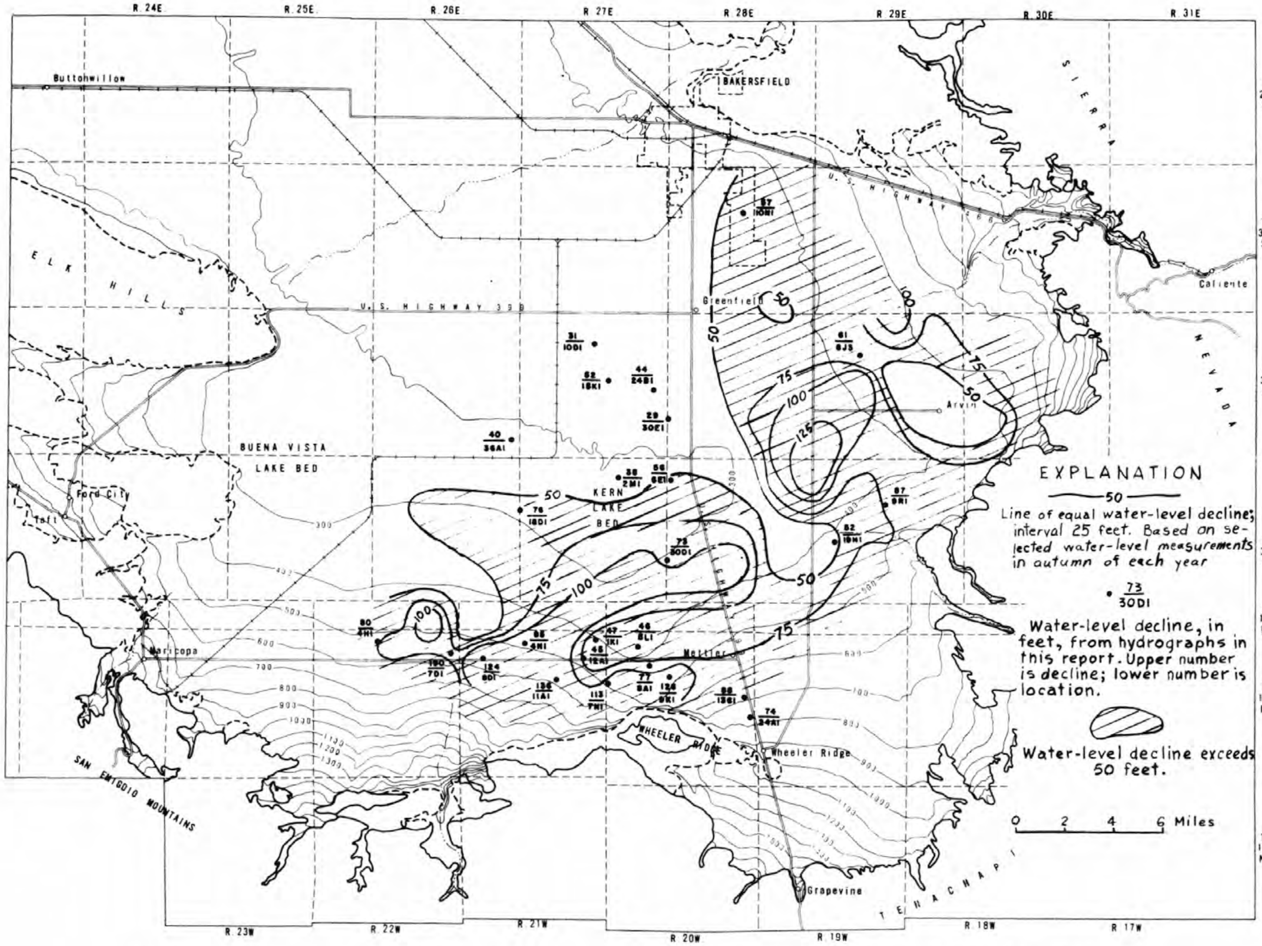


FIGURE 21B.—Decline of head in the confined and deep semiconfined aquifer system, 1957-65.

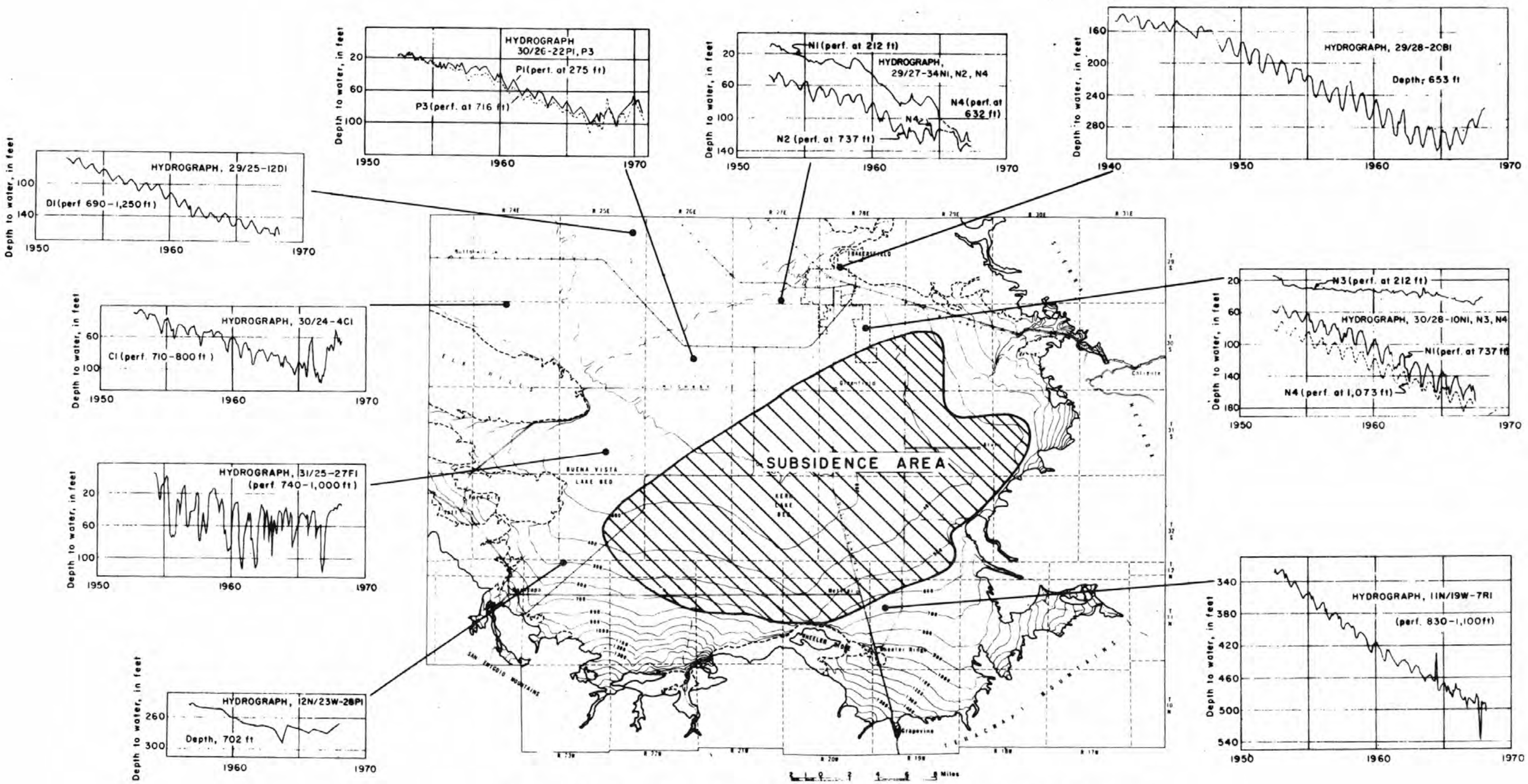


Figure 22. — Water-level trend outside the principal subsidence area.

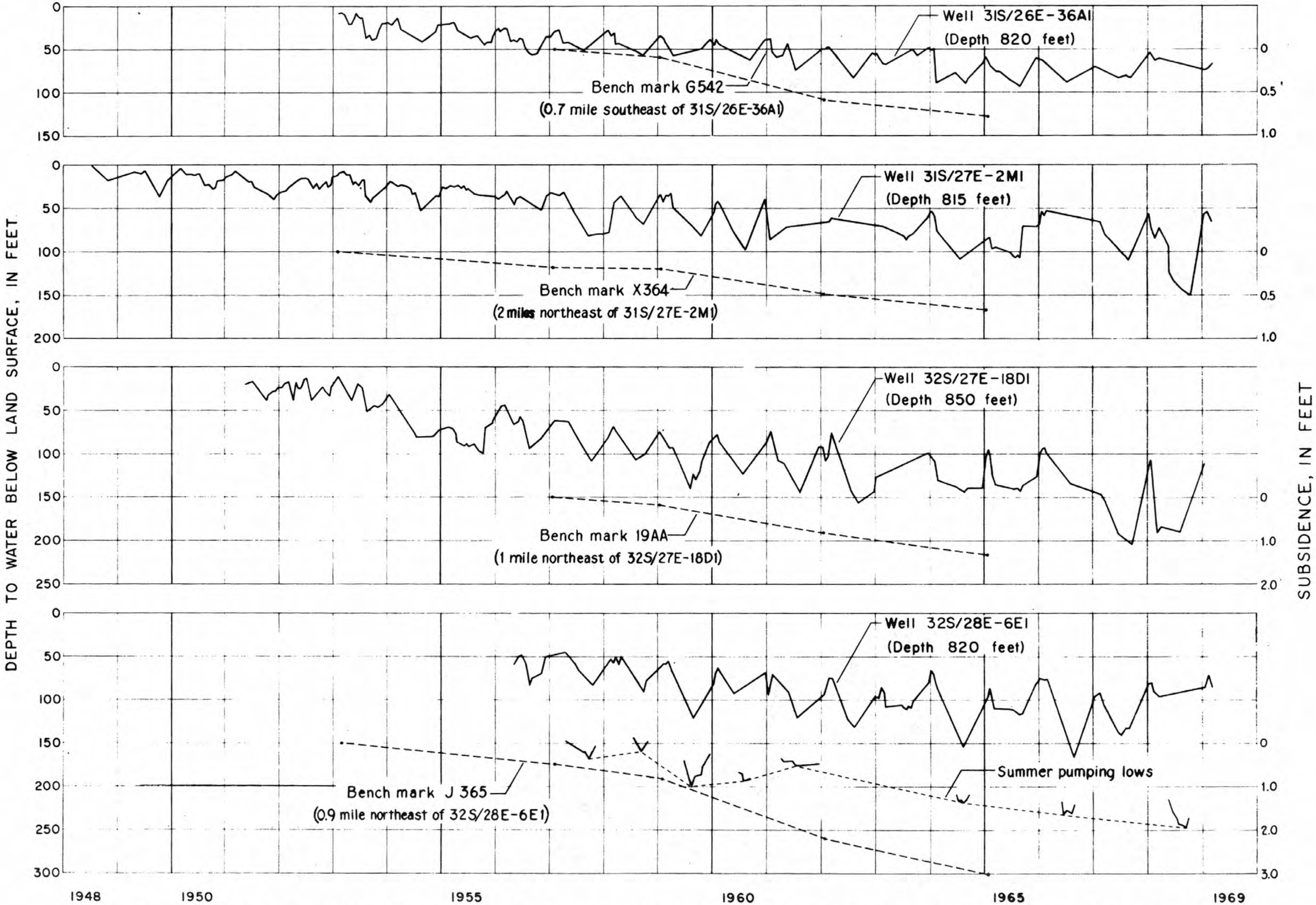


FIGURE 23.—Hydrographs of four wells, 815-850 feet deep, tapping the confined aquifer system beneath and north of Kern lake bed, and subsidence graphs of nearby bench marks. See figure 32 for location of wells and bench marks.

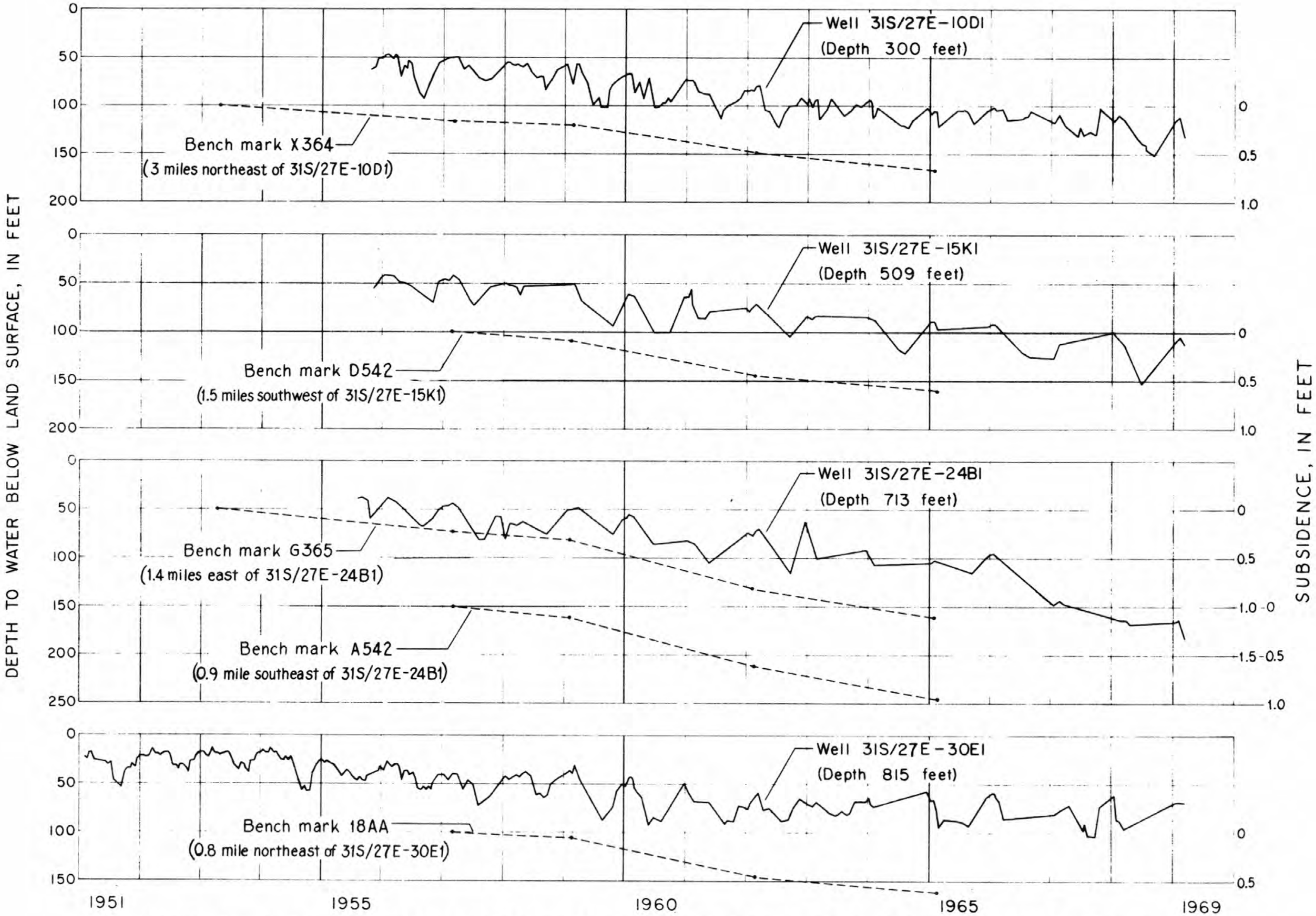


FIGURE 24.—Hydrographs of four wells tapping the confined aquifer system north of Kern lake bed, and subsidence graphs of nearby bench marks. See figure 32 for location of wells and bench marks.

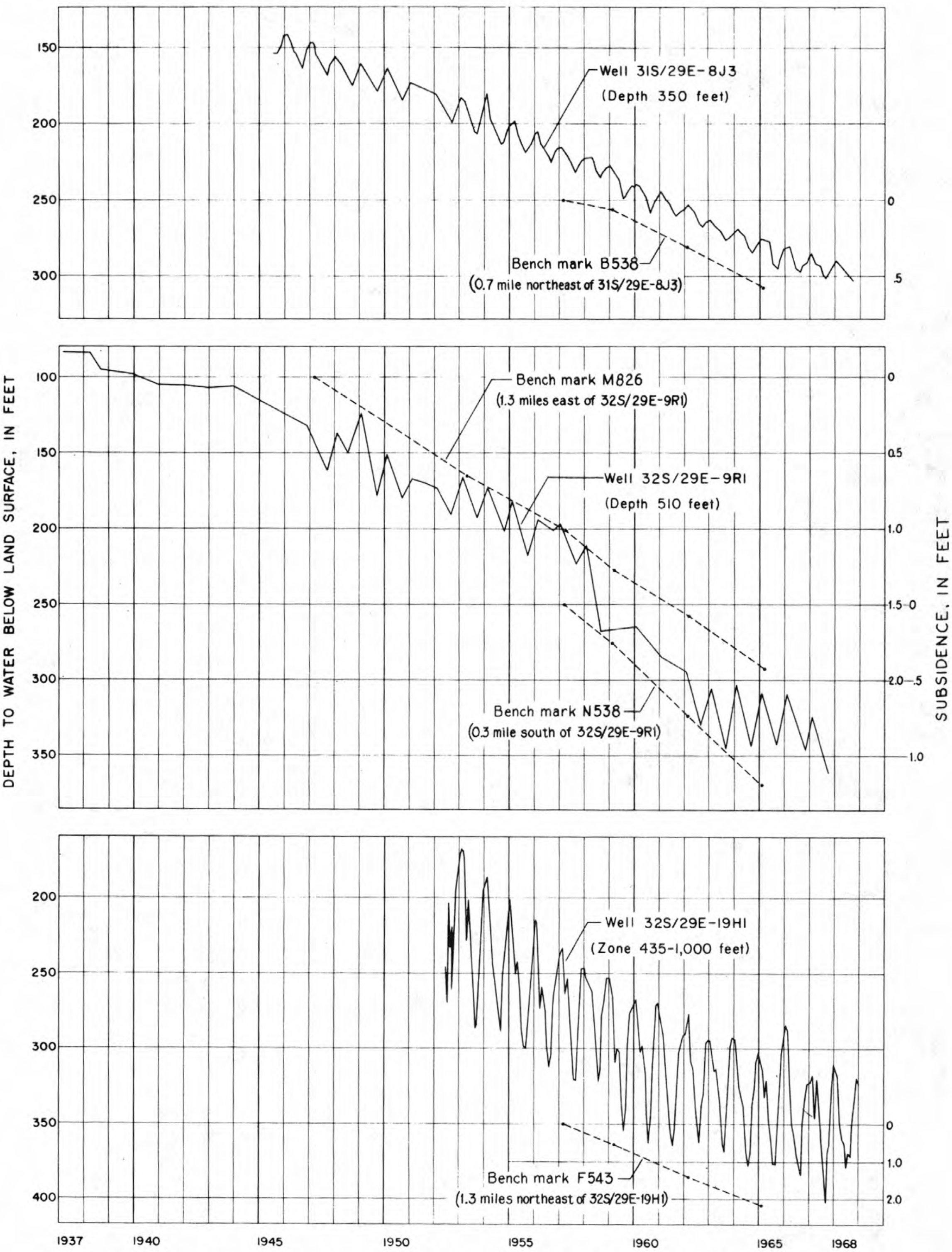


FIGURE 25.—Hydrographs of three wells tapping the semiconfined and confined aquifer system on the eastern margin of the subsidence area, and subsidence graphs of nearby bench marks. See figure 32 for location of wells and bench marks.

Reduce this

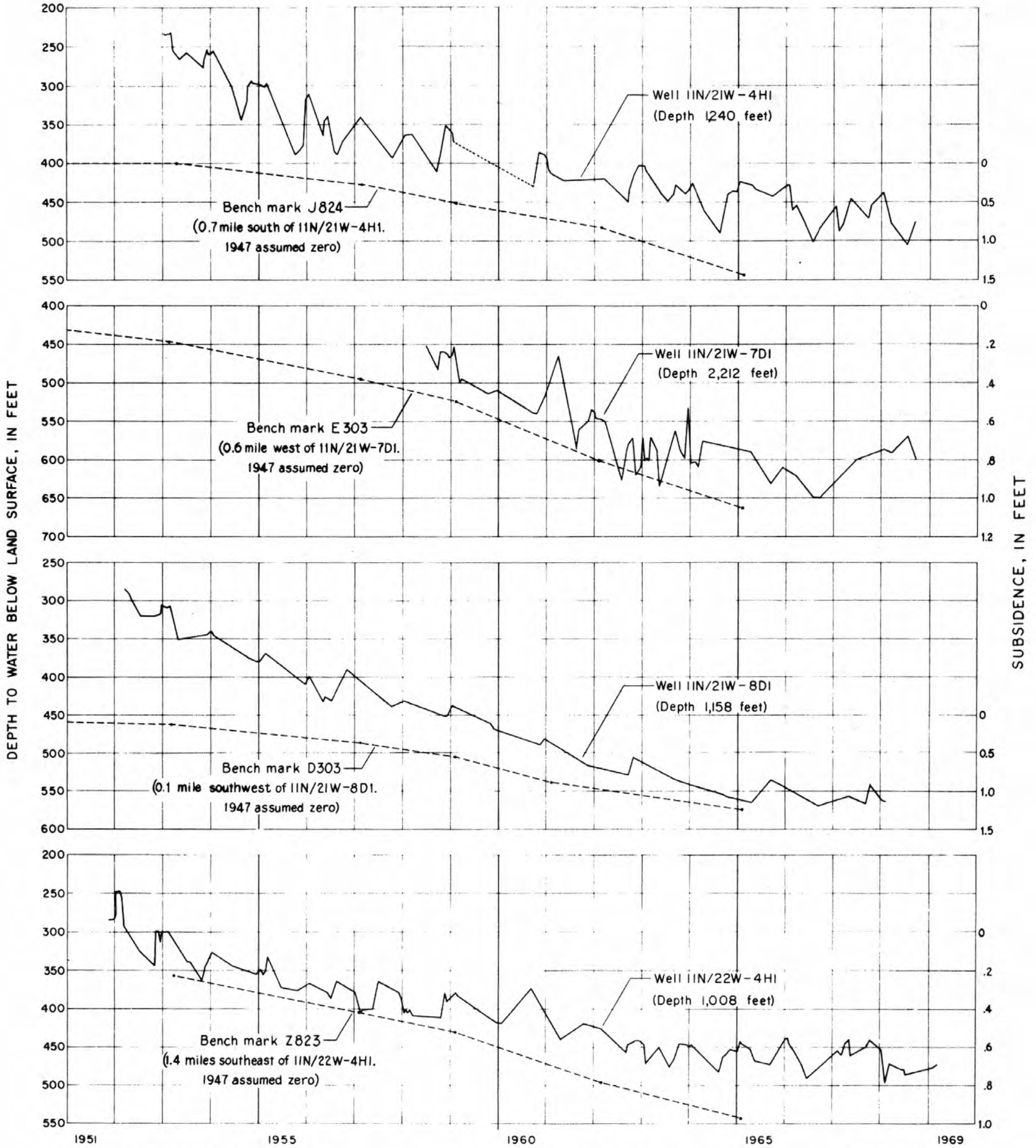


FIGURE 26.—Hydrographs of four deep wells tapping the semiconfined aquifer system on the southwest margin of the subsidence area, and subsidence graphs of nearby bench marks. See figure 32 for location of wells and bench marks.

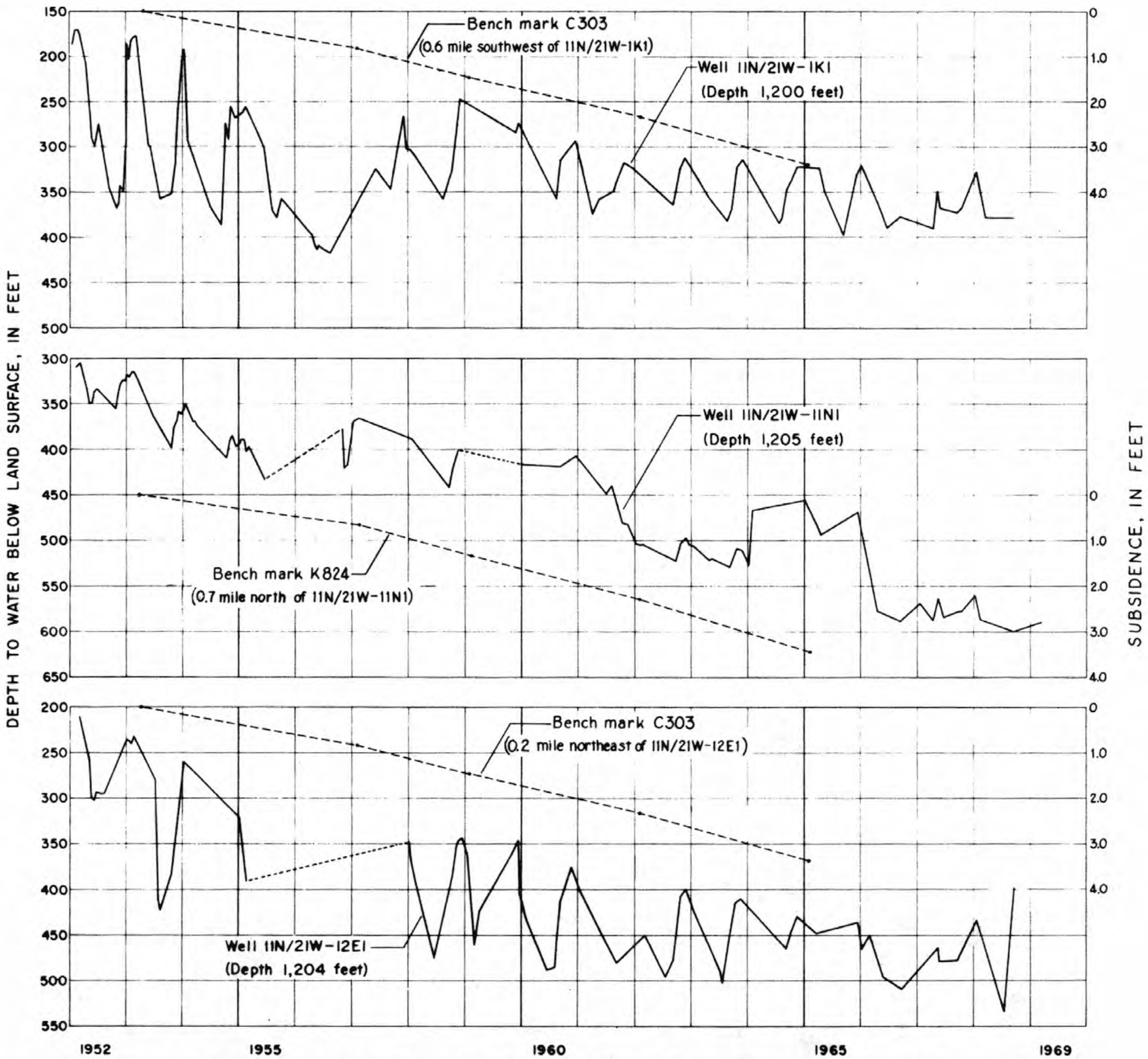


FIGURE 27.—Hydrographs of three deep wells tapping the semiconfined aquifer system on the southern margin of the subsidence area, and subsidence graphs of nearby bench marks. See figure 32 for location of wells and bench marks.

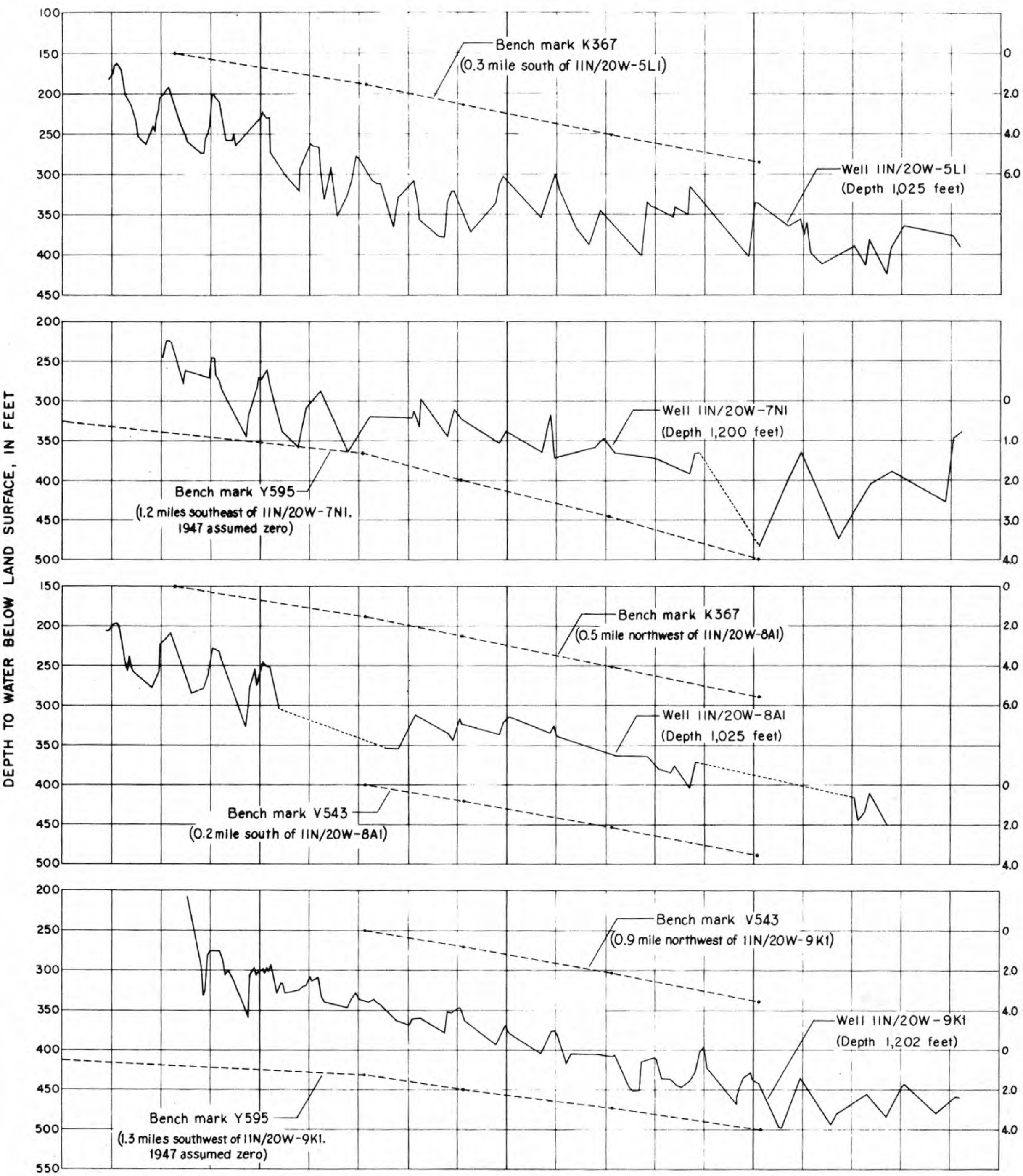


FIGURE 28.—Hydrographs of four wells tapping the semiconfined aquifer system in the interfan reentrant north of Wheeler Ridge, and subsidence graphs of nearby bench marks. See figure 32 for location of wells and bench marks.

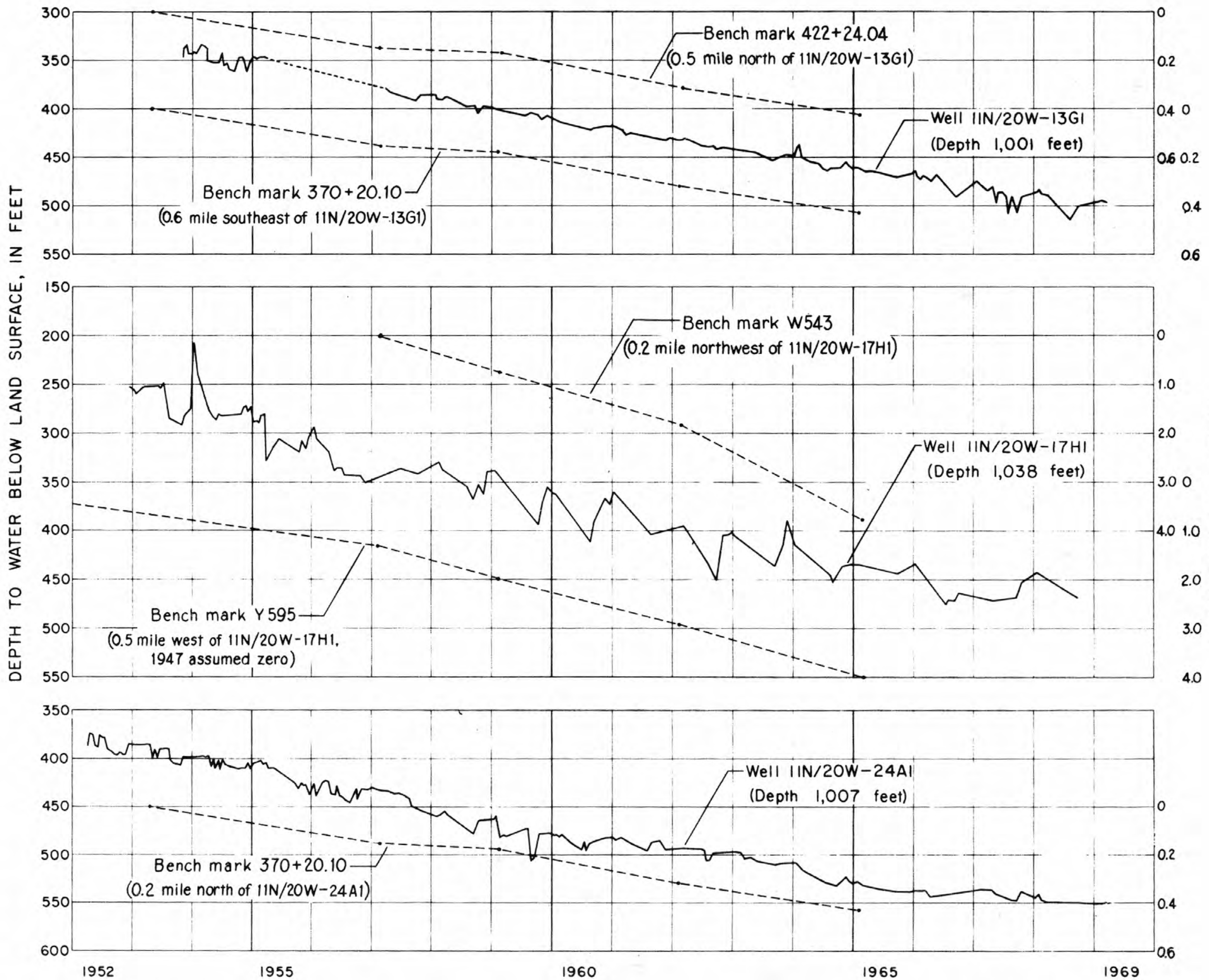


FIGURE 29.—Hydrographs of three wells tapping the semiconfined aquifer system on the north flank of Wheeler Ridge, and subsidence graphs of nearby bench marks. See figure 32 for location of wells and bench marks.

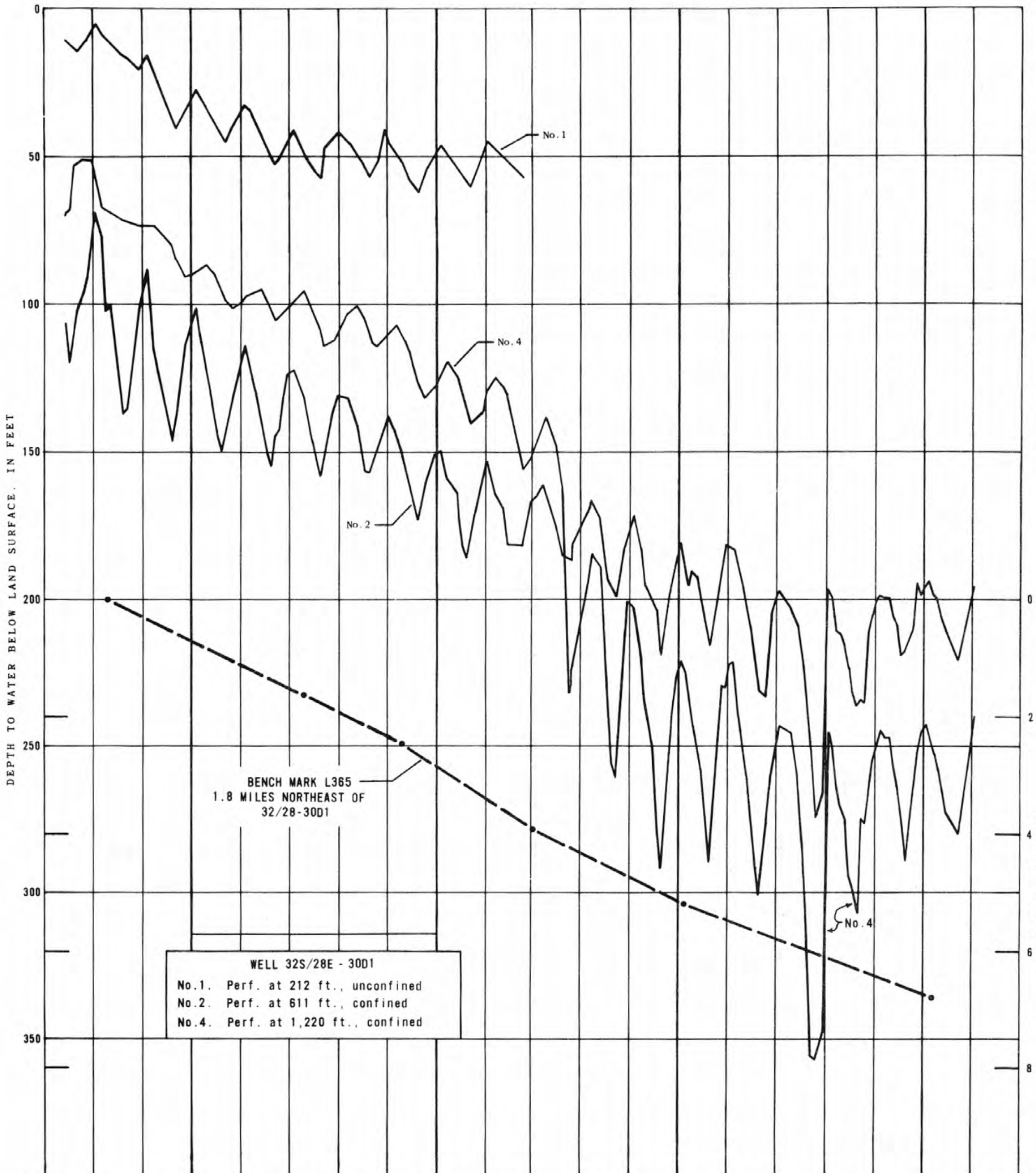


FIGURE 30.--Hydrographs of three piezometers at 32S/28E - 30D1 in the center of the subsidence area, and the subsidence graph of a nearby bench mark. See figure 32 for location of piezometers and bench mark.

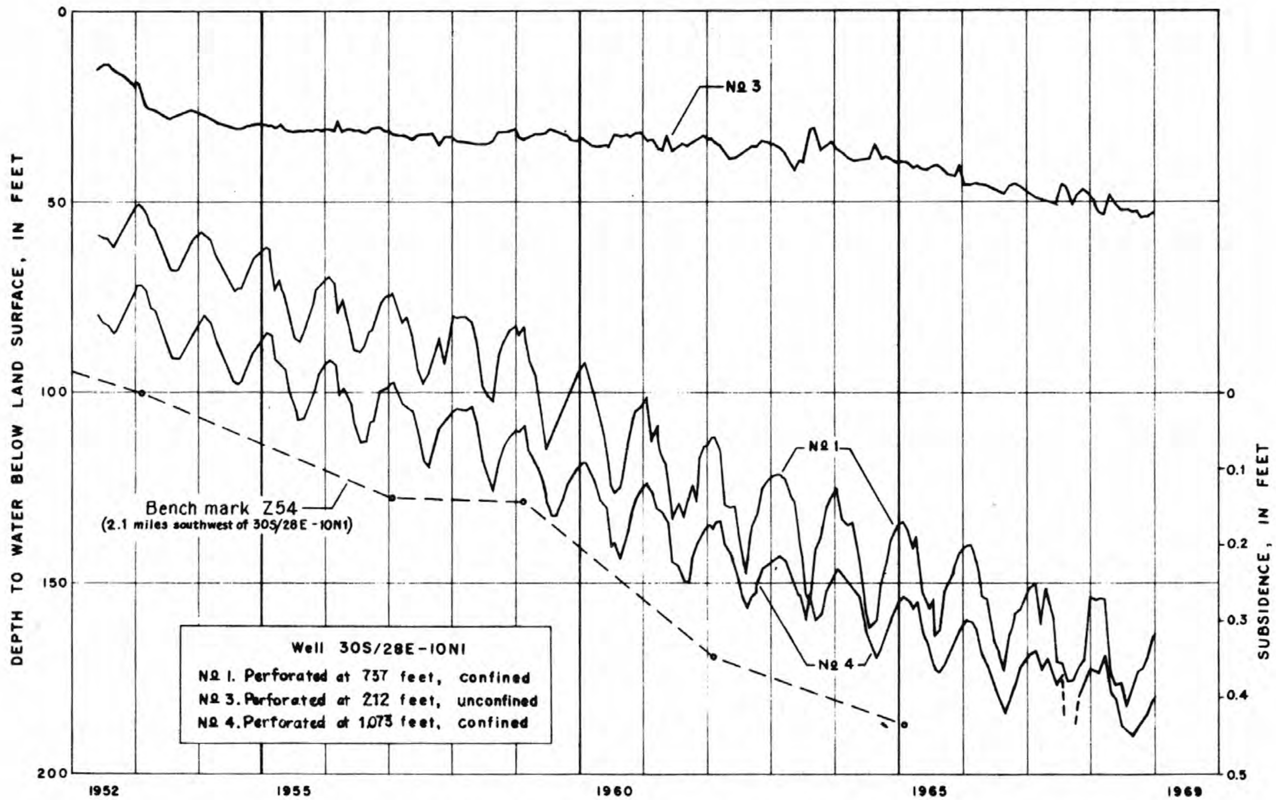


FIGURE 31.—Hydrographs of three piezometers at 30S/28E-10N1 in south Bakersfield, and the subsidence graph of a distant bench mark. See figure 32 for location of piezometers and bench mark.

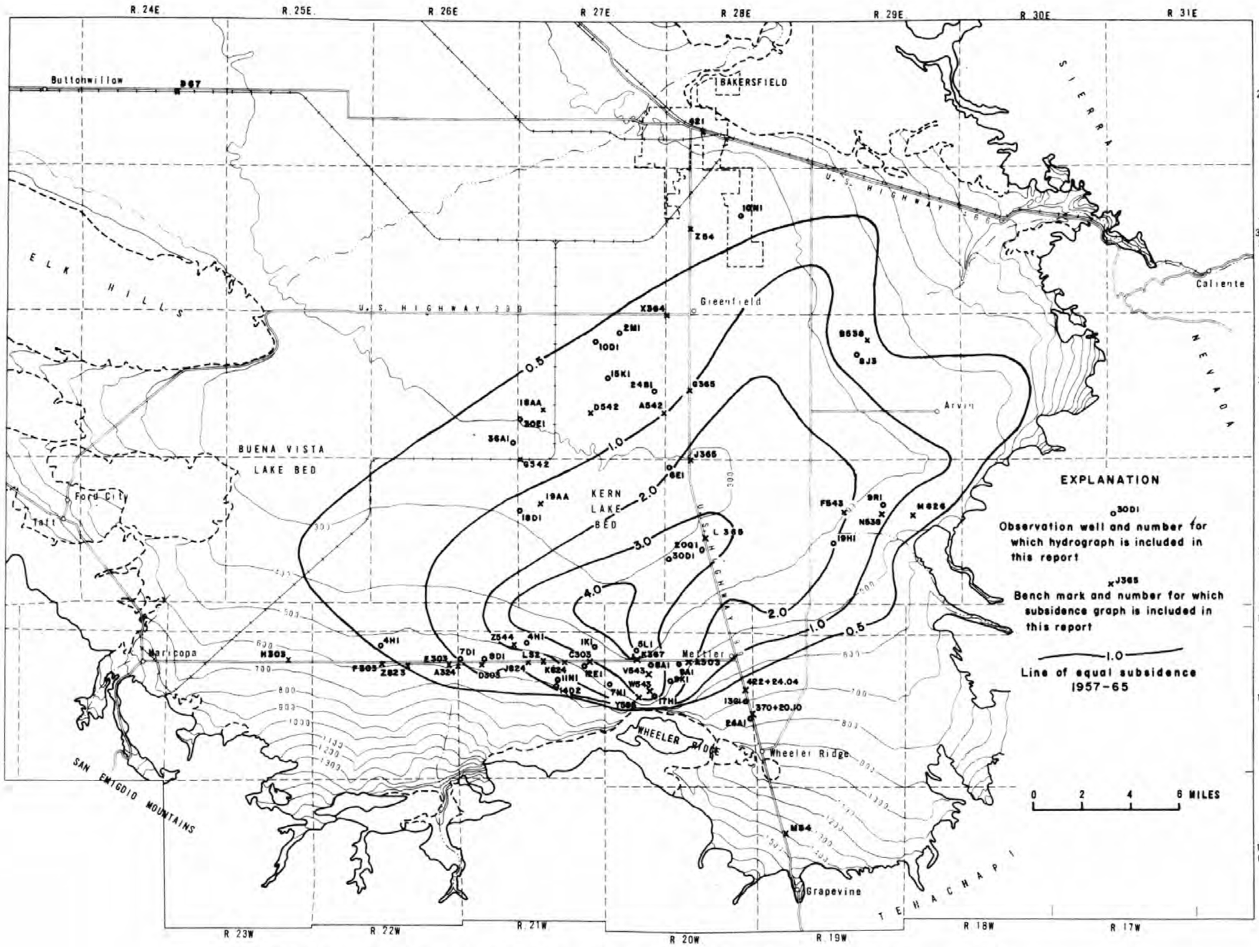


FIGURE 32.— Location of selected wells and bench marks in the Arvin — Maricopa subsidence area for which graphs are included in this report.

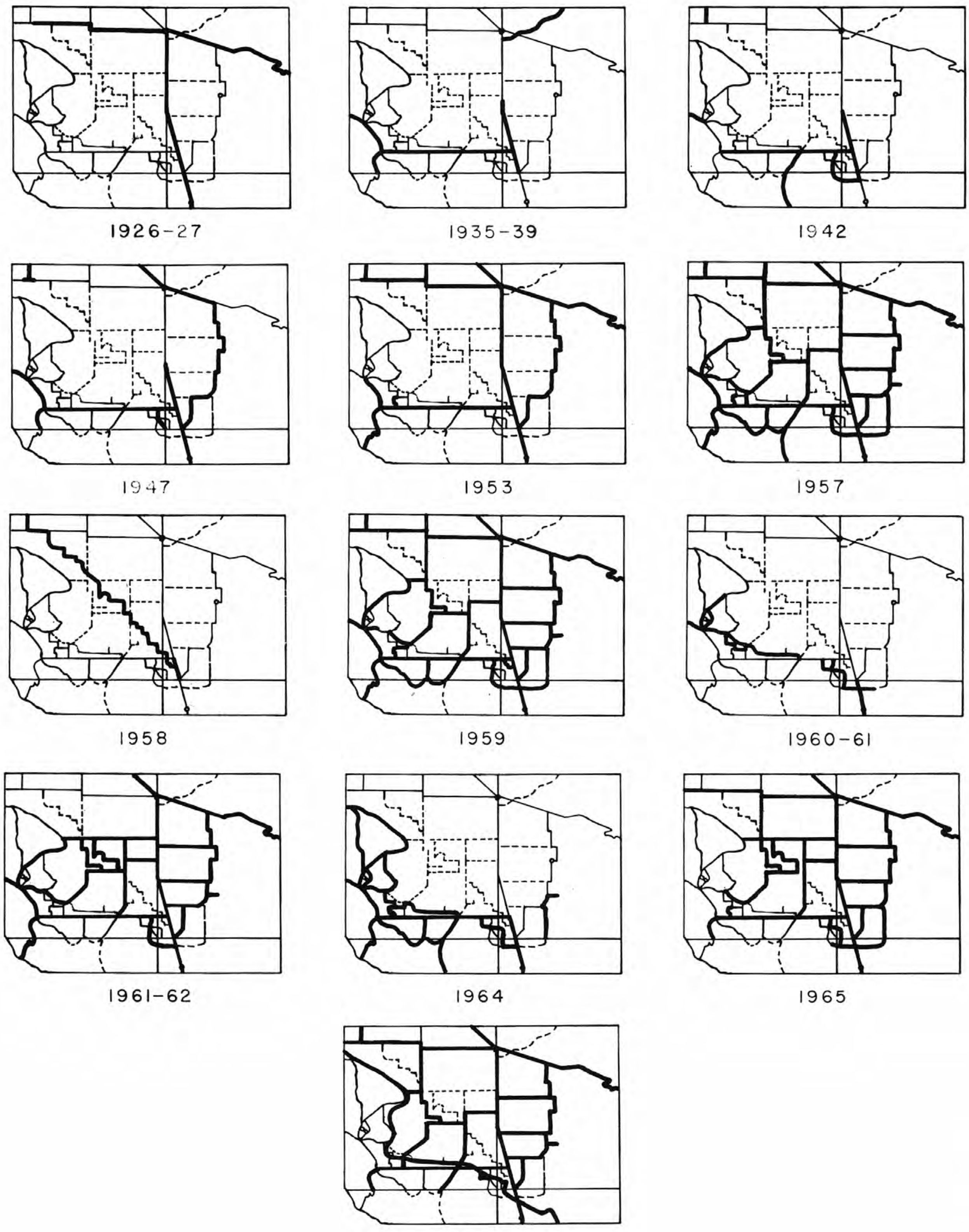


FIGURE 33. — Time and extent of leveling in the Arvin — Maricopa area by the U.S. Coast and Geodetic Survey.

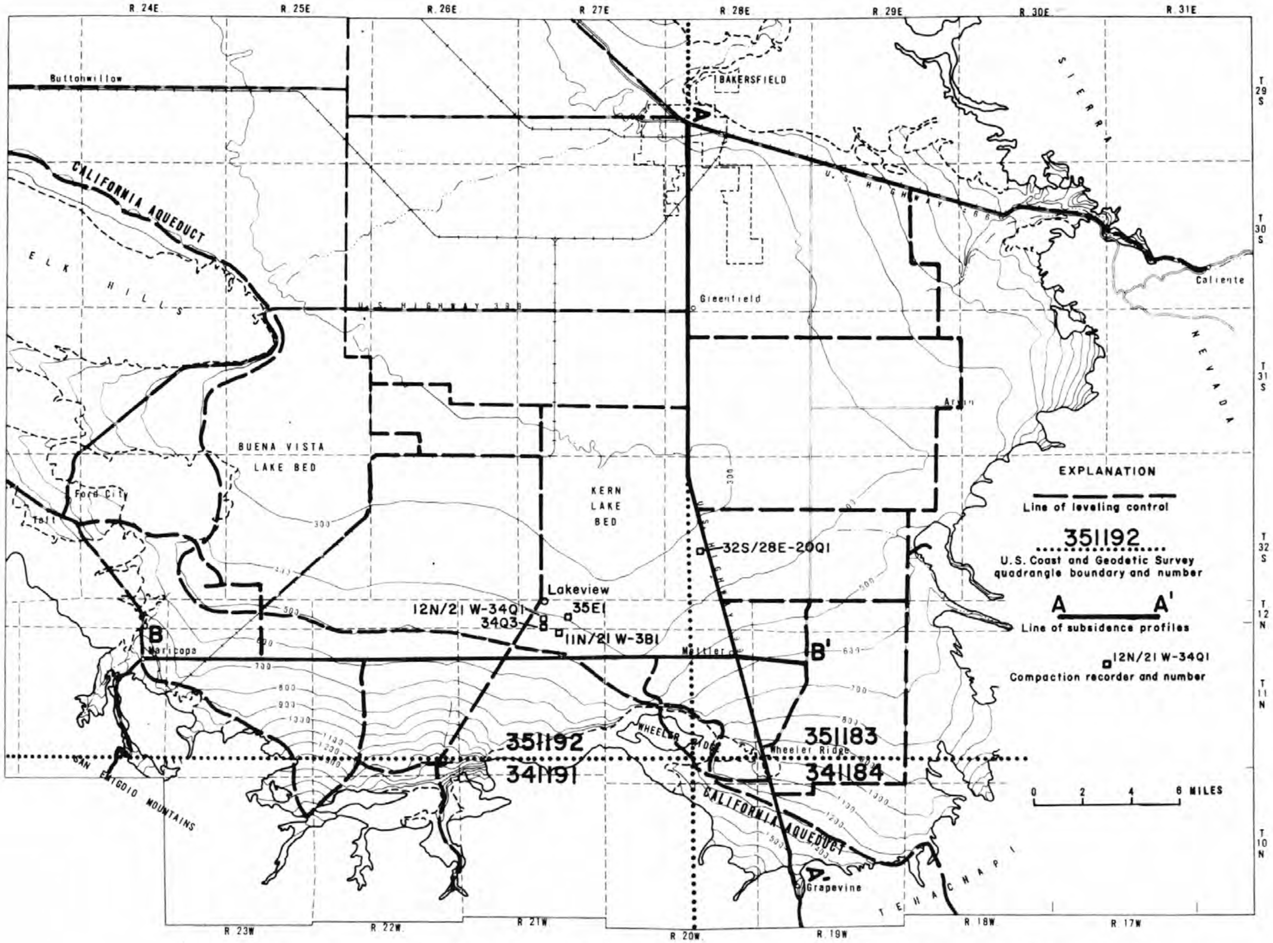


FIGURE 34. Network of periodic leveling by the U.S. Coast and Geodetic Survey, location of land - subsidence profiles, and location of compaction recorders.

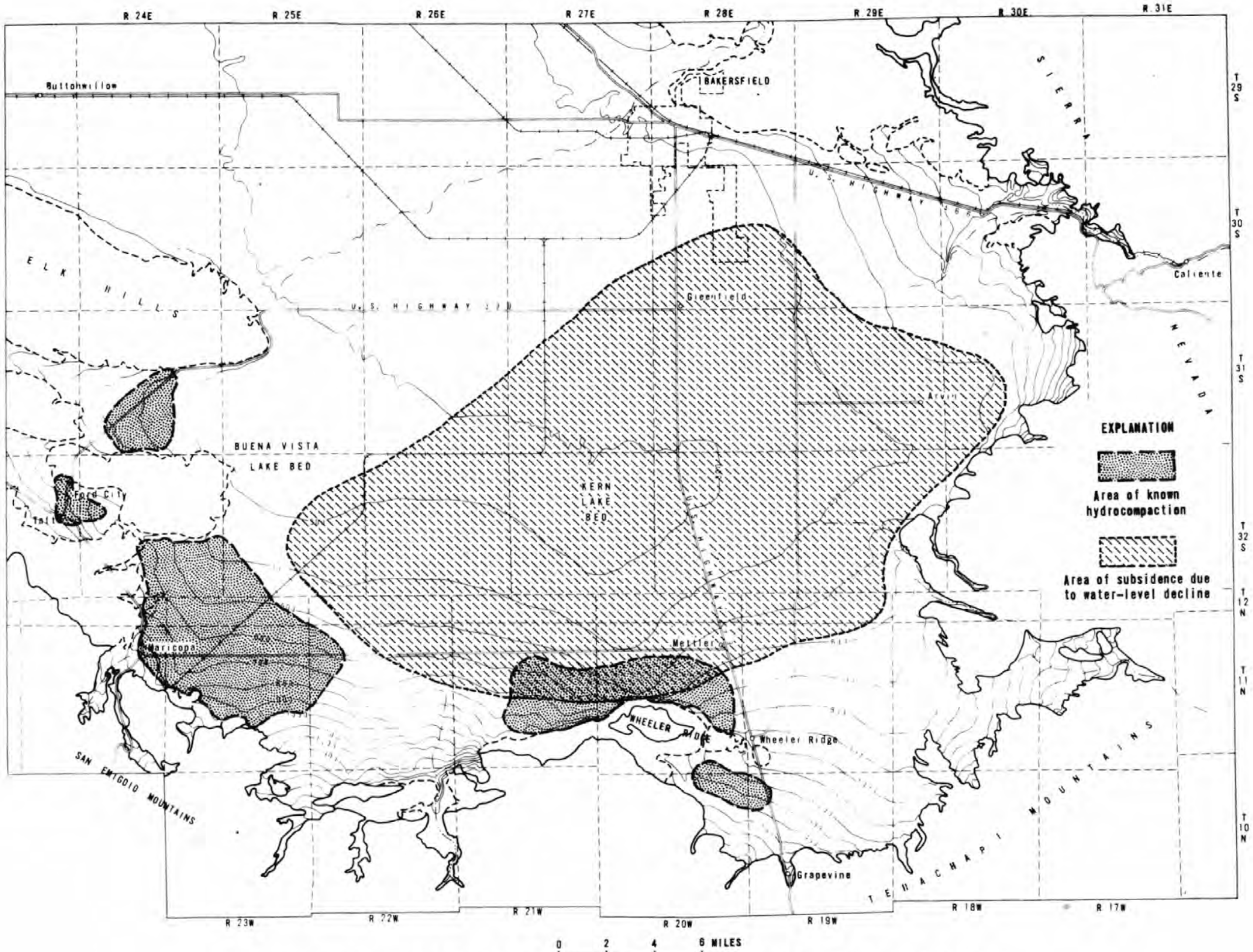


FIGURE 35.—Areas of known hydrocompaction in the Arvin – Maricopa area.

Chiefly from mapping of California Department of Water Resources (1960, pl.1)

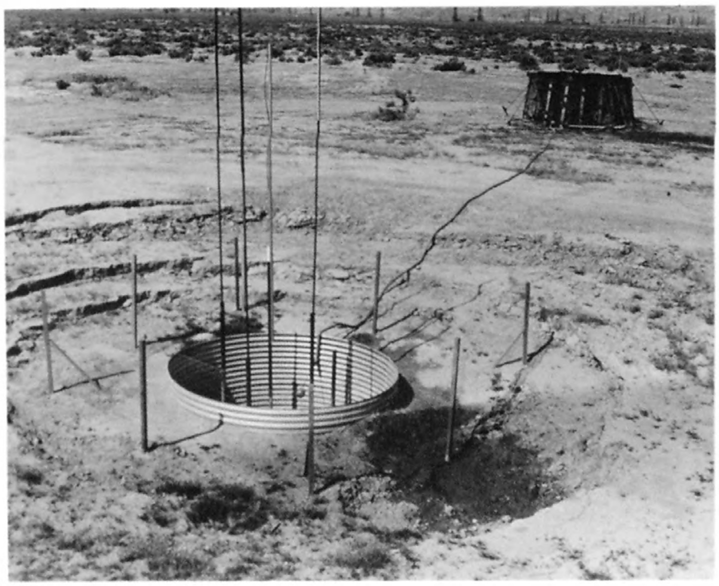


Figure 36--.Settlement and cracking due to hydrocompaction around an 8-foot infiltration tank northeast of Maricopa. (Photo by Calif. Dept. of Water Resources)

Figure 37.--Aerial view of preconstruction infiltration ponds along the alinement of the California Aqueduct north of Wheeler Ridge.

(Photo by F. S. Riley)

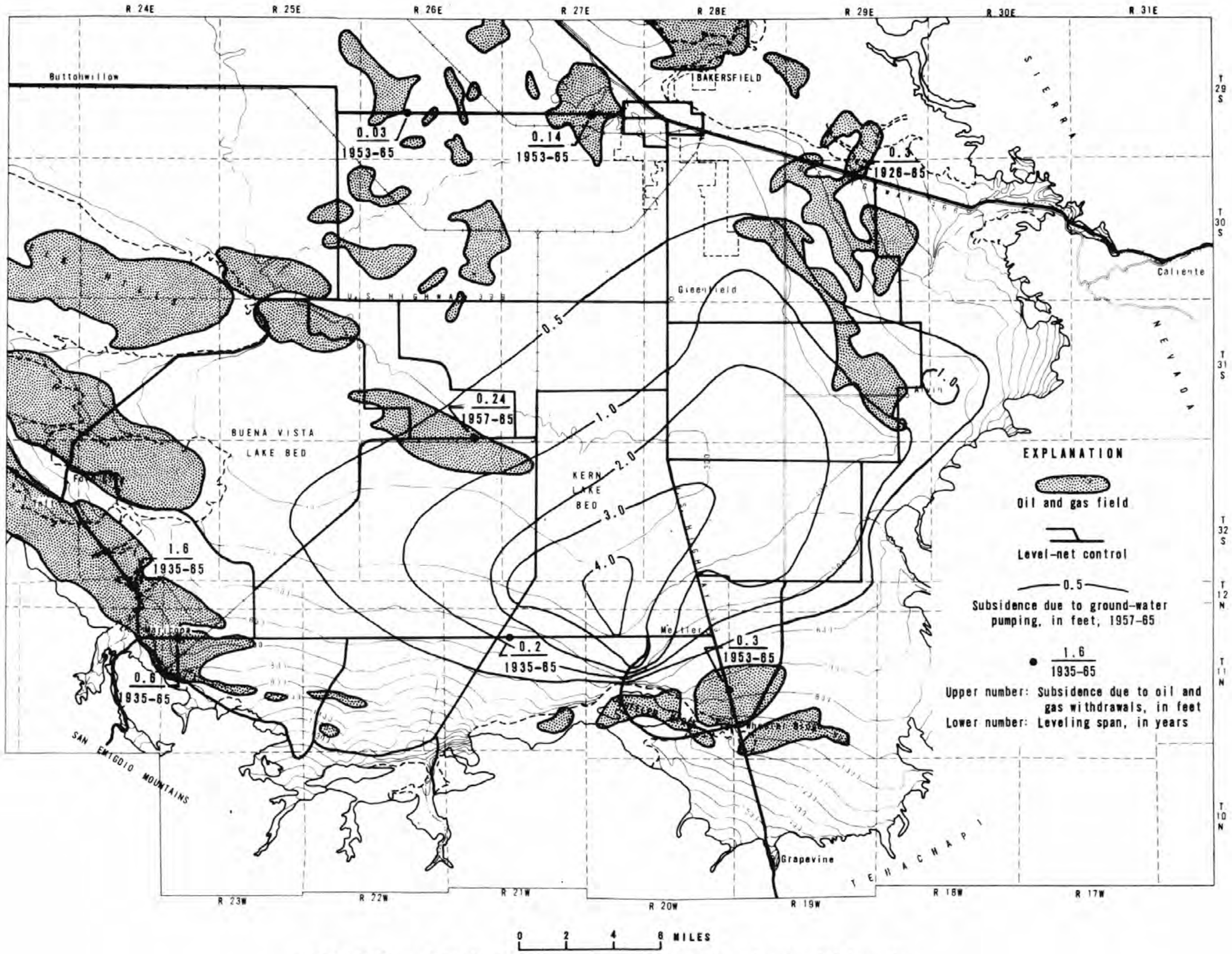


FIGURE 38.—Oil-field subsidence due to oil and gas withdrawals.

From maps of Calif. Div. Oil and Gas, Pt.1, Dist.4, 1960

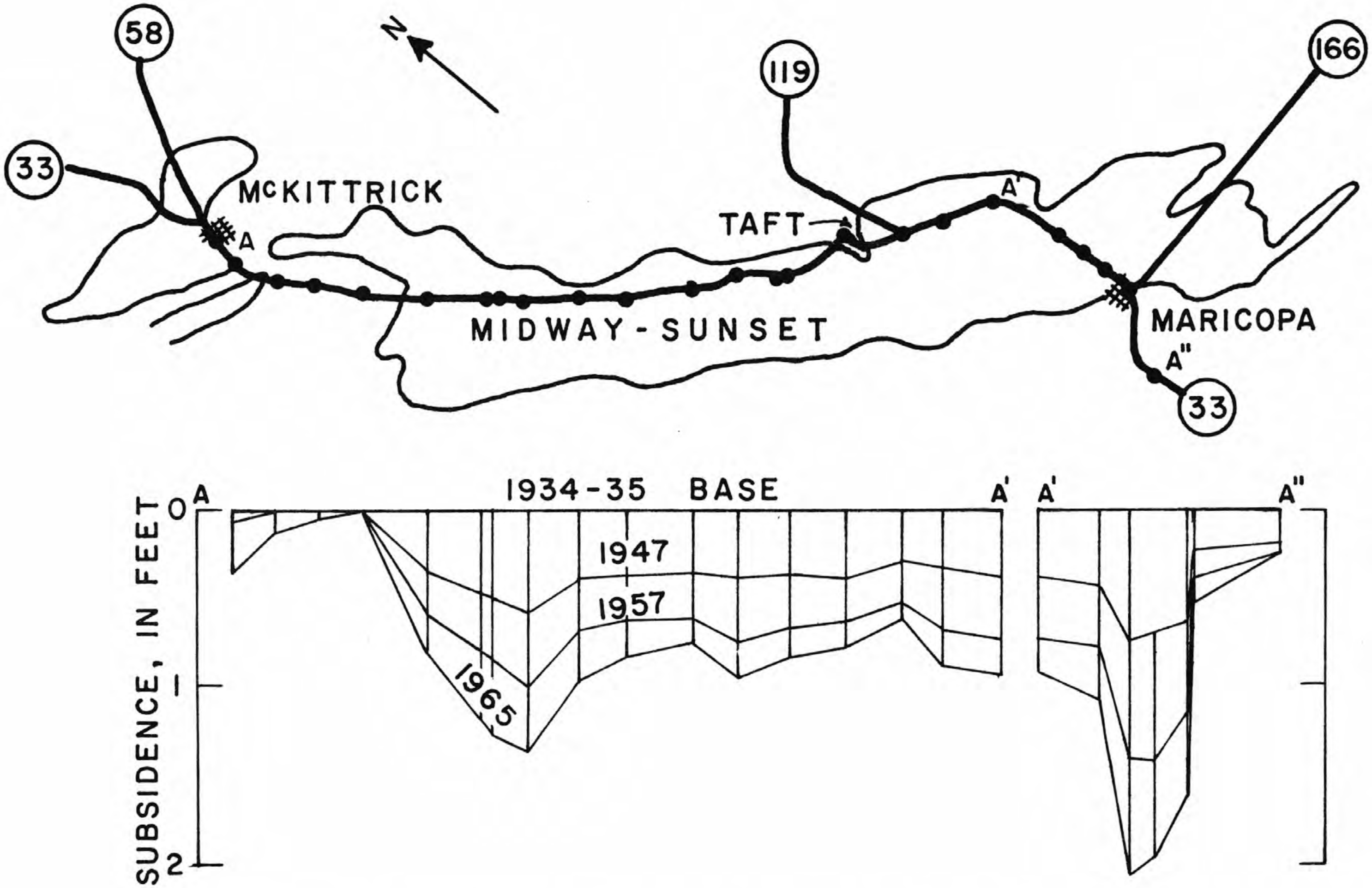


FIGURE 39.—Subsidence profiles across the Midway-Sunset oil field, 1934-35 to 1965.

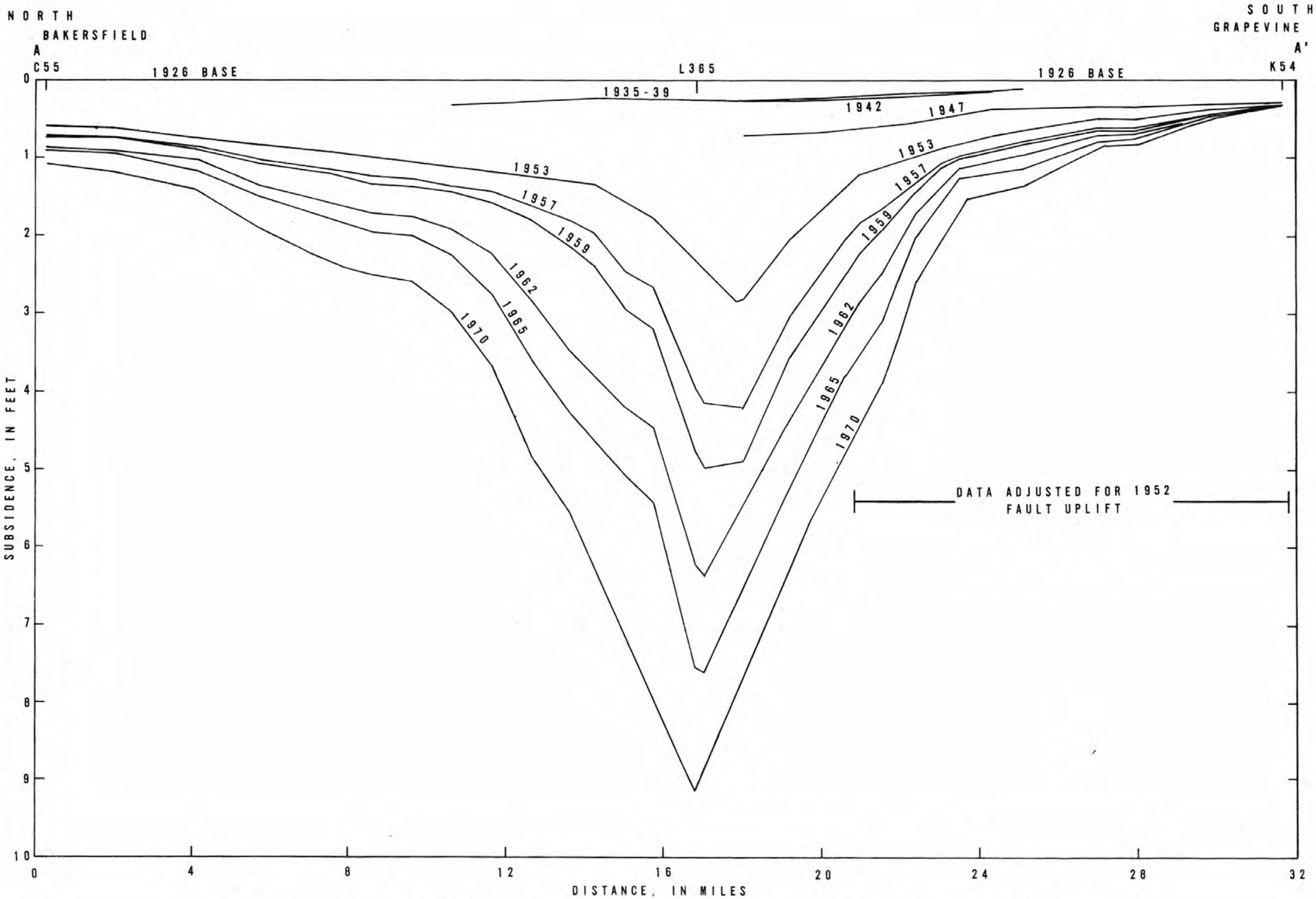


FIGURE 40.--Profiles of land subsidence A — A', along U.S. Highway 99, Bakersfield to Grapevine, 1926 — 70

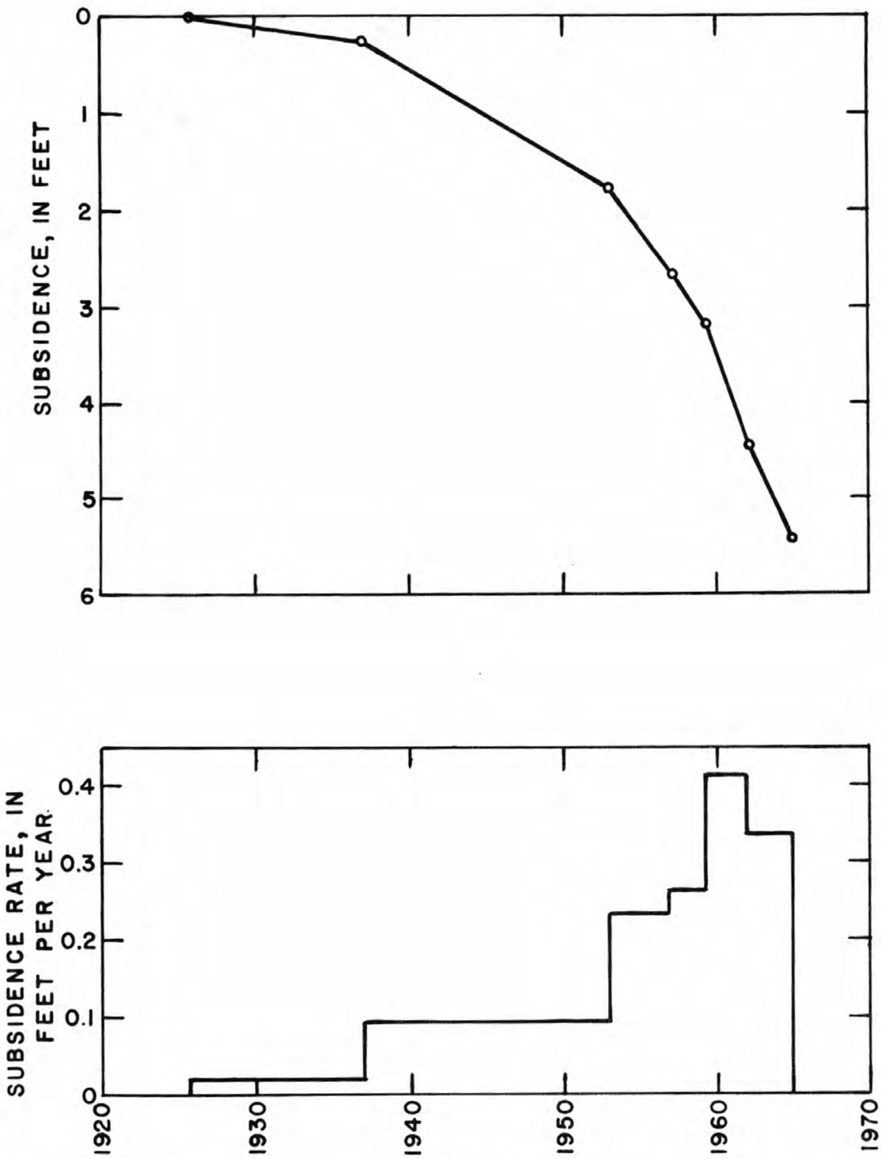


FIGURE 41.—SUBSIDENCE AT BENCH MARK T54 (RESET) FOR PERIODS OF AVAILABLE CONTROL.

Bench mark destroyed after 1965 (fig.40)

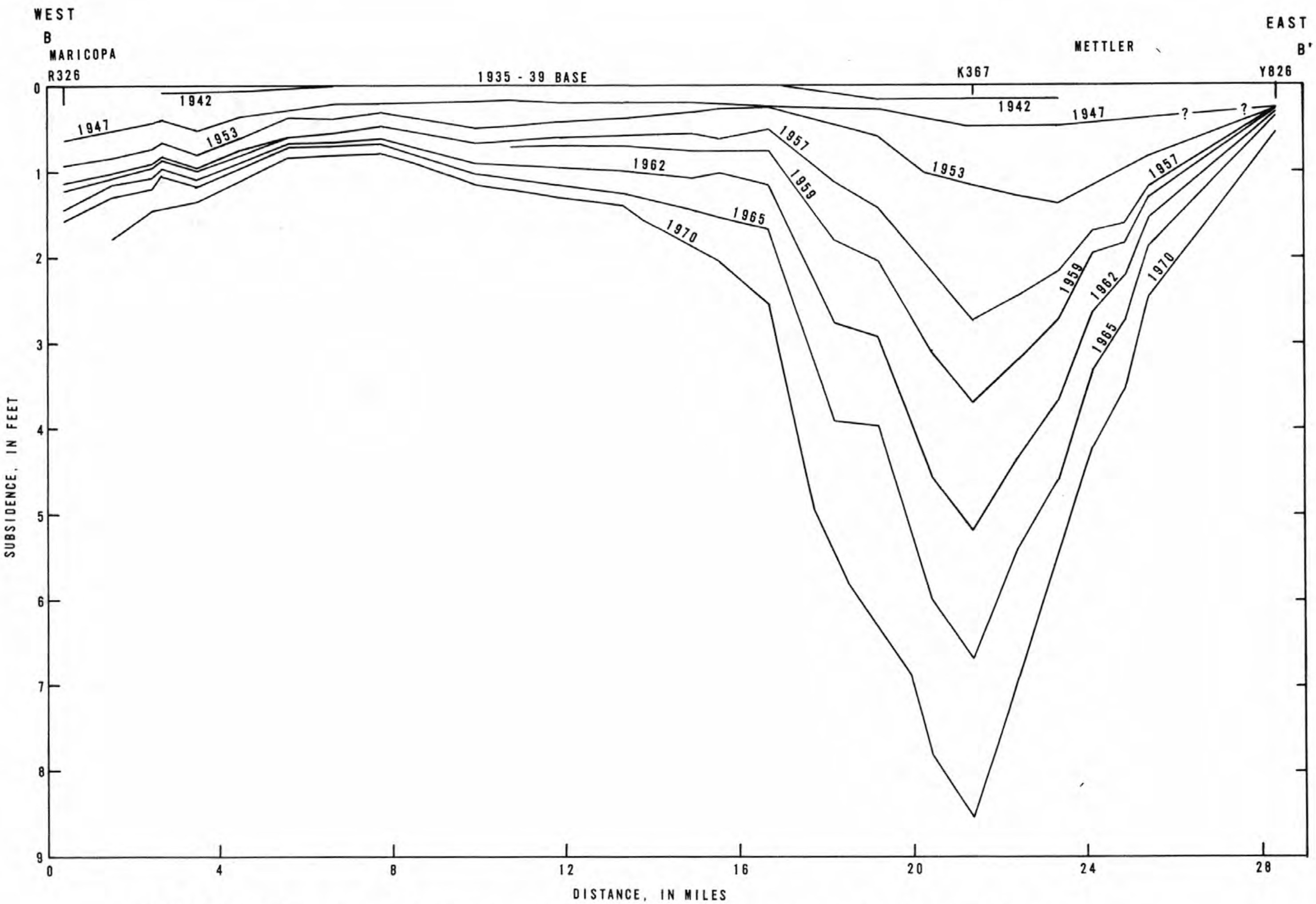


FIGURE 42.--Profiles of land subsidence B—B', along the Maricopa Road, Maricopa to Mettler, 1935 - 39 to 1970

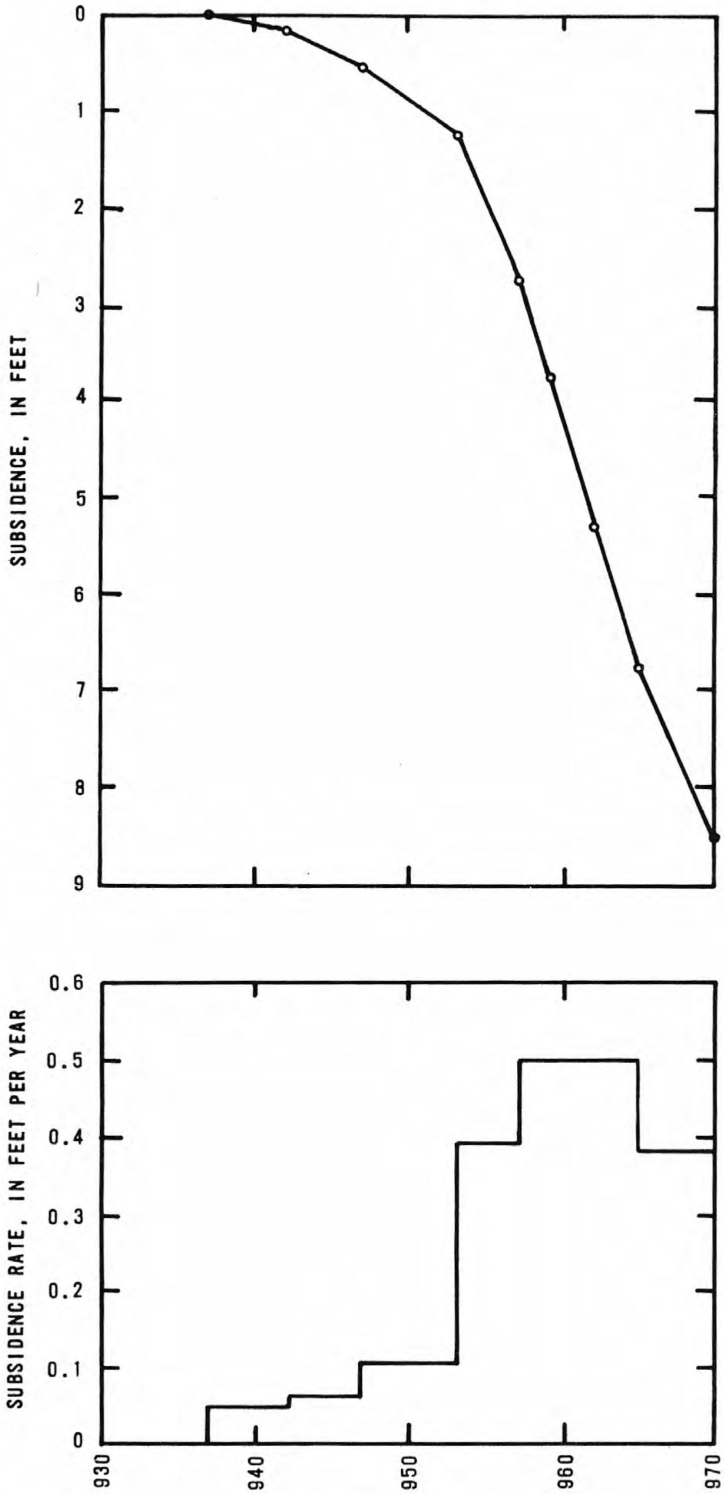


FIGURE 43.—SUBSIDENCE AT BENCH MARK K367, 4 MILES WEST OF METTLER.

Record prior to 1953 extrapolated from fig.42

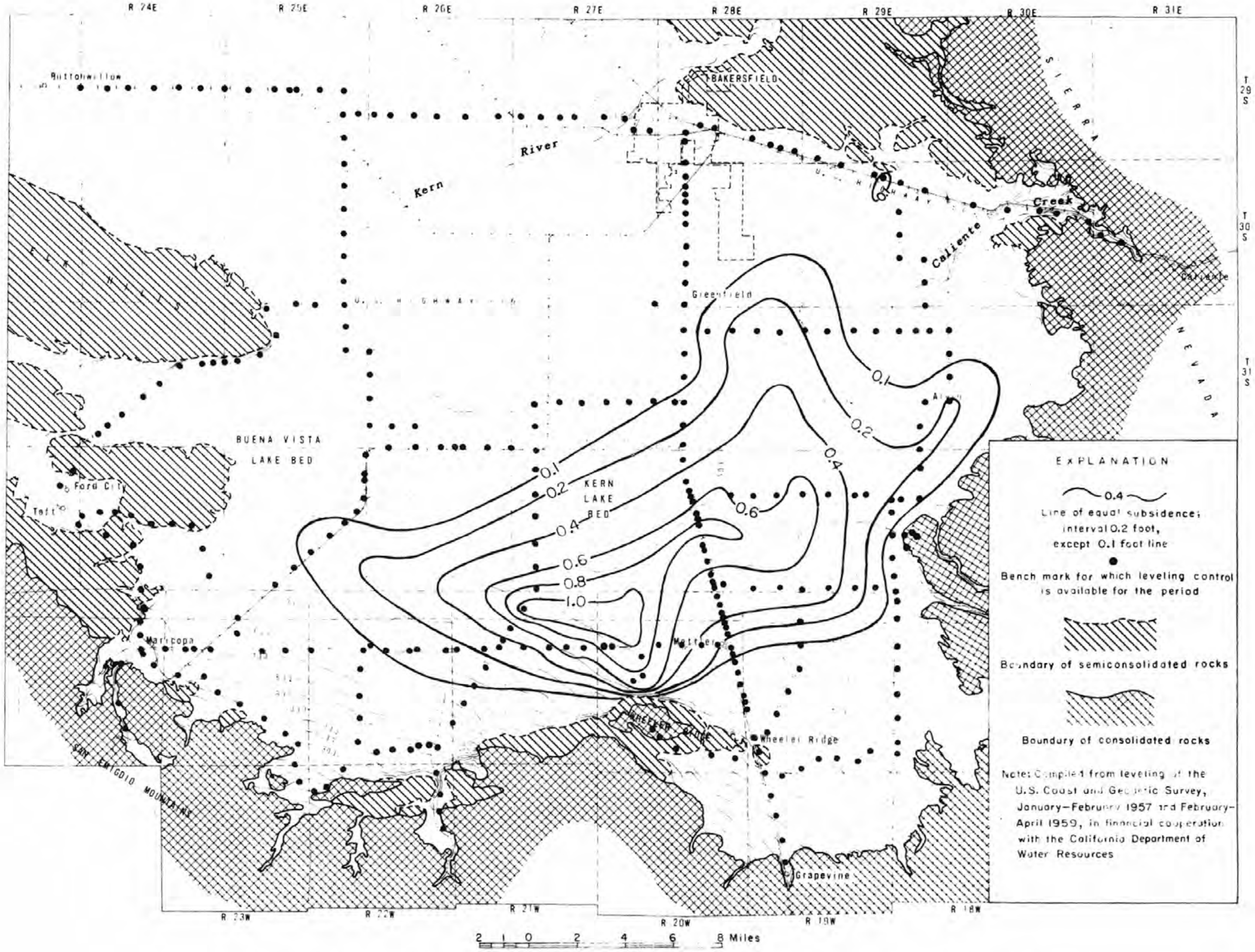


FIGURE 44.—LAND SUBSIDENCE IN THE ARVIN-MARICOPA AREA, 1957–59

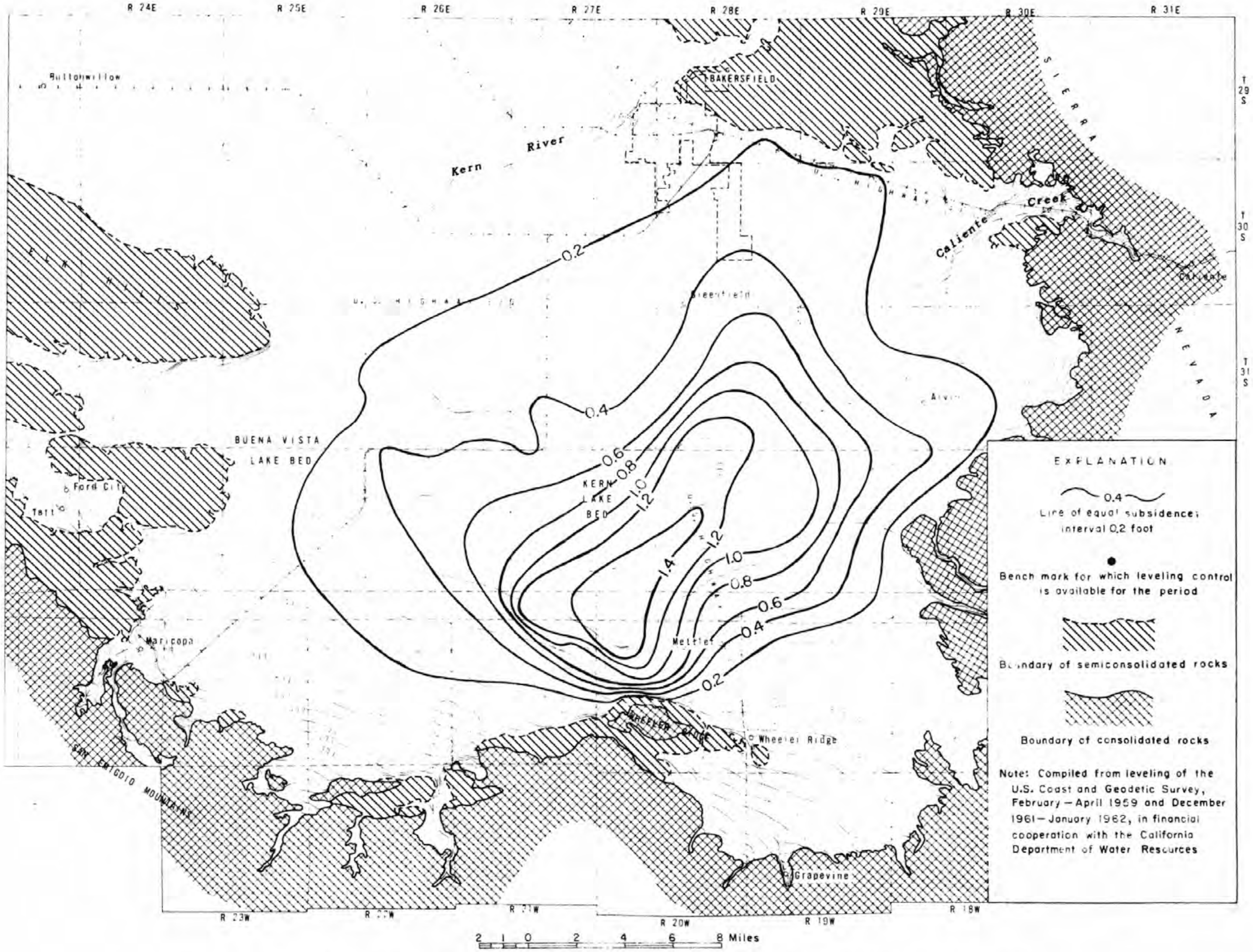


FIGURE 45.— LAND SUBSIDENCE IN THE ARVIN-MARICOPA AREA, 1959-62

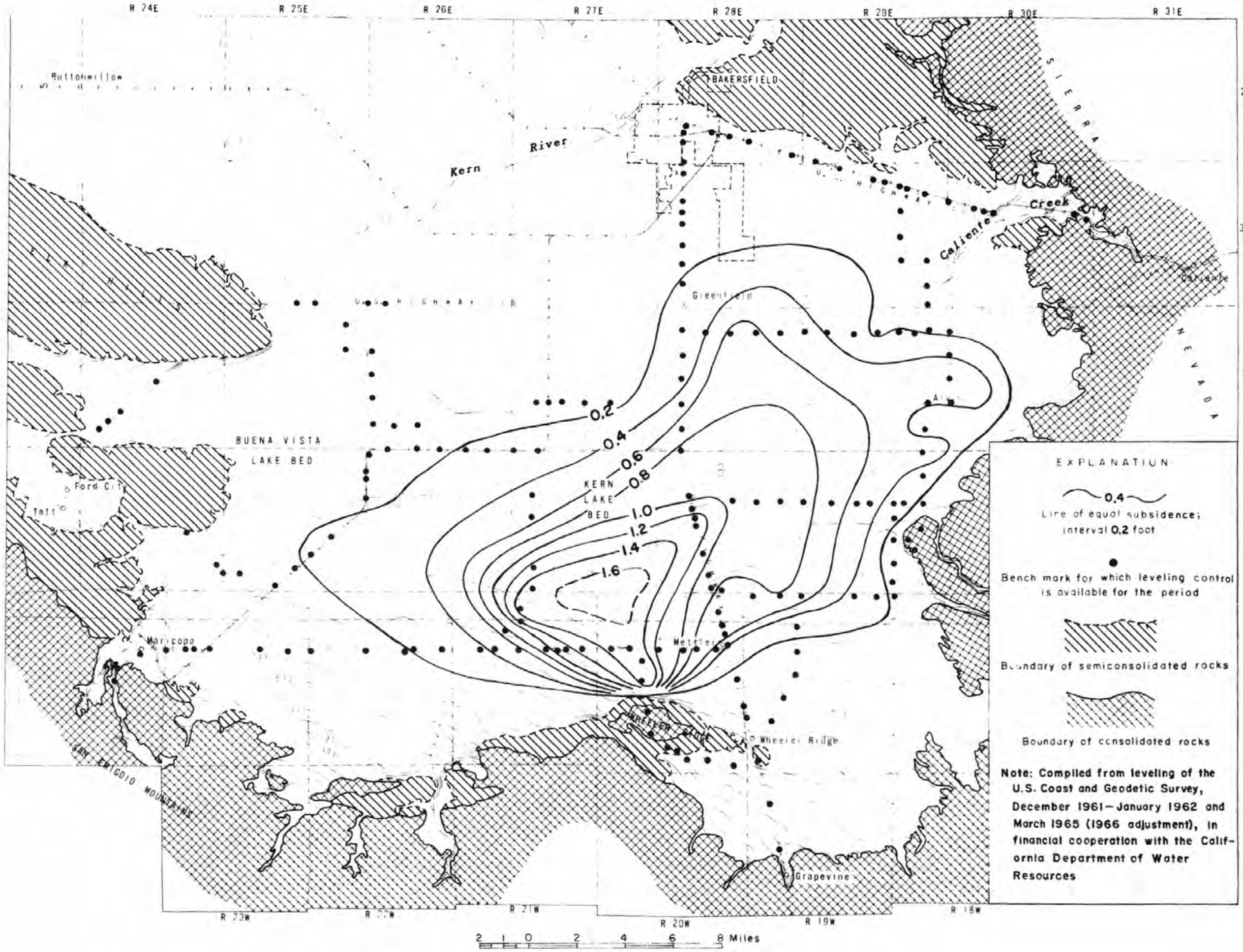


FIGURE 46.— LAND SUBSIDENCE IN THE ARVIN–MARICOPA AREA, 1962–65

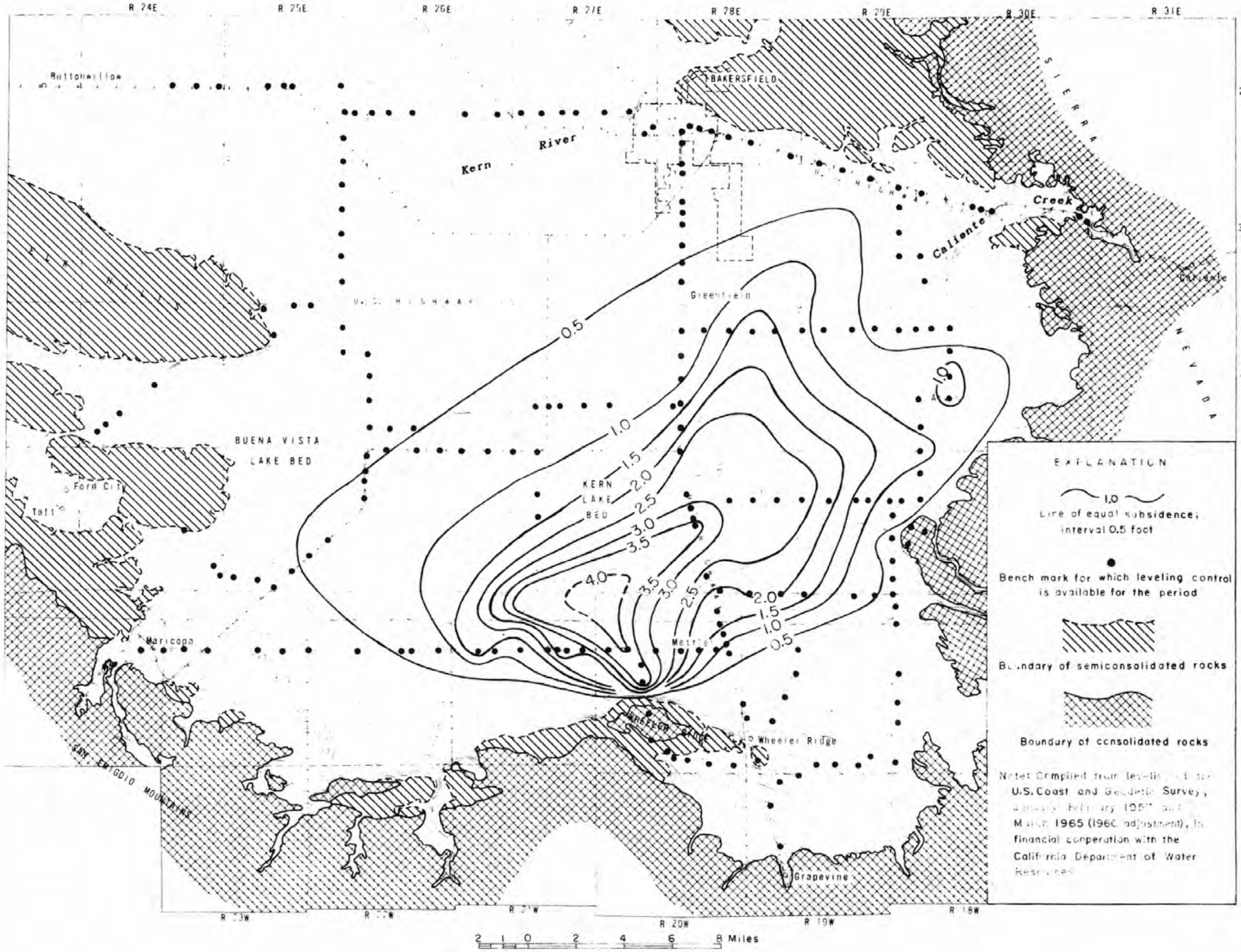
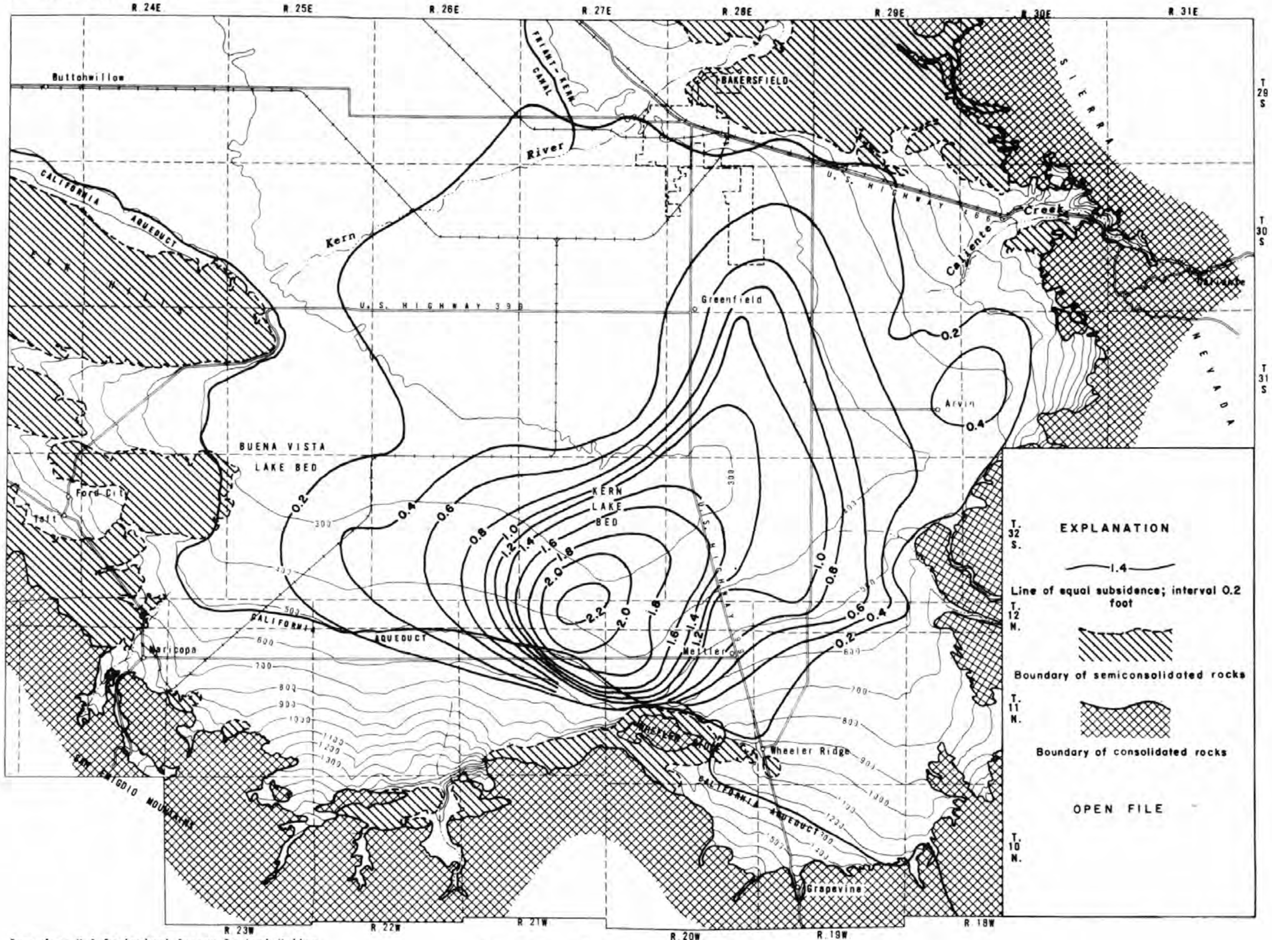


FIGURE 47. —LAND SUBSIDENCE IN THE ARVIN-MARICOPA AREA, 1957-65

U.S. GEOLOGICAL SURVEY



Base from U.S. Geological Survey Central Valley, California, South Area, 1958 -- 1:250,000

FIGURE 47A. --Land subsidence, 1965-70, in the Arvin-Maricopa area, California

Compiled from leveling of the U.S. Coast and Geodetic Survey, March 1965 and January-May 1970, in financial cooperation with the California Department of Water Resources, U.S. Bureau of Reclamation, and the Kern County Water Agency.

U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CALIFORNIA DEPARTMENT OF WATER RESOURCES

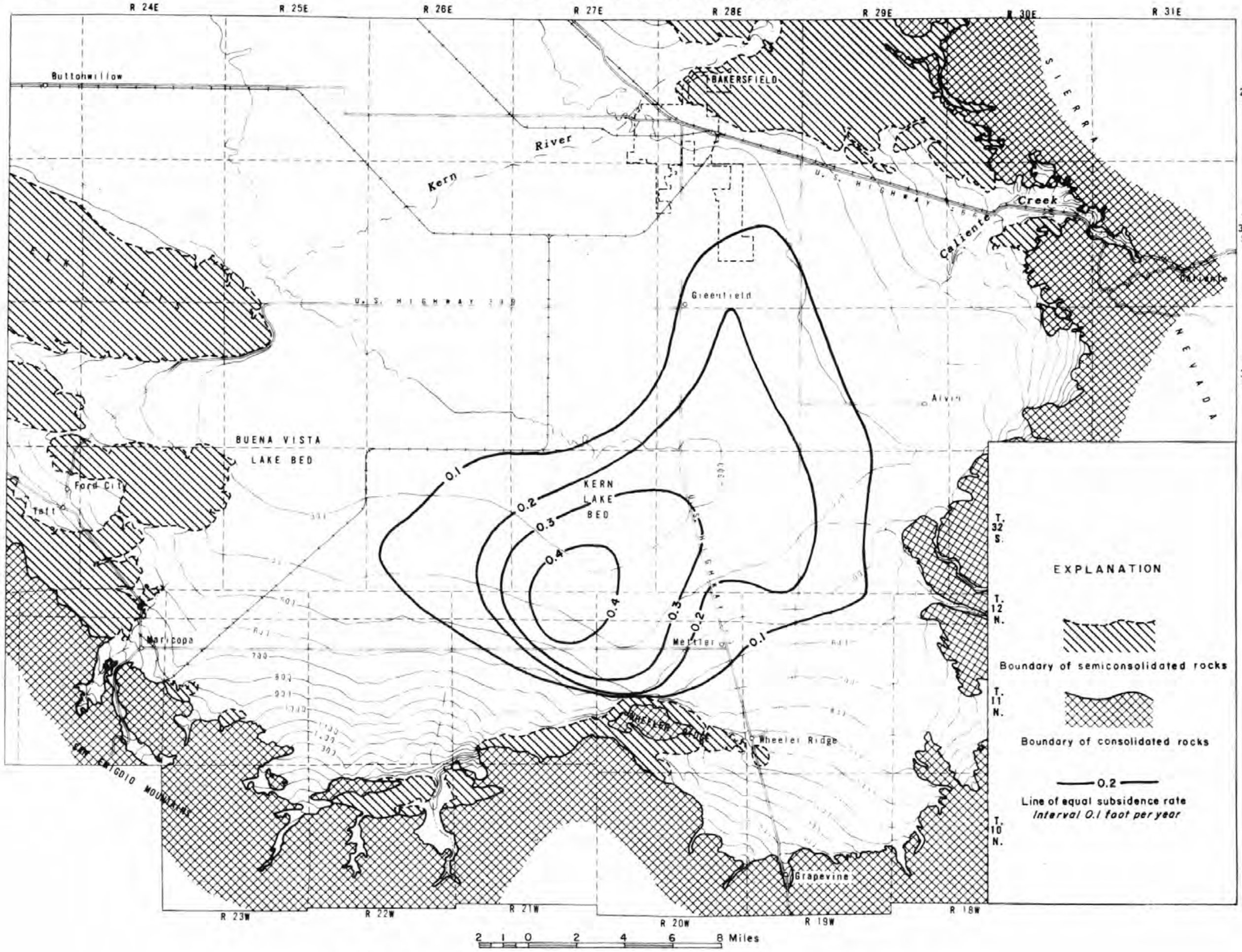
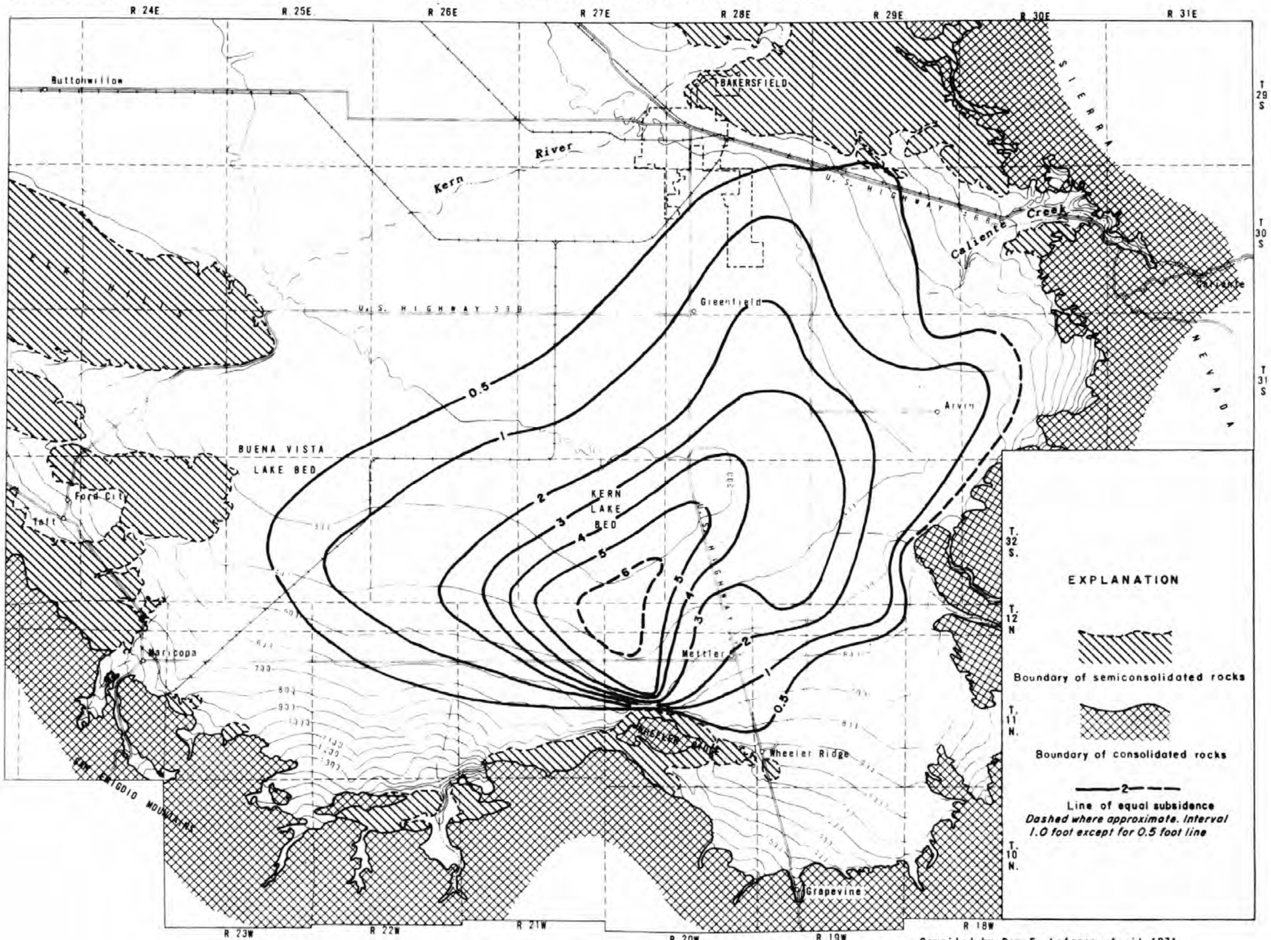


FIGURE 48.--Average annual rate of subsidence, 1965-70, Arvin-Maricopa area
Based on data of figure 47A

U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
CALIFORNIA DEPARTMENT OF WATER RESOURCES



2 1 0 2 4 6 8 Miles

Compiled by Ben E. Lofgren, April 1971

FIGURE 48A.--Land subsidence, 1957-70, Arvin-Maricopa area

Compiled from leveling of the U.S.Coast and Geodetic Survey, January-February 1957 and January to May 1970.

U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the CALIFORNIA DEPARTMENT OF WATER RESOURCES

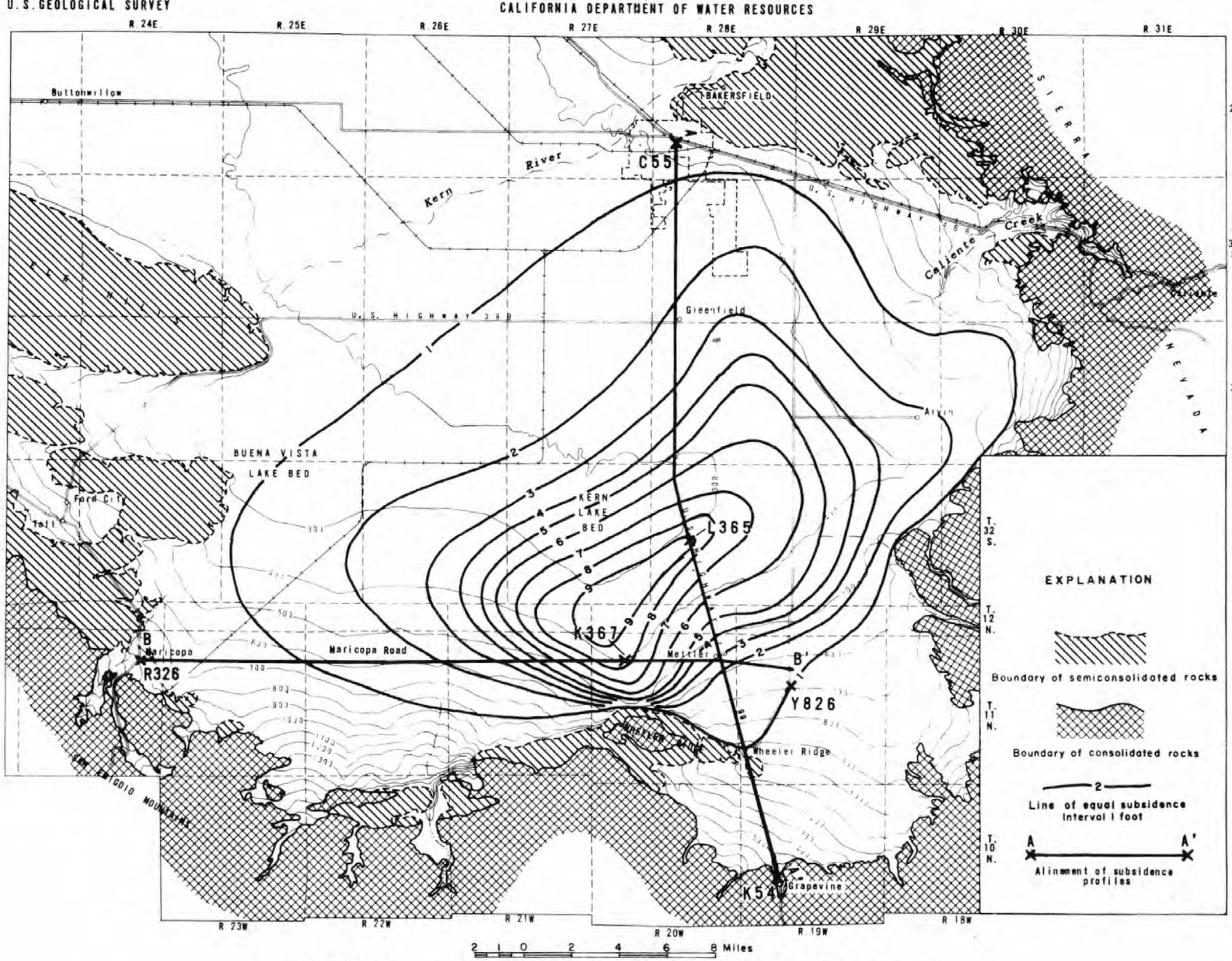


FIGURE 49.—Land subsidence, 1926–70, in the Arvin – Maricopa area.

Compiled chiefly as the sum of; (1) approximated subsidence from 1926 to 1957 from leveling data of the U.S.Coast and Geodetic Survey along U.S.Highway 99 and along Maricopa Road, and (2) 1957–70 subsidence from figure 47A

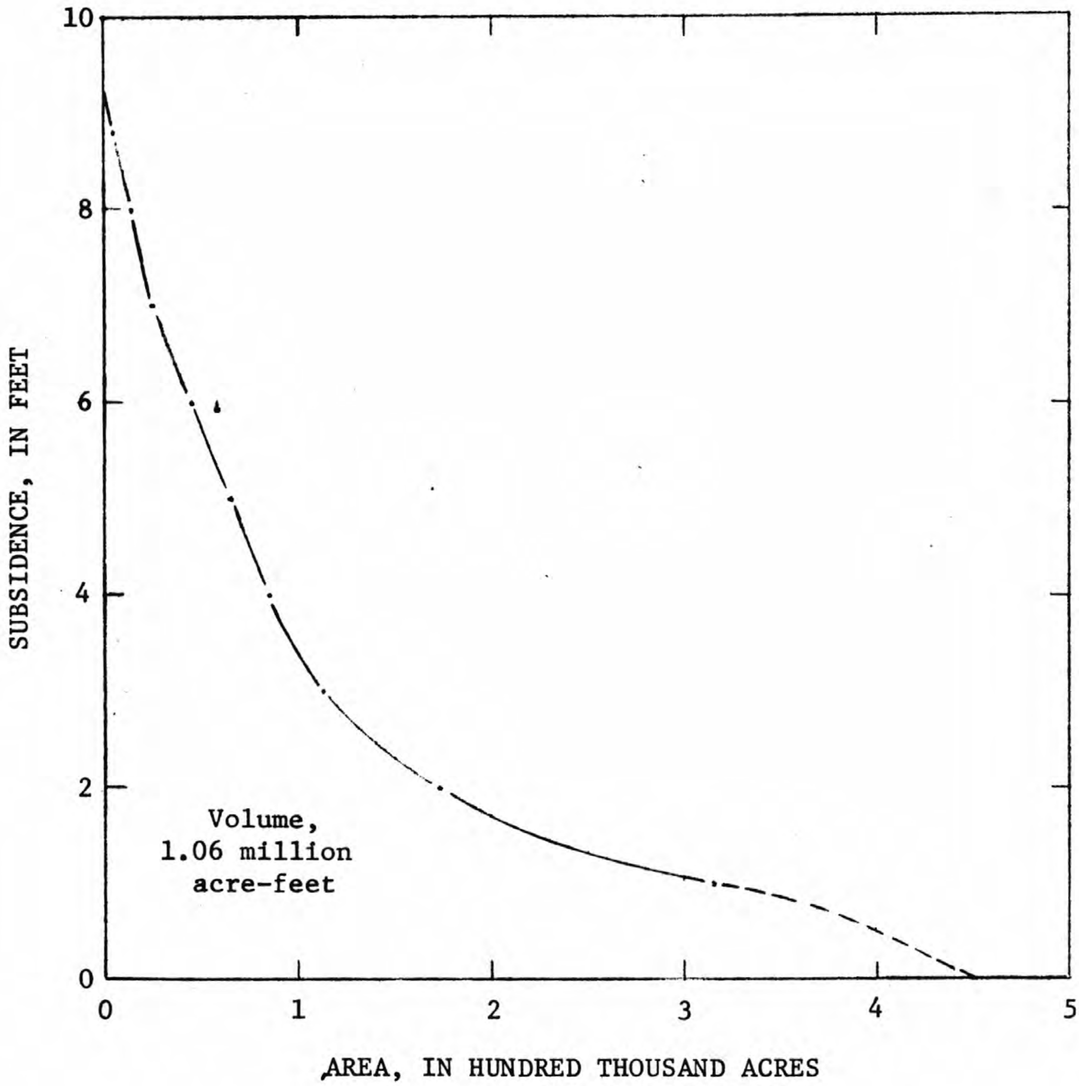


FIGURE 50.--Relation of magnitude to area of subsidence, 1926-70, Arvin-Maricopa area.

Area under curve equals the volumne of subsidence

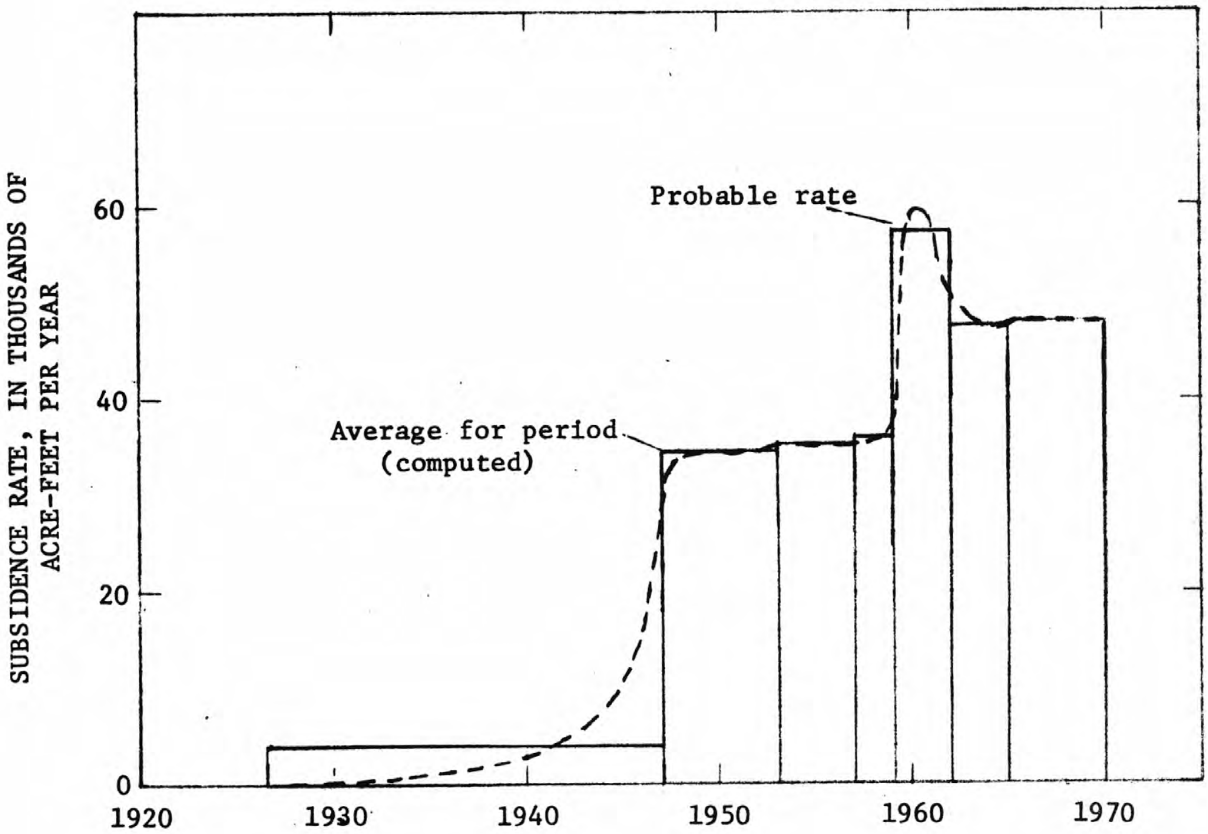


FIGURE 51.--Rate of subsidence in the Arvin-Maricopa area, 1926-70.

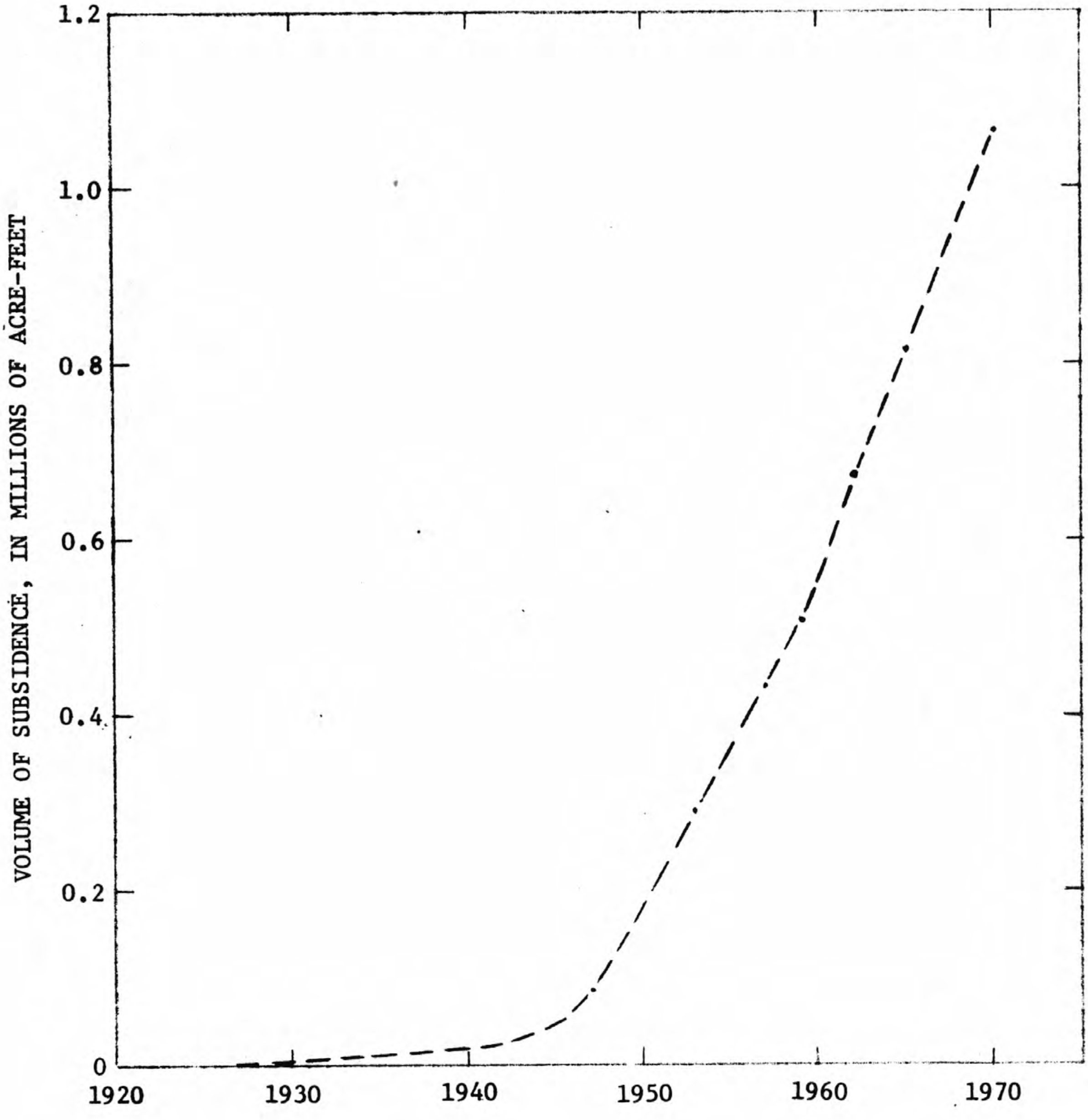


FIGURE 52. --Cumulative volume of subsidence in the Arvin-Maricopa area, 1926-70. Points indicate times of leveling control.

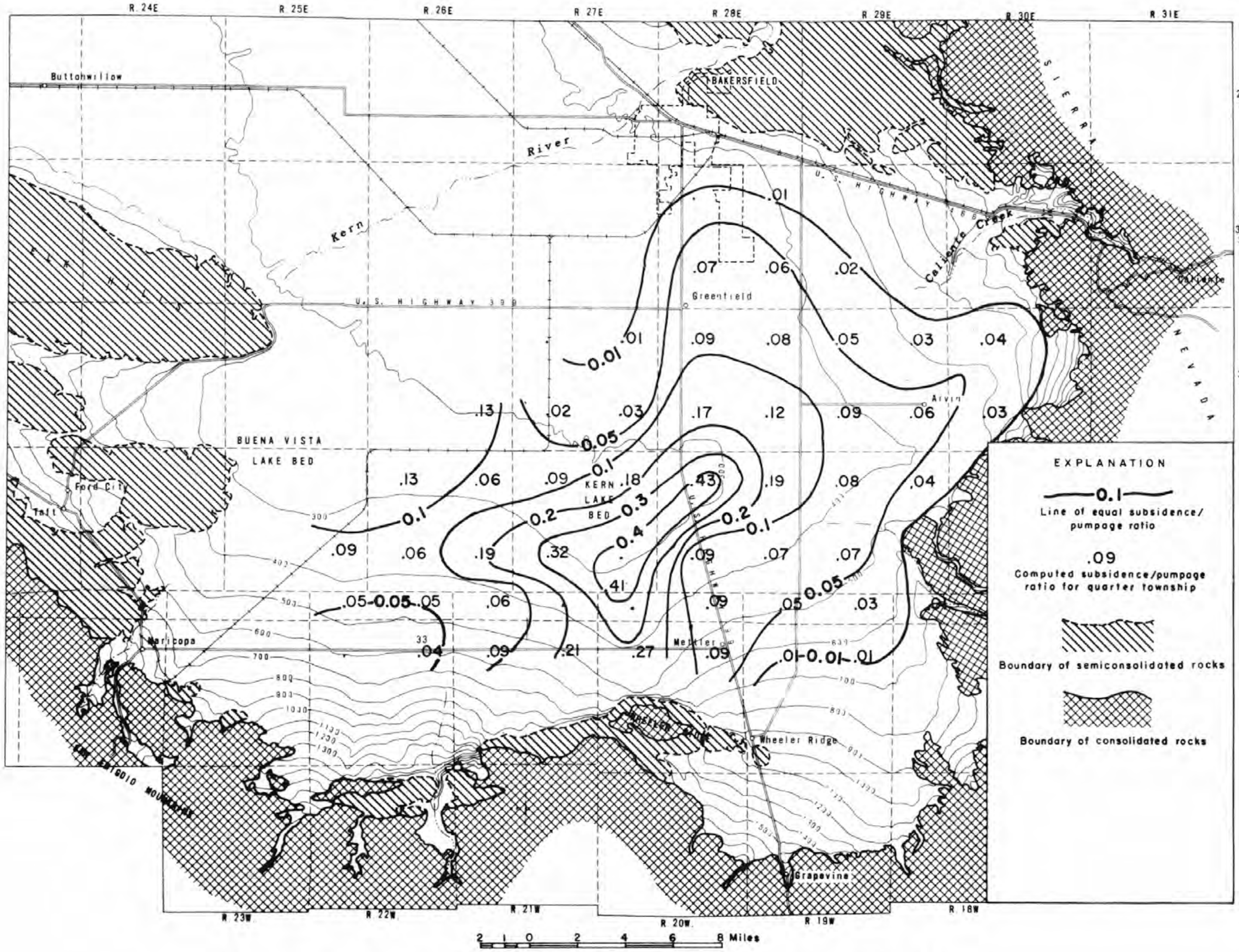


FIGURE 53.—Proportion of pumpage derived from water of compaction, 1962-65.

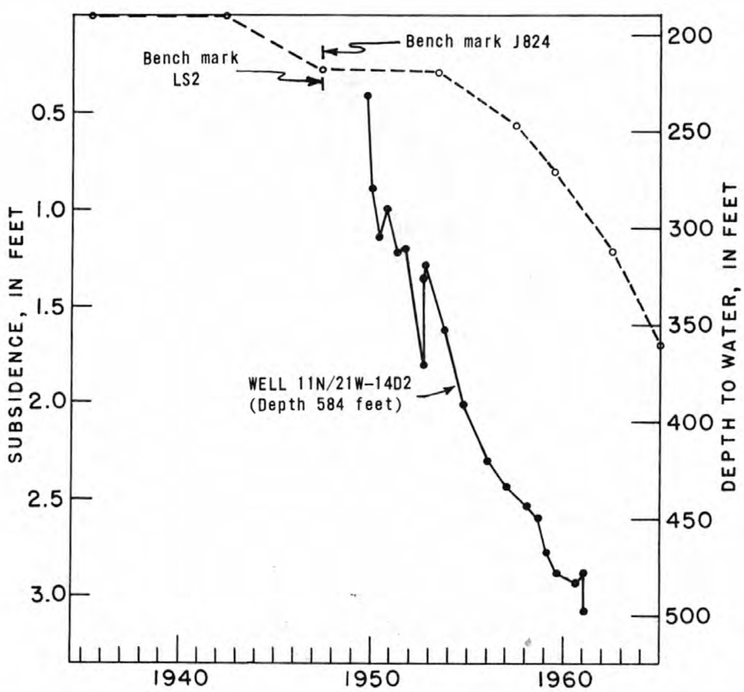


FIGURE 54.—CORRELATION OF SUBSIDENCE WITH WATER-LEVEL DECLINE, 8 MILES WEST OF METTLER.

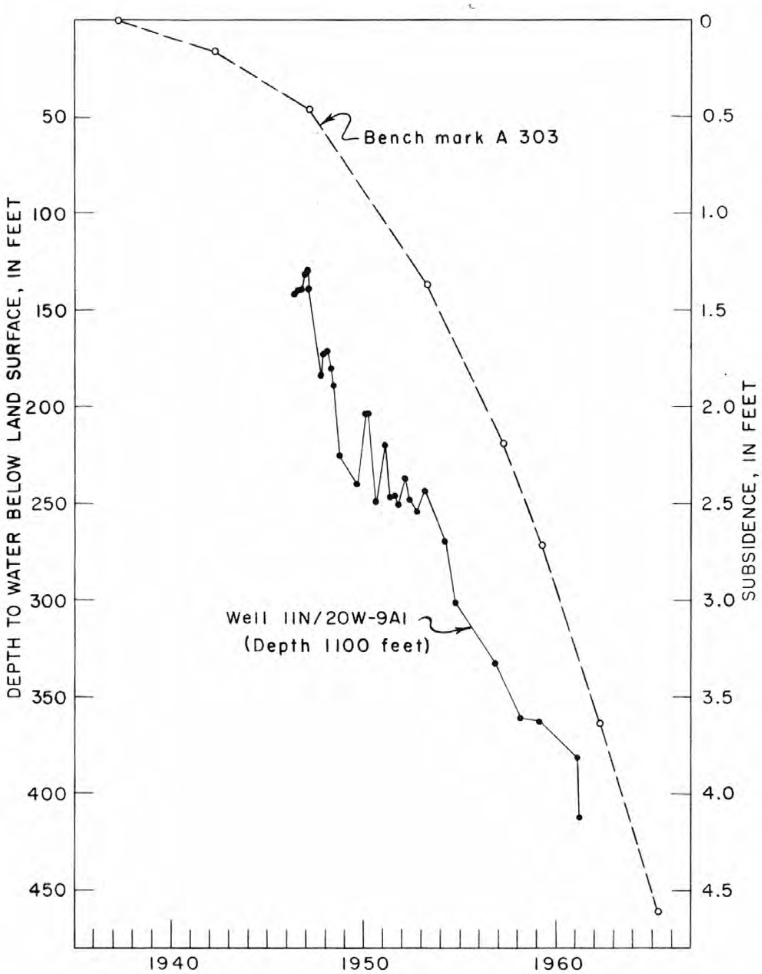


FIGURE 55.—SUBSIDENCE AND WATER-LEVEL DECLINE, 2 MILES WEST OF METTLER

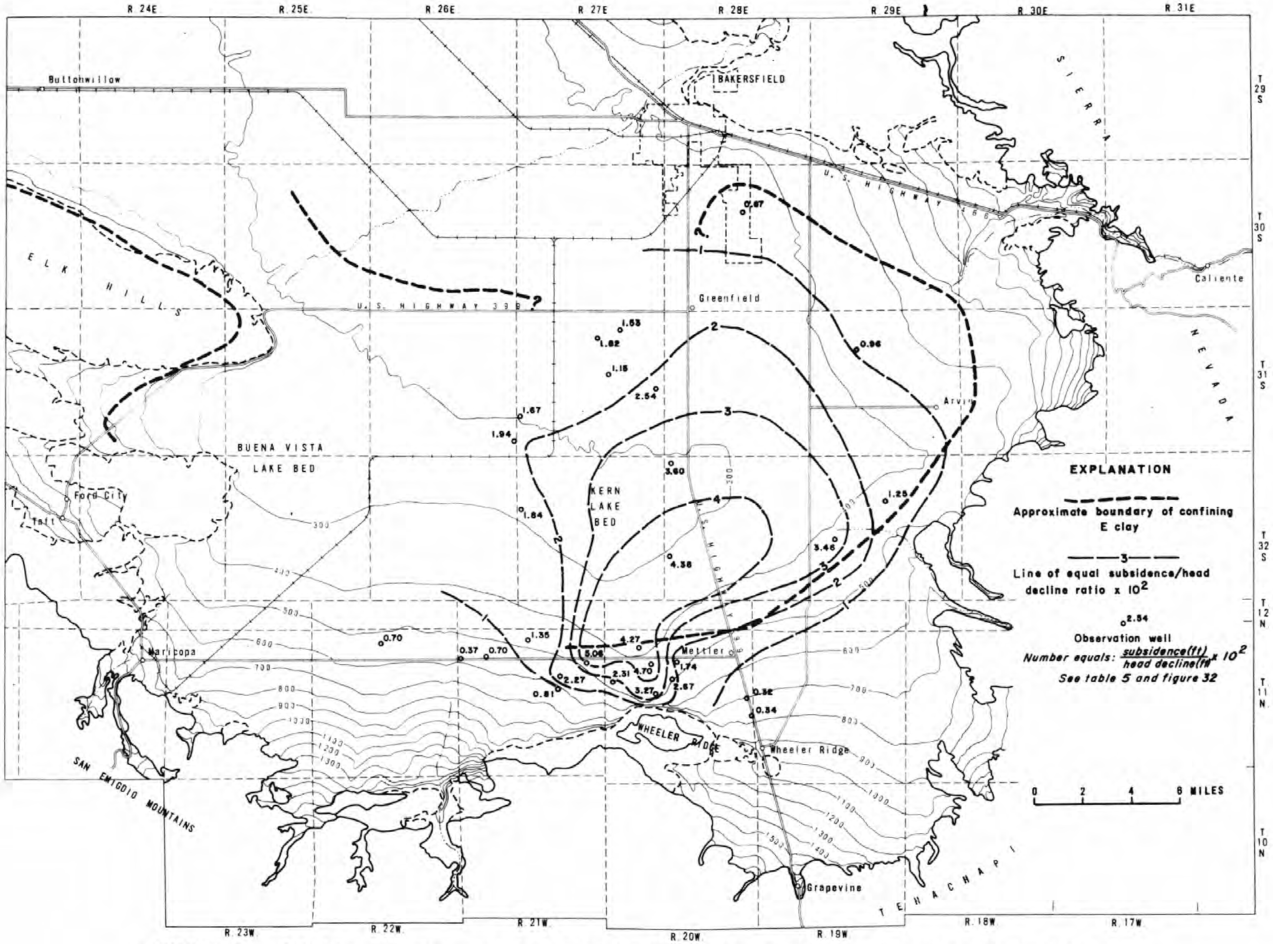


FIGURE 56.—Subsidence to head-decline ratios for the Arvin – Maricopa subsidence area, 1957-65.
Based on graphs of Figures 23-31, 54 and 55.

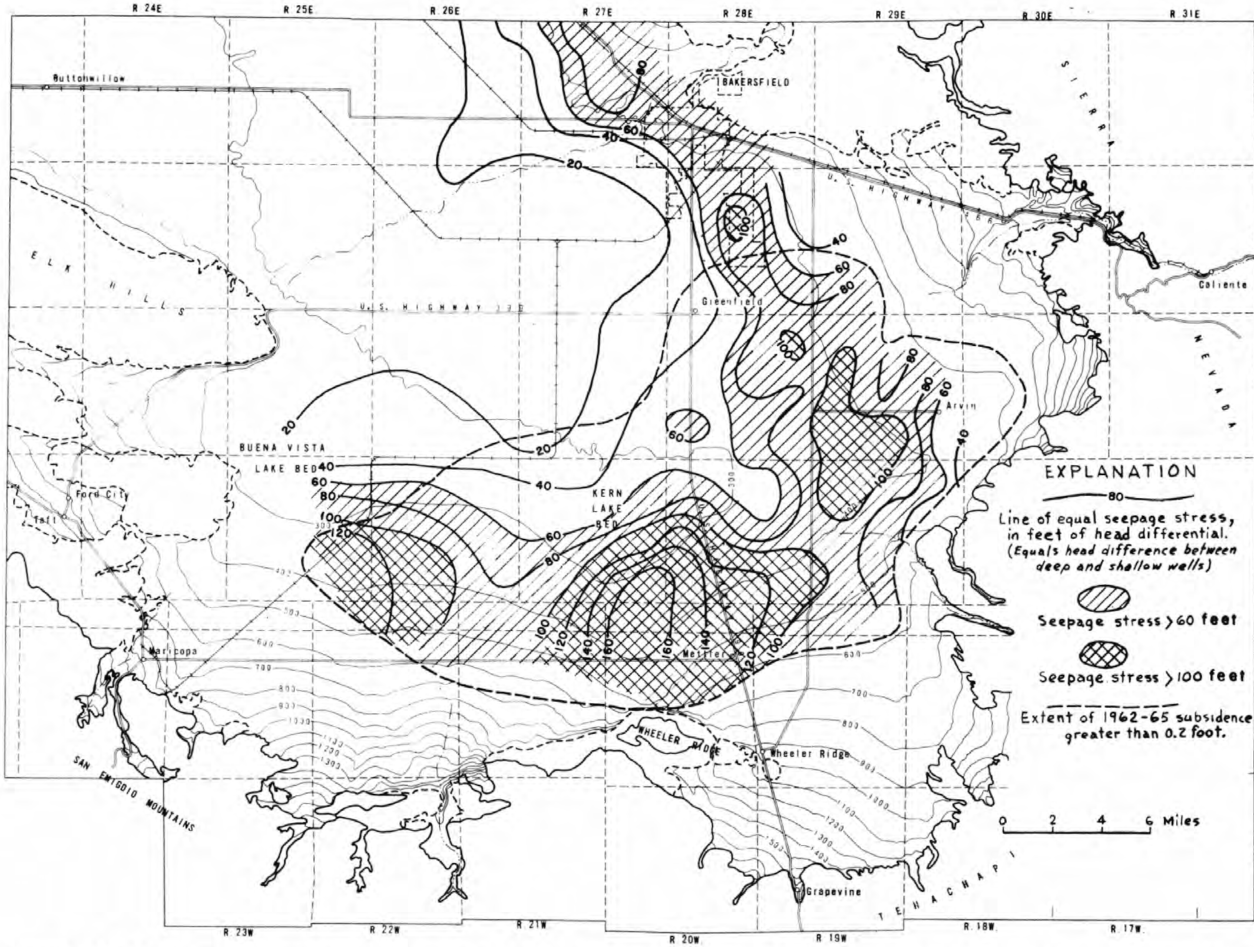


FIGURE 56 A.—Estimated seepage stress, in feet of hydraulic-head difference, spring 1965. Based on water-level maps of the California Department of Water Resources.

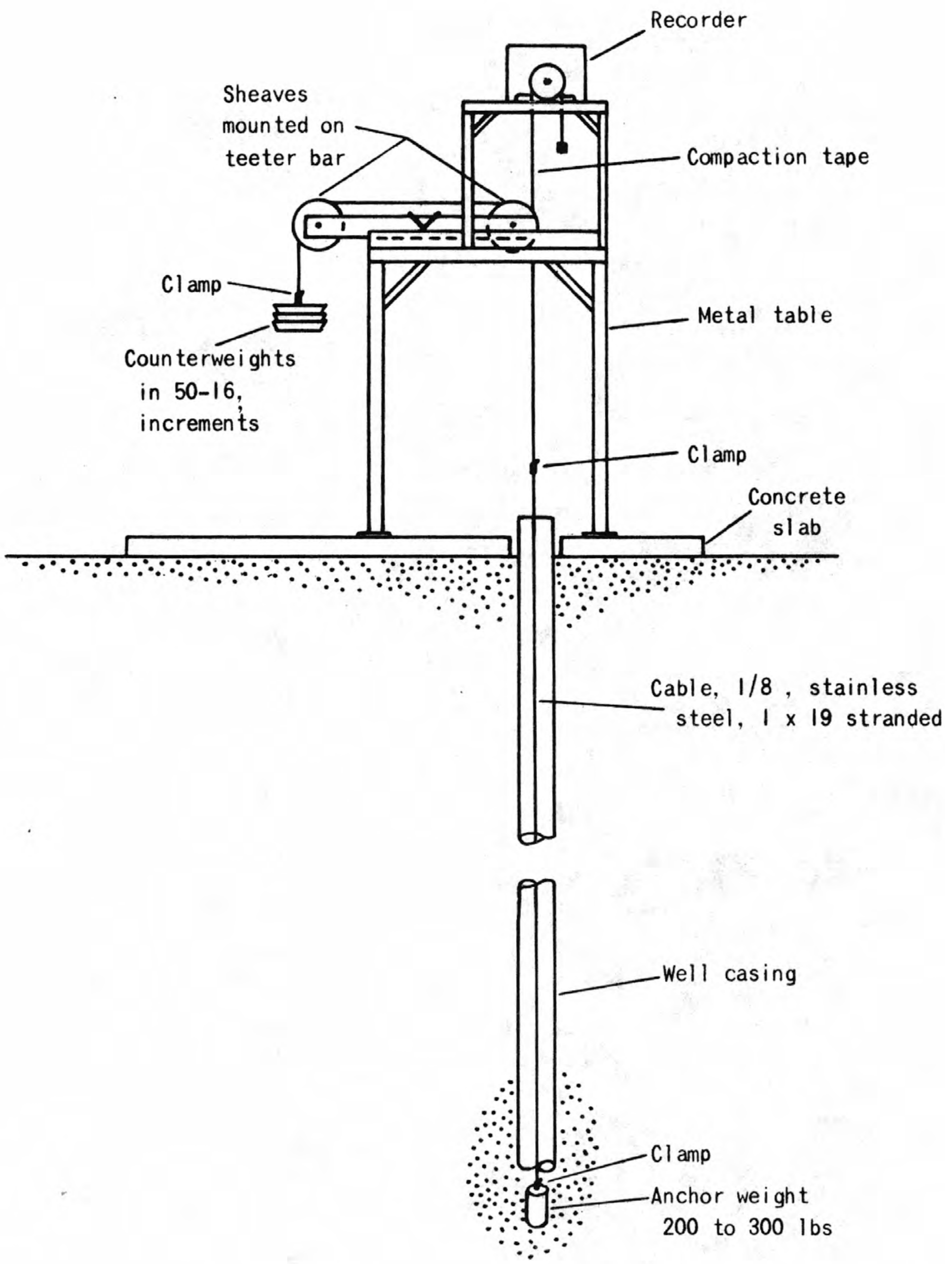


FIGURE 57.--Diagram of compaction-recorder installation

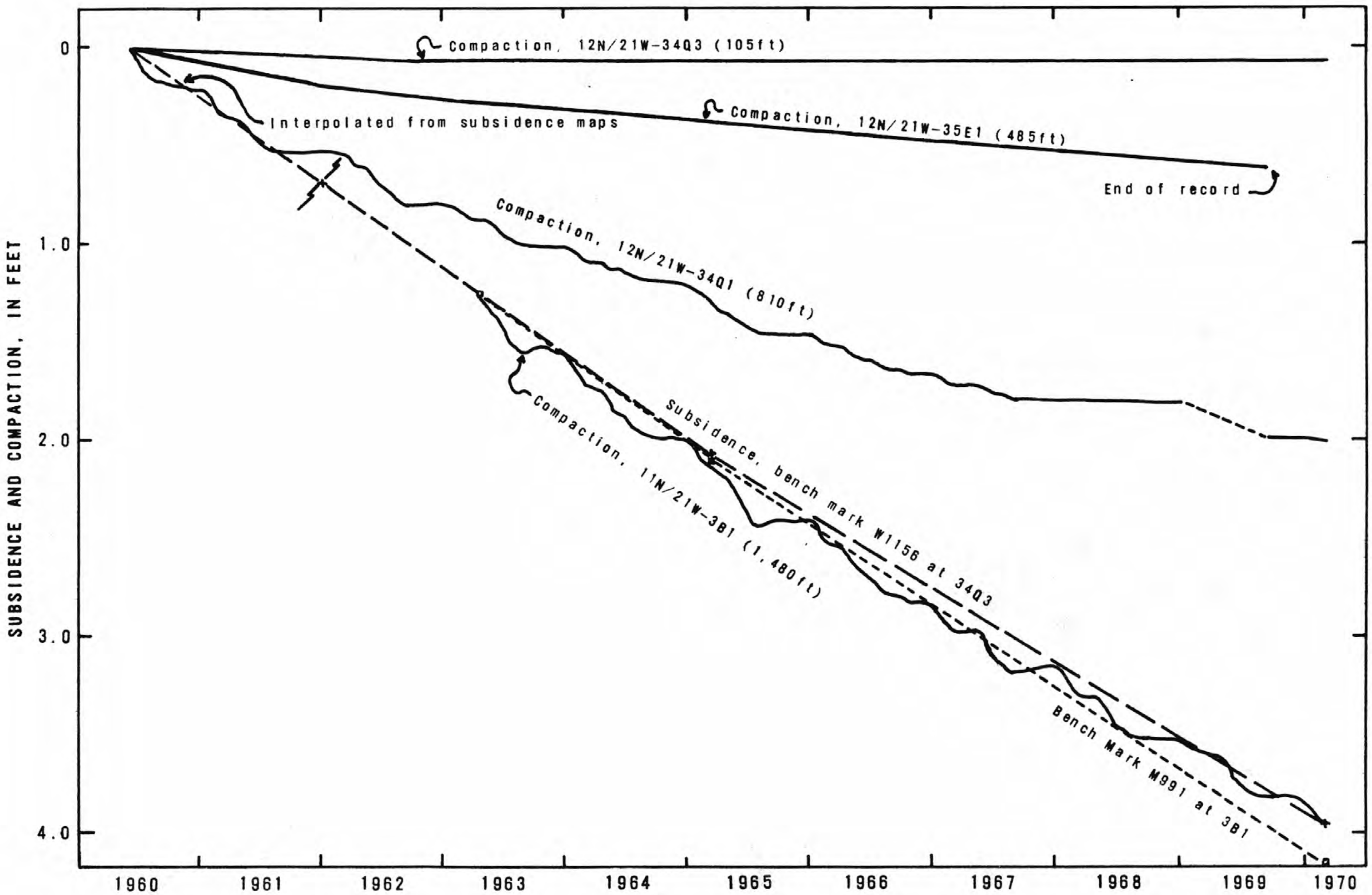


FIGURE 58.—Measured compaction and subsidence at Lakeview, California, 1960-70.

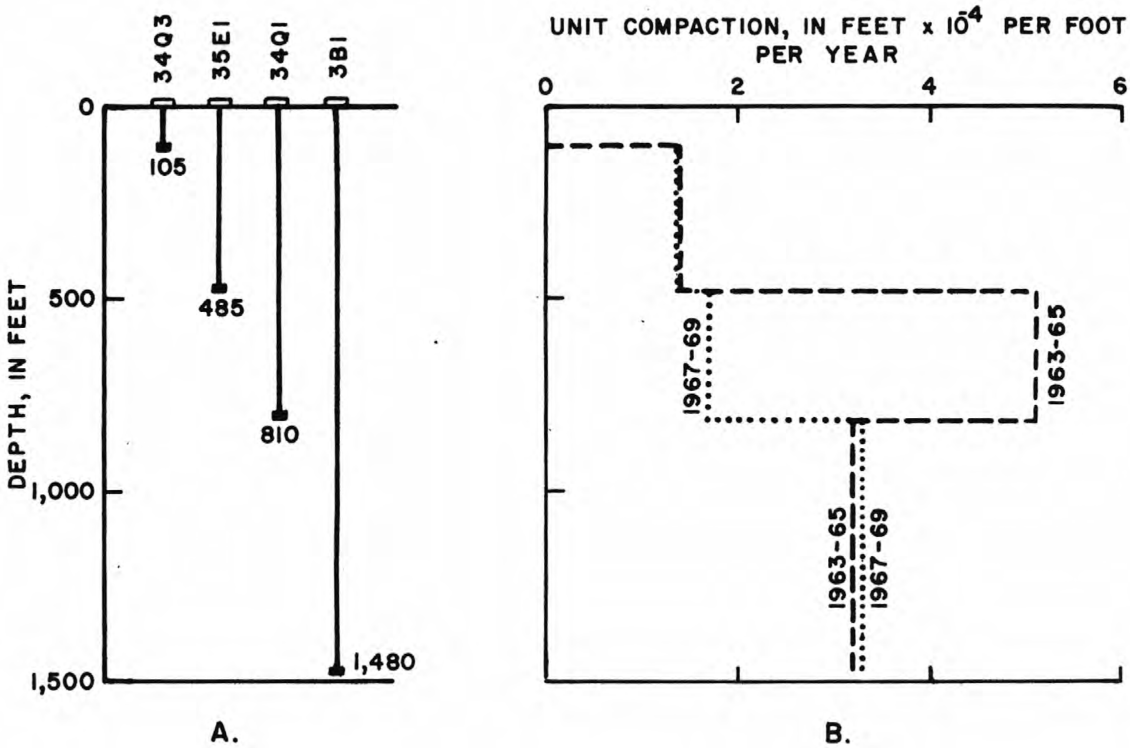


FIGURE 59.—Annual rate of compaction of deposits in three depth zones at Lakeview, 1963-65 and 1967-69. A, Depth relation of the recorders. B, Measured compaction rate in the three depth zones for two 3-year periods

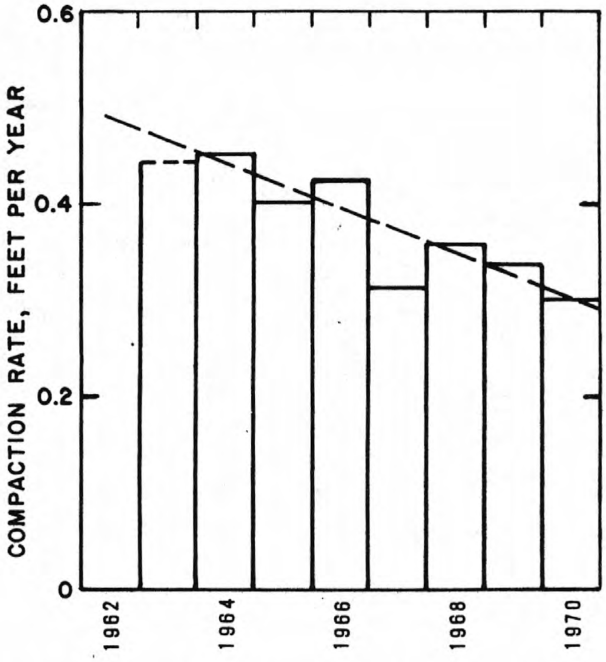


FIGURE 60. — Annual rate of compaction to 1,480-foot depth at Lakeview, 1963-70.

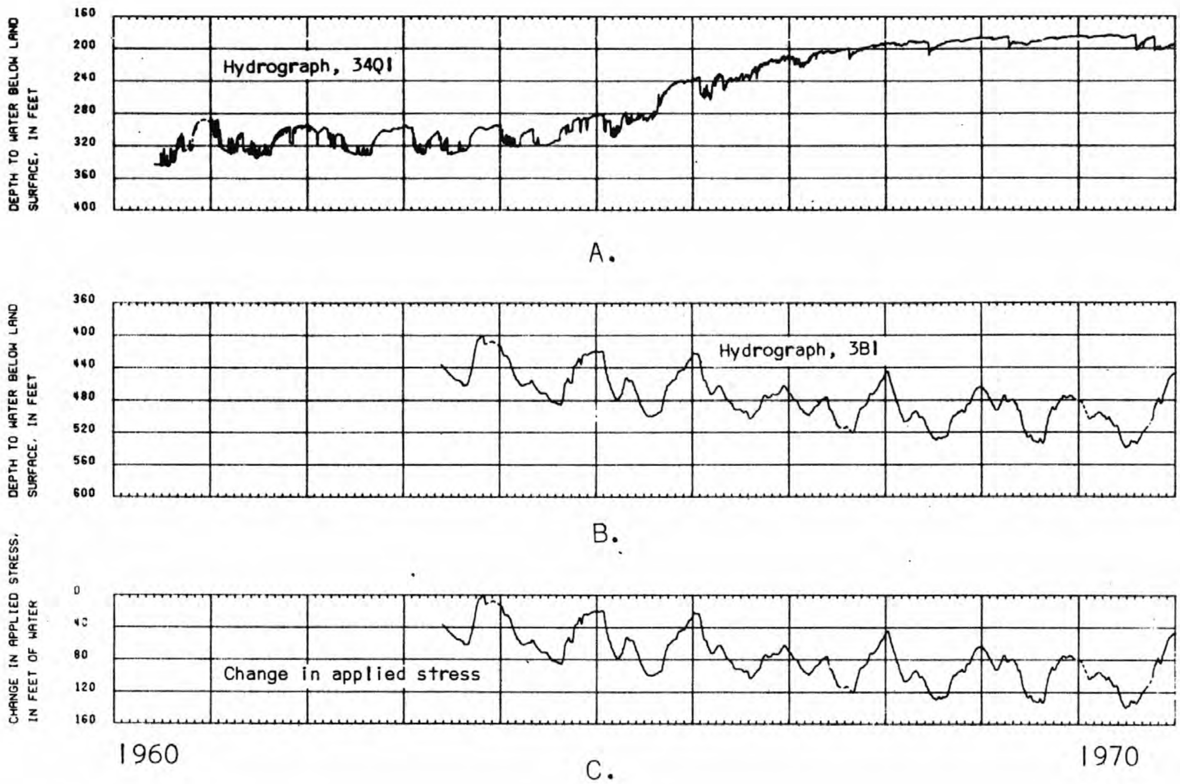


FIGURE 61.--Hydrographs of the intermediate and lower zones of the producing aquifer system at Lakeview, and calculated change in applied stress in deposits below 810 feet.

A. Hydrograph of well 12N/21W-34Q1, perforated 400-800 feet.

B. Hydrograph of well 11N/21W-3B1, perforated 1037-1237 feet.

C. Calculated change in applied stress, assuming no change in the depth to the water-table.

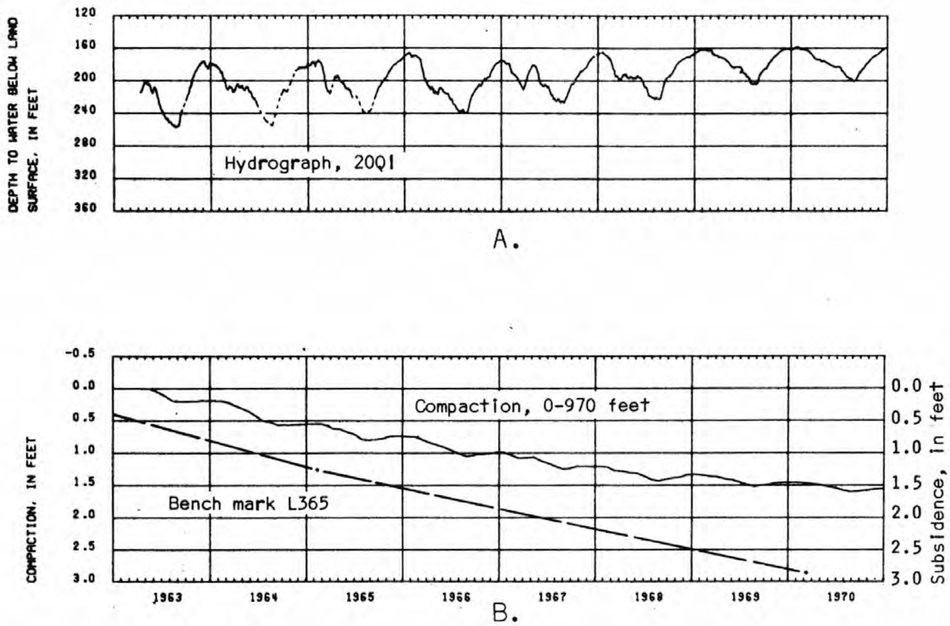


FIGURE 62.--Water-level fluctuations, measured compaction, and subsidence 5 miles northwest of Mettler.

A. Hydrograph of well 32S/28E-20Q1, depth 970 feet.

B. Measured compaction to 970-foot depth in well 32S/28E-20Q1 and subsidence of bench mark L365.(0.6 mile north of 32S/28E-20Q1)

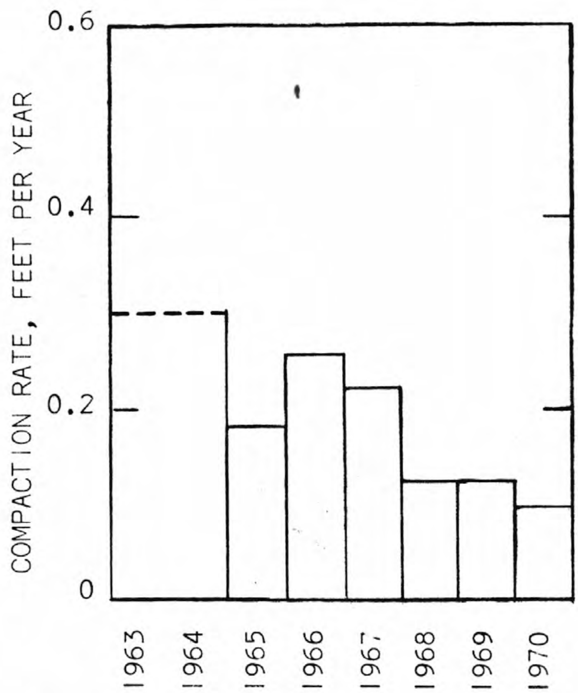


FIGURE 63.--Annual rate of compaction to 970-foot depth 5 miles northwest of Mettler, 1963-70.