Land Subsidence in the Santa Clara Valley, California, as of 1982

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 497-F

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By J.F. POLAND *and* R.L. IRELAND

M E C H A N I C S   O F   A Q U I F E R   S Y S T E M S

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A history of land subsidence in the Santa Clara Valley from 1916 to 1982 caused by water-level decline

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Poland, J.F. (Joseph Fairfield), 1908-
Land subsidence in the Santa Clara Valley, California, as of 1982.

(Mechanics of aquifer systems) (U.S. Geological Survey Professional Paper 497–F)
Bibliography
Supt. of Docs. No.: I 19.16:497–F
1. Subsidences (earth movements)—California—Santa Clara Valley (San Benito County and Santa Clara County). I. Ireland, R.L. II. Series. III. Series: U.S. Geological Survey Professional Paper 497–F.
QE75.P9 No. 497–F 557.72 s 87–600268
[QE600.3.U6] [551.3'53]

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CONVERSION FACTORS

The inch-pound system of units is used in this report. For readers who prefer the International System of Units (SI), the conversion factors for the terms used are listed below:

Multiply	By	To obtain
acre	4047	m^2 (square meter)
acre-ft (acre-foot)	1233	m^3 (cubic meter)
ft (foot)	0.3048	m (meter)
gal/min (gallons per minute)	.003785	m^3/min (cubic meters per minute)
(gal/min)/ft (gallons per minute per foot)	.207	(L/s)/m (liters per second per meter)
in. (inch)	2.54	cm (centimeter)
mi (mile)	1.609	km (kilometer)
mi^2 (square mile)	2.590	km^2 (square kilometer)

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

LAND SUBSIDENCE IN THE SANTA CLARA VALLEY, CALIFORNIA, AS OF 1982

By J.F. Poland and R.L. Ireland

ABSTRACT

From 1916 to 1966 in the San Jose area of the Santa Clara Valley, California, generally deficient rainfall and runoff was accompanied by a fourfold increase in withdrawals of ground water. In response, the artesian head declined 180 to 220 feet. As a direct result of the artesian-head decline, the land surface subsided as much as 12.7 feet in San Jose, due to the compaction of the fine-grained compressible confining beds and interbeds as their pore pressures decreased. The subsidence resulted in flooding of lands bordering the southern part of San Francisco Bay, and the compaction of the sediments caused compressional failure of well casings in several hundred water wells. The gross costs of subsidence to date are estimated to be $30 to $40 million.

The recovery of artesian head since 1967 has been substantial. In downtown San Jose, the artesian head recovered 70 to 100 feet in the 8 years to 1975. Recovery of water levels was due to a fivefold increase in surface-water imports from 1965 to 1975, favorable local water supply, decreased withdrawal, and increased recharge.

In 1960, the U.S. Geological Survey installed extensometers in core-holes 1,000 feet deep in San Jose and Sunnyvale. Measurements obtained from these extensometers demonstrate the marked decrease in annual compaction of the confined aquifer system in response to the major head recovery since 1967. In San Jose, for example, the annual compaction decreased from about 1 foot in 1961 to 0.24 foot in 1967 and to 0.01 foot in 1973. Net expansion (land-surface rebound) of 0.02 foot occurred in 1974.

INTRODUCTION

LOCATION AND GENERAL FEATURES

The Santa Clara Valley is a long, narrow structural trough that extends about 90 mi southeastward from San Francisco. San Francisco Bay occupies much of its northern one-third. The valley is bounded on the southwest by the Santa Cruz Mountains and on the northeast by the Diablo Range (fig. 1). The San Andreas fault system is a few miles southwest of the valley, and the Hayward fault borders the valley on the northeast. Both fault systems are active.

Land subsidence occurs in the central one-third of the valley in an area of intensive ground-water development. This report discusses only this densely populated central one-third of the valley, which extends southeastward about 30 mi from Redwood City and Niles to Coyote, at the bedrock narrows about 10 mi southeast of downtown San Jose.

The subsidence area is almost wholly in Santa Clara County. Southeast of Coyote Hills, the subsidence area extends into Alameda County, and north of Palo Alto it extends into San Mateo County (fig. 1).

Santa Clara County extends 30 mi southeast of Coyote. Ground water is pumped from wells in this area. Therefore, to avoid confusion, the project area is defined as north Santa Clara County when clarification is needed. For example, tables of ground-water pumpage and surface-water imports listed in this report are for north Santa Clara County, as indicated by their titles.

Minor subsidence also has occurred in the Hollister area (not shown). It is reported that as of the late 1960's, subsidence of 1 to 2 ft had occurred at bench marks in Hollister (T.H. Rogers, Woodward-Clyde Consultants, oral commun., November 1983.) However, Hollister is in San Benito County, 10 mi south of the south boundary of Santa Clara County, and thus this subsidence is not discussed further in this report.

SCOPE OF STUDY AND PURPOSE OF REPORT

Since the late 1950's the U.S. Geological Survey has carried on a modest study of land subsidence in the Santa Clara Valley, financed by Federal funds for study of the mechanics of aquifer systems. The study has been similar to concurrent studies of land subsidence in the San Joaquin Valley (Poland and others, 1975; Ireland and others, 1984), but on a much smaller scale. The principal field activities of the program have been twofold. First, in 1960 the Geological Survey drilled core holes at the centers of subsidence in San Jose and Sunnyvale. They were drilled to a depth of 1,000 ft—the maximum depth tapped by most water wells as of 1960. Cores were tested in the laboratory for physical and hydrologic properties and for clay-mineral analysis. Results have been released in several publications (Johnson and others, 1968; Meade, 1967).

Second, in 1960 extensometers (compaction recorders) were installed in the 1,000-ft core holes and in nearby satellite holes in order to measure the compaction or expansion of the sediments in that depth range and compare it with change in artesian head and with subsidence in the same time interval. Aquifer-system compaction and expansion and water-level change (change in applied stress) have been measured for 22 years. The change in artesian head was monitored by the Geological Survey, and subsidence was monitored by the National Geodetic Survey. These records from 1960 to 1980 are included in full in this report as computer-plotted stress-strain or stress-compaction relationships (see figs. 31–42). The Geological Survey terminated measurements of water level and of compaction or expansion at the end of 1982. Measurements of these data for the 3 years 1980–82, inclusive, have also been included in this report (table 3; figs. 43–48).

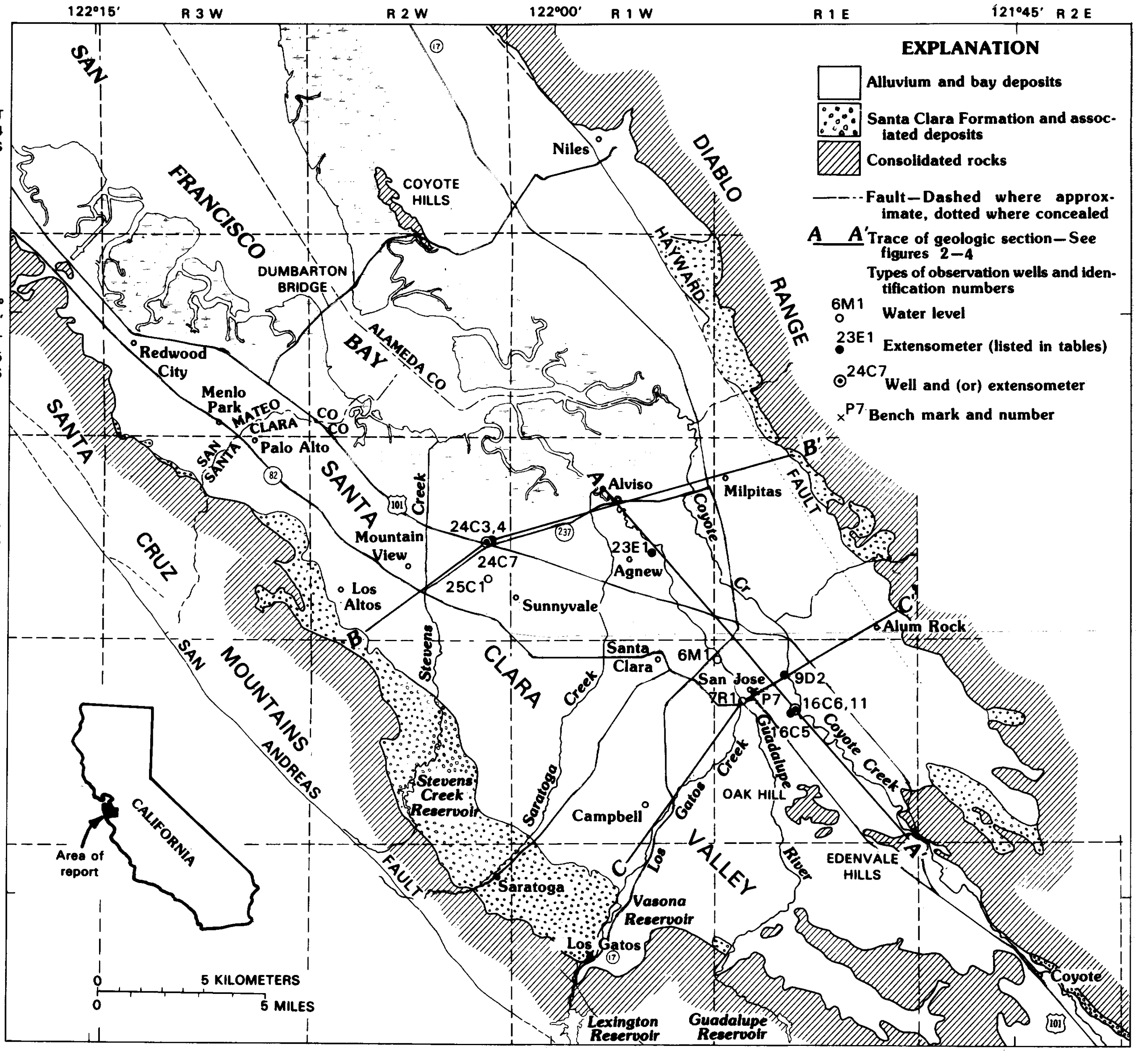


FIGURE 1.—Generalized geologic map of north Santa Clara County.

In addition to the principal field activities, development of a one-dimensional mathematical model that calculates idealized aquifer-system compaction and expansion was a highly significant accomplishment. The model has been applied to observed water-level fluctuations and to the resulting observed transient compaction and expansion behavior of a total thickness interval at several sites in the Santa Clara Valley (Helm, 1977).

The principal purposes of this report are (1) to present a summary of measured land subsidence through 1982, including the overall extent and magnitude; (2) to report the measured annual compaction and water-level change from 1960 through 1982 at extensometer sites; (3) to show the relationship between water-level change (stress change), measured compaction, and subsidence, chiefly by use of computer plots of Geological Survey field data; (4) to record the yearly pumpage of ground water in north Santa Clara County from 1915 to 1980; and (5) to report the yearly surface-water imports from 1955 to 1980 via the Hetch Hetchy and South Bay Aqueducts.

Reports and papers published to date on various aspects of the Geological Survey study in the Santa Clara Valley have been published in several different sources. Therefore, to assist the interested reader, this report includes a brief annotated bibliography of published reports prepared by Geological Survey authors as a result of these studies.

WELL-NUMBERING SYSTEM

The well-numbering system used in California by the U.S. Geological Survey and the State of California shows the locations of wells according to the rectangular system for the subdivision of public land. That part of the number preceding the slash (as in 7S/1E-16C6) indicates the township (T. 7 S.); the number following the slash is the range (R. 1 E.); the digit following the hyphen is the section (sec. 16); and the letter following the section number indicates the 40-acre subdivision of the section. Within each 40-acre tract the wells are numbered serially, as indicated by the final digit.

In this report, wells are referenced to the Mount Diablo base and meridian; all wells are south of the base but are both east and west of the meridian.

ACKNOWLEDGMENTS

We acknowledge the cooperation of Federal, State, and local agencies, private companies, and individuals. All leveling data used in the preparation of the subsidence maps and graphs and in calculating magnitude and rates of subsidence were by the National Geodetic Survey (formerly the U.S. Coast and Geodetic Survey). Water-level data utilized in this report were chiefly from field measurements by the Geological Survey, but the Santa Clara Valley Water District was most helpful in supplying records of ground-water levels from its well-measuring programs. The California Division of Highways and the San Jose Water Works granted permission to drill core holes and maintain compaction-measuring equipment on their properties.

Core descriptions in the field were by W.B. Bull, J.H. Green, R.L. Klausing, R.H. Meade, G.A. Miller, and F.S. Riley (all of the Geological Survey). J.H. Green prepared figures 2, 3, and 4 (geologic sections), figures 5 and 6 (composite logs of core holes), and figure 19 (land subsidence from 1934–60).

ANNOTATED BIBLIOGRAPHY OF REPORTS BY U.S. GEOLOGICAL SURVEY AUTHORS

1962, Poland, J.F., and Green, J.H., Subsidence in the Santa Clara Valley, California—A progress report: U.S. Geological Survey Water-Supply Paper 1619–C, 16 p. By maps and profiles, this report illustrates the subsidence that had occurred by 1954; bench mark P7 in San Jose had subsided 7.75 feet. The first complete survey of the bench-mark network was in 1934. Subsidence maps are included for 1934–54, 1940–54, and 1948–54.

1962, Green, J.H., Compaction of the aquifer system and land subsidence in the Santa Clara Valley, California: U.S. Geological Survey Professional Paper 450–D, p. 175–178. Results of laboratory tests on the compressibility of fine-grained cores from two 1,000-ft core holes and records of the fluctuation of artesian head since 1915 were used to compute the compaction of the confined aquifer system up to the 1960 releveling of the bench-mark network. Computed compaction was in general agreement with actual subsidence, but the procedure is highly subjective when applied to such heterogeneous deposits.

1964, Green, J.H., The effect of artesian-pressure decline on confined aquifer systems and its relation to land subsidence: U.S. Geological Survey Water-Supply Paper 1779–T, 11 p. This report summarizes the use of one-dimensional consolidation tests on cores and known declines of artesian head to compute compaction of fine-grained clayey beds. It also describes the use of void ratio values derived from one-dimensional consolidation tests to compute change in porosity in response to change in effective stress.

1967, Meade, R.H., Petrology of sediments underlying areas of land subsidence in central California: U.S. Geological Survey Professional Paper 497–C, 83 p. This paper describes petrologic characteristics that influence compaction of water-bearing sediments in the San Joaquin and Santa Clara Valleys, including particle size, clay minerals, and associated ions. The analytical procedures used in the clay-mineral studies are discussed. In addition, particle-size data for cored sediments in the Santa Clara Valley are tabulated, as are clay minerals and associated ions from fine-grained cored sediments and from fine-grained surface sediments (see p. 38–45 and 63–78). Montmorillonite is the dominant clay mineral, comprising between 5 and 25 percent of the sediments, depending on the general fineness of their particle size. Calcium is the dominant exchangeable cation.

1968, Johnson, A.I., Moston, R.P., and Morris, D.A., Physical and hydrologic properties of water-bearing deposits in subsiding areas in central California: U.S. Geological Survey Professional Paper 497–A, 71 p. To provide information on the water-bearing deposits in the areas of maximum subsidence (in San Jose and in Sunnyvale), two core holes were drilled in the Santa Clara Valley. In all, 87 samples from these core holes were tested by the Geological Survey for physical and hydrologic properties, and 21 samples were tested by the U.S. Bureau of Reclamation for engineering properties, including one-dimensional consolidation tests. The report presents core-hole logs and laboratory data in tabular and graphic form, describes methods of laboratory analysis, and shows interrelationships of some of the physical and hydrologic properties. For a summary of the results of laboratory analyses, see p. 43–45.

1968, Meade, R.H., Compaction of sediments underlying areas of land subsidence in central California: U.S. Geological Survey Professional Paper 497–D, 39 p. A study, partly statistical, of the factors that influence the pore volume and fabric of water-bearing sediments compacted by effective overburden loads ranging from 40 to 1,000 lb/in^2. Paper includes summary of pertinent previous studies that identify these factors and that indicate the nature and degree of their influence on compaction processes (p. 3–14).

1969, Poland, J.F., and Davis, G.H., Land subsidence due to the withdrawal of fluids: Geological Society of America, Reviews in Engineering Geology, v. 2, p. 187–269. A review of the known (1963) examples of appreciable land subsidence due to fluid withdrawal throughout the world, with a brief examination of the principles involved in the compaction of sediments and of aquifer systems as a result of increased effective stress. Special emphasis is given to subsidence studies in the San Joaquin (p. 238–252) and Santa Clara (p. 252–262) Valleys and to the Wilmington oil field (p. 200–214) in the Los Angeles and Long Beach Harbor area.

1969, Poland, J.F., Land subsidence and aquifer-system compaction, Santa Clara Valley, California, USA: *in* Tison, L.J., ed., Land subsidence, v. 1, International Association of Scientific Hydrology Publication 88, (is now International Association of Hydrological Sciences), p. 285–292. Intensive withdrawal of ground water from the confined aquifer system, 800 ft thick, in the San Jose area of the Santa Clara Valley has drawn down the artesian head as much as 220 ft since 1915. Resulting land subsidence, which began about 1916, was 12.7 ft in 1967. Report includes graphs of measured compaction, water-level change, and subsidence to 1969 in Sunnyvale and San Jose, log-log plots of compressibility of fine-grained samples from the Sunnyvale core hole, and a map of land subsidence from 1934 to 1967.

1972, Poland, J.F., Lofgren, B.E., and Riley, F.S., Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U.S. Geological Survey Water-Supply Paper 2025, 9 p. The glossary defines 25 terms as they are used in Geological Survey research reports concerned with the mechanics of stressed aquifer systems and of land subsidence. Most are terms that have appeared in engineering or hydrologic literature, but several have been introduced as a result of the Survey's studies.

1973, Webster, D.A., Map showing areas bordering the southern part of San Francisco Bay where a high water table may adversely affect land use: U.S. Geological Survey Miscellaneous Field Studies Map MF–530, 1 sheet, scale 1:125,000. Map presents general information about the depth to the top of the saturated zone (water table), shown in four depth zones 0–5, 5–10, 10–20, and >20 ft below land surface. Depth zones are based on data obtained from more than 1,000 soil borings made for foundation engineering studies. The problems caused by a shallow water table are also discussed.

1977, Helm, D.C., Estimating parameters of compacting fine-grained interbeds within a confined aquifer system by a one-dimensional simulation of field observations: International Association of Hydrological Sciences, International Symposium on Land Subsidence, 2d, Anaheim, California, December 1976, Publication 121, p. 145–156. A one-dimensional mathematical model that calculates idealized aquifer-system compaction and expansion has been applied to observed water-level fluctuations and to the resulting observed transient compaction-and-expansion behavior of a total thickness interval at several sites in the Santa Clara Valley. For established values of total cumulative thickness of fine-grained interbeds (aquitards) within the confined aquifer system, the weighted average thickness of these inter-

beds, and the initial distribution of preconsolidation pressure, it is demonstrated that carefully evaluated values of the vertical components of hydraulic conductivity and nonrecoverable compressibility can be used to predict aquifer-system behavior with reasonable accuracy over periods of several decades. The paper includes plots of simulated compaction based on measured water level and compaction data at eight sites in the Santa Clara Valley for periods of record ranging from 12 to 59 years.

1977, Poland, J.F., Land subsidence stopped by artesian-head recovery, Santa Clara Valley, California: International Association of Hydrological Sciences, International Symposium on Land Subsidence, 2d, Anaheim, California, December 1976, Publication 121, p. 124–132. From 1916 to 1966, generally deficient rainfall and runoff was accompanied by a fourfold increase in withdrawals of ground water. In response, the artesian head declined 180 to 220 ft, causing the land surface to subside as much as 12.7 ft in San Jose, due to compaction of the fine-grained compressible aquitards as the pore pressures decreased. From 1967 to 1975 the artesian head recovered 70 to 100 ft. This water-level recovery was due to a fivefold increase in surface-water imports from 1965 to 1975, favorable local water supply, decreased withdrawal, and increased recharge. Extensometers installed in 1960 to measure change in thickness of the confined system demonstrated the marked decrease in annual compaction in response to the major head recovery. In San Jose, the annual compaction decreased from about 1 ft in 1961 to 0.01 ft in 1973.

1978, Helm, D.C., Field verification of a one-dimensional mathematical model for transient compaction and expansion of a confined aquifer system: *in* Verification of mathematical and physical models in hydraulic engineering: American Society of Civil Engineers, Proceedings of Specialty Conference, College Park, Maryland, p. 189–195. Land subsidence due to ground-water withdrawal from a confined aquifer system is an expression at land surface of net compaction (vertical consolidation) at depth of compressible layers within the system. Water-level fluctuations within coarse-grained aquifers produce stress changes on the upper and lower boundaries of slow-draining aquitards. Within a confined system, any lag in compactive response to such a load increase is usually ascribed to slow vertical drainage from the aquitards. The emphasis of this paper is threefold: First, the author describes the trial-and-error method used to find vertical hydraulic conductivity, K', and nonrecoverable specific storage, S'_{skv}; second, the values of these parameters so estimated are listed in table 1; and finally, based on these values, predictions of critical stress and ultimate compaction values are presented.

HYDROGEOLOGY

A generalized geologic map of north Santa Clara County (the central part of the Santa Clara Valley) is shown in figure 1. The map was compiled chiefly from geologic maps prepared by Jennings and Burnett (San Francisco sheet, 1961), Rogers (San Jose sheet, 1966), and Dibblee (Palo Alto 15-minute quadrangle, 1966). The consolidated rocks, shown as a single unit on the map, range in age from Jurassic to Pliocene; they consist principally of consolidated sedimentary rocks but also include substantial areas of metamorphic rocks—the greenstones of the Franciscan Formation, which are probably metamorphosed submarine basalt flows (Dibblee, 1966). These rocks are highly compressed but yield small quantities of water to domestic wells from fractures induced by tensional and compressional forces.

Except for the two major regional faults—the San Andreas and Hayward faults—no attempt has been made to include faults on this generalized map because detailed geologic mapping was beyond the scope of the study. For more geologic detail, in addition to the sources cited, the reader is referred to a geologic map published by the California Department of Water Resources (1967, pl. 3). That map shows subsea contours on the buried surface of rocks of the Franciscan Formation for much of the valley. From the Dumbarton Bridge southeast to Sunnyvale, the buried surface plunges from 300 to 3,000 ft below sea level.

The Santa Clara Formation of Pliocene and Pleistocene age unconformably overlies the consolidated rocks and is exposed intermittently along both flanks of the valley. Dibblee (1966) designated a type area as the exposures between Saratoga and Stevens Creeks, with a type section as exposed in Stevens Creek. About 2,200 ft of the Santa Clara Formation is exposed in the type area. Where exposed, the formation consists of semiconsolidated conglomerate, sandstone, siltstone, and claystone. The conglomerate and sandstone are poorly sorted and have a fine-grained matrix; thus the formation has a low permeability and, where exposed or at shallow depth, yields only small to moderate quantities of water to wells, rarely enough for irrigation purposes.

Along the western border of the valley, the Santa Clara Formation was warped and folded during the last uplift of the Santa Cruz Mountains. Dips of 25° to 35° are common. Beneath the valley the formation may be undisturbed and in part conformable with overlying beds.

In his map of the Palo Alto 15-minute quadrangle, Dibblee (1966) discriminated a geologic unit overlying the Santa Clara Formation that he calls "older alluvium." The only extensive outcrop covers about 4 mi^2 in the Saratoga area. He described the unit as stream-laid gravel composed of cobbles and pebbles in a matrix of sand and silt, derived from adjacent hills, generally undeformed, dissected where elevated, as much as 50 ft exposed, and age presumably late Pleistocene.

Because this unit has been mapped only on the west side of the valley and is of little importance in water supply, its outcrop area has been combined with that of the Santa Clara Formation in the stipple pattern of figure 1.

Unconsolidated alluvium and bay deposits of clay, silt, sand, and gravel of late Pleistocene and Holocene age overlie the Santa Clara Formation and associated deposits; their upper surface forms the valley floor. Well logs indicate that permeable alluvial deposits attain a thickness of 1,000 ft or more in the valley trough. Wells range in depth from 200 to 1,200 ft (California Department of Water Resources, 1967, pl. 4). The deeper wells probably tap the upper part of the Santa Clara Formation, although the contact with the overlying alluvium and bay deposits has not been distinguished in well logs because of the lithologic similarity.

Coarse-grained deposits predominate in the alluvial-fan and stream-channel deposits near the valley margins, where the stream gradients are steeper. The proportion of clay and silt layers increases bayward. For example, a well-log section extending 12 mi northward from Campbell to Alviso (Tolman and Poland, 1940, fig. 3) shows that to a depth of 500 ft the cumulative thickness of clay layers in the deposits increases from 25 percent near Campbell to 80 percent near Alviso.

Well yields in the valley range from 300 to 2,500 gallons per minute (gal/min), and the specific capacity [(gal/min)/ft drawdown] ranges from 10 near the valley margin to 70 in mid-valley, exceeding 300 in both San Jose and Santa Clara (California Department of Water Resources, 1967, pl. 6).

Geologic sections *A–A′* (fig. 2), *B–B′* (fig. 3), and *C–C′* (fig. 4) illustrate the general nature of the alluvial water-bearing deposits that underlie the valley floor. Fine-grained materials such as clay, silt, and sandy clay, which retard the vertical movement of confined ground water, constitute the major part of the valley fill near the bay (figs. 2, 3). Sand and gravel occur in lesser amounts near the bay, but they are more abundant near the valley margins, where locally they are predominant. None of the distinctive layers or lenses can be traced laterally for more than a mile or two. Inspection of the three figures indicates that the well-log section *B–B′* (fig. 3), which traverses mostly lowland areas near the bay, contains a preponderance of clay. On the other hand, sections *A–A′* and *C–C′* (figs. 2, 4) traverse chiefly upland areas, and many of the well logs indicate a preponderance of coarse-grained material.

In the central two-thirds of the valley below a depth of 150 to 200 ft, ground water is confined. The confinement extends northward from the southern part of San Jose to Palo Alto and Milpitas and beneath the bay. In much of the area of confinement, wells more than 200 ft deep flowed in the early years of urban development (see fig. 13). The confined aquifer system is as much as 800 ft thick. Around the valley margins, ground water is generally unconfined, and most of the natural recharge to the ground-water reservoir percolates from stream channels crossing alluvial-fan deposits.

The confining member overlying the confined aquifer system has a thickness of 150 to 200 ft (see fig. 3, central part; also see fig. 5). Although predominantly composed of clay and silt, it also contains some channel fillings and lenses of permeable sand and gravel. This confining member supports a shallow water table distinguished by an irregular surface. As of 1965–70, the shallow water table overlying much of the confined system was less than 30 ft below the land surface (Webster, 1973). At least near the bay, the shallow water table did not fluctuate appreciably during the period of prolonged artesian-head decline terminating in 1966, indicating little change of stress in the shallow confining member.

In 1960, the Geological Survey drilled core holes 1,000 ft deep at the two centers of subsidence: in Sunnyvale (well 6S/2W-24C7) and in San Jose (well 7S/1E-16C6). An electric log was obtained for each core hole after coring was completed. Graphic logs and generalized lithologic descriptions were prepared from the geologists' logs made at the drill site, supplemented by interpretation of the electric log in zones not cored or of poor recovery. These three elements were combined to give a composite log for each core hole (figs. 5, 6). The depths of the samples tested also were plotted on the composite logs.

In all, 87 samples from these core holes were tested by the Geological Survey in the laboratory for physical and hydrologic properties, including particle-size distribution, specific gravity of solids, dry unit weight, porosity and void ratio, hydraulic conductivity (normal and parallel to bedding), and Atterberg limits (Johnson and others, 1968, p. A1 and tables 5 and 6).

Compressibility characteristics of fine-grained compressible layers (aquitards) can be obtained by making one-dimensional consolidation tests of "undisturbed" fine-grained cores in the laboratory. As one phase of the research on compaction of the aquifer system, laboratory consolidation tests were made by the U.S. Bureau of Reclamation on 21 selected fine-grained cores from the two core holes (see sample depth and number in composite log). Properties tested included the compression index, C_c, a measure of the nonlinear compressibility of the sample, and the coefficient of consolidation, C_v, a measure of the time rate of consolidation. Complete results of these laboratory tests have been published (Johnson and others, 1968, tables 8 and 9, and figs. 12 and 21c). The 21 samples tested spanned a depth range from 141 to 958 ft below land surface. The range of the compression index, C_c, was small compared with the range in the San Joaquin Valley: the maximum value was 0.33, the minimum was 0.13, and the mean was 0.24. Of the 21 samples, 15 had C_c values falling between 0.20 and 0.30. This suggests that the nonlinear compressibility characteristics of the aquitards in the confined aquifer system do not vary widely. The consolidation-test curves for the 11 samples from core hole 6S/2W-24C7 and the 10 samples from core hole 7S/1E-16C6 are shown in figures 7 and 8.

The plot of void ratio against the logarithm of load (effective stress) is known as the e-log p plot. The compression index, C_c, representing the compressibility of the sample, can be obtained graphically from the e-log p

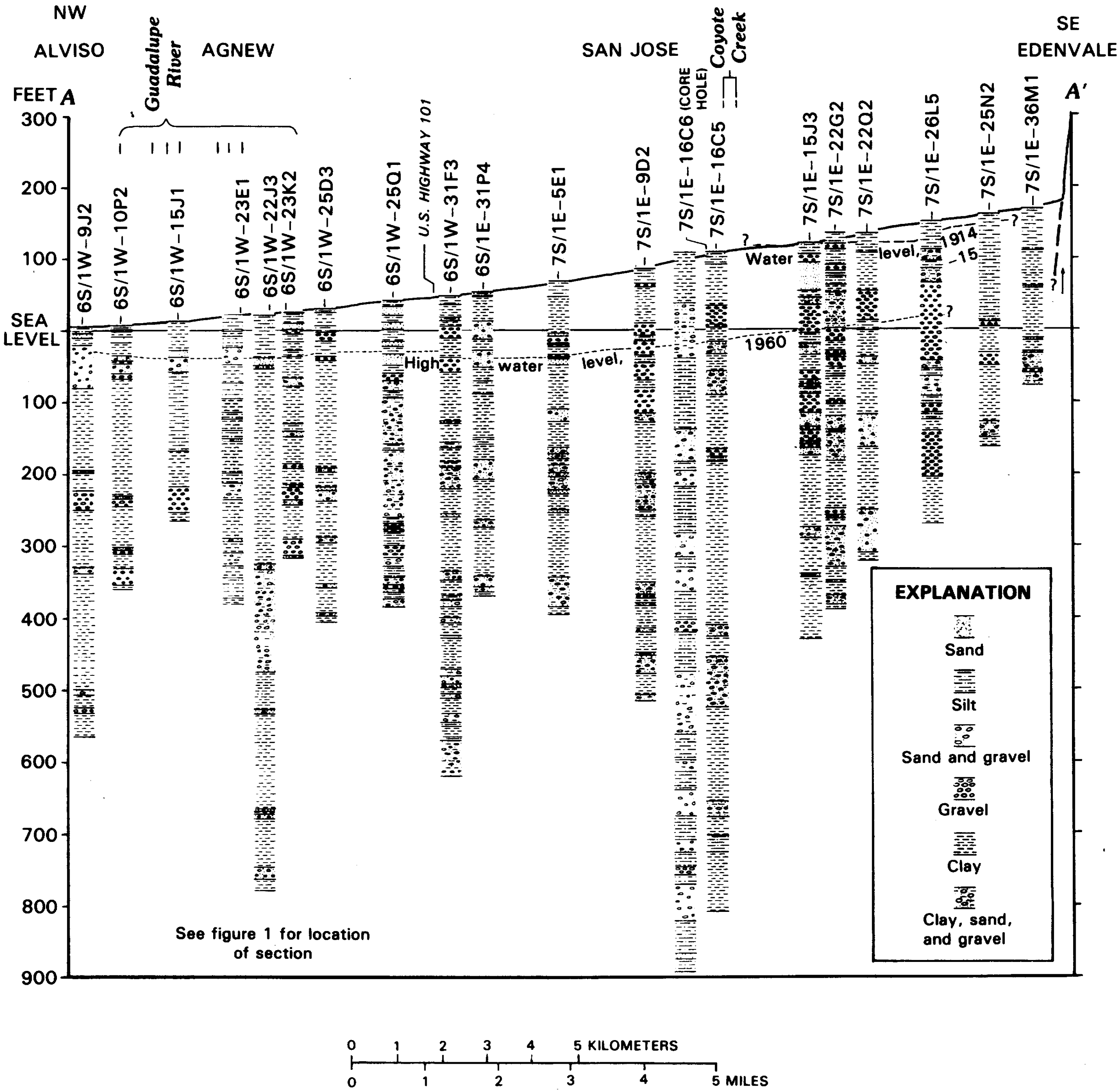


FIGURE 2.—Geologic section A-A' from Alviso southeast to Edenvale Hills.

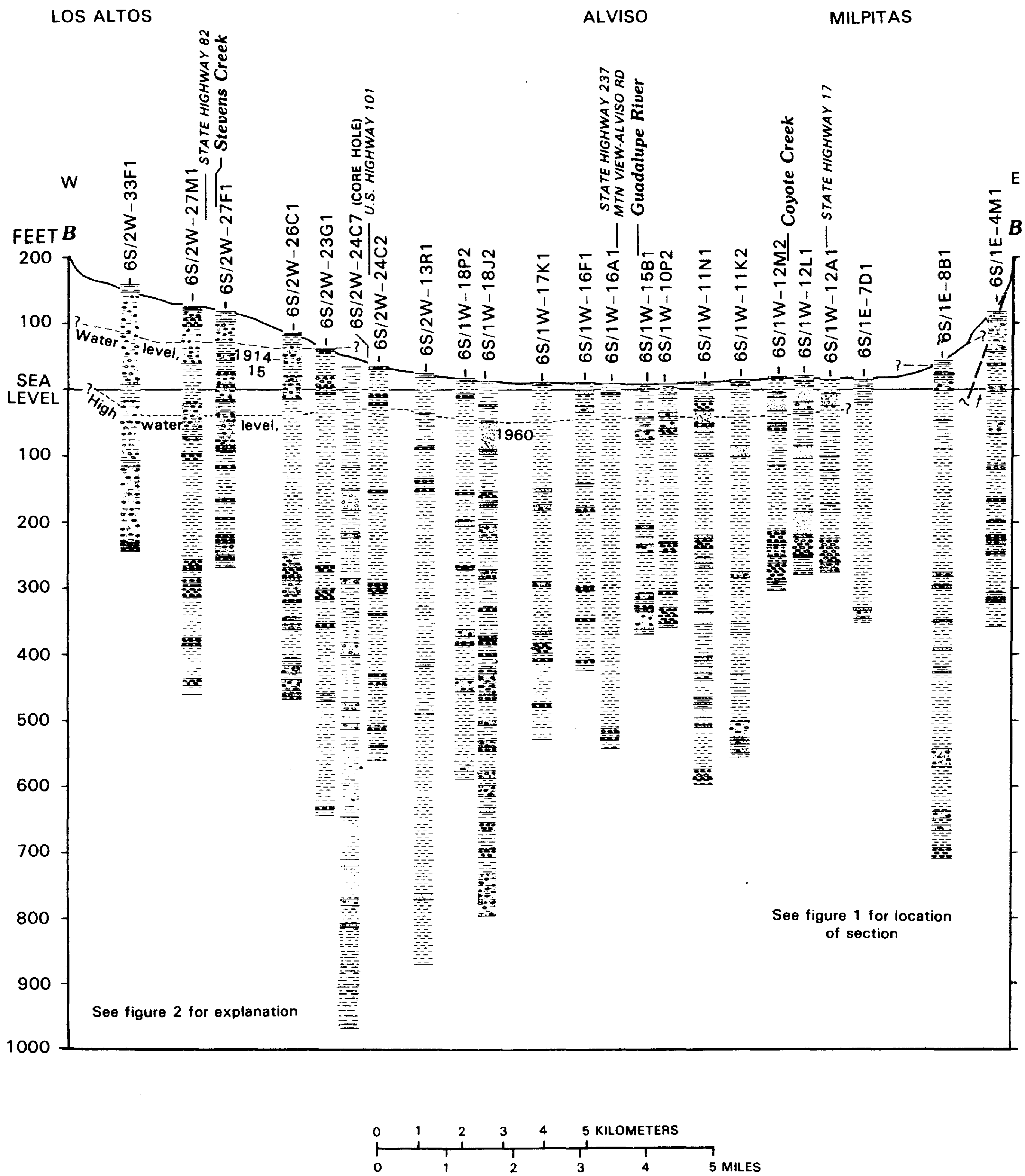


FIGURE 3.—Geologic section *B-B'* from Los Altos east to Milpitas.

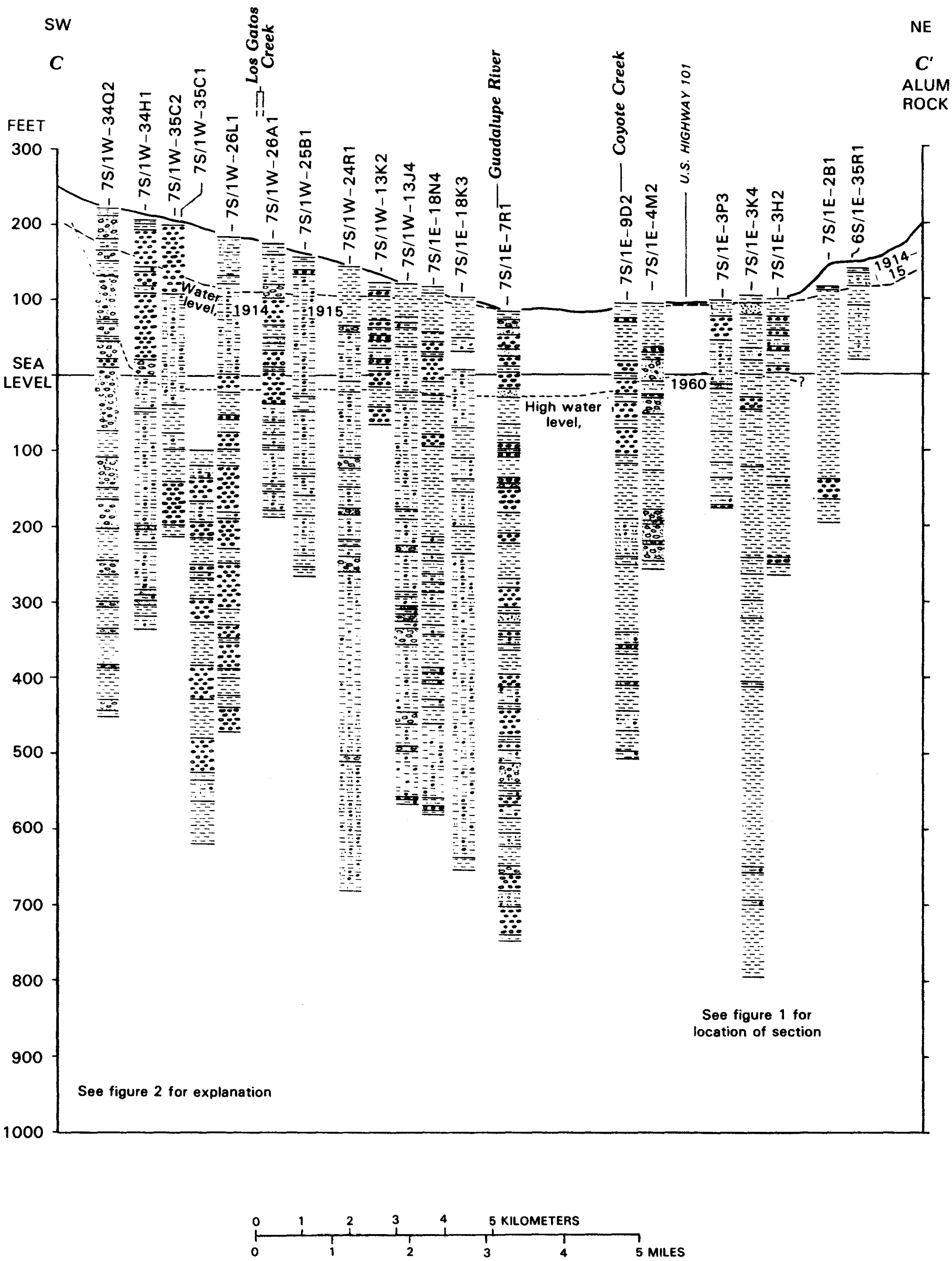
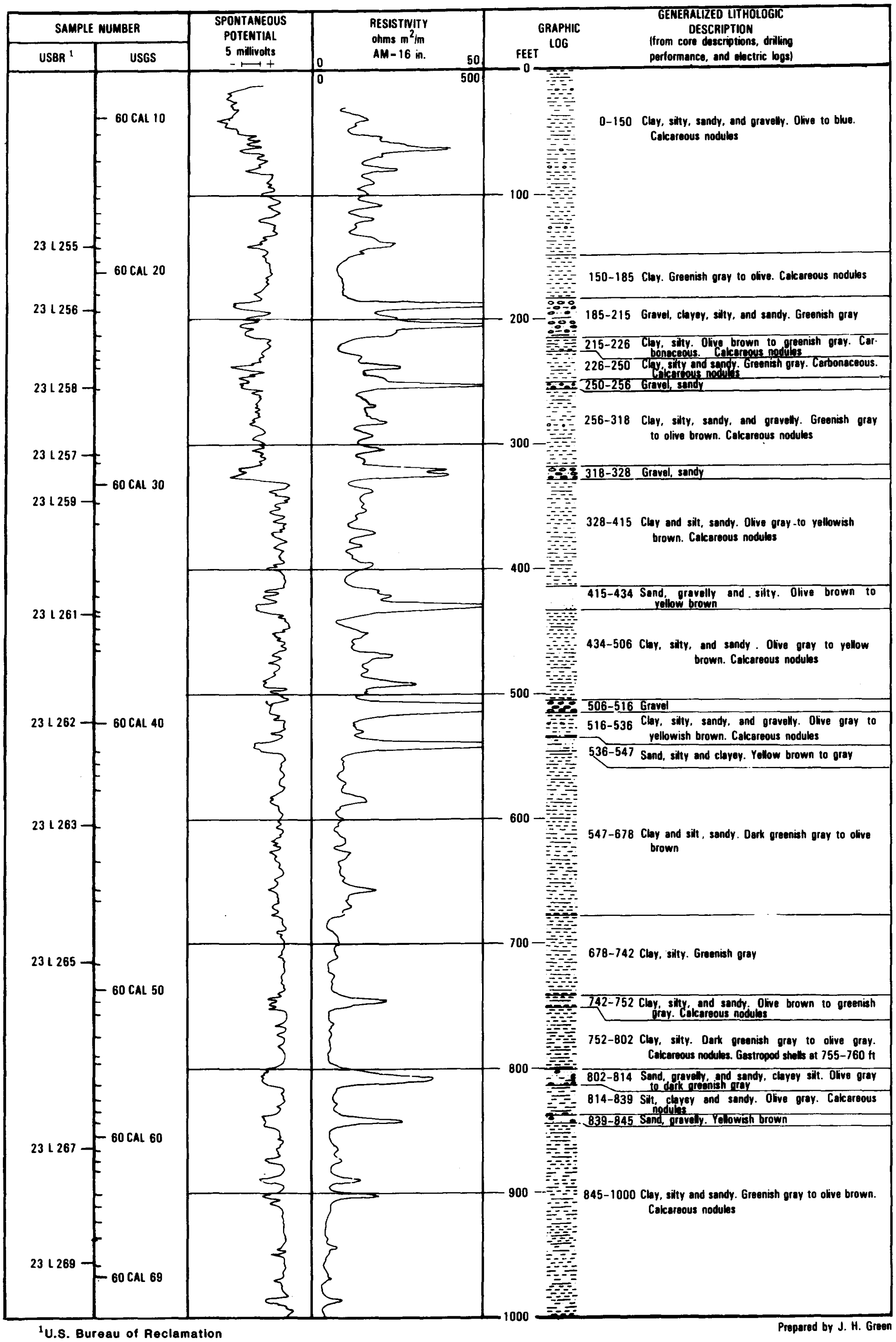


FIGURE 4.—Geologic section C–C′ from near Los Gatos northeast to Alum Rock.



[1]U.S. Bureau of Reclamation

FIGURE 5.—Composite log of core hole 6S/2W-24C7 in Sunnyvale.

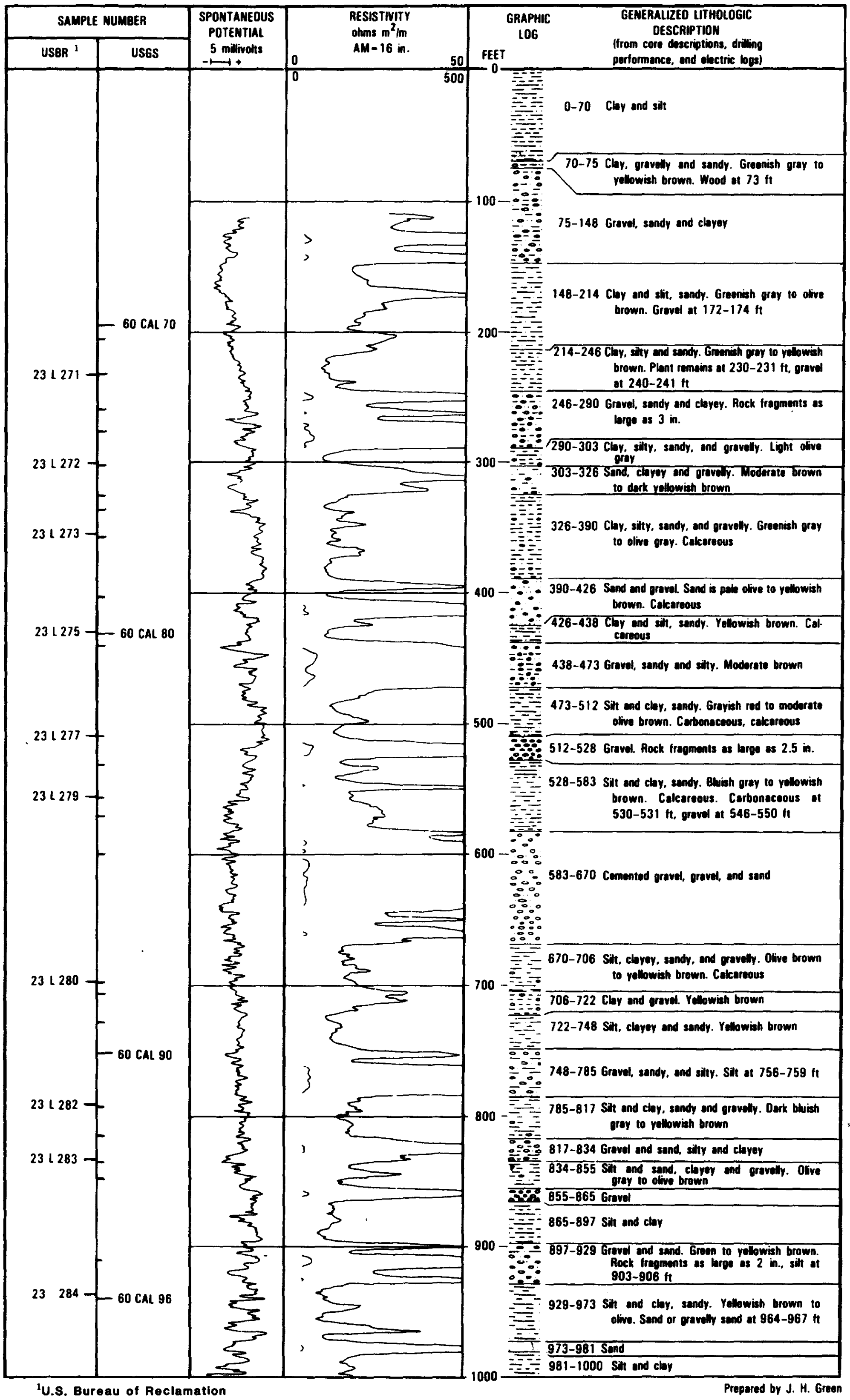


FIGURE 6.—Composite log of core hole 7S/1E-16C6 in San Jose.

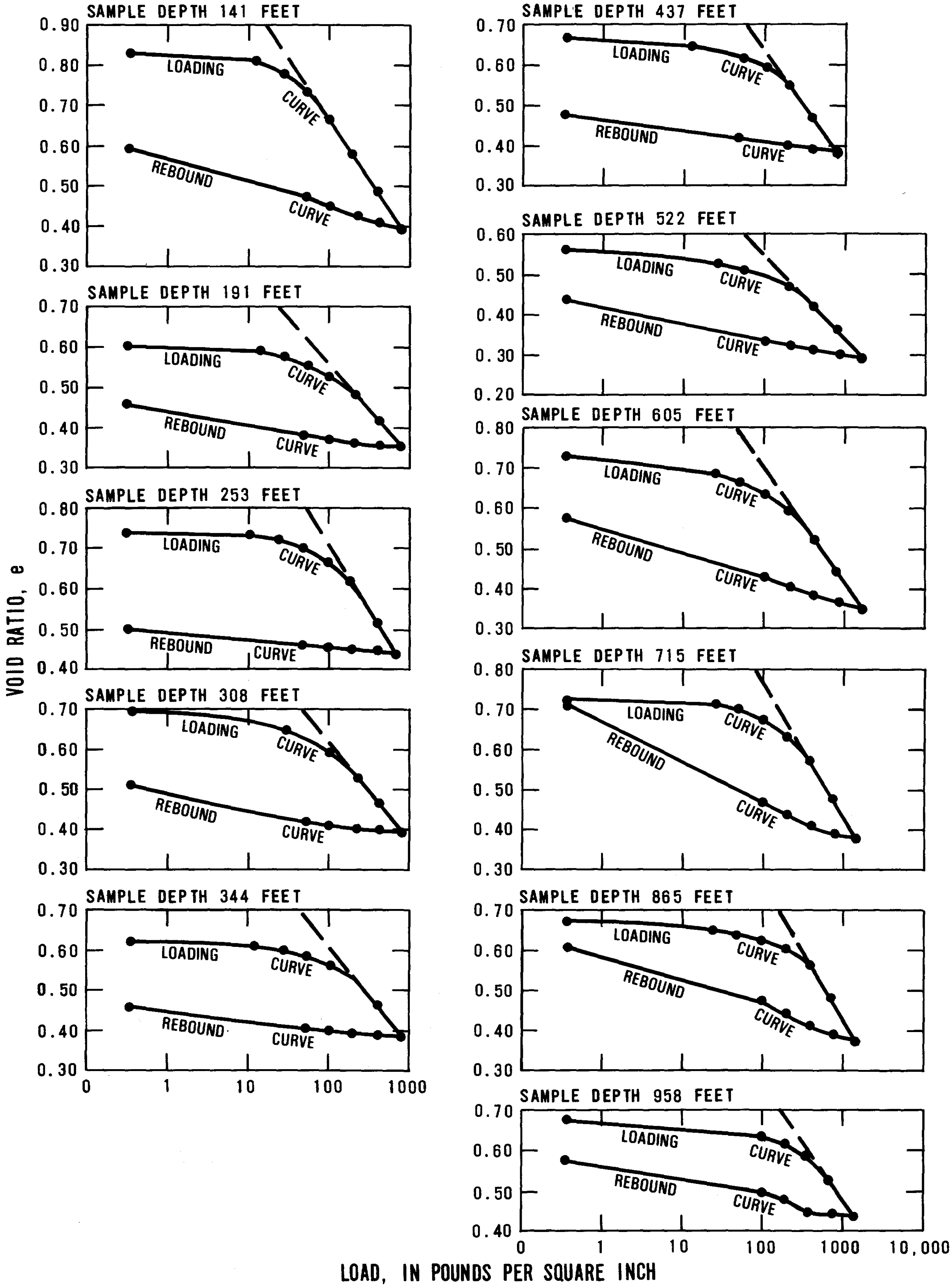


FIGURE 7.—Consolidation-test curves for samples from core hole 6S/2W-24C7. Sample depths are in feet below land surface.

curve: It is the slope of the straight-line portion of the loading curve or its dashed extension. Note that several points were obtained on the rebound as well as the loading branch of the curve in order to compare void-ratio increases due to unloading.

Based on a study of the cores recovered from the two core holes, Meade (1967, table 1 and p. 39–43) described the types of deposits encountered to the 1,000-ft depth as nonmarine and mostly alluvial, with possibly a few lacustrine deposits at depths below 700 ft. Although both core holes are near San Francisco Bay (the Sunnyvale hole is only 3 mi from the bay), Meade reported that neither core contained sediments that could be recognized as estuarine. He listed several pieces of evidence indicating

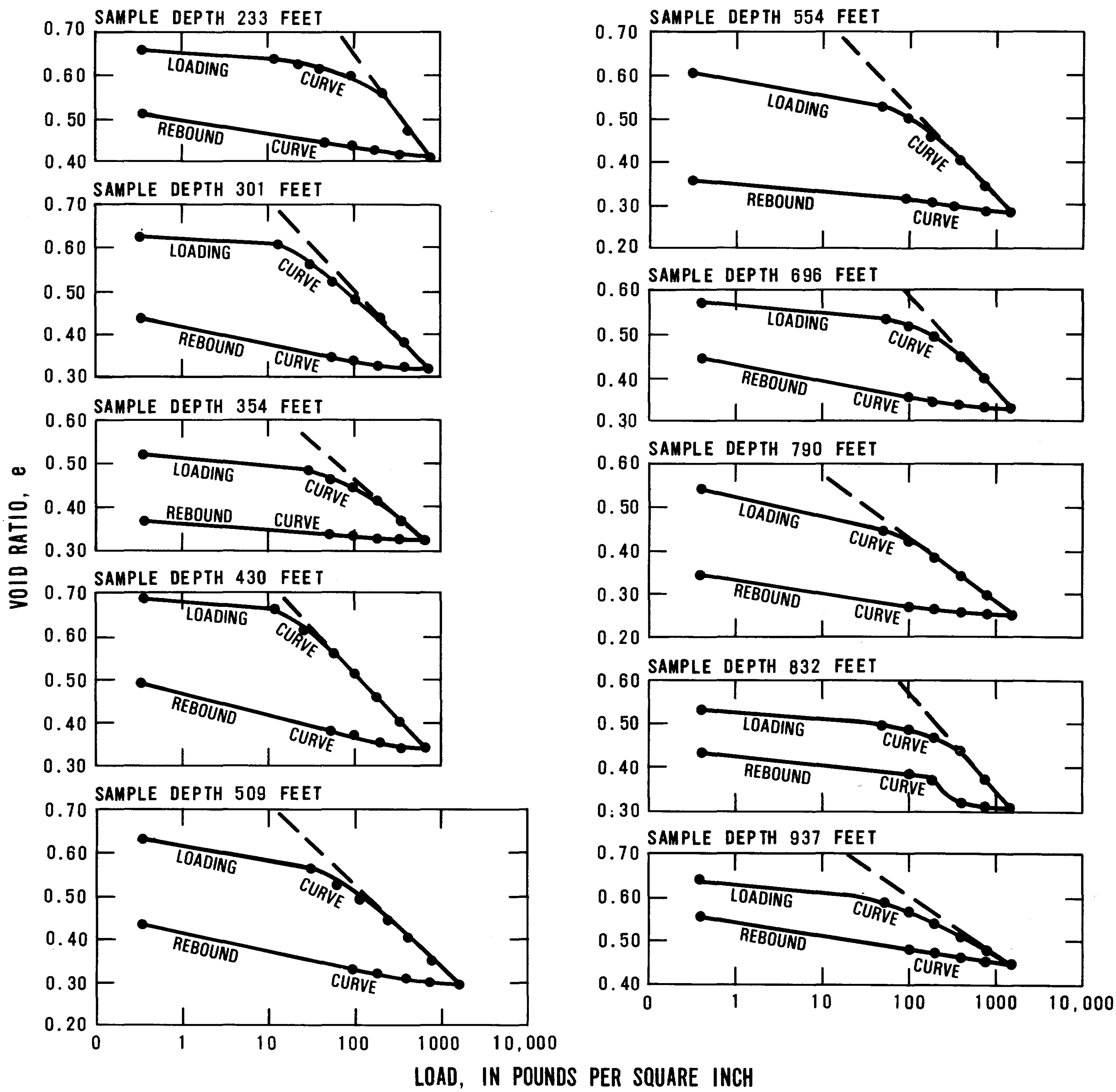


FIGURE 8.—Consolidation-test curves for samples from core hole 7S/1E-16C6. Sample depths are in feet below land surface.

the absence of estuarine sediments, including a complete lack of marine or estuarine fossils.

It is of interest to note that at the Dumbarton Bridge crossing of San Francisco Bay, 9 mi northwest of the Sunnyvale core hole, Atwater and others (1977, pl. 1, cross section *C–C′*) found two intervals of estuarine deposits above a depth of 180 ft, respectively 0 to 60 ft and 120 to 160 ft below sea level and each about 6 mi wide. Their study of late Quaternary depositional history is based on detailed examination of sediments from 18 boreholes at three San Francisco Bay toll crossings (Bay Bridge, San Mateo Bridge, and Dumbarton Bridge). Three geologic cross sections show detailed descriptions of samples to a maximum depth of 200 ft below present sea level. Emphasis is on the estuarine deposits.

X-ray diffraction studies of 20 samples from the two core holes indicate that montmorillonite composes about 70 percent of the clay-mineral assemblage in these deposits. Other constituents are chlorite (20 percent) and illite (5 to 10 percent) (Meade, 1967, p. 44, fig. 33, and tables 14 and 15). Montmorillonite is the most compressible of the clay minerals.

HYDROLOGY

RAINFALL

Precipitation that falls within the drainage basin is the ultimate source of all local ground water. The rainfall at San Jose has developed definite trends in the past 100 years (fig. 9). A plot of the cumulative departure of rainfall at San Jose from the seasonal mean for the period of record clearly defines these trends.[1] The rainfall record for San Jose began in 1874–75. For the 106-year period to 1979–80, the seasonal mean rainfall (July 1 to June 30) was 14.13 in. From about 1890 to about 1915 the generally rising curve defined by the yearly points indicates that the cumulative surplus exceeded the cumulative deficiency by about 55 in. Thus, the average yearly surplus in this wet 25-year period exceeded the seasonal mean by about 2 in.

On the other hand, for the 50 years from about 1916 to about 1966 the declining curve defined by the yearly points indicates that the cumulative deficiency exceeded the cumulative surplus by about 60 in. Thus, the average yearly deficiency in the 50-year dry period was below the seasonal mean by about 1.2 in.

[1]The cumulative departure curve is determined by calculating the seasonal mean for a period of record, calculating each season's departure (plus or minus) from that mean, and then summing those departures. Thus, the first season had a deficiency of 6 in. and the second season had a surplus of 5 in., resulting in a cumulative deficiency of 1 in. for the first two seasons.

GROUND-WATER PUMPAGE

The intensive development of irrigated agriculture in the valley began about 1900. Tibbetts and Kieffer (1921, pl. 7) reported that the number of irrigation wells in north Santa Clara County increased from 115 in 1890 to 1,590 in 1920.

Year	1890	1900	1910	1920
Wells	115	235	440	1,590

Agricultural pumpage increased from about 40,000 acre-ft/yr in 1915–20 to a maximum of 103,000 acre-ft/yr in 1945–50 (fig. 10, table 1). After 1945, population pressures caused a great transition of land use from agricultural to urban and industrial development. By 1970–75 most of the orchards had been replaced by houses, and agricultural pumpage had decreased to 20,000 acre-ft/yr. Municipal and industrial pumpage, on the other hand, increased from 22,000 acre-ft/yr in 1940–45 to 131,000 acre-ft/yr in 1970–75. Total pumpage (fig. 10, table 1) increased nearly fourfold from 1915–20 to 1960–65—from 49,000 to 185,000 acre-ft/yr—but then decreased 19 percent to 150,000 acre-ft/yr by 1970–75 in response to a rapid increase in surface-water imports.

SURFACE-WATER IMPORTS

The import of surface water to Santa Clara County began about 1940 when San Francisco began selling surface water imported from Hetch Hetchy Reservoir in the Sierra Nevada to several municipalities. This import increased from 6,000 acre-ft in 1955 to 12,000 acre-ft in 1960 and to about 50,000 acre-ft in the 1970's (fig. 11, table 2). Imports before 1955 are not known.

Surface water imported from the Central Valley through the State's South Bay Aqueduct first became available in 1965; during the 1970's, deliveries through the aqueduct exceeded 100,000 acre-ft four different years (table 2, fig. 11).

Unused imported water was recharged to the ground-water reservoir through stream channels and percolation ponds. The yearly quantity diverted to channels (stippled segment of yearly bars, fig. 11) in the 15 years has averaged about 40,000 acre-ft and represents about 48 percent of the total import from the South Bay Aqueduct.

DECLINE OF ARTESIAN HEAD, 1916–66

In the spring of 1916, the artesian head in index well 7S/1E-7R1 in San Jose stood 12 ft above the land surface (fig. 12). At that time there were only about 1,000 irrigation wells in north Santa Clara County. The cumulative departure graph of rainfall at San Jose (fig. 9) shows that

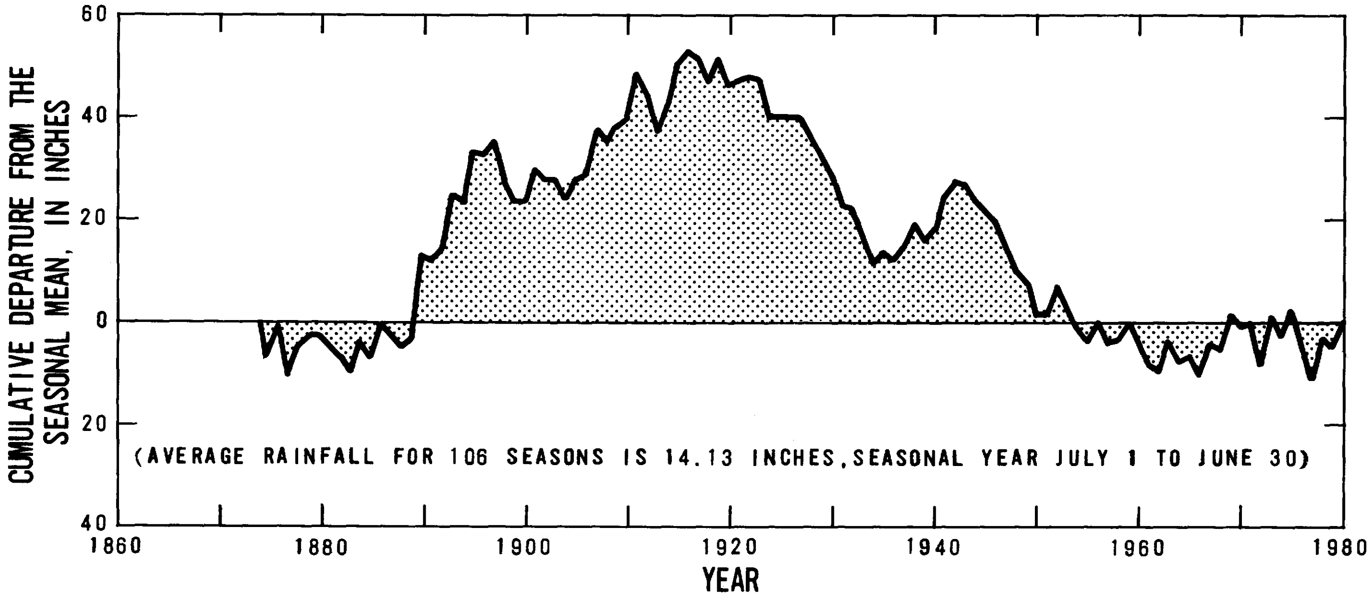


FIGURE 9.—Cumulative departure of rainfall at San Jose from the seasonal mean for the 106-year period 1874–75 to 1979–80. (Data from U.S. Weather Bureau and National Weather Service.)

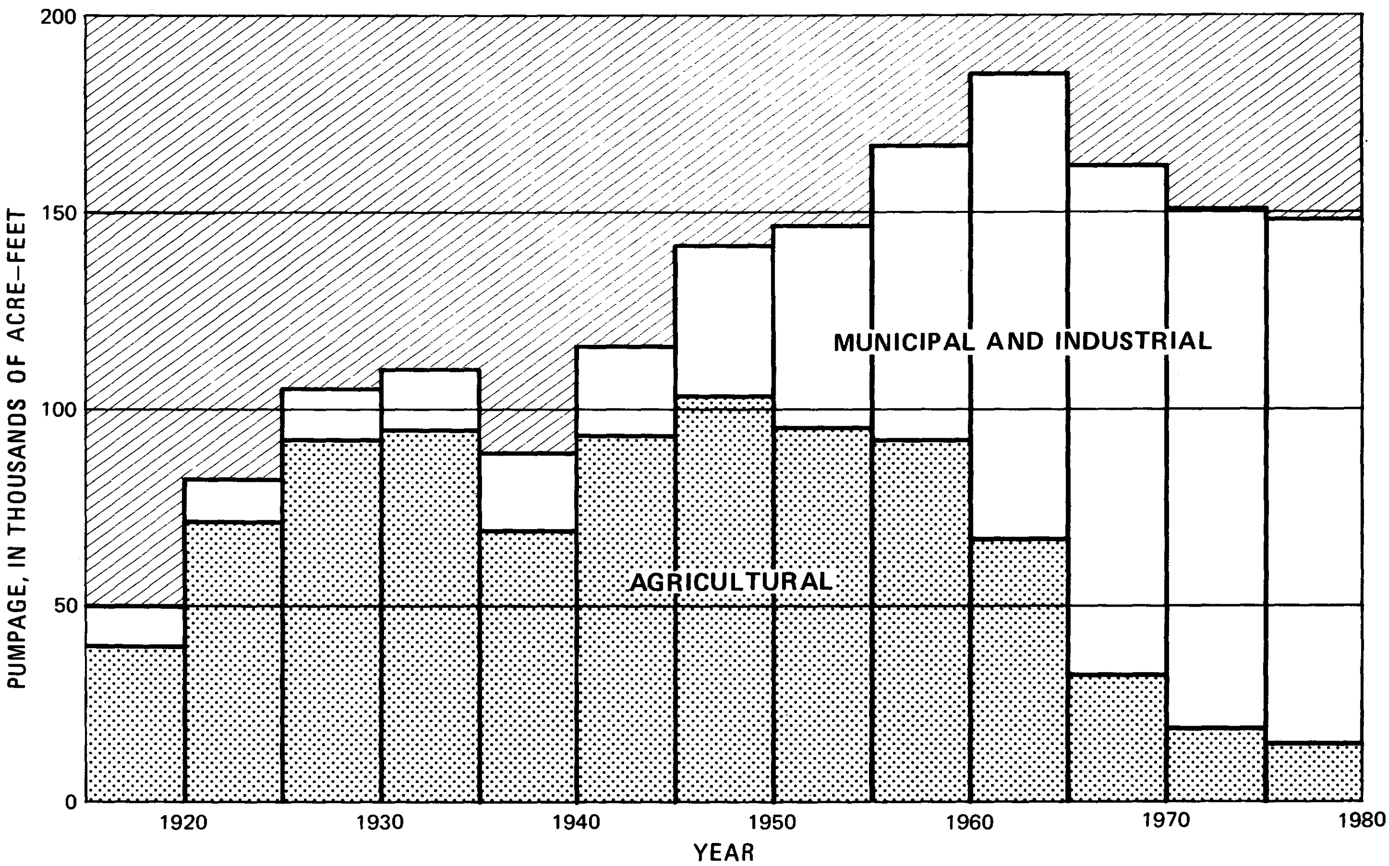


FIGURE 10.—Ground-water pumpage in north Santa Clara County, 1915–80.

TABLE 1.—*Ground-water pumpage, north Santa Clara County, 1915–80, in acre-feet*

[From 1915 to 1966 agricultural pumpage was estimated by the Santa Clara Valley Water District from agricultural power sales of Pacific Gas and Electric Company and is reported by fiscal year. To 1966 municipal and industrial pumpage is listed by calendar year; municipal pumpage is metered, industrial is estimated. Since 1966 all pumpage is metered and is reported here by fiscal year July 1–June 30. Industrial pumpage was estimated as follows: 1915–34, 5,000 acre-ft/yr; 1935–43, 10,000 acre-ft/yr; 1944–50, 15,000 acre-ft/yr; 1951–60, 20,000 acre-ft/yr; 1961–66, 22,000 acre-ft/yr]

Year	Agricultural		Municipal and industrial	Total	
	Yearly	5-year average		Yearly	5-year average
1915-16	22,800		8,600	31,400	
1916	31,500		9,200	40,700	
1917	41,300		9,800	51,100	
1918	45,500		10,700	56,200	
1919-20	56,000	39,420	10,200	66,200	49,120
1920-21	63,000		10,800	73,800	
1921	54,600		10,500	65,100	
1922	56,700		10,700	67,400	
1923	97,500		10,800	108,300	
1924-25	82,500	70,860	14,700	97,200	82,360
1925-26	76,000		12,600	88,600	
1926	74,000		12,500	86,500	
1927	90,000		12,000	102,000	
1928	118,000		12,700	130,700	
1929-30	102,000	92,000	15,400	117,400	105,040
1930-31	122,000		14,600	136,600	
1931	84,000		17,000	101,000	
1932	104,000		14,400	118,400	
1933	108,000		14,900	122,900	
1934-35	56,000	94,800	15,100	71,100	110,000
1935-36	68,100		18,900	87,000	
1936	63,700		19,800	83,500	
1937	61,400		20,100	81,500	
1938	77,600		20,200	97,800	
1939-40	73,000	68,760	22,100	95,100	88,980
1940-41	72,600		20,700	93,300	
1941	84,000		20,000	104,000	
1942	97,600		18,700	116,300	
1943	117,900		19,600	137,500	
1944-45	96,100	93,640	33,500	129,600	116,140
1945-46	100,800		34,200	135,000	
1946	104,900		36,400	141,300	
1947	114,100		38,200	152,300	
1948	98,200		41,600	139,800	
1949	95,700	102,740	44,200	139,900	141,600
1950-51	84,000		49,500	133,500	
1951	81,100		46,600	127,700	
1952	95,700		50,700	146,400	
1953	92,500		52,700	145,200	
1954	121,800	95,020	55,600	177,400	146,040
1955-56	90,200		64,900	155,100	
1956	94,300		66,100	160,400	
1957	78,600		77,100	155,700	
1958	102,600		79,800	182,400	
1959	90,000	91,140	93,200	183,200	167,360

TABLE 1.—*Ground-water pumpage, north Santa Clara County, 1915–80, in acre-feet*—Continued

Year	Agricultural		Municipal and industrial	Total	
	Yearly	5-year average		Yearly	5-year average
1960-61	84,800		106,400	191,200	
1961	63,400		121,300	184,700	
1962	54,400		119,400	173,800	
1963	76,200		109,700	185,900	
1964-65	57,200	67,200	131,400	188,600	184,840
1965-66	40,200		122,300	162,500	
1966-67	29,800		140,100	155,390	
1967-68	35,400		139,200	174,630	
1968-69	28,600		136,670	165,270	
1969-70	29,320	32,660	126,040	155,360	162,630
1970-71	23,710		124,500	148,210	
1971	24,090		142,390	166,480	
1972	17,450		137,820	155,270	
1973	15,940		129,125	145,060	
1974-75	16,903	19,620	120,526	137,430	150,490
1975-76	20,036		148,764	168,800	
1976-77	16,714		136,329	153,043	
1977-78	11,702		115,581	127,283	
1978-79	12,027		137,678	149,705	
1979-80	9,793	14,050	139,764	149,557	149,680
1980-81	9,568		151,558	161,126	

1916 was the end of a wet period beginning about 1890. Hunt (1940) reported that in 1912, 29 percent of the valley lands were irrigated, but that by 1920, 67 percent were irrigated, including 90 percent of the orchards; nearly all of these lands were irrigated with ground water from wells. By the autumn of 1966, the head in well 7S/1E-6M1 in San Jose was about 210 ft below land surface (fig. 12).[2]

The principal factors in this major 50-year decline of about 220 ft are shown in figure 12. The upper line is a replot (fig. 9) of the cumulative departure, in inches, from 1910 to 1980 of the seasonal rainfall at San Jose from the seasonal mean for the 106-year period since 1874–75. Except for the 6-year wet period 1936–42, the departure in the 50 years from 1916 to 1966 was substantially negative, and the cumulative departure represents a cumulative deficiency of 60 in.

The bottom graph of figure 12 shows the estimated total ground-water pumpage for the 65-year period 1915–80; the plot is similar to figure 10 except that the increase in pumpage is plotted downward to reflect its influence on the artesian head in the index wells. Estimates from 1915 to 1965 are based chiefly on electric-power consumption for agricultural use and are graphed as 5-year averages; since then, virtually all pumpage has been metered.

The 50-year decline in artesian head plainly was caused by generally deficient rainfall and constantly increasing pumping draft. The curve of artesian-head decline conforms reasonably well with the cumulative departure curve of the seasonal rainfall at San Jose.

Water levels in a relatively full ground-water basin at the end of the prolonged wet period beginning in 1890 are shown in figure 13. The water-level contours are generalized from plate XIV of Clark (1924), which was drawn from measurements of depth to water in wells in the spring and summer of 1915. Both figures 13 and 14 are maps prepared by P.R. Wood and K.S. Muir (U.S. Geological Survey, written commun., June 1972). Clark's area of artesian flow as of 1915 (from pl. XIV) and his "boundary of former area of artesian flow" (from pl. XV)

[2]The record of depth to water in index well 7S/1E-7R1 extends from 1915 to date. However, during the last two decades the artesian head in this well has been higher than the head in nearby representative deep wells, such as well 7S/1E-6M1 (803 ft deep). Accordingly, the composite hydrograph of figure 12 represents the artesian head in well 7R1 to 1959 and the head in well 6M1 from 1959 to 1980.

are both shown in figure 13. Obviously the confined aquifer system must extend beyond Clark's "former area of artesian flow." The boundary between confined and free ground-water conditions is not easily determined or recognized in parts of the Santa Clara Valley. In this report, however, the 1-ft subsidence line of 1934–67 (fig. 21) is considered to be a general approximation of the boundary of the confined area, and accordingly it is plotted in figure 13.

It is of interest to note that the California Department of Water Resources (1967, p. 85 and pl. 11) defined the boundary of the confined aquifer system as the boundary of their San Jose subarea. That boundary agrees in general with the 1-ft subsidence line of 1934–67 (fig. 21), except near Oak Hill and Penitencia Creek.

In general, the water-level contours of figure 13 are assumed to represent a free water table near the valley margins and the potentiometric surface of the confined aquifer system in the central area included within the 1-ft subsidence line. The water-level contours by 1915 had not yet been distorted appreciably from the conditions that prevailed before man began the steady increase in ground-water withdrawal. The water-level contours indicate a generally northwesterly movement of ground water toward San Francisco Bay in 1915. In the San Jose area, the water levels in wells ranged from 60 to 100 ft above sea level, and artesian wells were still flowing in downtown San Jose.

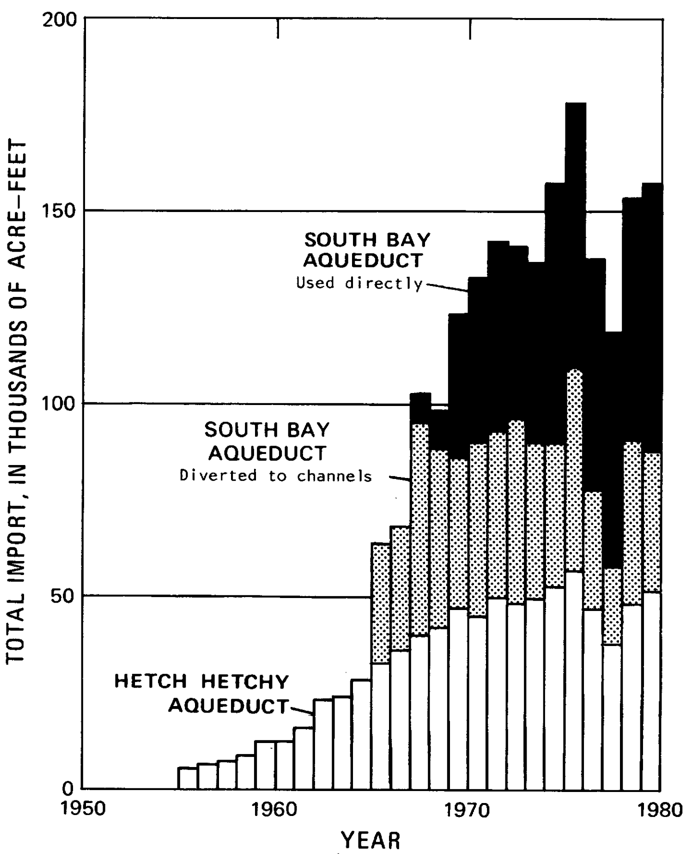


FIGURE 11.—Surface-water imports to north Santa Clara County, 1955–80.

By 1967, after a half century of exploitation, water levels in wells had been drawn down below sea level in much of the ground-water basin. The hydraulic gradient toward San Francisco Bay in wells tapping the confined system had been reversed, and movement was now toward large cones of pumping depression as much as 200 ft below 1915 levels, surrounding heavily pumped municipal well fields. In central San Jose, the artesian head of 1967 was 160 to 180 ft below 1915 levels (fig. 14). In part of the confined aquifer system in 1967, water levels in wells had been drawn down below the base of the confining member, which near the bay is 150 to 200 ft below the land surface. Therefore, it is not practical to draw a boundary between water table and confined conditions as of 1967 on the basis of figure 14.

RECOVERY OF ARTESIAN HEAD, 1967–80

The recovery of water level since the middle 1960's has been substantial. By 1975, the spring high-water level at index well 7S/1E-6M1 (fig. 12) was 60 ft higher than in 1966 and about equal to the 1935 level. Subsequent recovery was affected by the drought of 1976 and 1977, but the high level of 1980 was still 60 feet higher than the 1963–66 lows.

From 1958 through 1982, the Geological Survey measured depth to water in well 7S/1E-16C5 at the 12th and Martha Street well field of the San Jose Water Works. This well is 908 ft deep and is about 1.5 mi east of well 7S/1E-7R1 (fig. 1). The record of depth to water in well 7S/1E-16C5 is shown from 1958 through 1979 in figure 41*A* and from 1980 through 1982 in figure 47*A*. The recovery of artesian head in this index well from the 1966 low to the 1978 low was about 80 ft.

This major recovery of artesian head was due to several factors, including increased imports of surface water, favorable local water supply, decreased pumpage, and increased recharge (fig. 12). The most important factor was the increase in imports.

The import of surface water to Santa Clara County began in about 1940. As shown by table 2, by 1966–67 yearly import through the Hetch Hetchy and South Bay Aqueducts was 36,000 and 32,000 acre-ft, respectively. By 1979–80, total import was about 158,000 acre-ft, considerably more than double the import of 1966–67.

The average seasonal rainfall at San Jose was above normal in the 14-year period 1966–80. The cumulative departure graph (fig. 9) indicates a positive increase of about 15 in. in the 14 years.

TABLE 2.—*Surface-water imports to north Santa Clara County, 1955–80, in acre-feet per fiscal year*
[Data from Santa Clara Valley Water District; total imports rounded to 5 acre-ft]

Year (July 1-June 30)	Hetch Hetchy Aqueduct	South Bay Aqueduct		Total imports
		Total	Diverted to channels	
1955-56	5,965			
1956	6,300			
1957	7,445			
1958	9,690			
1959-60	12,300			
1960-61	12,765			
1961	15,578			
1962	22,970			
1963	24,072			
1964-65	29,536	495	495	30,030
1965-66	33,572	29,680	29,680	63,250
1966	35,784	31,785	31,480	67,570
1967	39,902	63,032	55,213	102,935
1968	41,675	57,663	46,466	99,340
1969-70	47,203	77,234	38,072	124,435
1970-71	45,288	88,486	44,024	133,775
1971	49,744	92,432	43,596	142,175
1972	48,890	92,582	47,586	141,470
1973	49,467	86,565	41,076	136,030
1974-75	53,273	104,052	36,196	157,325
1975-76	58,229	118,692	52,607	176,920
1976	47,657	89,693	29,318	137,350
1977	38,052	79,776	20,126	117,830
1978	49,434	105,107	41,308	154,540
1979-80	51,806	105,868	35,628	157,675

The average yearly pumpage of ground water, which reached a peak of about 185,000 acre-ft in 1960–65, decreased to about 150,000 acre-ft in 1970–75 and 1975–80 (table 1). A principal reason for this 19-percent decrease is the tax on ground-water pumpage applied since 1964 for water extracted from the ground-water basin. In 1970–71, for example, the ground-water tax was levied at $8 per acre-ft for ground water extracted for agricultural purposes and at $29 per acre-ft for ground water extracted for other uses. For water delivered on the surface in lieu of extraction, the cost was $10.50 per acre-ft for water used for agriculture and $31.50 per acre-ft for water used for other purposes. The economic advantage of using surface water where available is obvious when one considers the cost of ground-water extraction in addition to the tax.

Local agencies have been working since the 1930's to obtain water supplies adequate to stop the ground-water overdraft and raise the artesian head. Their program has involved (1) salvage of flood waters from local streams that would otherwise waste to the bay, and (2) importation of water from outside the valley. In 1935–36, five storage dams were built on local streams to provide detention reservoirs with combined storage capacity of about 50,000 acre-ft, to retain flood waters, and to permit controlled releases to increase streambed percolation (Hunt, 1940). The storage capacity of detention reservoirs was increased to 144,000 acre-ft by the early 1950's (California State Water Resources Board, 1955, p. 51).

Recharge from stream channels and percolation ponds to the ground-water reservoir has been augmented since 1965 by water from the South Bay Aqueduct that could not be delivered directly to the user. The quantity diverted to recharge areas in the 15 years has averaged about 40,000 acre-ft per year and represents 48 percent of the total import from the South Bay Aqueduct. (See stippled segment of yearly bars, fig. 11, and upper right graph, fig. 12).

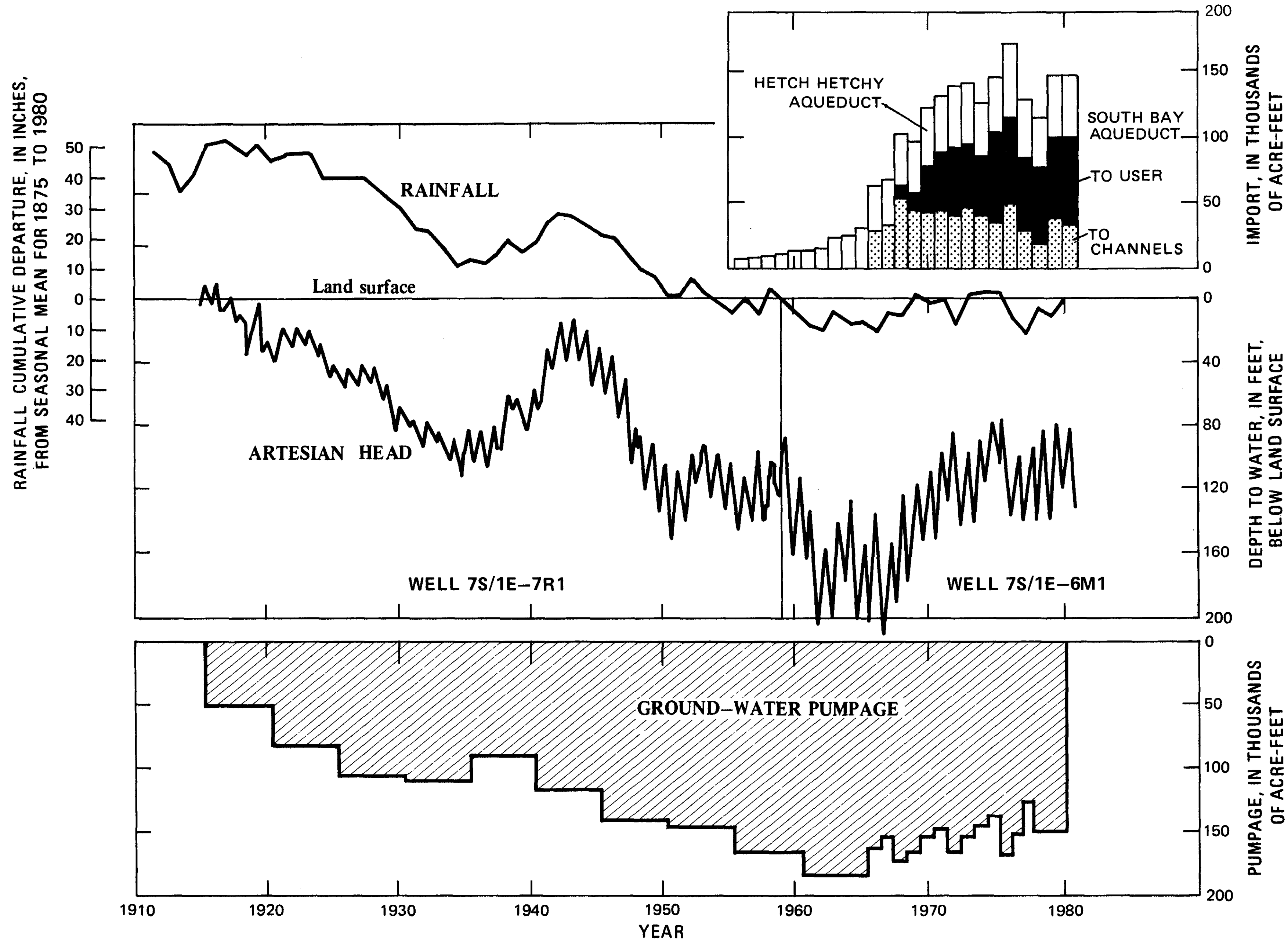


FIGURE 12.—Artesian-head change in San Jose in response to rainfall, pumpage, and water imports.

LAND SUBSIDENCE

HISTORY OF LEVELING CONTROL

The first precise leveling of bench marks within the subsiding area in Santa Clara County was carried out in 1912 on a line from Bingham, Utah, to San Francisco through Niles, San Jose, and Redwood City. This initial line and all subsequent leveling described in this report were accomplished by the National Geodetic Survey (formerly the U.S. Coast and Geodetic Survey).

In 1919, a line of first-order levels was run southward from San Jose. This leveling revealed subsidence of 0.4 ft at San Jose (fig. 22, bench mark P7). The first releveling early in 1932 showed subsidence since 1912 ranging from 0.35 ft in Palo Alto (bench mark I7) to 3.66 ft in San Jose. More extensive leveling early in 1933 confirmed the subsidence and provided additional control on its extent.

As a result of the great scientific interest in this regional subsidence, and through the joint efforts of A.L. Day, C.F. Tolman, and the National Geodetic Survey (Tolman and

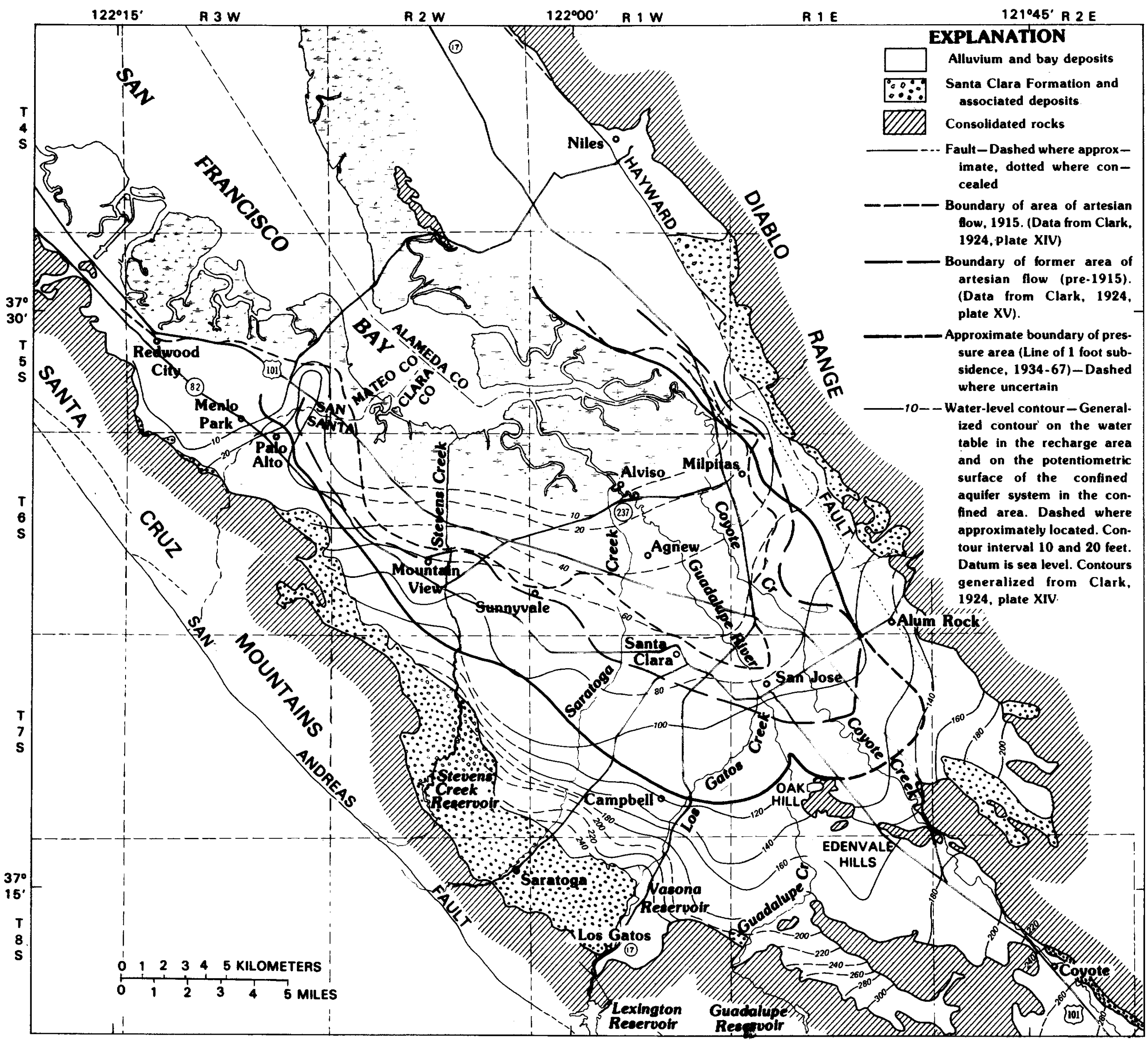


FIGURE 13.—Generalized water-level contours for spring and summer, 1915, north Santa Clara County.

Poland, 1940, p. 29), an extensive network was laid out in 1933 to determine by periodic releveling the extent, magnitude, and rate of subsidence.

The extent of the network is shown in figures 15 and 16. Initially numbered with single or double digits (fig. 15), the lines were renumbered by the National Geodetic Survey in the late 1950's using three-digit numbers (fig. 16). The network was completely leveled for the first time in the spring of 1934. The total length of survey lines composing this bench-mark net is about 250 mi. As shown in figure 15, level line 1 extends from Morgan Hill northwestward to San Jose and then northward along the east side of San Francisco Bay past Niles. Line 2 extends along the west side of the bay from San Jose northwestward past Redwood City. Three transverse lines (3, 18, and 9) extend southwestward across the San Andreas fault, and three (1, 4, and 6) extend eastward across the Hayward fault.

The times and extent of leveling of the net are shown in figure 17. Heavy lines drawn on the screened background define the leveling accomplished in a designated year, which may range from a single line to complete

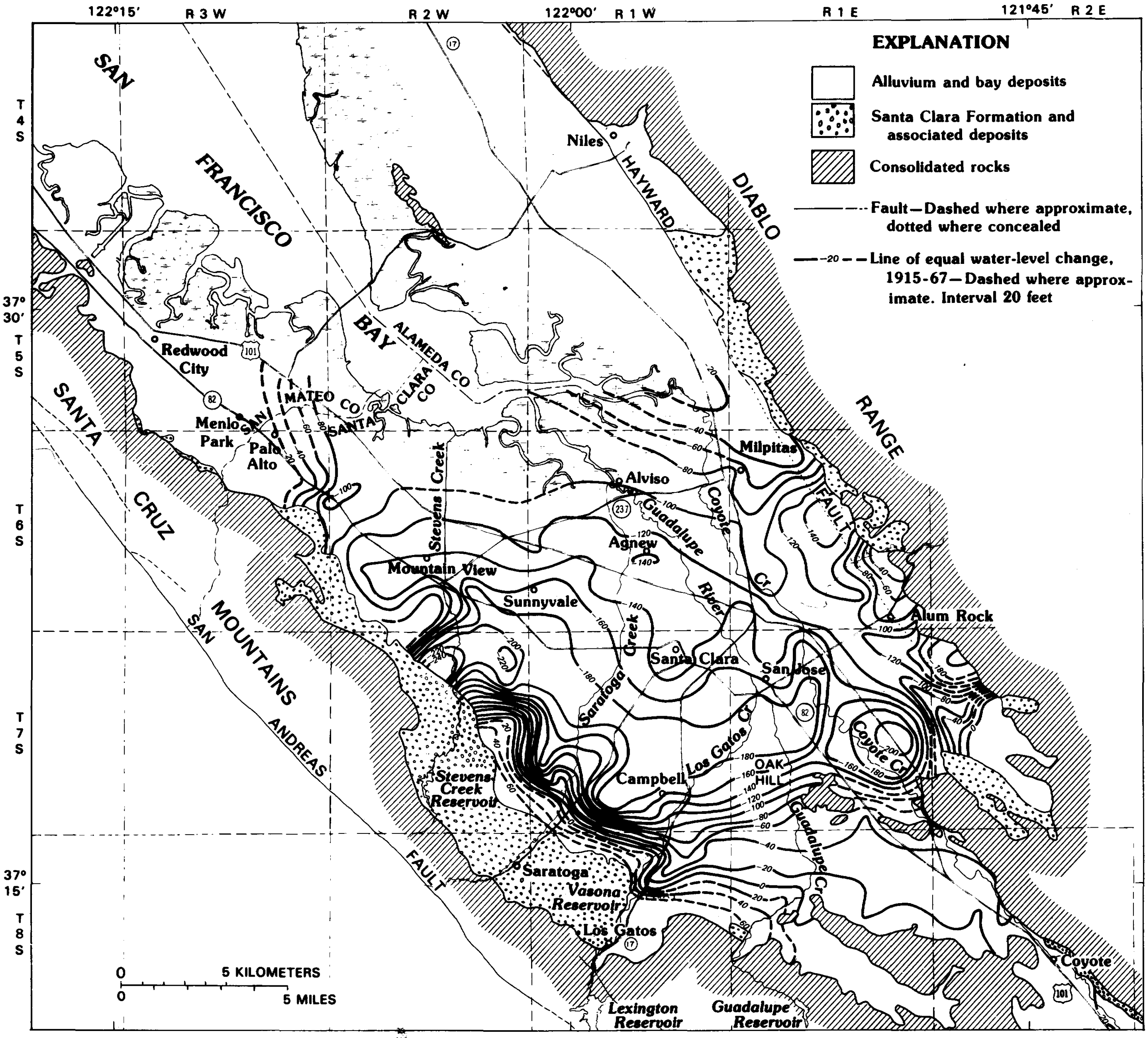


FIGURE 14.—Change in water level, 1915–67, north Santa Clara County.

coverage of the net, as in 1954 and 1960. In 1956, the National Geodetic Survey published a chronologic compilation of adjusted elevations, in feet, through 1954 for all bench marks in the network (U.S. Coast and Geodetic Survey, 1956).

Since the late 1950's, the primary control for identifying bench-mark elevations is the National Geodetic Survey's 30-minute quadrangle (for example, see parts of National Geodetic Survey quadrangles 371221, 371222, 371213, and 371214 in figure 16). Almost all the network is in National Geodetic Survey quadrangles 371213 and 371222. When requesting bench-mark elevations in subsiding areas from the National Geodetic Survey, one should specify quadrangle, line number, and year or years of leveling.

EXTENT AND MAGNITUDE OF SUBSIDENCE

The subsidence record for bench mark P7 in San Jose is plotted in figure 18, together with the fluctuation of artesian head in nearby index well 7S/1E-7R1-6M1 taken from figure 12. The black dots on the subsidence curve

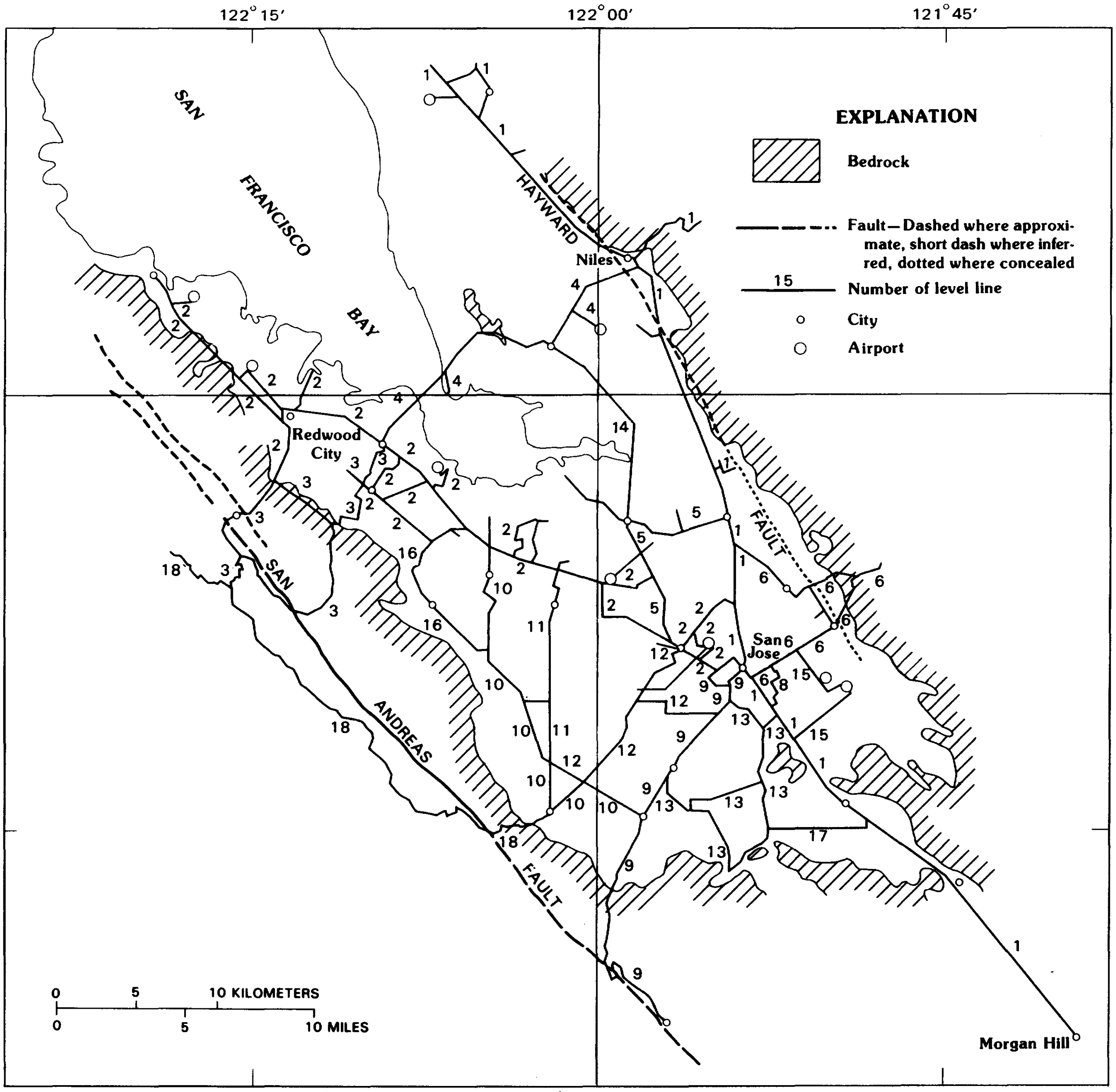


FIGURE 15.—Network of level lines in the San Jose subsidence area; initial numbering of level lines.

indicate times of bench-mark surveys. The fluctuation of artesian head represents the change in stress on the aquifer system, and the subsidence is the resulting strain. Subsidence at bench mark P7 began about 1916 and was 5.4 ft by 1938. From 1938 to 1947, subsidence stopped during a period of artesian-head recovery but resumed in 1947 coincident with a rapidly declining head. It attained its fastest average rate in 1960–63 (0.7 ft/yr). By 1967 the bench mark had subsided 12.67 ft. Releveling of bench mark P7 in 1969 showed a further small increase in subsidence to 12.88 ft.

Maps showing lines of equal subsidence for the periods 1934–54, 1948–54, and 1940–54 have been published earlier (Poland and Green, 1962, figs. 4, 5, and 6). Three additional subsidence maps are included in this report. They show subsidence from 1934 to 1960 (fig. 19), subsidence from 1960 to 1967 (fig. 20), and overall subsidence from 1934 to 1967 (fig. 21). To date (1984), 1967 was the last year of releveling of the bench-mark network.

From 1934 to 1960, maximum subsidence exceeded 5 ft at centers in San Jose and Sunnyvale (fig. 19). In that period subsidence beneath the bay tidelands ranged from

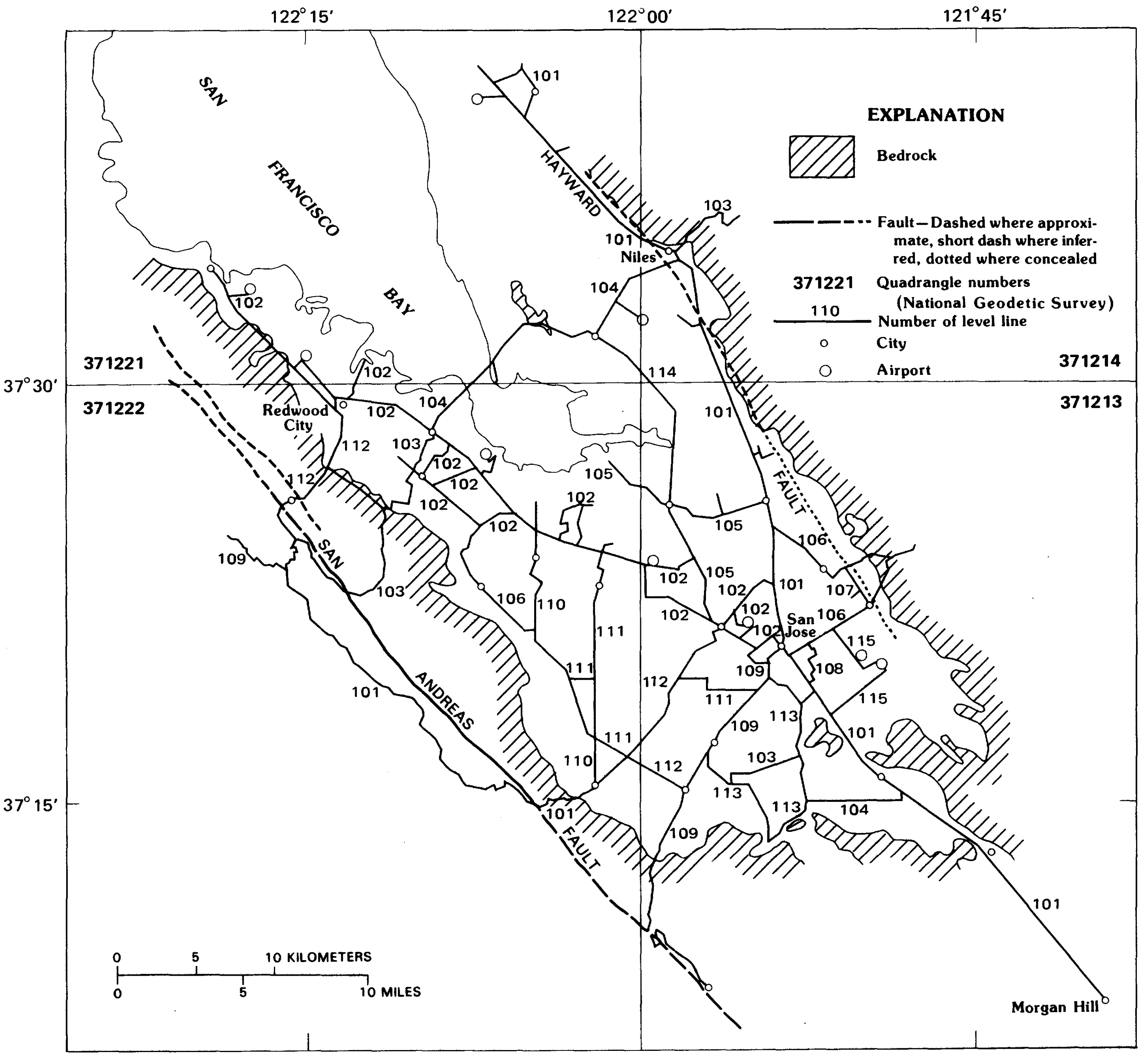


FIGURE 16.—Network of level lines in the San Jose subsidence area; numbering of level lines revised to three digits in the late 1950's.

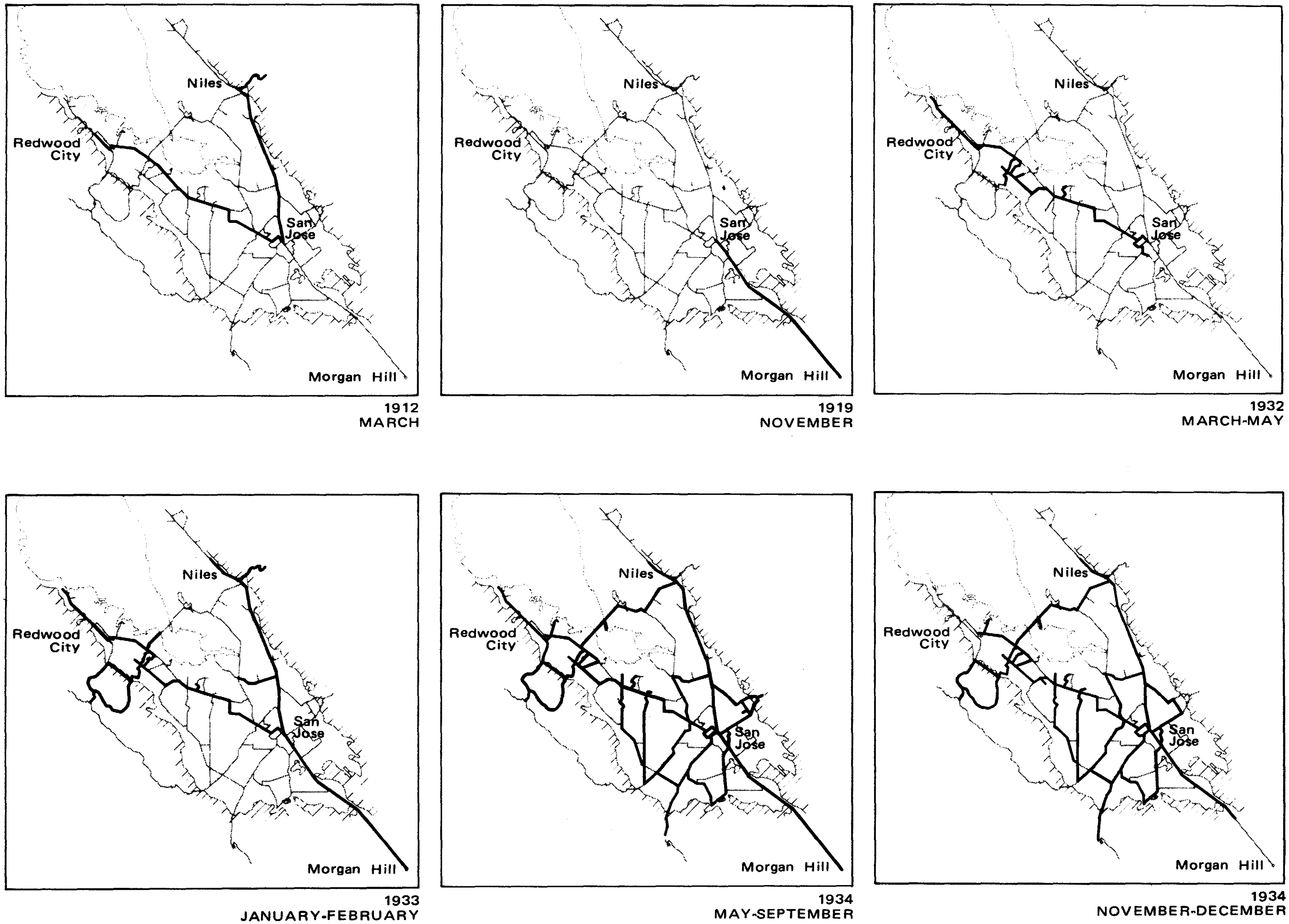


FIGURE 17.—Times and extent of leveling in the San Jose subsidence area.

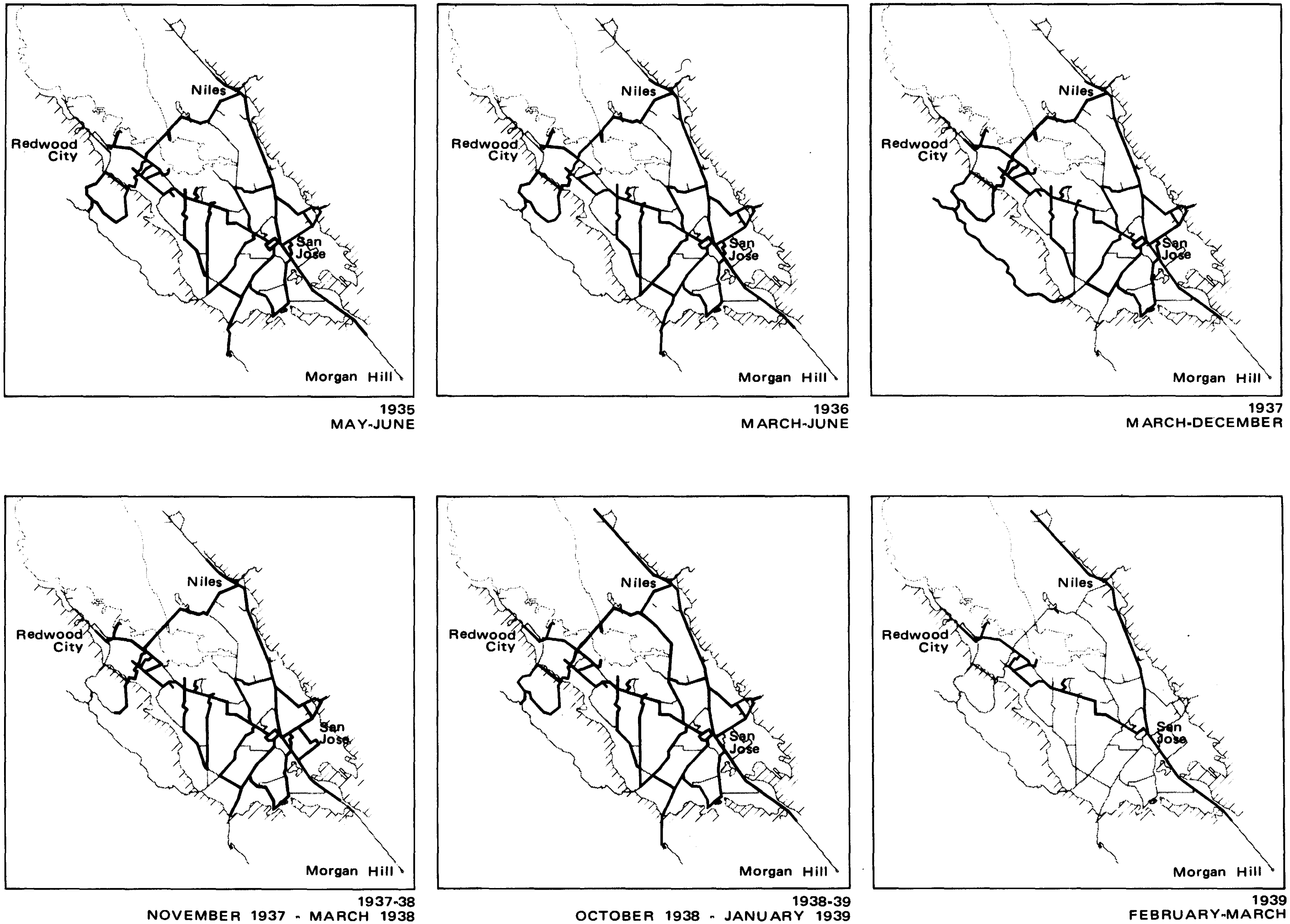


FIGURE 17.—Continued.

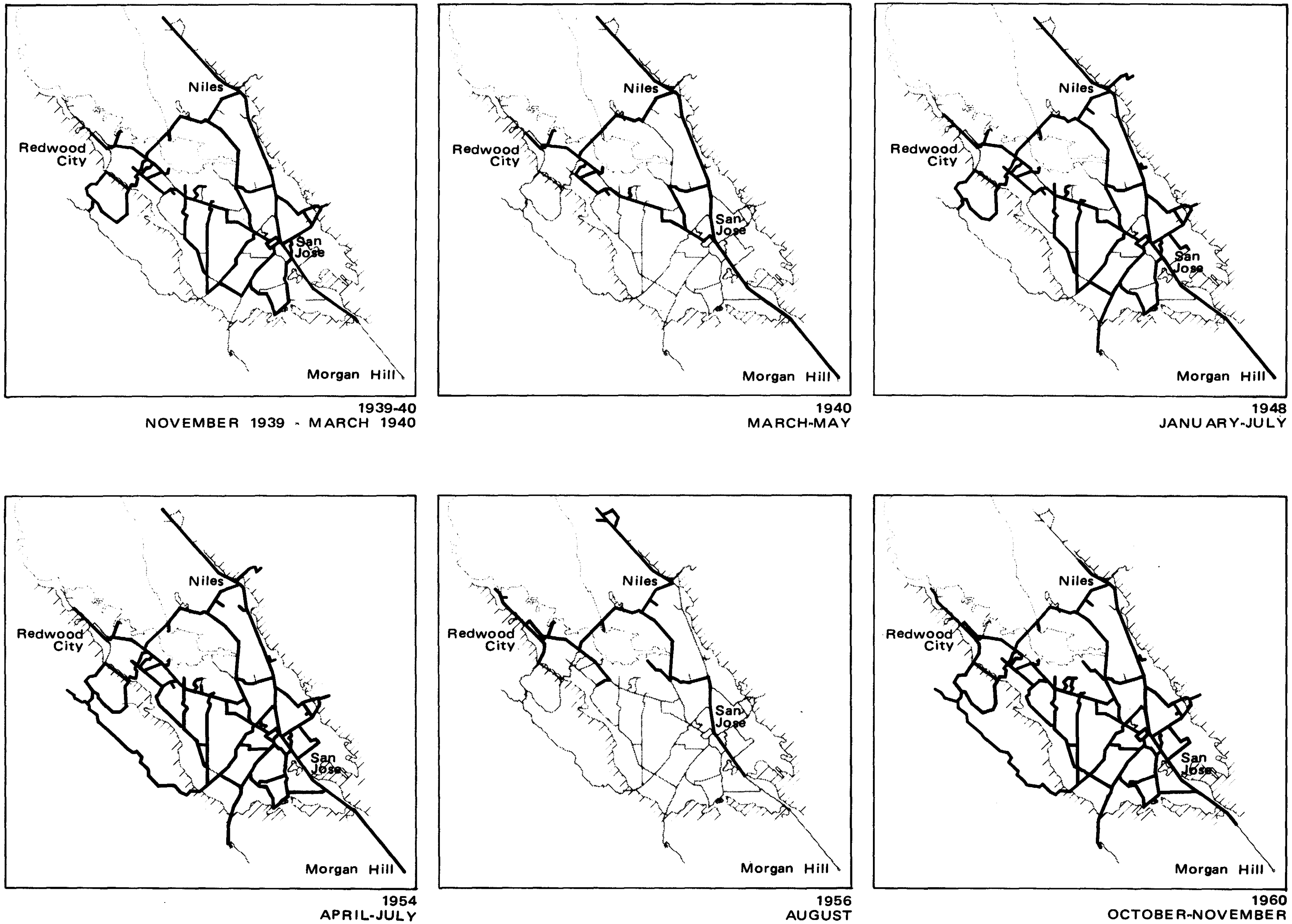


FIGURE 17.—Continued.

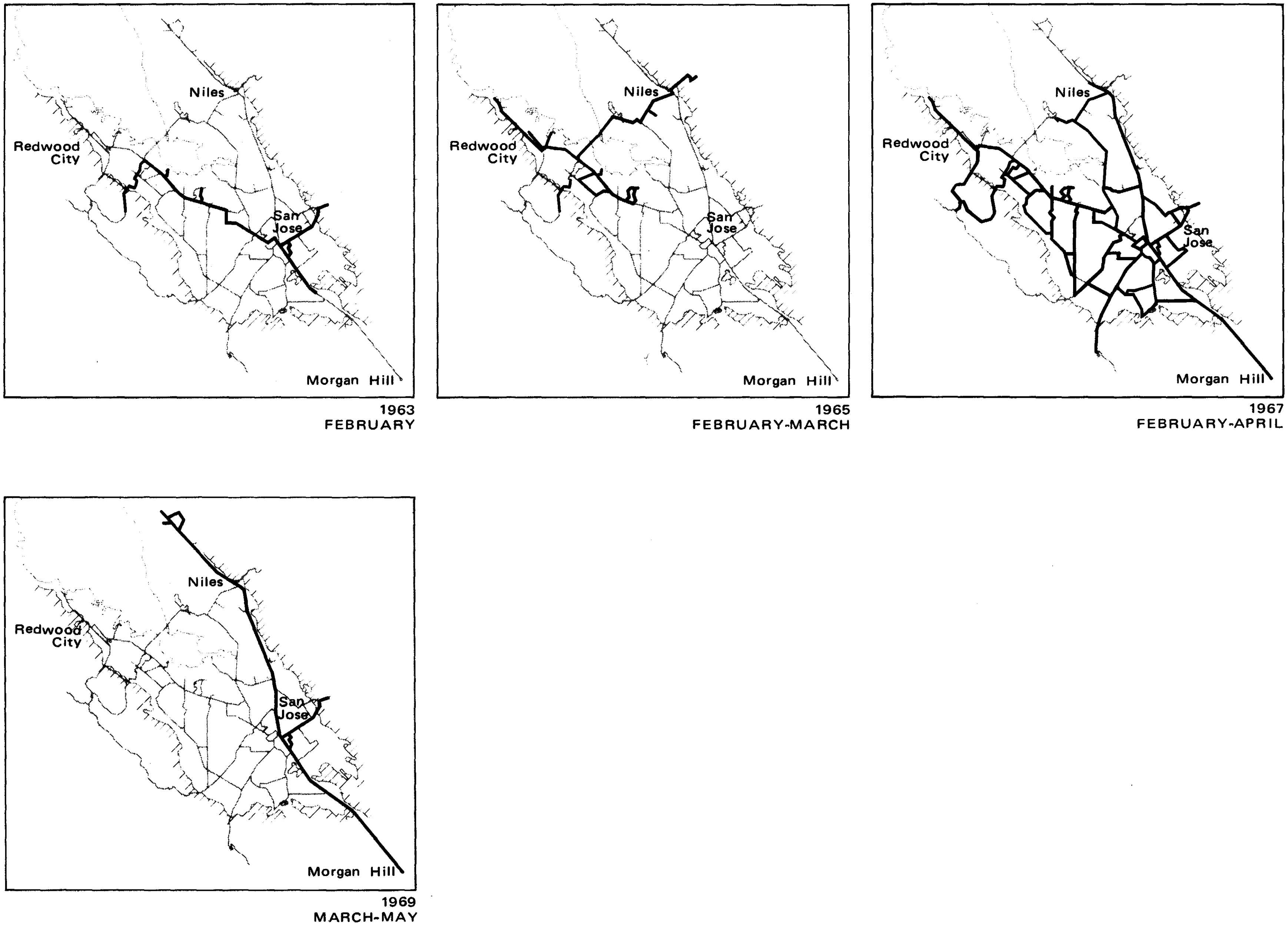


FIGURE 17.—Continued.

1 to 3 ft. As of 1960, the area of subsidence lay wholly within the area of alluvium and bay deposits. From 1960 to 1967, maximum subsidence exceeded 3.5 ft in San Jose and Santa Clara (fig. 20) and at one bench mark in San Jose was 3.9 ft. The average rate of subsidence was 0.5 ft/yr, the most rapid rate of subsidence in any 7-year period.

From 1934 to 1967, the National Geodetic Survey resurveyed the network from "stable" bedrock ties a dozen times to determine changes in altitude of the bench marks. During the 33-year period 1934–67, subsidence ranged from 2 to 5 ft under the bay and its tidelands to 8 ft in San Jose and Santa Clara (fig. 21). The volume of subsidence (pore-space reduction) planimetered from the 1934–67 subsidence map is about 500,000 acre-ft. If the ratio of the pre-1934 subsidence volume to the 1934–67 subsidence volume is assumed to be equal to the ratio of the pre-1934 subsidence of bench mark P7 to the 1934–67 subsidence of that bench mark, then the total subsidence volume from 1912 to 1967 is about 800,000 acre-ft.

When a line of bench marks in a subsidence area has been releveled a number of times, one of the most informative means of presenting subsidence information is to draw a series of subsidence profiles (figs. 22–24).

Land-subsidence profiles along line *D–D′* from Redwood City to Coyote from 1912 through 1969 are shown in figure 22 (for location of line *D–D′*, see fig. 21). The spring 1934 leveling was used as a reference base because it was the first complete leveling of the net. Subsidence before 1934 is plotted above the reference base, and subsidence after 1934 is shown below it. The marked increase in rate of subsidence after 1948 from Palo Alto to San Jose plainly is due to the increased decline of artesian head (fig. 18) in response to increased ground-water withdrawal (fig. 10). Note that from 1934 to 1967 maximum subsidence of 8.6 ft was near bench mark W111 3 mi northwest of bench mark P7; in addition, note that from 1934 to 1960 the greatest subsidence along line *D–D′* was 5.7 ft at bench mark J111 reset in Sunnyvale. Changes in the rate and magnitude of withdrawal and of artesian-head decline doubtless have caused much geographic variation in subsidence rate and magnitude with time.

Profiles of land subsidence along transverse line *E–E′* from Mountain View to Milpitas from 1933 to 1967 (fig. 23) have a pattern similar to that of the profiles in figure 22. The rate of subsidence prior to 1948 is low compared with the great increase in the rate thereafter. Benchmark J111 reset is common to both lines *D–D′* and *E–E′*; from 1934 to 1967 it subsided 7.8 ft.

Land-subsidence profiles along line *F–F′* from Los Gatos through San Jose to Alum Rock Park from 1934 to 1969 are displayed in figure 24. Bench mark I19 in San

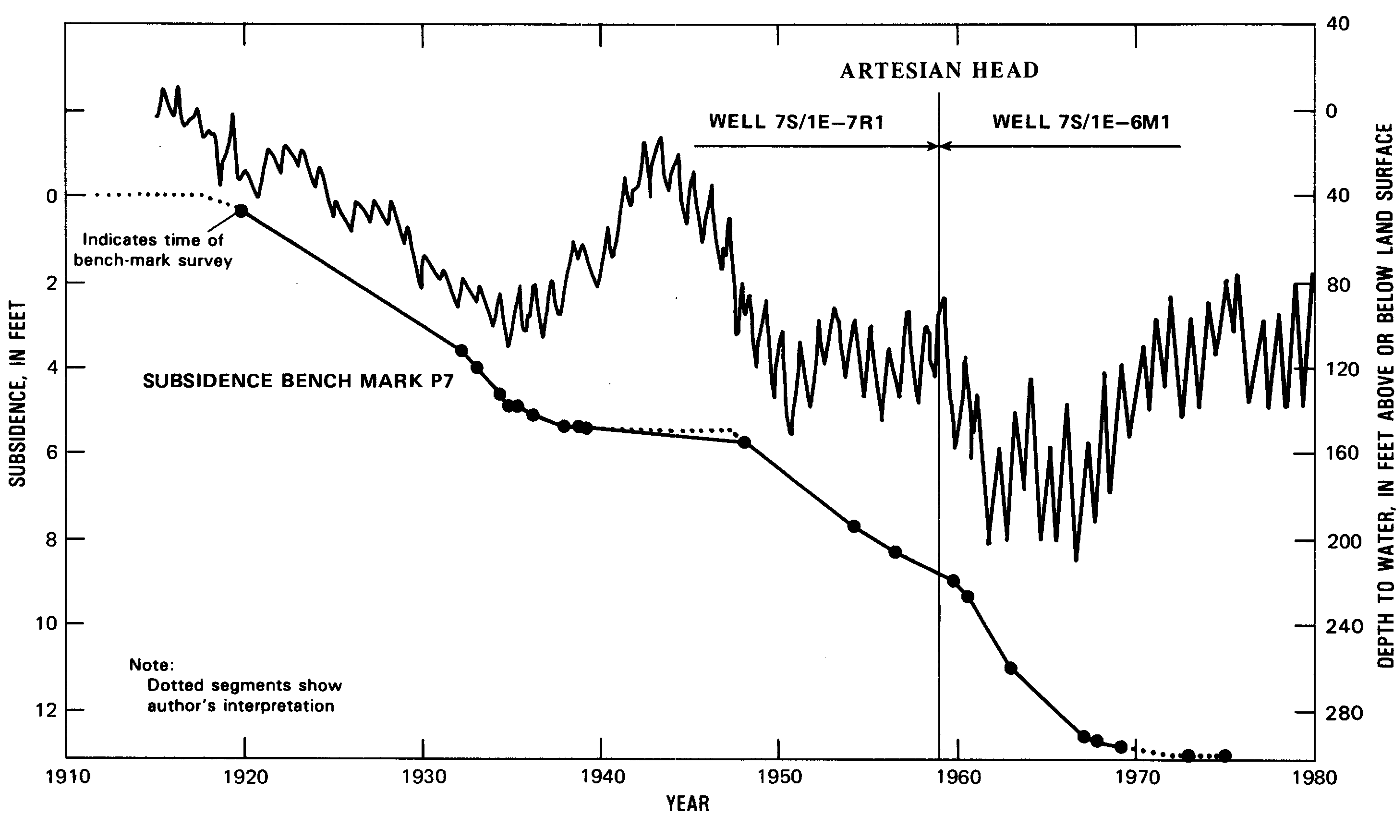


FIGURE 18.—Artesian-head change and land subsidence, San Jose.

Jose is common to both line D–D' and F–F'; it subsided 7.7 ft from 1934 to 1969 and was exceeded only by bench mark E176, which sank 8.7 ft in the same period. Although line F–F' crosses the concealed Hayward fault at Alum Rock, about 2.5 mi from the east end of the line, the relevelings from 1934–69 do not indicate any differential displacement across the fault.

ECONOMIC AND SOCIAL IMPACTS

Subsidence has caused several major problems. Lands adjacent to San Francisco Bay have sunk 3 to 9 ft since 1916, requiring construction and repeated raising of levees to restrain landward movement of the saline bay water as well as construction of flood-control levees near the bayward ends of the valley streams. The subsidence has affected stream channels in two ways: Channel grades crossing the subsidence bowl have been downwarped, and saline bay water has moved upstream. These changes tend to cause channel deposition near the bay and reduce channel capacity, creating the need for higher levees. Intrusion may occur where wells tapping shallow aquifers are pumped, inducing downward movement, especially through rusted well casings.

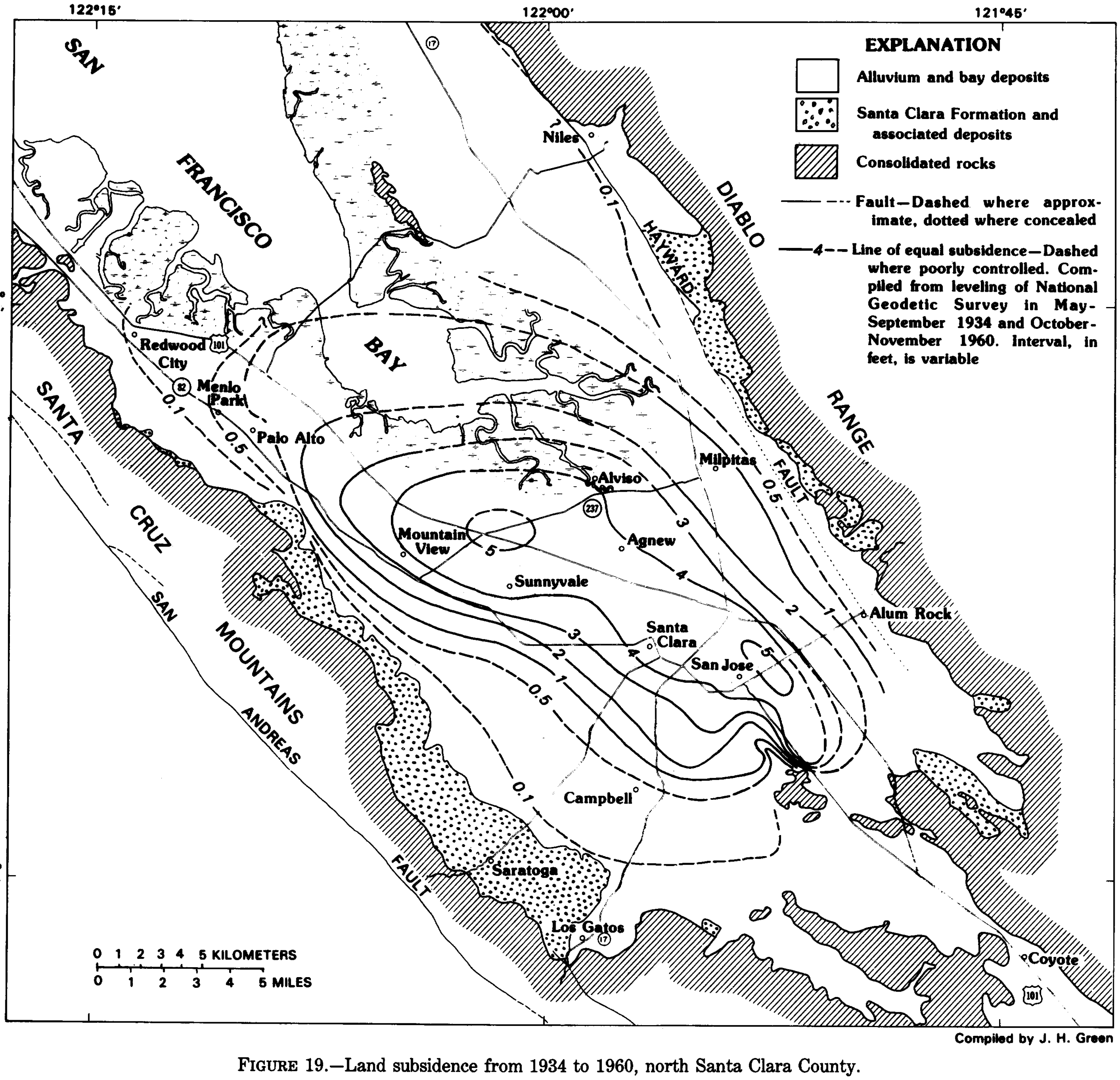
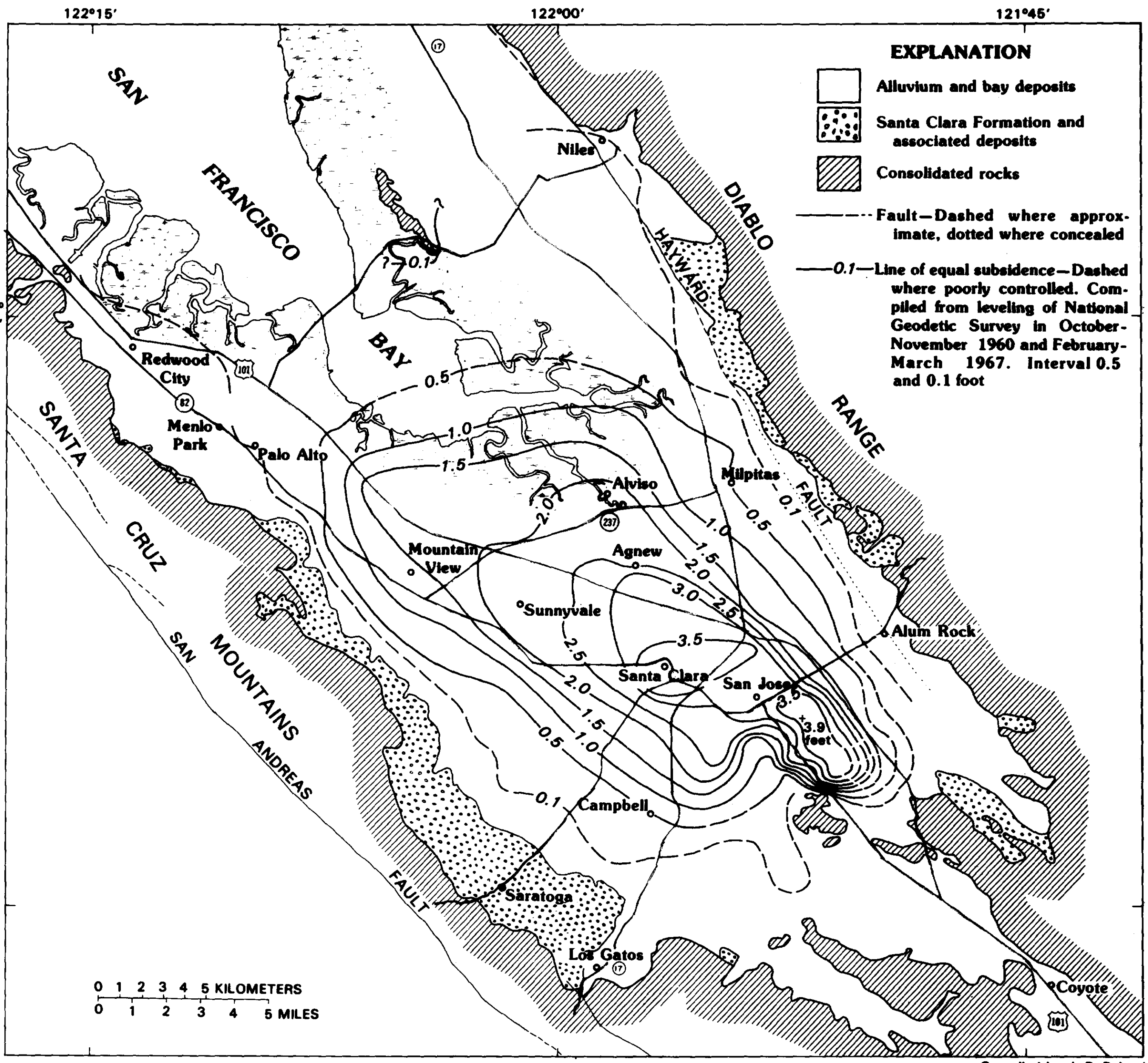


FIGURE 19.—Land subsidence from 1934 to 1960, north Santa Clara County.

About 30 mi^2 of evaporation ponds from Palo Alto around the south end of the bay are used for salt production. Behind the landward chain of dikes bordering these ponds, at least 17 mi^2 of land lie below the highest tide level of 1967. Currently these lands are protected by the dikes and stream-channel levees, but they as well as the bay-front levees are considered inadequate. Extensive flooding of the Alviso area in March to April 1983 attests to the inadequacy of the stream-channel levees.

By making use of the table of annual compaction (table 3) and the compaction-subsidence ratios for the 1,000-ft core holes (table 5), we can derive a rough estimate of the subsidence that occurred from 1969 through 1982. The measured compaction at 6S/2W-24C7 from 1969 through 1982 was 0.24 ft. If the ratio of compaction to subsidence for the 13-year period remained at 105 percent, the subsidence would be about 0.25 ft. The measured compaction at 7S/1E-16C11 from 1969 through 1982 (table 3) was 0.44 ft. If the ratio of compaction to subsidence for the 13-year period remained at 99 percent,the subsidence would also be 0.44 ft. These figures suggest that the subsidence for the 13-year period was on the order of half a foot at San Jose (16C11) and a quarter of a foot in Sunnyvale (24C7).



Compiled by J. F. Poland

FIGURE 20.—Land subsidence from 1960 to 1967, north Santa Clara County.

About $9 million of public funds had been spent to 1974 on flood-control levees to correct for subsidence effects, according to Lloyd Fowler, former Chief Engineer of the Santa Clara Valley Water District. In addition, the Leslie Salt Co. has spent an unknown but substantial amount maintaining levees on the 30 mi^2 of salt ponds to counter as much as 9 ft of subsidence in the Alviso area. Several hundred water-well casings have failed in vertical compression as a result of compaction of the sediments. The protrusion of well casings as much as 2 to 3 ft above land surface also has been observed (Tolman, 1937, p. 344). The cost of repair or replacement of such damaged wells has been estimated as at least $4 million (Roll, 1967). Including funds spent on maintaining the salt-pond levees, establishing and resurveying the bench-mark net, repairing railroads, roads, and bridges, replacing or increasing the size of storm and sanitary sewers, installing drainage pumping plants, and making private engineering surveys, the direct costs of subsidence must have been at least $30 to $40 million to date. Fowler (1981) has estimated that the direct costs of subsidence, including the estimated cost of a proposed new levee system, all figured in 1979 dollars, would exceed $100 million.

A major earthquake could cause failure of the bay-margin levees, which would result in the flooding of areas presently below sea level. The bay-margin levees were

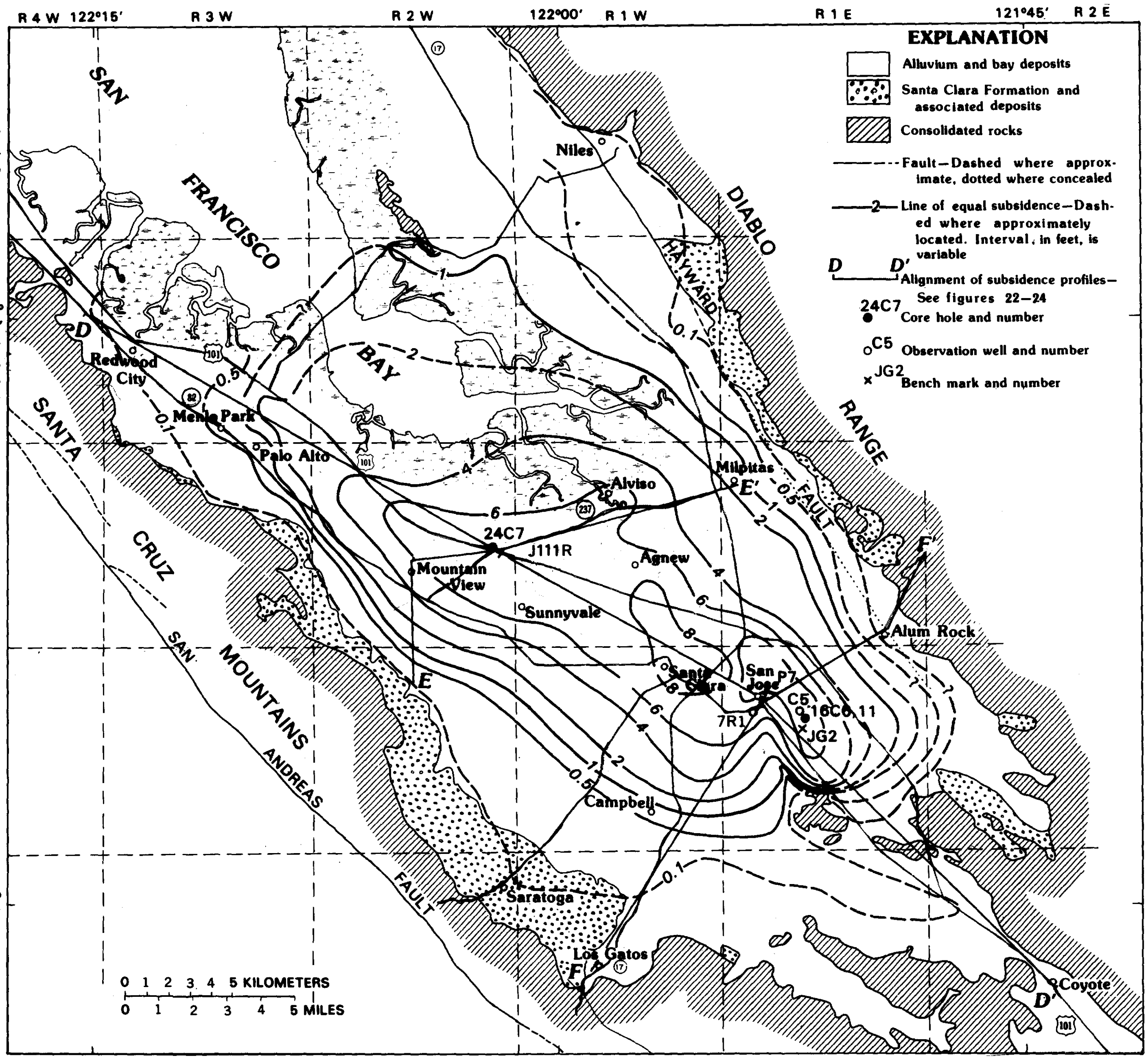


FIGURE 21.—Land subsidence from 1934 to 1967, north Santa Clara County.

constructed of locally derived weak materials and were designed only to retain salt-pond water under static conditions (Rogers and Williams, 1974). The potential for such an earthquake poses a continuing threat to flooding of the estimated 17 mi^2 of land standing below the high-tide level of 1967. Such a threat has probably reduced the value of this land substantially compared with its value if it all still stood above sea level as it did in 1912. This decrease in land values should be included in the gross costs of subsidence.

MONITORING OF COMPACTION AND CHANGE IN HEAD

MEASUREMENT OF COMPACTION

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

The first extensometer (compaction recorder) in the Santa Clara Valley was installed in 1958 at well 6S/1W-23E1 in Agnew. In 1960, extensometers were installed in the cased core holes 1,000 ft deep at the centers of subsidence in San Jose (7S/1E-16C6) and in Sunnyvale (6S/2W-24C7), in two satellite holes in Sunnyvale (24C3 and 24C4), and in two unused water wells. They have

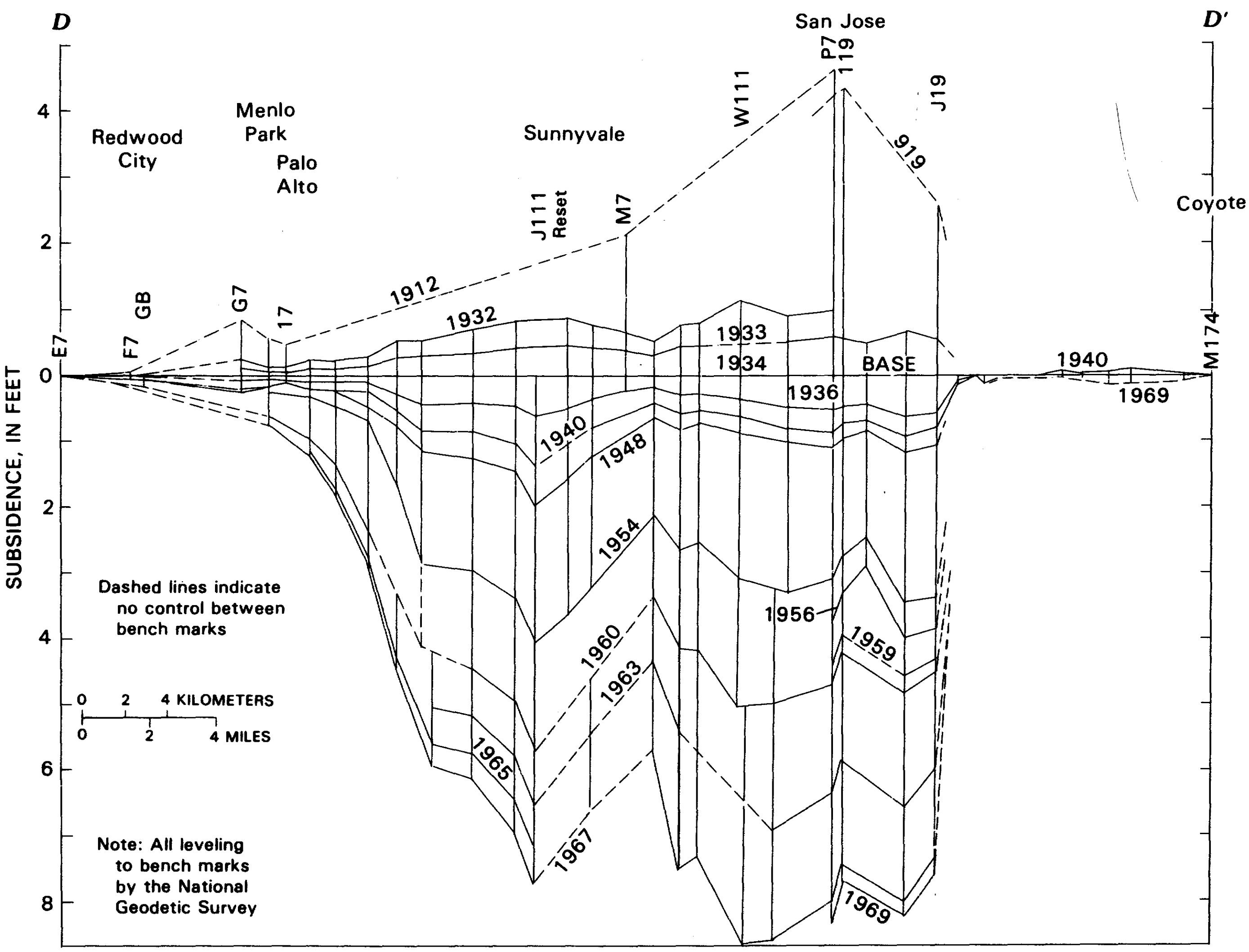


FIGURE 22.—Profiles of land subsidence, *D-D'*, Redwood City to Coyote, 1912–69.

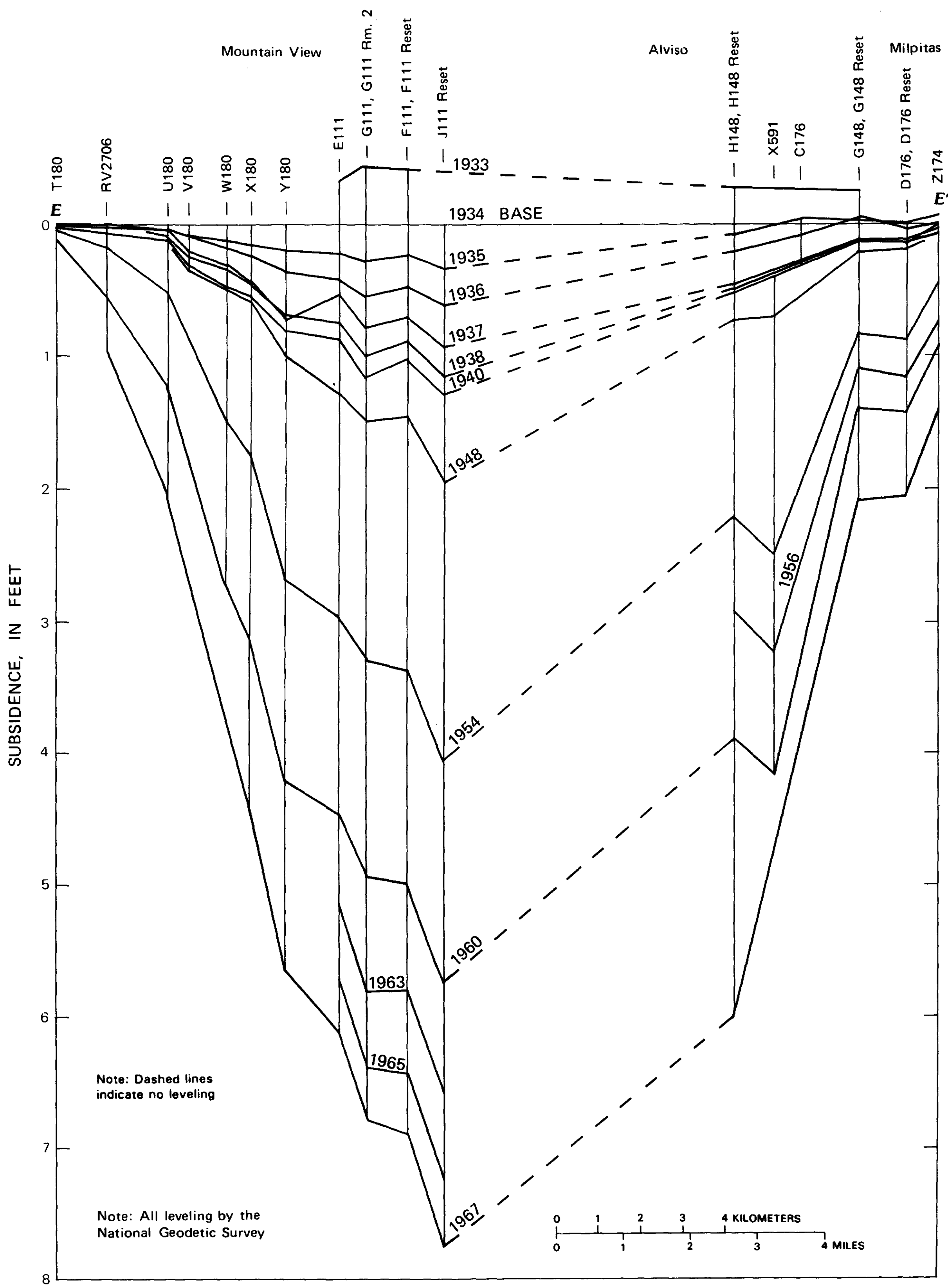


FIGURE 23.—Profiles of land subsidence, *E-E'*, Mountain View to Milpitas, 1933–67.

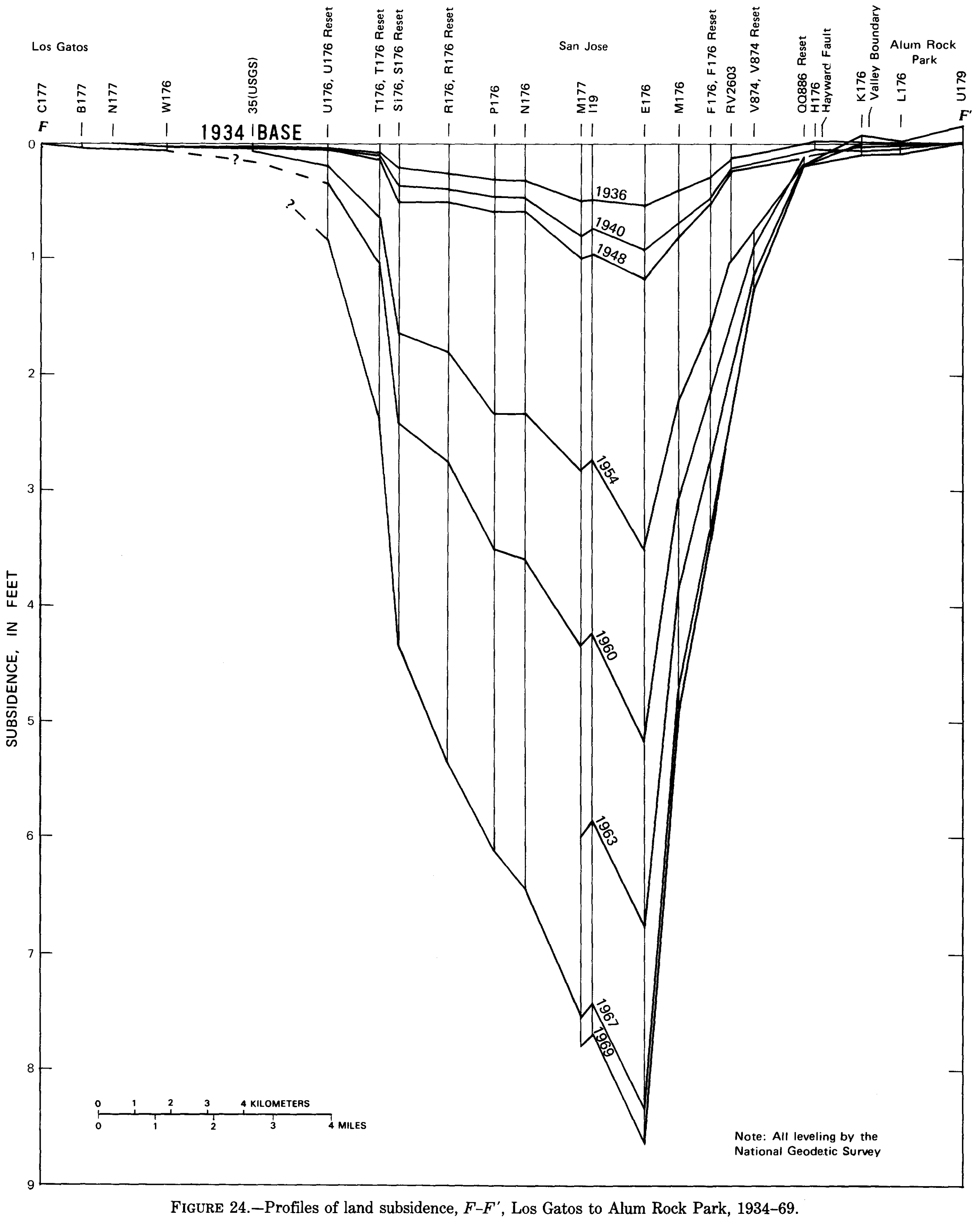


FIGURE 24.—Profiles of land subsidence, *F–F′*, Los Gatos to Alum Rock Park, 1934–69.

recorded compaction or expansion of the confined aquifer system for 22 years.

Core hole 7S/1E-16C6 was destroyed in 1969 during the construction of a freeway. It was replaced in 1969 by another 1,000-ft extensometer, well 7S/1E-16C11.

Extensometers of two types are in use (fig. 25). In the cable type (fig. 25*A*), an anchor weight is attached to the extensometer cable, lowered into the well, and set below the bottom of the well casing. This anchor acts as a depth bench mark. The extensometer cable is maintained

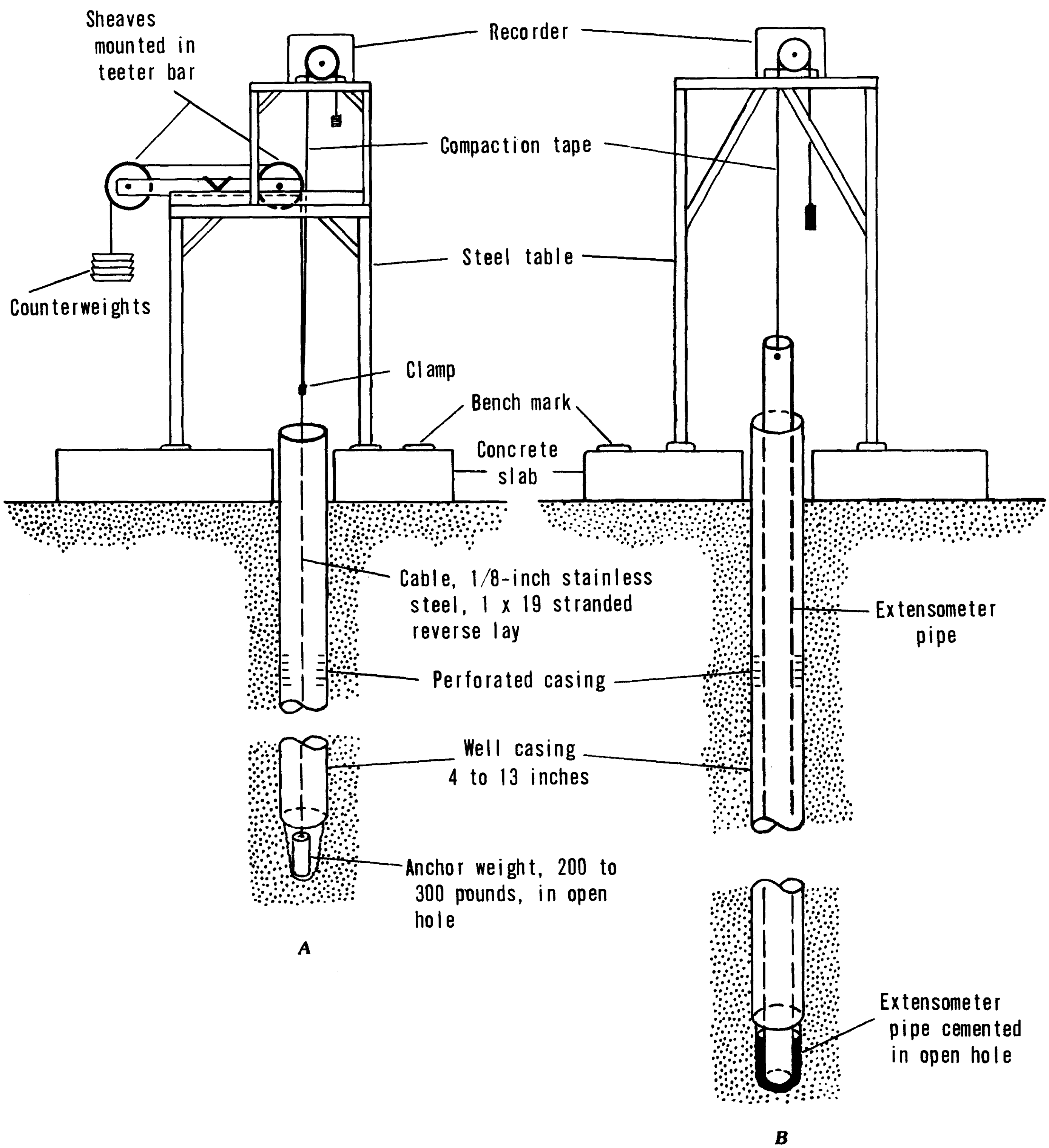


FIGURE 25.—Recording extensometer installations. *A*, Anchored cable assembly. *B*, Pipe assembly.

(ideally) under constant tension by a counterweight at the land surface. As the aquifer system compacts, an equivalent length of cable appears to emerge from the well; this movement is measured by a mechanical recorder attached to the compaction cable at land surface. In the free-standing pipe extensometer (fig. 25*B*), the pipe is lowered into the well and set below the bottom of the well casing. A mechanical recorder attached to the extensometer pipe measures the movement of the land surface relative to the nonmoving pipe and thus measures the compaction or expansion of the aquifer system.

The accuracy of the compaction record is dependent largely on the ability of the extensometer cable or pipe to maintain a constant length between the bottom-hole reference point and the above-ground reference point. Friction tends to develop between the extensometer cable or pipe and the deforming well casing, which shortens and moves downward in the grip of the compacting sediments. Because of its much greater cross section, the pipe is more competent than the cable to resist frictionally induced length changes. Therefore it generally produces a better record in typical wells of moderate depth, but other factors may be involved in selecting the design for a specific site.

When initally installed, all the extensometers were of the anchored-cable type. To reduce the friction problem and increase the accuracy of measurement, the three paired Sunnyvale extensometers (6S/2W-24C3, C4, and C7) and 7S/1E-16C11 in San Jose were modified in the early 1970's by replacing the anchored cable with a free-standing pipe of 1.5-in. diameter (fig. 25*B*) in the casing. Well 16C11 has 6-in. casing, the other three have 4-in. casing.

The kind of field record being obtained in 1981 at the multiple extensometer site at Sunnyvale (wells 6S/2W-24C3, C4, and C7) is illustrated in figure 26. The compaction was recorded on a chart with a vertical scale (compaction) of 10:1 and a horizontal scale of 10 days/in. The compaction records from the three extensometers were traced on a common chart base for a 1-year period from March 20, 1981, to March 26, 1982. The maximum compaction occurred on October 3, 1981.

Compaction and expansion in feet
[minus (−) indicates expansion]

Date	C4 (250 ft)	C3 (550 ft)	C7 (1,000 ft)
4/1/81	0	0	0
10/3/81	0.015	0.061	0.076
3/26/82	−.015	−.061	−.076
Net change from 4/1/81 to 3/26/82	0	0	0

These compaction plots are of interest for two reasons. First, they illustrate the sensitivity of the recording

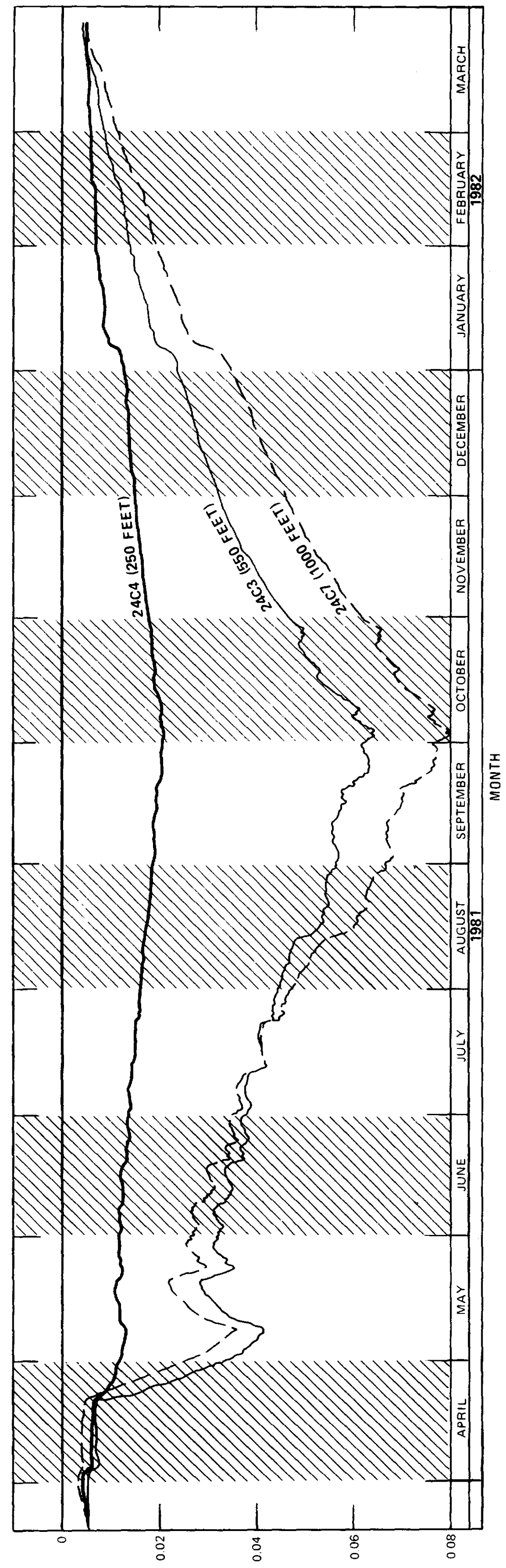


FIGURE 26.—Elastic response of multiple extensometers at the Sunnyvale site 6S/2W-24C, 1981–82.

extensometers to very small changes in applied stress. Secondly, we can see from the plots in figure 26 that the measured compaction from April 1, 1981, to March 26, 1982, at the Sunnyvale site all occurred within the elastic range of stress; that is, no permanent deformation occurred in the aquifer systems.

Continuous or periodic water-level measurements are also necessary in a subsidence-monitoring program in order to define the cause-and-effect relationship of the subsidence process. Moreover, in order to produce reliable stress-strain or stress-compaction plots that can be utilized to derive storage and compressibility characteristics of the aquifer system, water-level measurements must represent the average change in stress in the compacting interval being measured.

At the Sunnyvale site, for example, wells 24C4 (250-ft depth) and 24C3 (550-ft depth) are open-bottom blank casings drilled primarily as extensometers. Periodic water-level measurements have been made and are recorded in the computer plots of field records (figs. 32, 34, 36) and supplementary records of 1980–82 (figs. 43, 44). The hydrograph for the 250-ft well (24C4) shows an annual fluctuation of about 50 ft and may be a fair representation of stress change for the confined depth interval from 200 to 250 ft (fig. 32*A*). The hydrograph for the 550-ft well (24C3), on the other hand, was very sluggish from 1964–74 (fig. 34*A*) and is not considered reliable as a measure of stress change in the depth interval 250 to 550 ft.

The Geological Survey terminated field monitoring of compaction and water-level change on this study in January 1983. At that time, extensometers were in use in five wells at two compaction and water-level monitoring sites (wells 6S/2W-24C3, C4 and C7 in Sunnyvale and wells 7S/1E-16C5 and C11 in San Jose; for location, see fig. 1). The five wells will continue to be monitored by the Santa Clara Valley Water District for compaction of the aquifer system and water-level change.

The net annual compaction or expansion (negative compaction) at each site for the entire period of record through 1982 is summarized in table 3, as are records of compaction or expansion in two additional depth intervals defined by multiple-depth installations. For example, at 6S/2W-24C, wells C3, C4, and C7 are respectively 550, 250, and 1,000 ft deep. The extensometer in well C7 records total compaction from land surface to the 1,000-ft depth, and the extensometer in C3 measures the compaction from land surface to the 550-ft depth. By subtracting the compaction in C3 from that in C7, the compaction of the 550- to 1,000-ft depth interval is calculated.

The marked decrease in the annual compaction in response to the substantial head recovery since 1966 is demonstrated graphically by the compaction records from the two deep extensometers in Sunnyvale and San Jose (fig. 27). The annual compaction in well 7S/1E-16C6-11 in San Jose decreased from about 1 ft in 1961 and 1962 to 0.24 ft in 1967 and to 0.01 ft in 1973. Net expansion (land-surface rebound) of 0.02 ft occurred in 1974. In 1976 the drought caused a sharp decline of artesian head (fig. 40), which in turn increased compaction to 0.11 ft at the San Jose site. In Sunnyvale, compaction of the aquifer system in well 24C7 decreased from about 0.45 ft in 1961 to 0.04 ft in 1973; net expansion of 0.016 ft and 0.04 ft occurred in 1974 and 1975, respectively.

The subsidence of surface bench marks from 1960 to 1967 (or 1969), plotted on the long-term compaction plots for wells 6S/2W-24C7 (fig. 38) and 7S/1E-16C6-11 (fig.

TABLE 3.—*Annual compaction at compaction-*

[In order to arrive at consistent sums, the amount of annual compaction is shown to 0.001 ft; however, many

Well number	Anchor depth when installed (feet)	Depth interval (feet)	Start of record	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
6S/1W-23E1---	425	0-425	9/10/58	0.093	0.214	0.141	0.270	0.253	0.119	0.153	0.142	0.145	0.027
6S/2W-24C4---	250	0-250	1/29/60			.037	.058	.040	.030	.053	.018	.027	.017
-24C3---	550	250-550	1/29/60			.200	.151	.152	.123	.144	.104	.125	.070
-24C3---	550	0-550	1/29/60			.237	.209	.192	.153	.197	.122	.152	.087
-24C7---	1,000	550-1,000	6/30/60				.244	.172	.177	.182	.174	.144	.126
-24C7---	1,000	0-1,000	6/30/60			.211	.453	.364	.330	.379	.296	.296	.213
7S/1E-9D2----	605	0-605	5/5/60			.094	.333	.408	[1].047				
-9D2----	605	0-605	1/14/65								.210	.200	.087
7S/1E-16C5---	908	0-908	8/16/60			.080	.712	.918	.429	.394	.397	.418	.226
-16C6---	1,000	0-1,000	6/30/60			.276	.966	1.021	.399	.506	.410	.477	.236
-16C11--	1,000	0-1,000	6/2/69										

[1]Record ends April 22, 1963 (equipment failure)
[2]Site abandoned May 1978
[3]C6 record ends June 2, 1969, and C11 starts on June 2, 1969

41), demonstrates that the measured compaction to the 1,000-ft depth is approximately equal to the measured subsidence as determined by bench-mark surveys. The close agreement of the compaction and subsidence values at the Sunnyvale and San Jose sites is shown in table 5. At the San Jose site (16C6), measured subsidence from October 1960 to May 1969 was 4.21 ft, and measured compaction for the same time period was 4.17 ft; thus the ratio of compaction to subsidence was 99 percent, which means that all of the subsidence is due to the measured compaction to the 1,000-ft depth.

ANALYSIS OF STRESSES CAUSING SUBSIDENCE

Increase in effective stress (grain-to-grain load) is the cause of compaction of sediments. The withdrawal of water from wells reduces the head in the aquifers that are tapped and increases the effective stress borne by the aquifer matrix. The reader interested in a quantitative analysis of stresses causing subsidence is referred to Lofgren (1968) and to Poland and others (1975, p. 39–44).

In summary, water-level fluctuations change effective stresses in the following two ways: (1) A rise of the water table provides buoyant support for the grains in the zone of the change, and a decline removes the buoyant support; these changes in gravitational stress are transmitted downward to all underlying deposits. (2) A change in position of either the water table or the artesian head, or both, may induce net vertical hydraulic gradients across confining or semiconfining beds and thereby produce a net seepage stress. The vertical normal component of this stress is algebraically additive to the gravitational stress that is transmitted downward to all underlying deposits. A change in effective stress results if the preexisting seepage stress across the bed is altered in direction or magnitude.

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

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

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

EXAMPLE OF STRESS-STRAIN GRAPH

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

Nineteen years (1960–79) of measured water-level change (well 7S/1E-16C5) and compaction (well 7S/1E-16C6-11) in San Jose are shown in figure 41, together with a computer plot of stress change versus strain. Well 16C5 is 908 ft deep, and compaction in well 16C6-11 is measured to 1,000 ft, spanning the full 800-ft thickness of the aquifer system from the 200- to the 1,000-ft depth. As the water levels at this San Jose site rose rapidly after 1967 (fig.

measuring sites in north Santa Clara County

measured yearly values are not accurate to less than a few hundredths of a foot. Minus (–) indicates expansion]

1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	Total measured compaction (feet)
0.028	-0.022	-0.031	0	0.024	-0.021	-0.024	-0.012	0.043	0.018	-0.027	0.003				1.536
.009	0	.009	.044	-.027	-.006	-.002	-.005	.004	.003	-.003	-.005	-0.001	0.003	-0.005	.298
.064	.021	-.008	-.032	.028	-.023	-.020	-.016	.022	-.002	.001	.004	-.002	.002	-.005	1.103
.073	.021	.001	.012	.001	-.029	-.022	-.021	.026	.001	-.002	-.001	-.003	.005	-.010	1.401
.092	.081	.020	.018	.024	.069	.006	-.016	.025	.008	.023	.001	-.004	.008	-.001	1.573
.165	.102	.021	.030	.025	.040	-.016	-.037	.051	.009	.021	0	-.007	.013	-.011	2.948
															.882
.041	.038	.010	.007	.057	-.003	-.019	-.014	.043	[2].036						.693
.156	.054	.044	.106	.123	.030	.021	.026	.095	.049	.027	.029	-.027	.040	-.028	4.319
.129	[3].023														4.443
	.071	.075	.064	.050	.007	-.019	.011	.114	.043	.006	.042	-.018	.028	-.035	.439

41*A*), the stress-strain curves obtained from the paired measurements of compaction and artesian head began to show seasonal expansion during the winter months when the water level was highest and the effective stress on the confined system was lowest (fig. 41*D*). These stress-strain loops can be used to obtain the compressibility of the confined system in the recoverable or elastic range of stresses (less than preconsolidation stress). The stress-strain curve for 1967–74 has been enlarged in figure 28. Depth to water is plotted increasing upward. Change in depth to water represents an average change in stress in all aquifers of the confined aquifer system tapped by well 16C5. The lower parts of the descending segments of the annual loops for the winters of 1967–68, 1969–70, and 1970–71 are approximately parallel, as shown by the dotted lines, indicating that the response is essentially elastic in both aquifers and aquitards when the depth to water is less than about 180 ft. The heavy dashed line drawn parallel to the dotted lines represents the average slope of the segments in the range of stresses less than preconsolidation stress. The reciprocal of the slope of this line is the component of the storage coefficient attributable to elastic or recoverable deformation of the aquifer-system skeleton, S_{ke}, and equals 1.5×10^{-3}. The component of average specific storage due to elastic deformation, S_{ske}, equals S_{ke}/800 ft = 1.87×10^{-6}/ft. If stresses are expressed in feet of water, and if γ_w (the unit weight of water) equals unity, the average elastic compressibility of the aquifer system skeleton, α_{ke}, is equal numerically to S_{ske}.

In these computations we have assumed that in the range of stresses less than preconsolidation stress, the compressibility of the aquitards and of the aquifers is the same. Therefore, the full thickness of the confined aquifer system, 800 ft, was used to derive the average specific storage component, S_{ske}, in the elastic range of stress.

COMPUTER SIMULATION OF AQUIFER-SYSTEM COMPACTION

As stated by Helm (1978), land subsidence due to ground-water withdrawal from a confined aquifer system

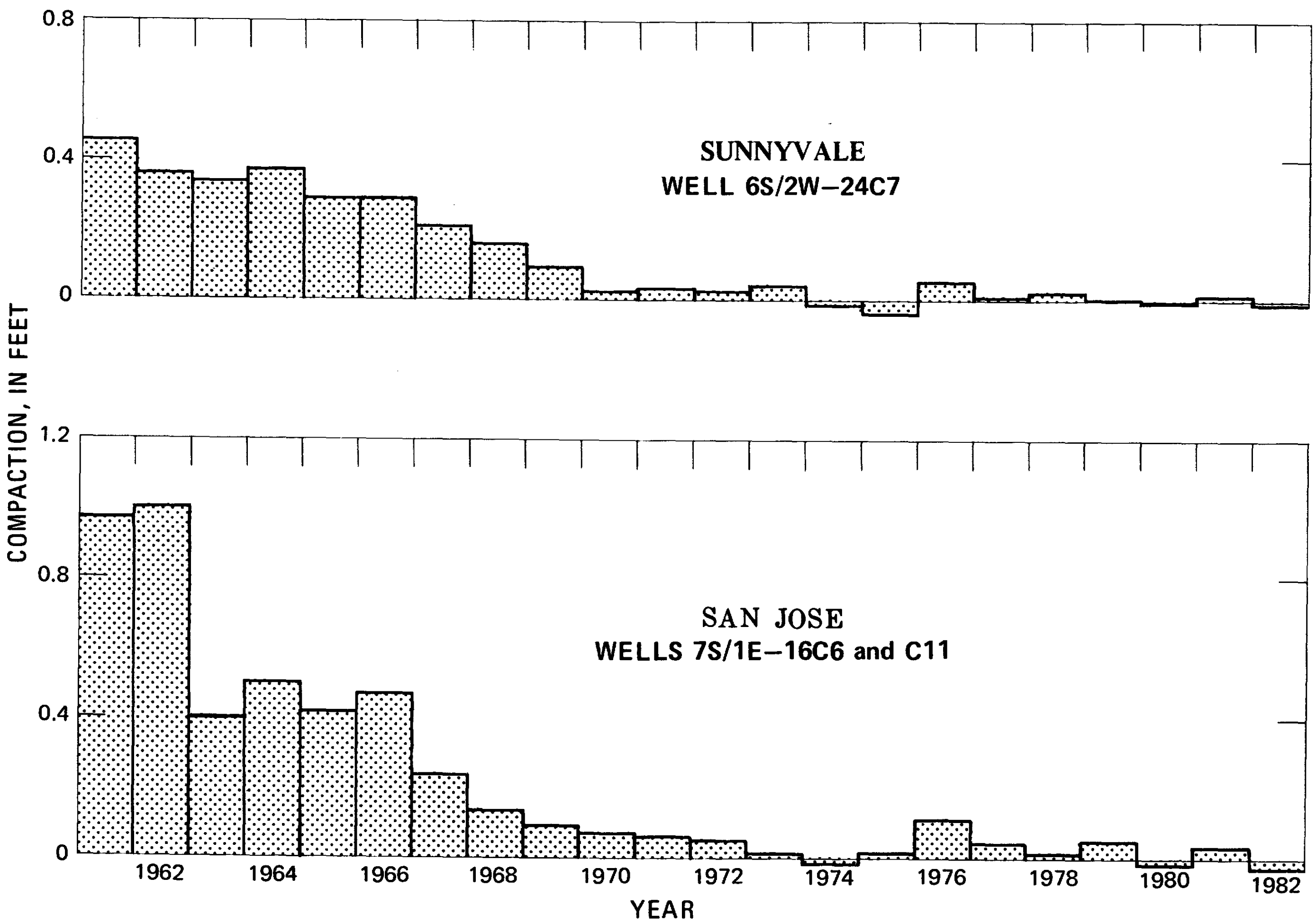


FIGURE 27.—Measured annual compaction in wells 1,000 ft deep in Sunnyvale and San Jose.

is an expression at land surface of net compaction (vertical consolidation) at depth of compressible layers within the system. Water-level fluctuations within coarse-grained aquifers produce stress changes on the upper and lower boundaries of slow-draining aquitards (compressible fine-grained interbeds). Indirectly, irregular and cyclic pumping drawdowns generate complex loading and unloading stress patterns in the aquifer system, causing compaction and expansion of the aquitards. Within a confined system, any lag in compactive response to such a load increase is usually ascribed to slow vertical drainage from the aquitards. After water levels in coarse-grained material rise during a period of water-level recovery, it has been observed during the next cycle of declining water levels that nonrecoverable compaction is reinitiated before water levels reach their prior lowest level.

Helm (1977) developed a one-dimensional mathematical model of vertical deformation based on a modification of Karl Terzaghi's consolidation theory; the model computes transient aquitard compaction and expansion due to arbitrarily specified changes in effective stress within an adjacent aquifer. This model has been applied by Helm (1977) to observed water-level fluctuations and to the resulting observed transient compaction-and-expansion behavior of the confined aquifer system at seven sites in the Santa Clara Valley.

According to Helm, values for total cumulative thickness b'_{sum} of fine-grained interbeds within the confined aquifer system, the weighted-average thickness b'_{equiv} of these interbeds, recoverable vertical compressibility S'_{ske}, and the initial distribution of preconsolidation pressure p'_{max} $(z, 0)$ must be approximated from field data independently of any subsequent simulation process. Only values for vertical components of hydraulic conductivity K' and nonrecoverable compressibility S'_{skv} are adjusted by trial-and-error to fit calculated-to-observed compaction history. The estimated values for K' at the sites studied range from 0.56×10^{-6} to 12.5×10^{-6} ft/d, those for S'_{skv} range from 1.4×10^{-4} to 13.1×10^{-4}/ft, and those for S'_{ske} range from 2.2×10^{-6} to 15.8×10^{-6}/ft (table 4).

For established values of b'_{sum}, b'_{equiv}, and p'_{max} $(z, 0)$,

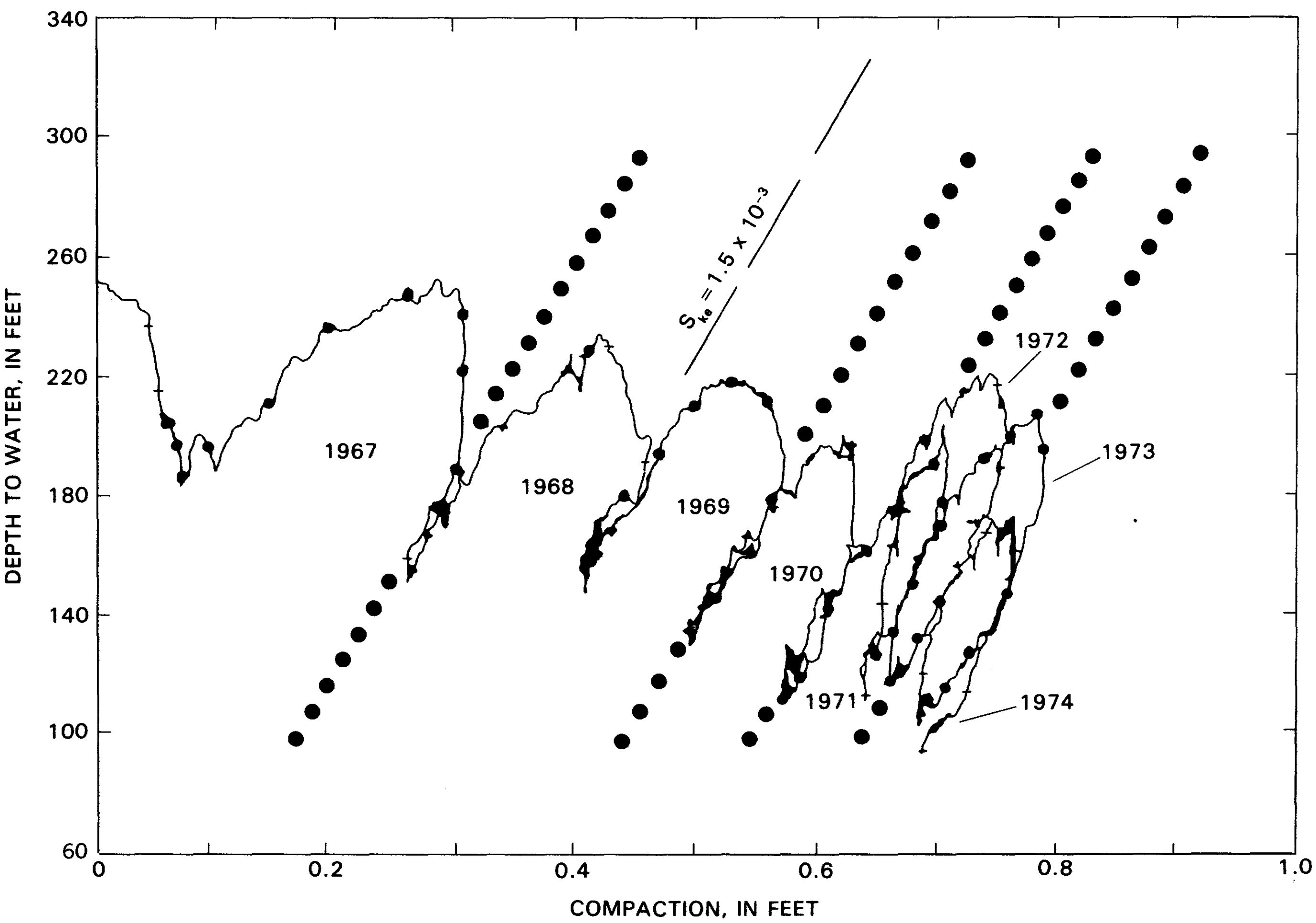


FIGURE 28.—Stress change and compaction, San Jose site. Depth to water in well 7S/1E-16C5, and compaction in well 7S/1E-16C6-11.

TABLE 4.—*Values of parameters used for simulating observed compaction at selected sites in north Santa Clara County*
[Modified from Helm (1977, table 1)]

Site of water-level data	Period of record (years)		Estimated thickness (feet)		Estimated values of parameters		
	Water-level data	Compaction data	Total b'_{sum}	Weighted average b'_{equiv}	K' $\frac{feet}{day}\times10^{-6}$	S'_{skv} $\frac{1}{foot}\times10^{-4}$	S'_{ske} $\frac{1}{foot}\times10^{-6}$
6S/1W-23E1	1958–72	1958–72	189	15.1	1.18	1.4	7.5
6S/2W-24C3	1960–72	1960–72	225	18	.56	13.1	3.96
6S/2W-24C7	1960–72	1960–72	422	53.1	12.5	3.35	2.60
6S/2W-25C1	1960–72	1960–72	255	18	.75	3.26	15.8
6S/2W-25C1	1921–74	1932–74	255	18	.72	3.29	--
7S/1E-7R1	1915–74	1916–74	477	18	1.87	2.25	--
7S/1E-9D2	1958–72	1960–63, 1965–72	258	18	.82	6.1	7.92
7S/1E-16C5	1958–72	1960–72	477	18	3.28	2.3	2.2

Helm (1977, figs. 9, 10) demonstrated that carefully evaluated values of K' and S'_{skv} can be used to predict aquifer-system behavior with reasonable accuracy over periods of several decades. A good example of the simulation result for six decades of record using values listed in table 4 is shown in figure 29 (from Helm, 1977, fig. 10).

COMPACTION-SUBSIDENCE RATIOS

The amounts of measured compaction and measured subsidence at extensometer sites where leveling data are available are shown in table 5. The ratio of measured compaction to measured subsidence, expressed as a percentage, was computed for the period of record available. Percentages are sometimes erratic for short periods of control at some sites, as shown by table 5; some periods of measured compaction and leveling are combined to make the compaction/subsidence ratios more consistent, and some are not shown as a result of incomplete data or mechanical problems at the extensometer site.

At extensometer site 6S/2W-24C, the compaction/subsidence ratio for the full period of the leveling record (November 1960 to February 1967) increased from 11 percent for C4 (the 250-ft extensometer) to 50 percent for C3 (the 550-ft extensometer) and to 105 percent for C7 (the 1,000-ft extensometer). For the shorter periods between levelings, the ratio for 24C3 was surprisingly consistent, whereas the ratio for 24C4 was erratic. For extensometer 24C7, the measured compaction during each of the shorter periods exceeded the measured subsidence and averaged 105 percent for the six years to February 1967. The 5-percent excess is attributed to mechanical problems in recording the compaction.

At extensometer site 7S/1E-16C5 (908 ft deep) the aquifer system is about 800-ft thick, from 200 to 1,000 ft below land surface. If the compaction potential was uniform with depth, the part measured by extensometer 16C5 would be 708/800, or 88 percent of the subsidence. Actually, for the 8.5 years from October 1960 to May 1969 the compaction measured at 16C5 equaled 87 percent of the subsidence.

At extensometer site 7S/1E-16C6, the extensometer cable anchor was landed at the 1,000-ft depth, believed to be the bottom of the aquifer system. For the full 8.5-year period to May 1969, the measured compaction was equal to 99 percent of the subsidence, indicating that the anchor truly was landed at the base of the compacting system.

In the 13.5 years from May 1969 through 1982 the cumulative compaction at the two 1,000-ft extensometers, 6S/2W-24C7 in Sunnyvale and 7S/1E-16C6-11 in San Jose, was 0.24 ft and 0.44 ft, respectively (table 3). During the six years 1977 to 1982, inclusive, the cumulative compaction was very small, about 0.03 ft at 6S/2W-24C7 and 0.07 ft at 7S/1E-16C6-11.

A.K. Williamson (U.S. Geological Survey, oral commun., 1981) noted an interesting relationship in the San Joaquin Valley between extensometer depth and the compaction-subsidence ratio (Ireland and others, 1984, p. I53 and fig. 67). We have plotted a similar figure for the few extensometers in north Santa Clara County (fig. 30). Compaction/subsidence ratios based on the full period of available records were used in preparing figure 30. Although there were only seven ratios to plot, they surveyed a wide range of extensometer depths: one was at shallow depth, three were at mid-depth (400 to 600 ft deep), and three were at full depth of the aquifer system (about 1,000 ft). All were centrally located within the confined system and at either of the two centers of maximum subsidence. Together, they defined a relatively "tight" curve, which indicates that all the compaction due to ground-water withdrawal occurs at depths between about 200 and 1,000 ft. Between these depths the compaction/subsidence ratio is shown to approximate a linear function of the logarithm of the depth. The least-squares regression equation of the function has an R-squared value of 0.95, which indicates that 95 percent of the variation of the ratio is explained by the equation, whereas 5 percent of its variation is random (or attributable to other factors not considered).

On the basis of the relation shown in figure 30, a 300-ft extensometer in a subsidence area in the Santa Clara Valley would record approximately 18 percent of the total subsidence measured at the well site, and a 700-ft extensometer would record approximately 72 percent of the total subsidence at the site.

COMPUTER PLOTS OF FIELD RECORDS

The records of compaction and of depth to water in the extensometer wells or in nearby observation wells have been computerized on a daily basis, and computer plots of these records through 1979 are included here as figures 31–42. Graphs of subsidence of a surface bench mark located at the measuring site, determined by periodic instrumental surveys to a stable bench mark, are also included for the first part of the period of compaction measurements. (No bench-mark surveys have been made since 1969.) Site locations are shown in figure 1.

The Geological Survey continued collecting field records of compaction and depth to water at these sites in the three years 1980–82 (figs. 43–48). Early in 1983 the operation and maintenance of the principal sites was taken over by the Santa Clara Valley Water District.

The computer program and extensometer and water-level data collected on this long-term (mechanics of aquifers) study on land subsidence are stored on computer tape Number 220691, type 6250BPI, at the U.S. Geological Survey Information Services Division, Reston, Virginia.

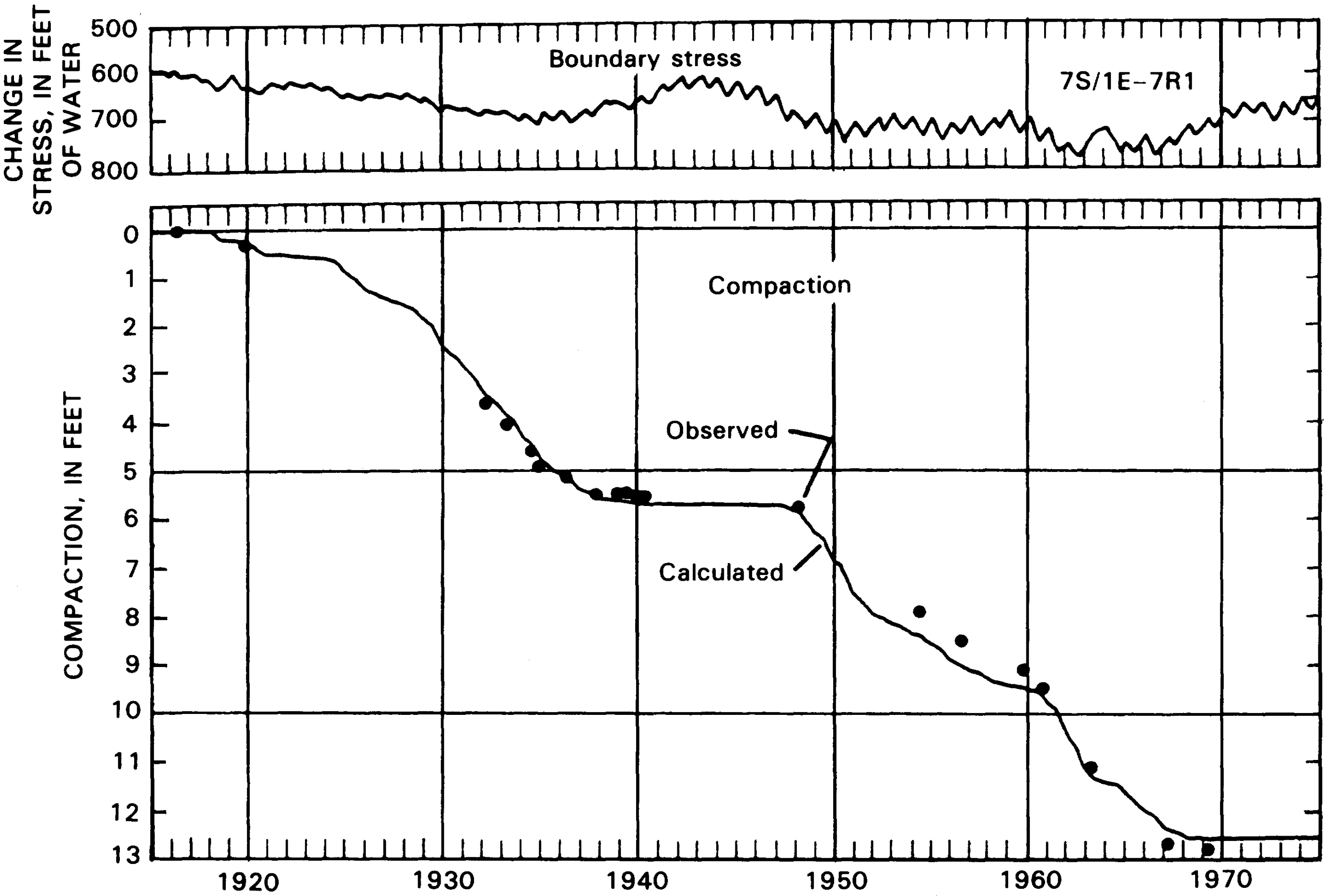


FIGURE 29.—Simulation of compaction based on water-level data for well 7S/1E-7R1 (1915–74) and on subsidence measured at bench mark P7 (from Helm, 1977, fig. 10).

TABLE 5.—*Compaction versus subsidence for periods of leveling in north Santa Clara County*

[Ratio of compaction/subsidence: value shown on total line is ratio for period of record]

Extensometer number	Depth (feet)	Bench mark number	Dates of leveling	Subsidence (feet)	Compaction (feet)	Ratio of compaction to subsidence (percent)
6S/1W-23E1	425	A176	11/60-2/67	2.392	1.033	43
6S/2W-24C4	250	J111	11/60-2/63	.807	.091	11
			2/63-4/65	.683	.085	12
			4/65-2/67	.544	.045	8
Total....................				2.034	.221	11
6S/2W-24C3	550	J111	11/60-2/63	.807	.414	51
			2/63-4/65	.683	.341	50
			4/65-2/67	.544	.267	49
Total....................				2.034	1.022	50
6S/2W-24C7	1,000	J111	11/60-2/63	.807	.845	105
			2/63-4/65	.683	.738	108
			4/65-2/67	.544	.547	101
Total....................				2.034	2.130	105
7S/1E-9D2	605	JG4	10/60-2/63	1.552	.762	48
			2/63-2/67	1.551	([1])	
			2/67-5/69	.230	.118	51
7S/1E-16C5	908	JG2	10/60-2/63	1.919	1.677	87
			2/63-3/67	1.923	1.604	83
			3/67-5/69	.366	.365	100
Total....................				4.208	3.646	87
7S/1E-16C6	1,000	JG2	10/60-3/67	3.842	3.812	99
			3/67-5/69	.366	.363	99
Total....................				4.208	4.175	99

[1]No extensometer data from 4/22/63 to 6/18/65.

The primary purpose of including these records is to show graphically the measured compaction and subsidence at specific sites, and (so far as possible) the change in effective stress in the pertinent aquifers at these sites, as indicated by the hydrographs. Because of the confining beds and multiple-aquifer/aquitard system, it is difficult to obtain water-level measurements that specifically represent the average stress change for the interval in which compaction is being measured.

Change in applied stress and stress-compaction or stress-strain relationships are plotted for figures 31–41. In these figures, compaction equals the change in thickness of the compacting interval, and strain refers to the compaction divided by the thickness of the compacting interval.

As indicated in table 6, stress-strain relationships are shown for figure 31 (extensometer 6S/1W-23E1) and for figures 40 and 41 at the San Jose core-hole site (extensometers 7S/1E-16C5 and 16C6-11, respectively).

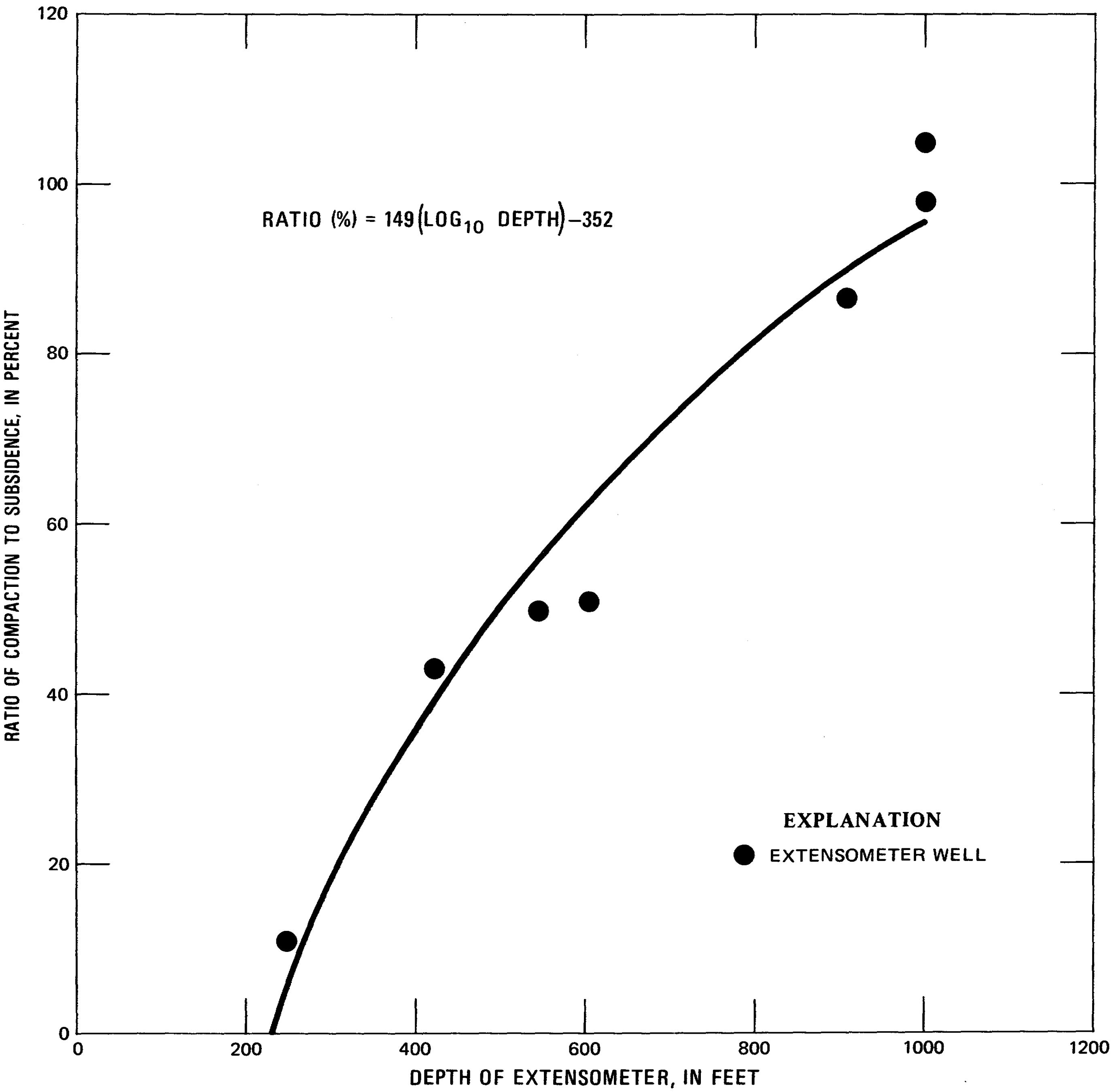


FIGURE 30.—Compaction/subsidence ratios versus depth at extensometer wells in north Santa Clara County.

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FIGURES 31-48; TABLE 6

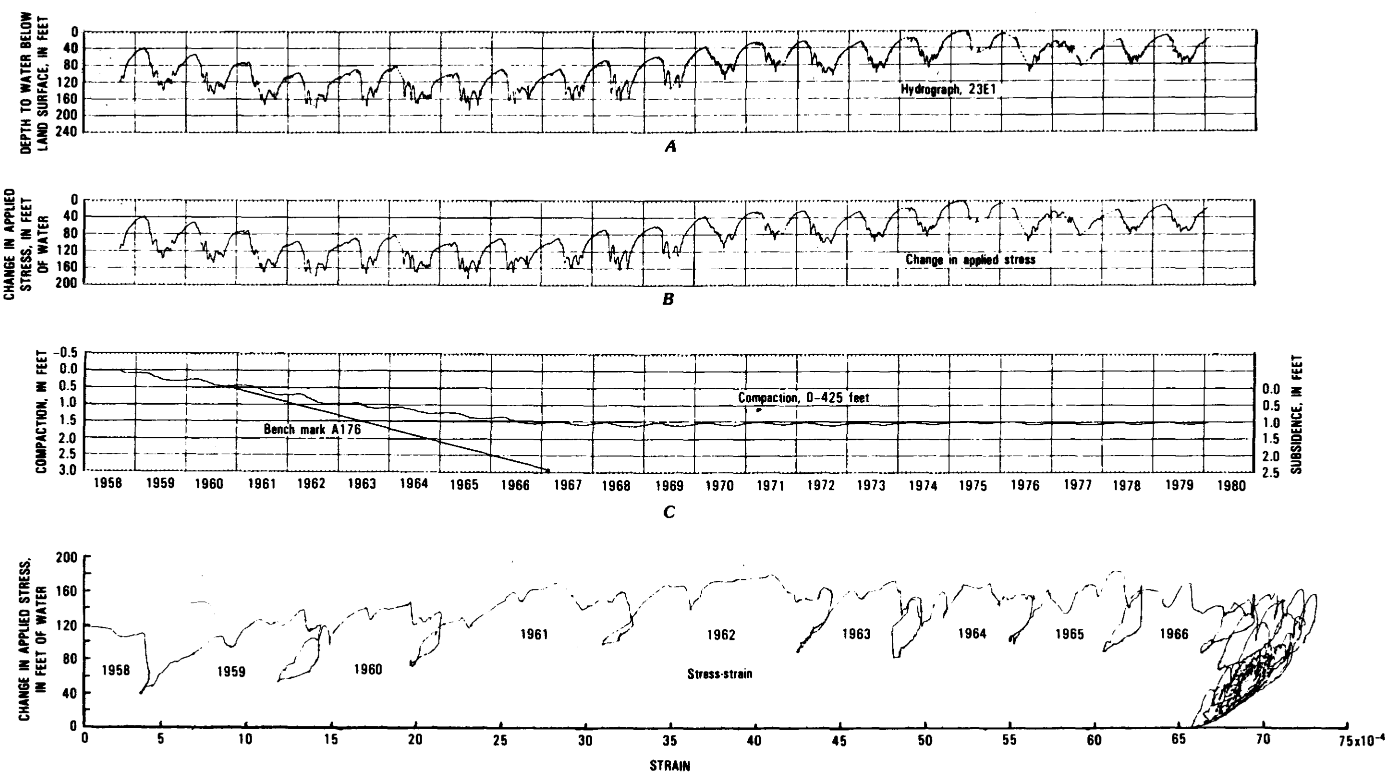

FIGURE 31.—Hydrograph, change in applied stress, compaction, subsidence, and stress-strain relationship, 6S/1W-23E1. *A*, Hydrograph of well 6S/1W-23E1, perforated 170–177, 244–255, 311–315, and 343–350 ft. *B*, Change in applied stress, water table assumed constant. *C*, Compaction to 425-ft depth at well 6S/1W-23E1 and subsidence of bench mark A176, 0.6 mi west. *D*, Stress change versus strain (225-ft thickness).

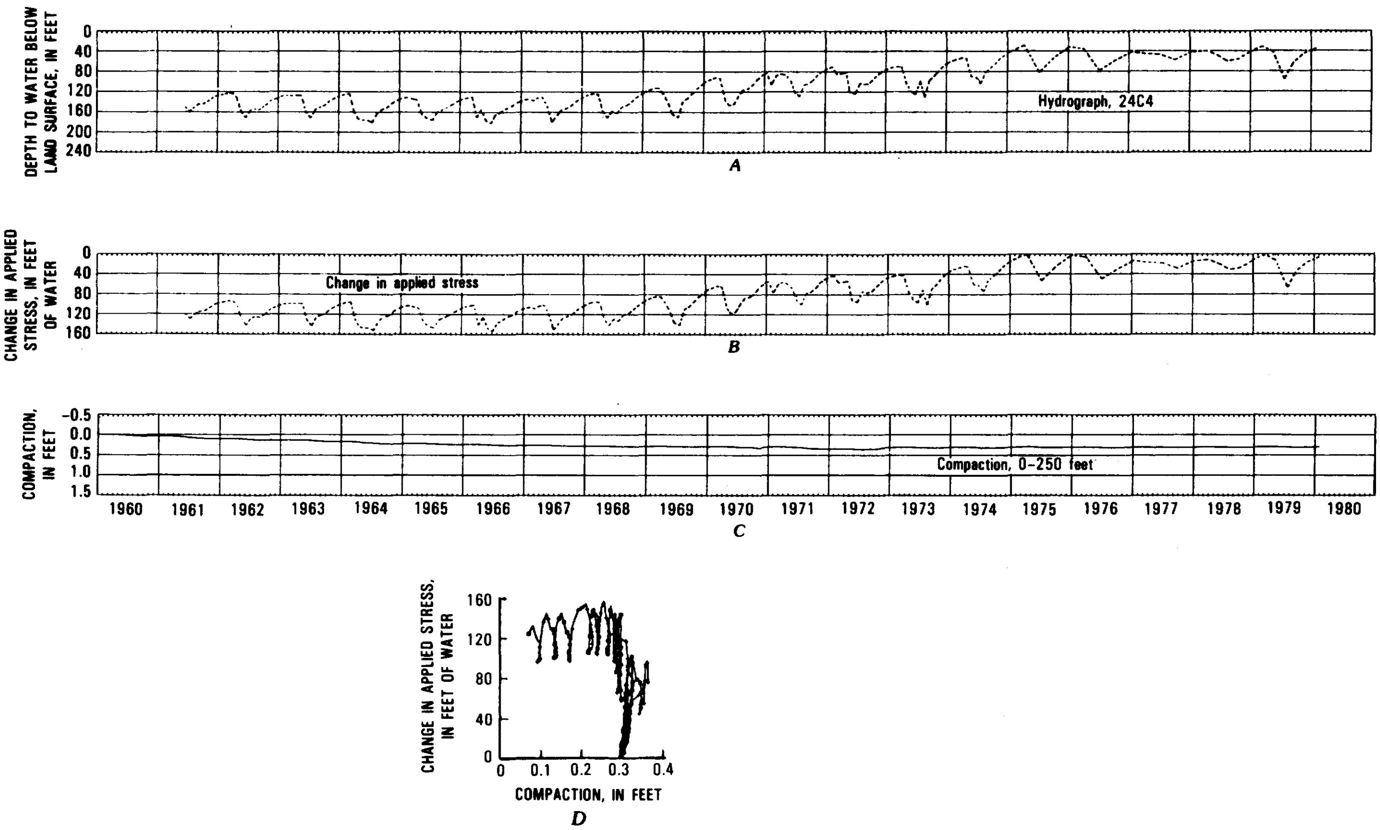

FIGURE 32.—Hydrograph, change in applied stress, compaction, and stress-compaction relationship, 6S/2W-24C4. *A*, Hydrograph of well 6S/2W-24C4, depth 250 ft. *B*, Change in applied stress, water table assumed constant. *C*, Compaction to 250-ft depth at well 6S/2W-24C4. *D*, Stress change versus compaction of deposits above 250-ft depth.

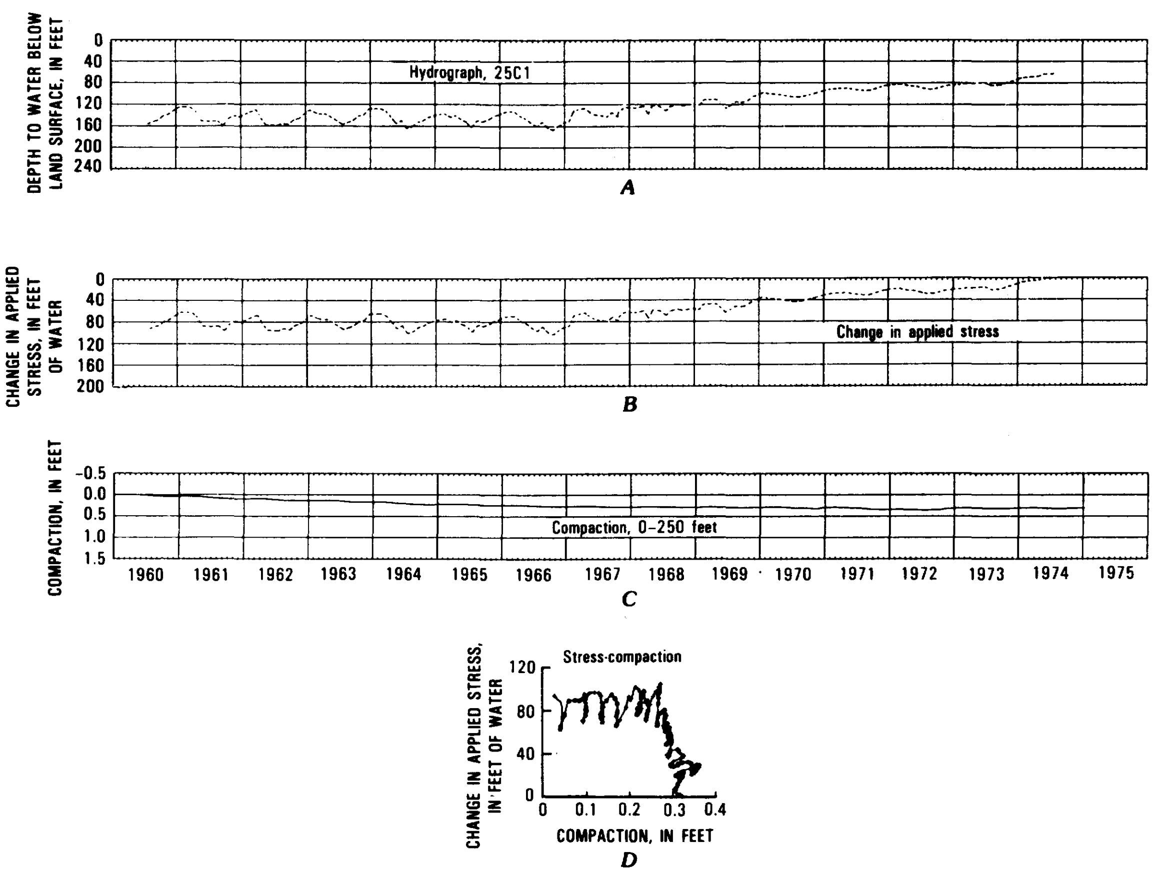

FIGURE 33.—Hydrograph and change in applied stress, 6S/2W-25C1; compaction and stress-compaction relationship, 6S/2W-24C4. *A*, Hydrograph of well 6S/2W-25C1, depth 500 ft. *B*, Change in applied stress, 6S/2W-25C1, water table assumed constant. *C*, Compaction to 250-ft depth at well 6S/2W-24C4. *D*, Stress change versus compaction of deposits above 250-ft depth.

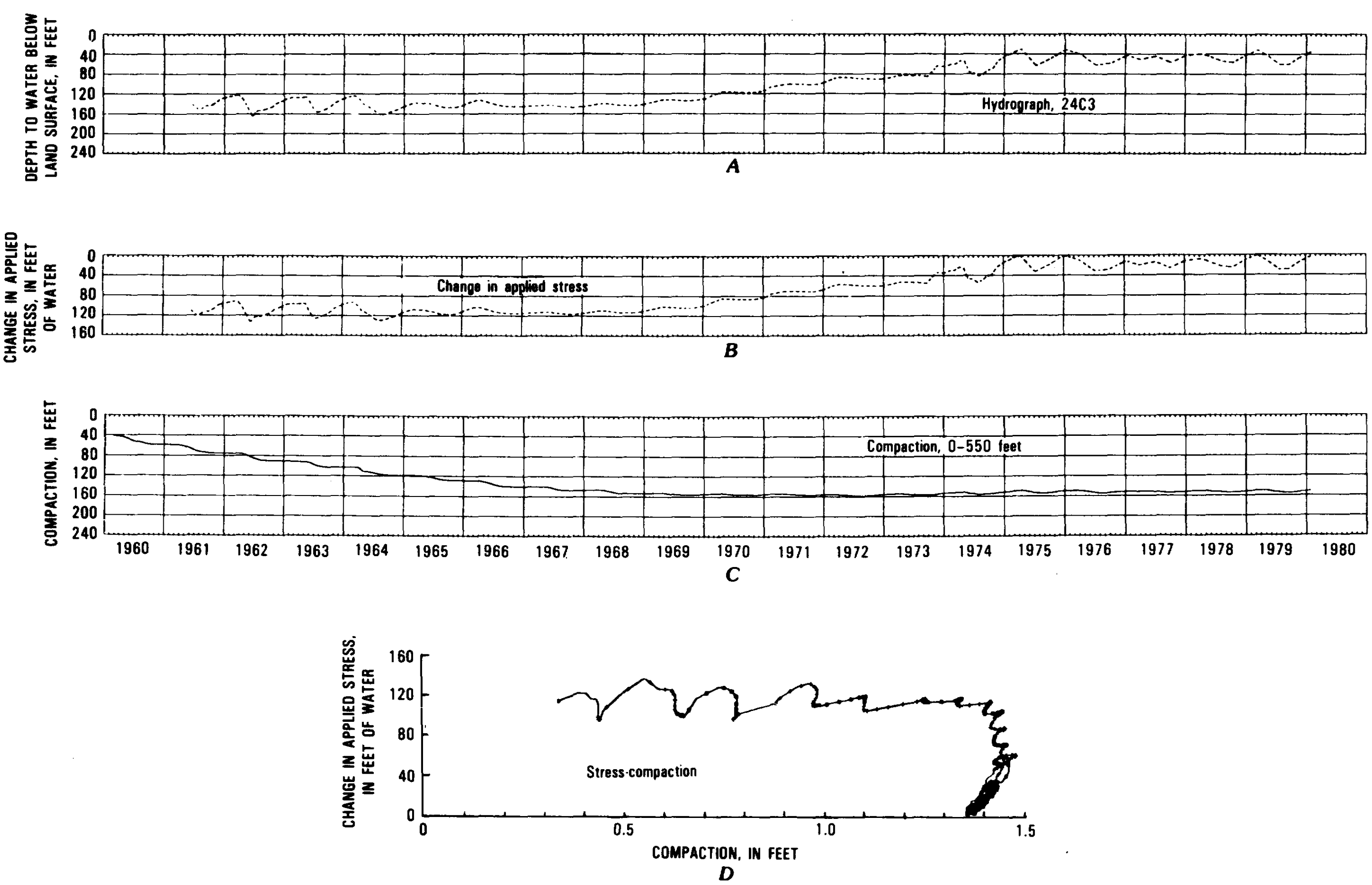

FIGURE 34.—Hydrograph, change in applied stress, compaction, and stress-compaction relationship, 6S/2W-24C3. *A*, Hydrograph of well 6S/2W-24C3, depth 550 ft. *B*, Change in applied stress, water table assumed constant. *C*, Compaction to 550-ft depth at well 6S/2W-24C3. *D*, Stress change versus compaction of deposits above 550-ft depth.

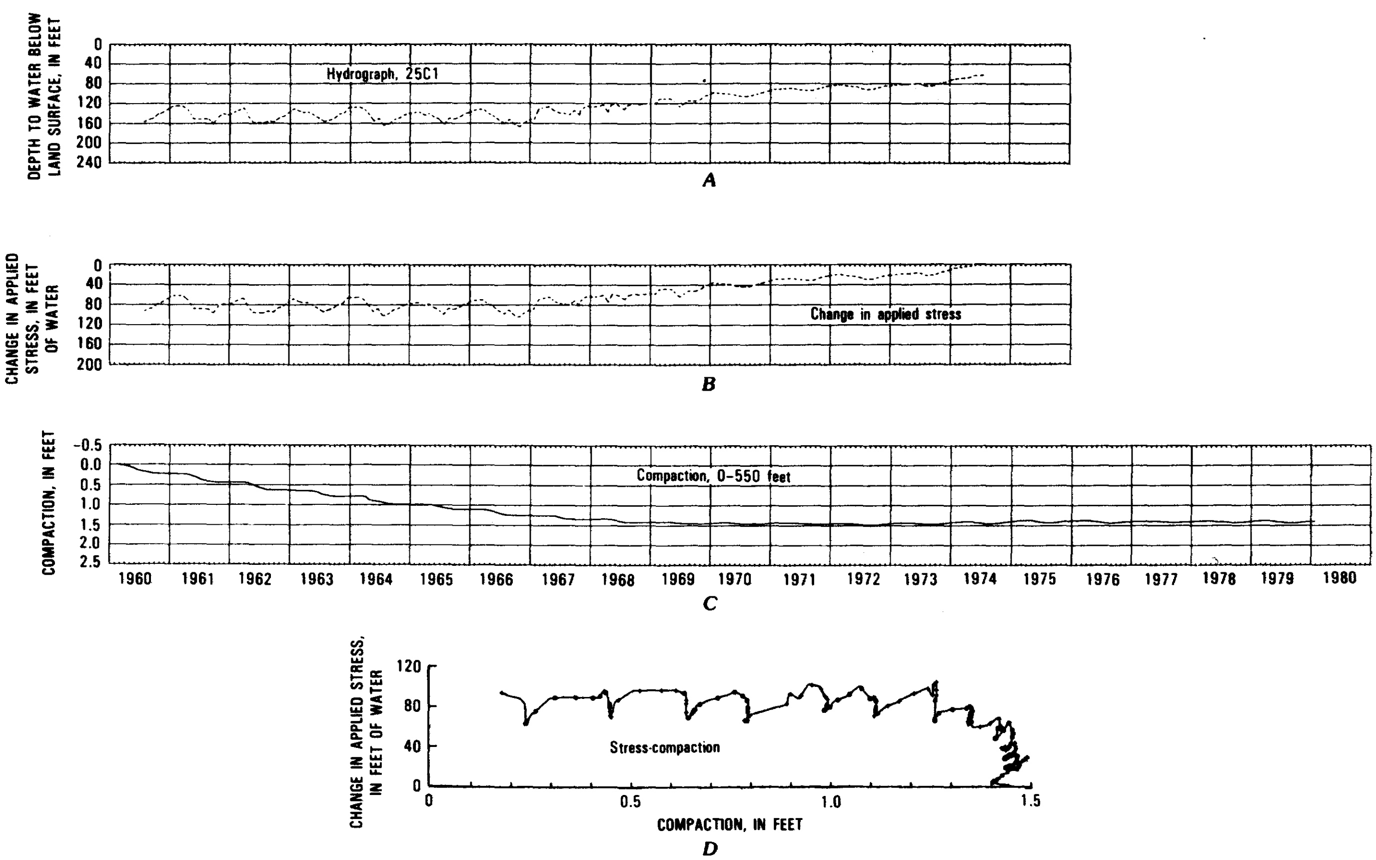

FIGURE 35.—Hydrograph and change in applied stress, 6S/2W-25C1; compaction and stress-compaction relationship, 6S/2W-24C3. *A*, Hydrograph of well 6S/2W-25C1, depth 500 ft. *B*, Change in applied stress, 6S/2W-25C1, water table assumed constant. *C*, Compaction to 550-ft depth at well 6S/2W-24C3. *D*, Stress change versus compaction of deposits above 550-ft depth.

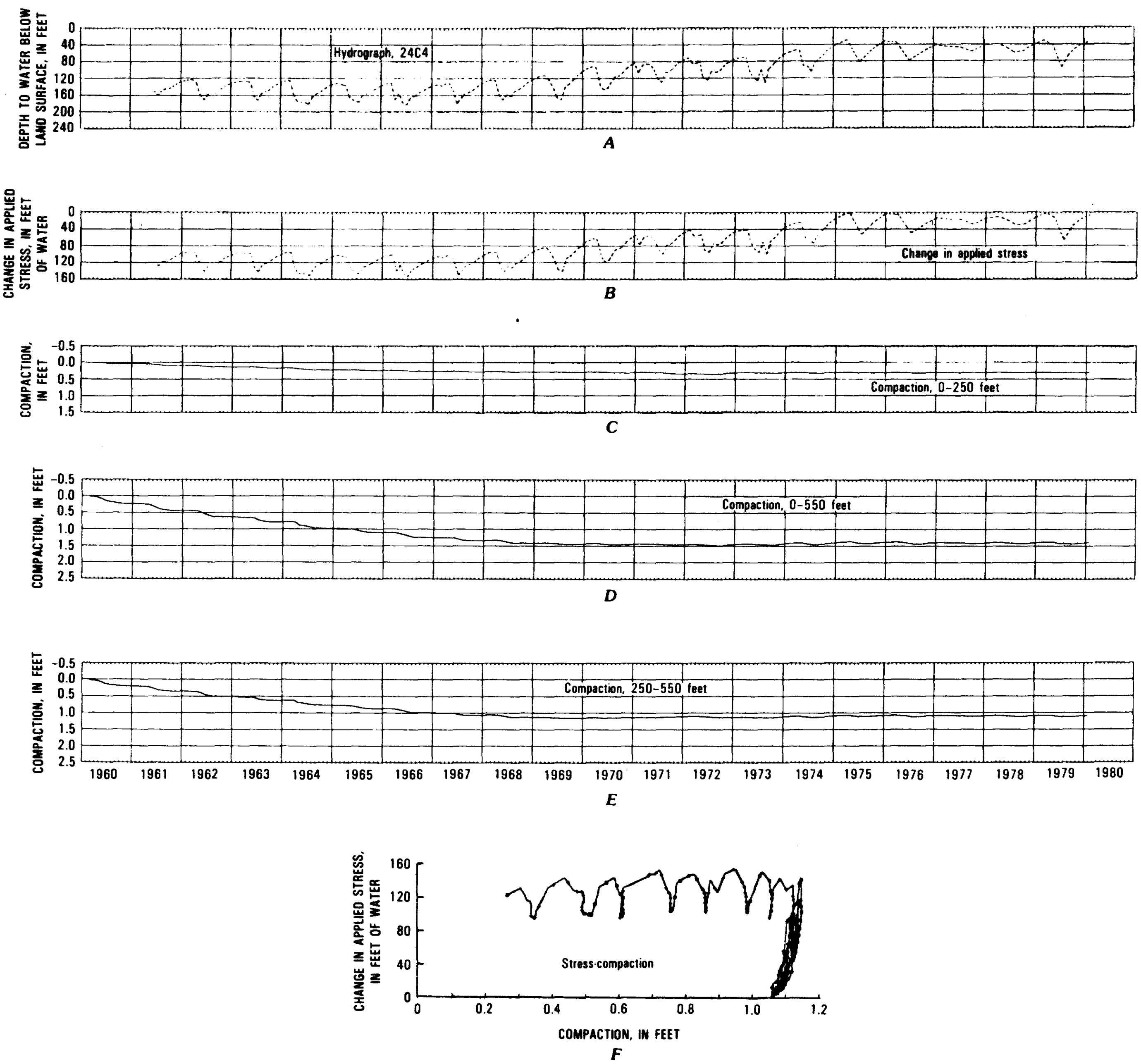

FIGURE 36.—Hydrograph and change in applied stress, 6S/2W-24C4; compaction and stress-compaction relationship, 6S/2W-24C3 and 6S/2W-24C4. *A*, Hydrograph of well 6S/2W-24C4, depth 250 ft. *B*, Change in applied stress, 6S/2W-24C4, water table assumed constant. *C*, Compaction to 250-ft depth at well 6S/2W-24C4. *D*, Compaction to 550-ft depth at well 6S/2W-24C3. *E*, Compaction in 250–550-ft depth interval. *F*, Stress change versus compaction of deposits from 250–550-ft depth.

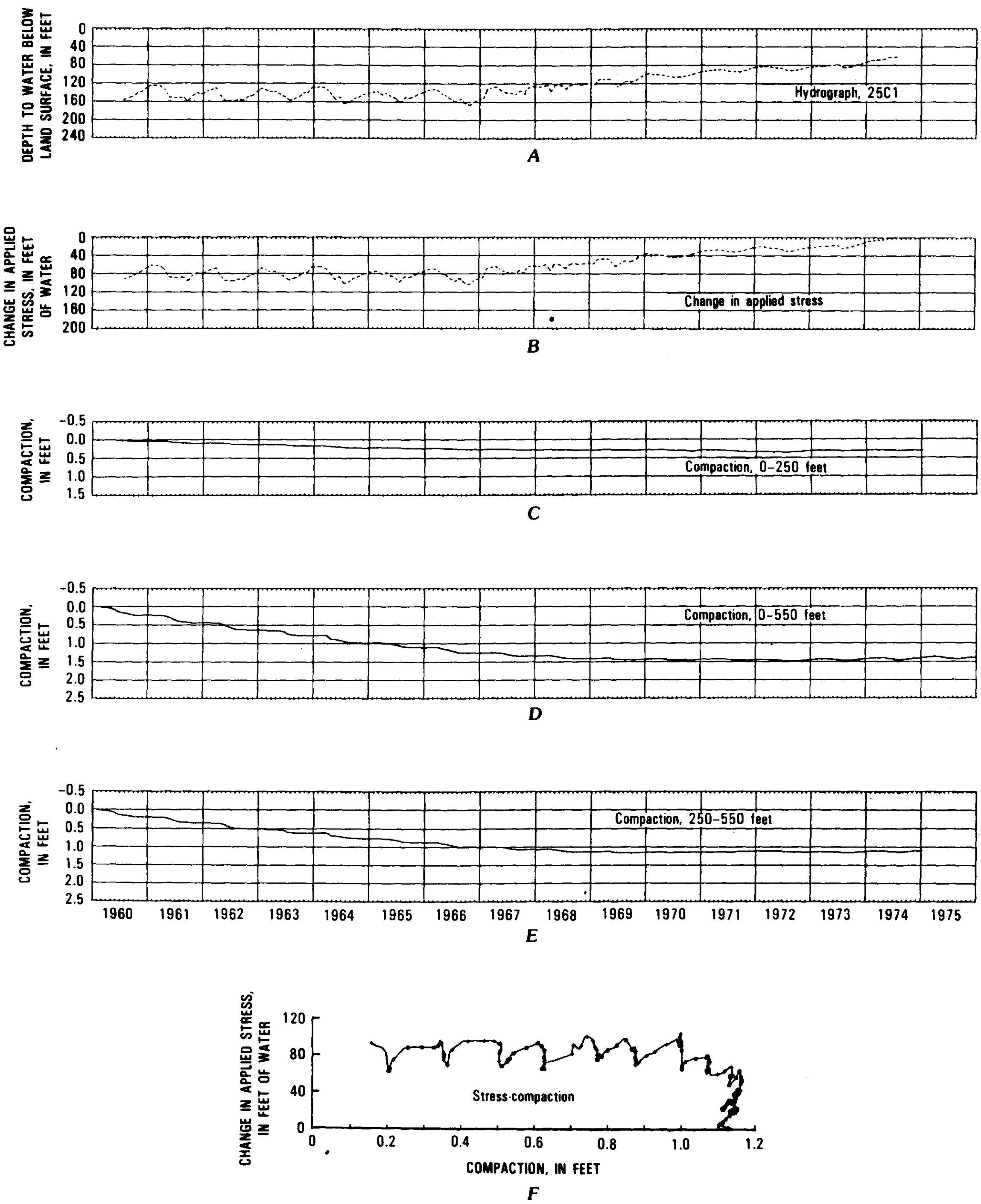

FIGURE 37.—Hydrograph and change in applied stress, 6S/2W-25C1; compaction and stress-compaction relationship, 6S/2W-24C3 and 6S/2W-24C4. *A*, Hydrograph of well 6S/2W-25C1, depth 500 ft. *B*, Change in applied stress, 6S/2W-25C1, water table assumed constant. *C*, Compaction to 250-ft depth at well 6S/2W-24C4. *D*, Compaction to 550-ft depth at well 6S/2W-24C3. *E*, Compaction in 250–550-ft depth interval. *F*, Stress change versus compaction of deposits from 250–550-ft depth.

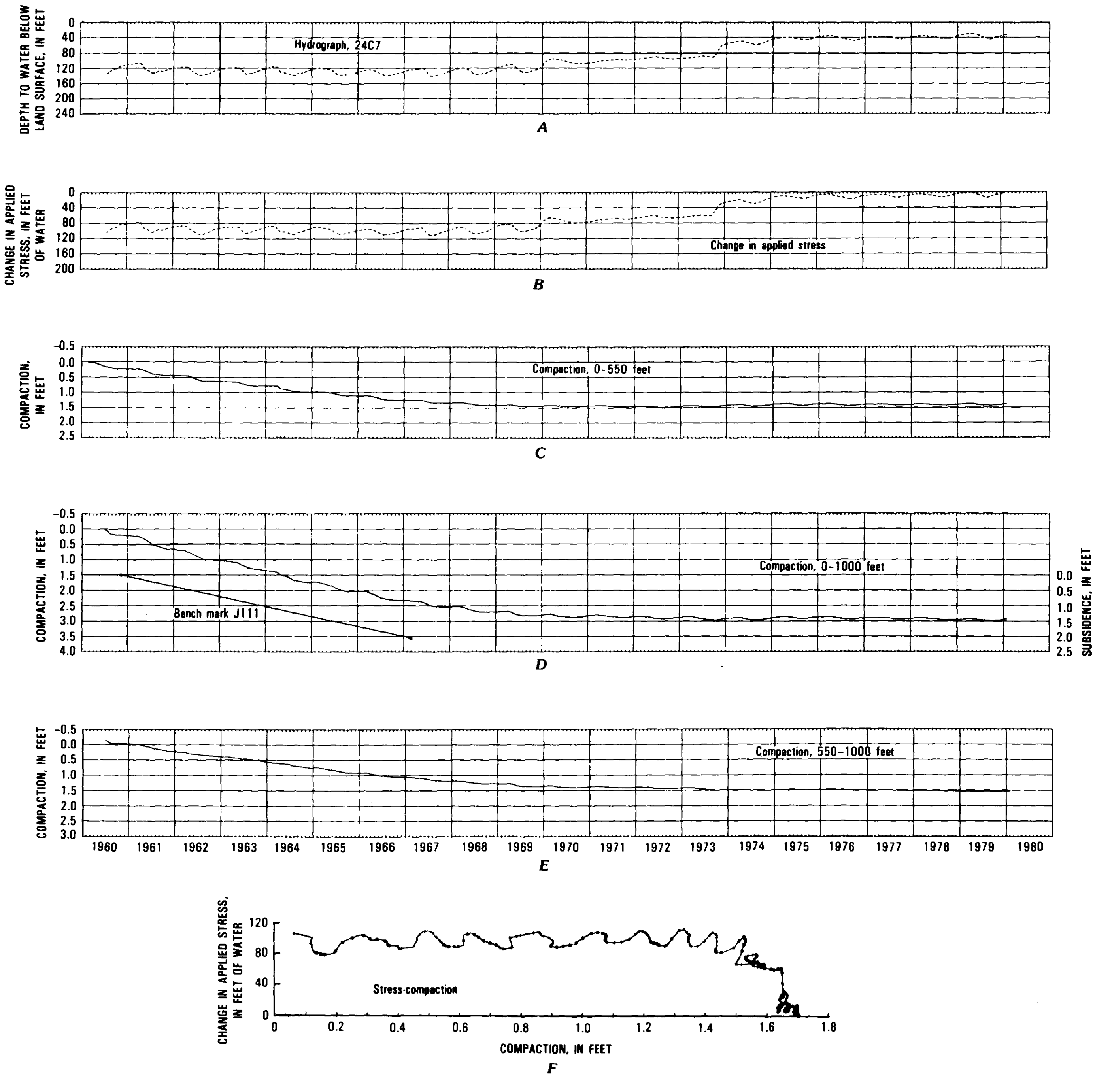

FIGURE 38.—Hydrograph and change in applied stress, 6S/2W-24C7; compaction, subsidence, and stress-compaction relationship, 6S/2W-24C3 and 6S/2W-24C7. *A*, Hydrograph of well 6S/2W-24C7, perforated 807–851 and 880–903 ft. *B*, Change in applied stress, 6S/2W-24C7, water table assumed constant. *C*, Compaction to 550-ft depth at well 6S/2W-24C3. *D*, Compaction to 1,000-ft depth at well 6S/2W-24C7, and subsidence at bench mark J111, 400 ft southeast. *E*, Compaction in 550–1,000-ft depth interval. *F*, Stress change versus compaction of deposits from 550–1,000-ft depth.

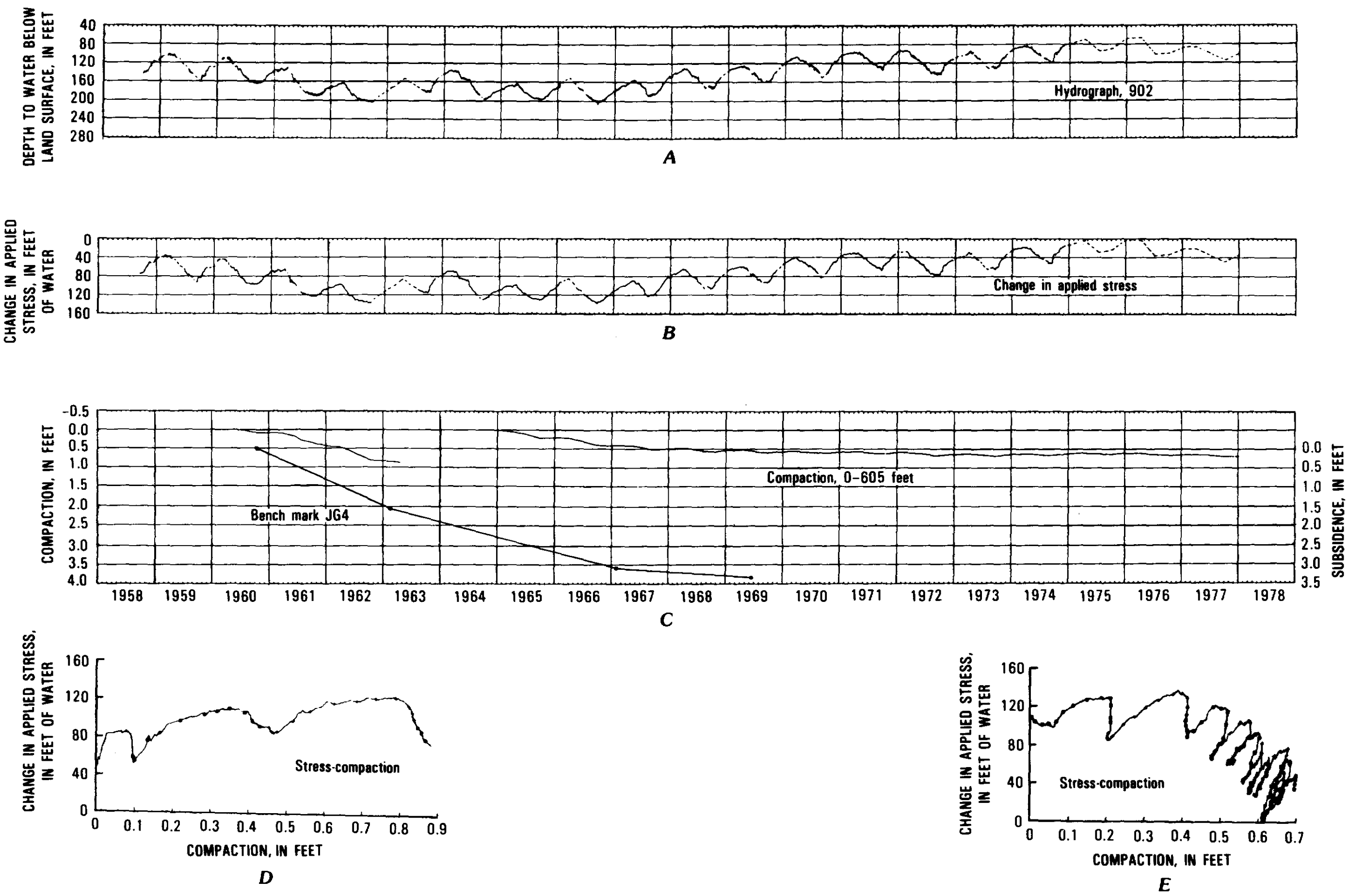

FIGURE 39.—Hydrograph, change in applied stress, compaction, subsidence, and stress-compaction relationship, 7S/1E-9D2. *A*, Hydrograph of well 7S/1E-9D2, depth 605 ft. *B*, Change in applied stress, water table assumed constant. *C*, Compaction to 605-ft depth from May 1960 to April 1963 and from January 1965 to January 1978, and subsidence of bench mark JG4 at well 7S/1E-9D2. *D*, Stress change versus compaction of deposits above 605-ft depth, May 1960 to April 1963. *E*, Stress change versus compaction of deposits above 605-ft depth, January 1965 to January 1968.

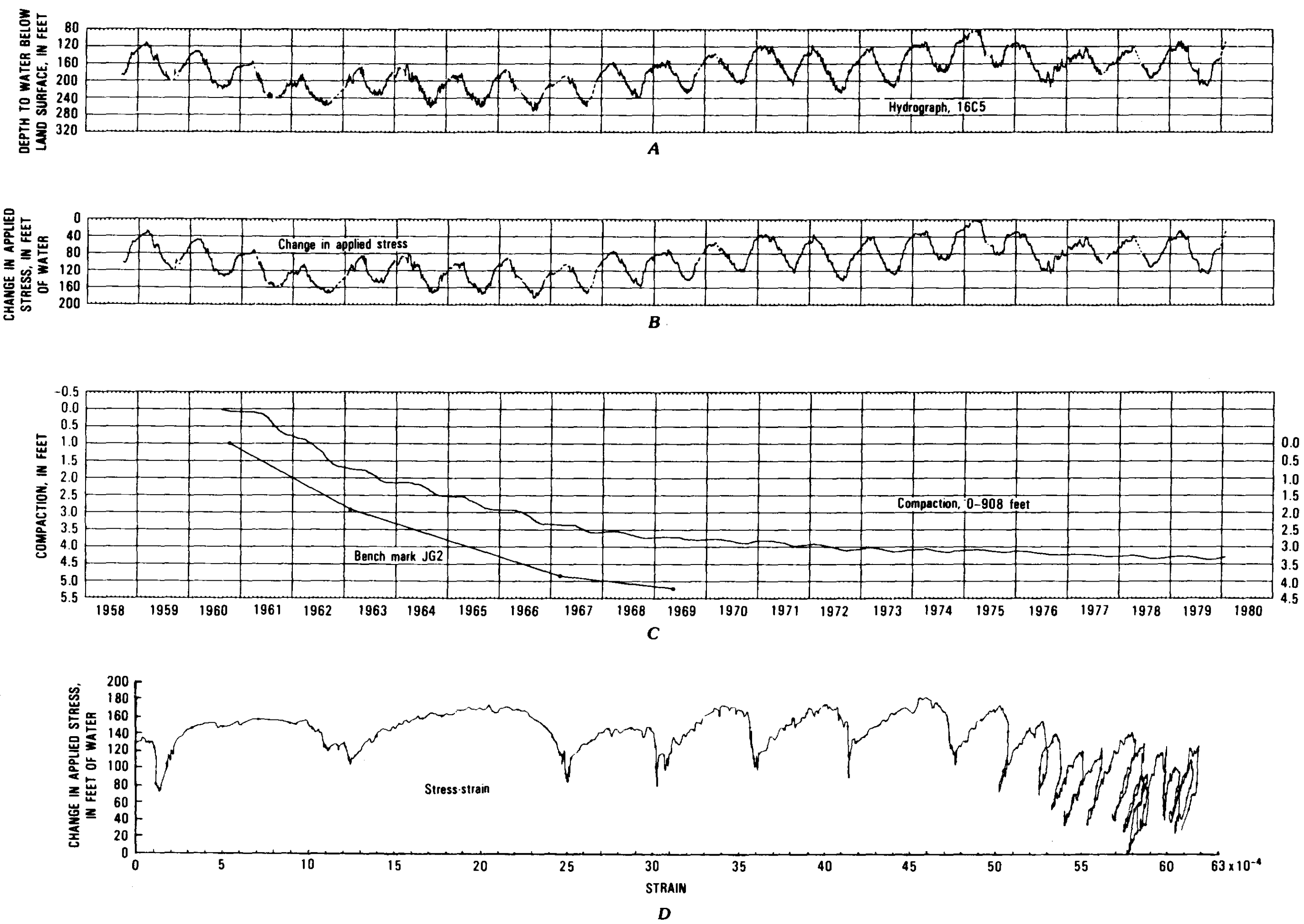

FIGURE 40.—Hydrograph, change in applied stress, compaction, subsidence, and stress-strain relationship, 7S/1E-16C5. *A*, Hydrograph of well 7S/1E-16C5, depth 908 ft. *B*, Change in applied stress, water table assumed constant. *C*, Compaction to 908-ft depth at well 7S/1E-16C5 and subsidence of bench mark JG2, located in top of northeast concrete curb of 12th Street, approximately 20 ft west of well 7S/1E-16C5. *D*, Stress change versus strain (708-ft thickness).

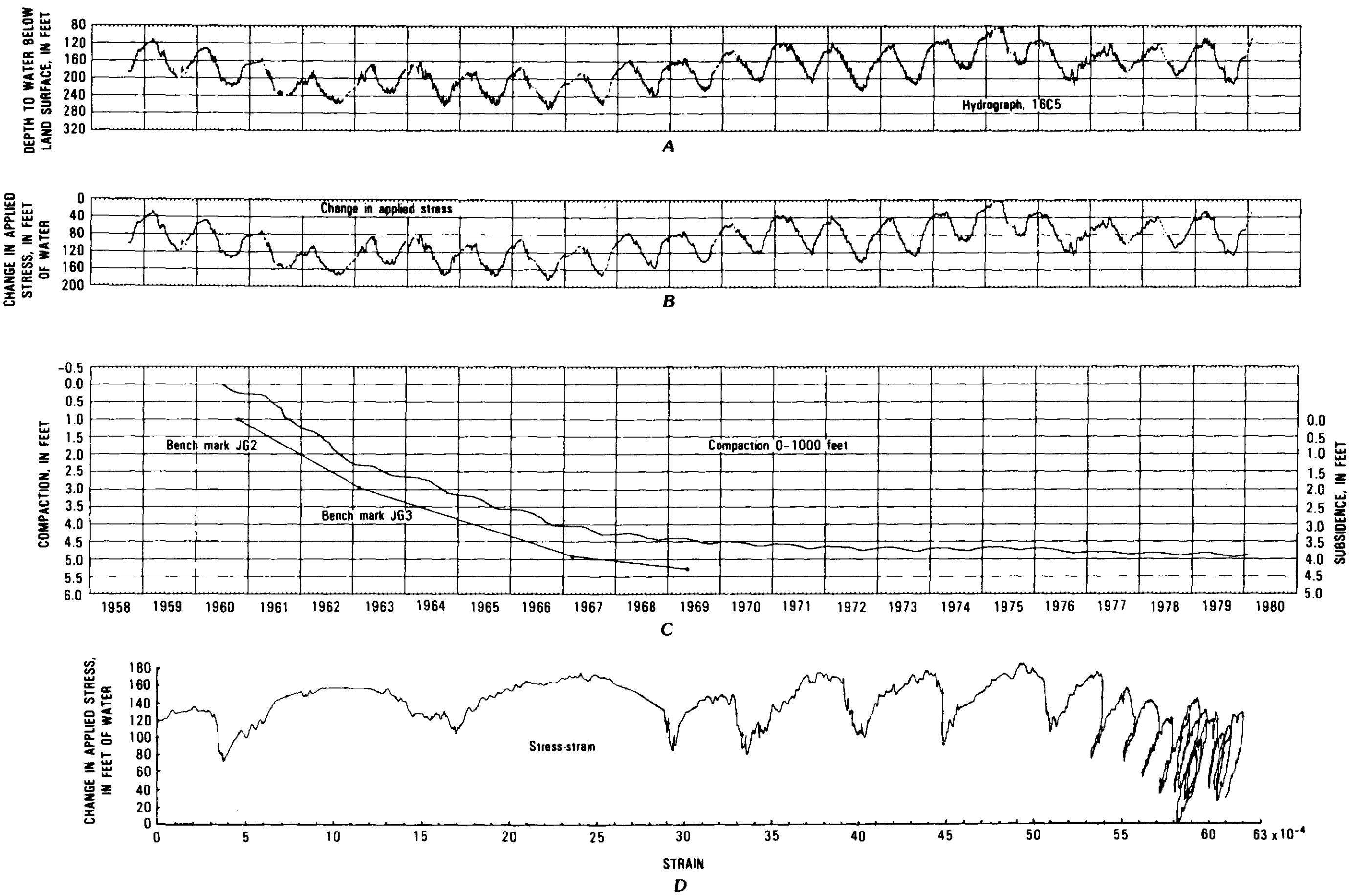

FIGURE 41.—Hydrograph and change in applied stress, 7S/1E-16C5; compaction, subsidence, and stress-strain relationship, 7S/1E-16C6-11. *A*, Hydrograph of well 7S/1E-16C5, depth 908 ft. *B*, Change in applied stress, 7S/1E-16C5, water table assumed constant. *C*, Compaction to 1,000-ft depth at well 7S/1E-16C6-11 (see fig. 42*B*) and subsidence at bench mark JG2 from October 1960 to February 1963 and bench mark JG3 from February 1963 to May 1969. (Bench mark JG2 is located in top of northeast concrete curb of 12th Street, approximately 20 ft west of well 7S/1E-16C5; bench mark JG3 is located approximately 300 ft north of bench mark JG2.) *D*, Stress change versus strain (800-ft thickness).

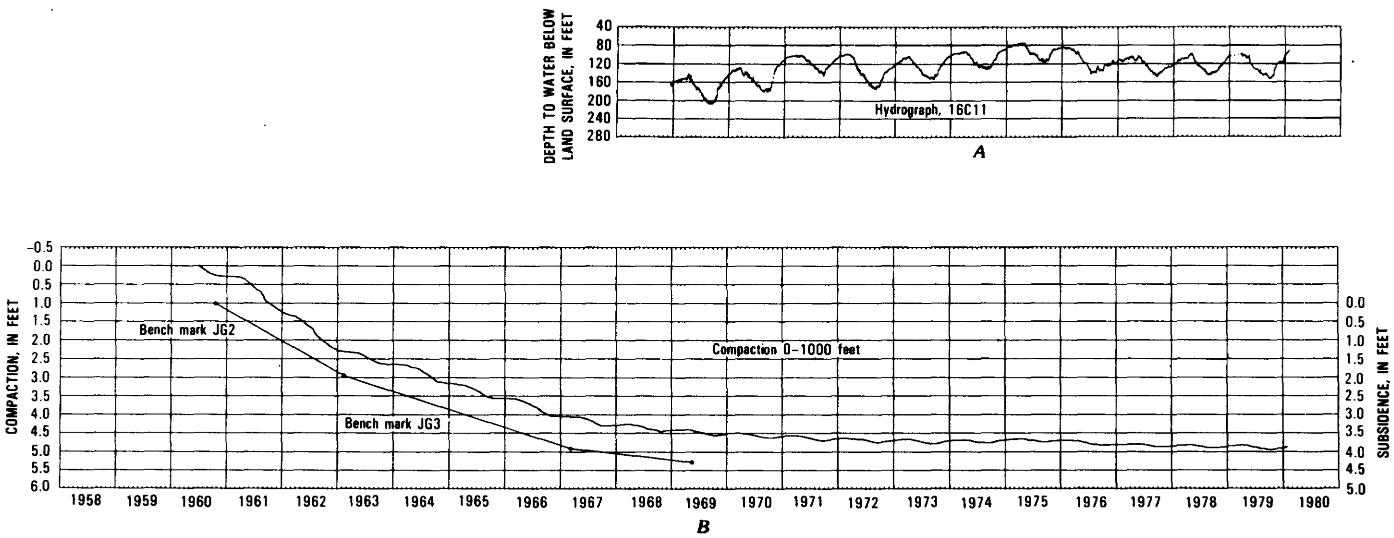

FIGURE 42.—Hydrograph, compaction, and subsidence, 7S/1E-16C6-11. *A*, Hydrograph of well 7S/1E-16C11, perforated 551–571, 598–618, and 640–660 ft. *B*, Compaction to 1,000-ft depth at well 7S1E-16C6-11 (7S/1E-16C6 from June 1960 to June 1969 and 7S/1E-16C11 from June 1969 to January 1980) and subsidence at bench mark JG2 from October 1960 to February 1963 and bench mark JG3 from February 1963 to May 1969. (Bench mark JG2 is located in top of northeast concrete curb of 12th Street, approximately 20 ft west of well 7S/1E-16C5; bench mark JG3 is located approximately 300 ft north of bench mark JG2.)

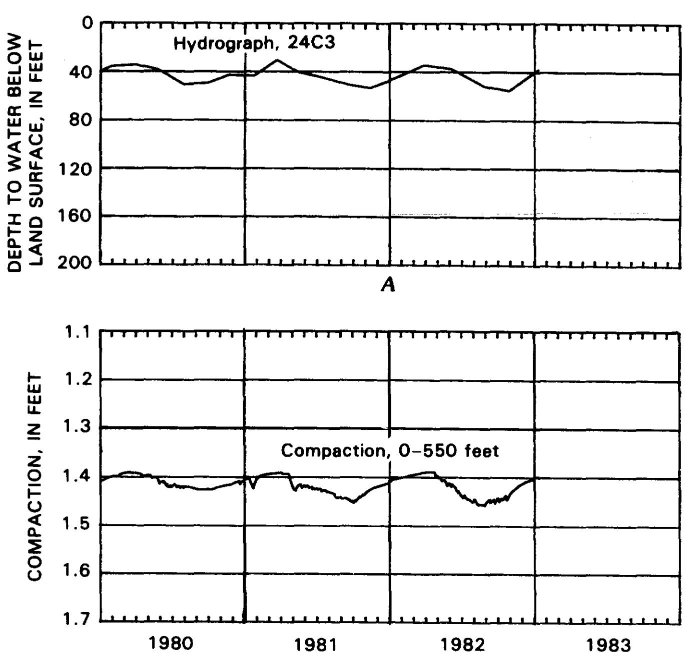

FIGURE 43.—Hydrograph and compaction, 6S/2W-24C3. *A*, Hydrograph of well 6S/2W-24C3, depth 550 ft. *B*, Compaction to 550-ft depth at well 6S/2W-24C3.

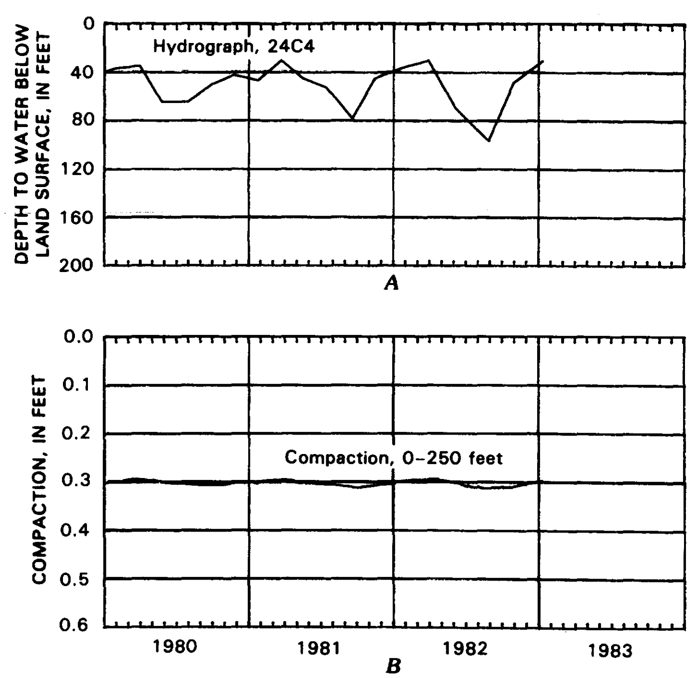

FIGURE 44.—Hydrograph and compaction, 6S/2W-24C4. *A*, Hydrograph of well 6S/2W-24C4, depth 250 ft. *B*, Compaction to 250-ft depth at well 6S/2W-24C4.

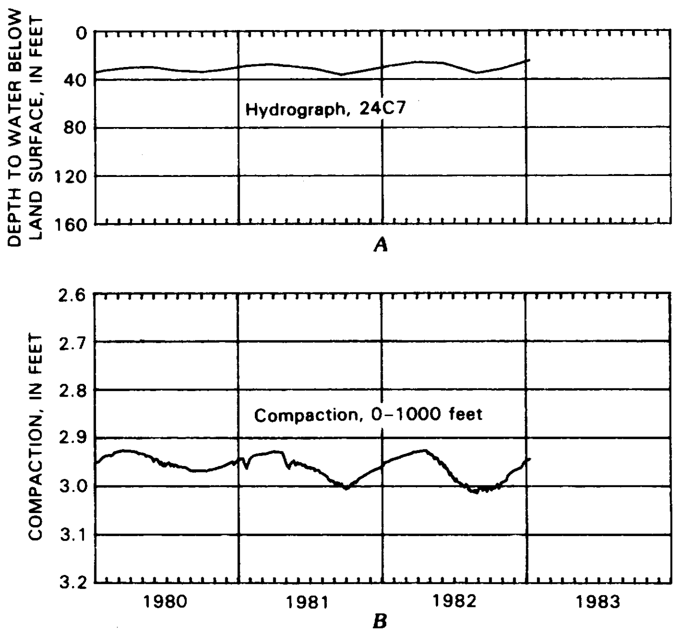

FIGURE 45.—Hydrograph and compaction, 6S/2W-24C7. *A*, Hydrograph of well 6S/2W-24C7, perforated 807–851 and 880–903 ft. *B*, Compaction to 1,000-ft depth at well 6S/2W-24C7.

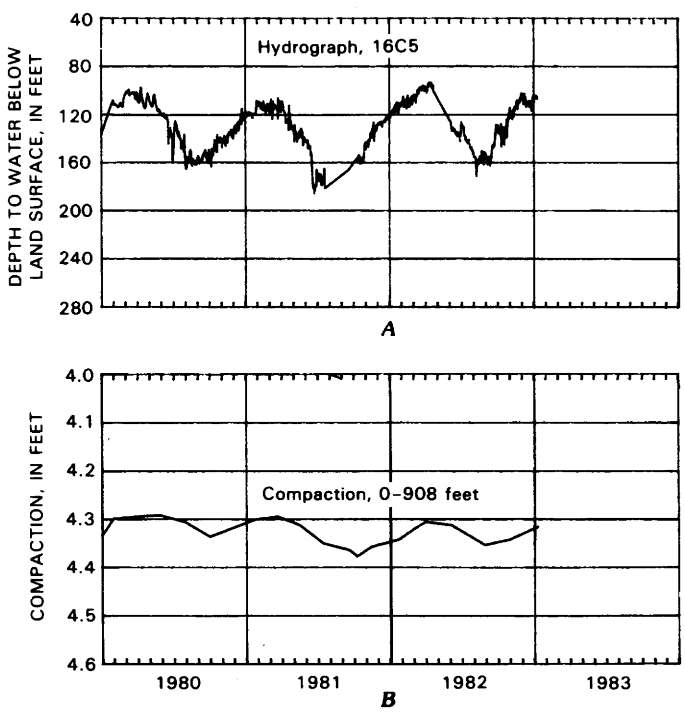

FIGURE 46.—Hydrograph and compaction, 7S/1E-16C5. *A*, Hydrograph of well 7S/1E-16C5, depth 908 ft. *B*, Compaction to 908-ft depth at well 7S/1E-16C5.

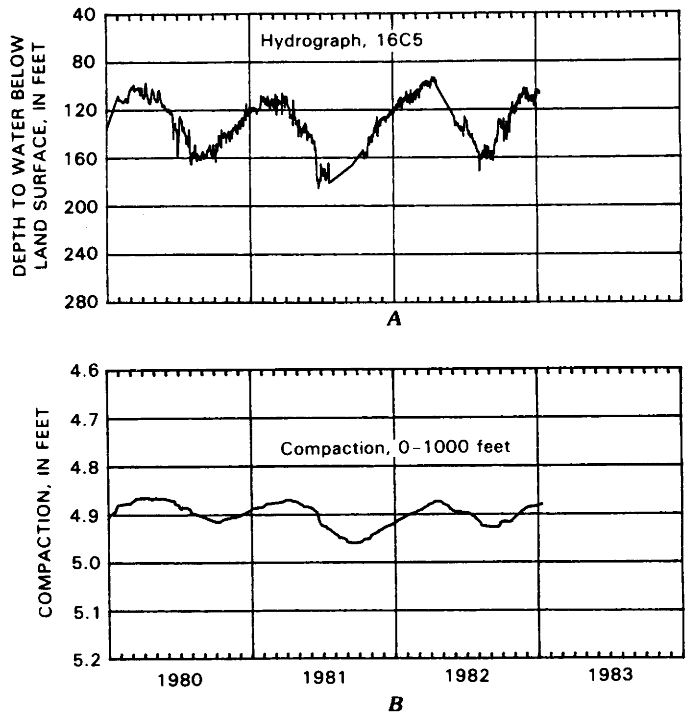

FIGURE 47.—Hydrograph 7S/1E-16C5, and compaction 7S/1E-16C11. *A*, Hydrograph of well 7S/1E-16C5, depth 908 ft. *B*, Compaction to 1,000-ft depth at well 7S/1E-16C11.

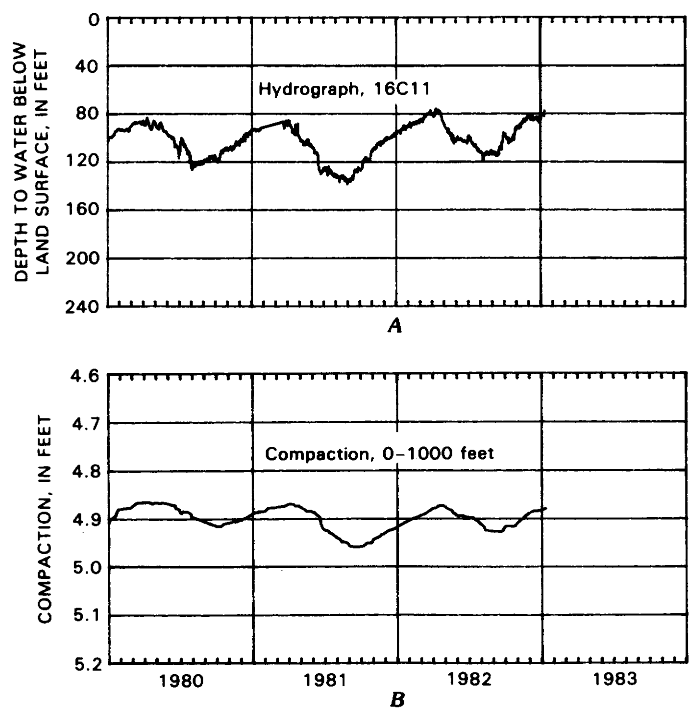

FIGURE 48.—Hydrograph and compaction, 7S/1E-16C11. *A*, Hydrograph of well 7S/1E-16C11, perforated 551–571, 598–618, and 640–660 ft. *B*, Compaction to 1,000-ft depth at well 7S/1E-16C11.

TABLE 6.—*Wells for which records are included in figures 31–42*

Figure number	Well number	Type of extensometer	Water-level recorder or observation well	Depth of well (feet)	Perforated interval (feet)	Remarks
31	6S/1W-23E1	Cable	Recorder	425	170–177 244–255 311–315 343–350	Stress-strain plot for 225-ft interval.
32	6S/2W-24C4	Cable and pipe.	Observation	250	---	Changed from cable to pipe assembly in October 1973.
33	-24C4	---do---	----do-----	250	---	
	-25C1	None	----do-----	500	unknown	
34	-24C3	Cable and pipe.	----do-----	550	---	Changed from cable to pipe assembly in October 1973.
35	-24C3	---do---	----do-----	550	---	
	-25C1	None	----do-----	500	unknown	
36	-24C4	Cable and pipe.	----do-----	250	---	
	-24C3	---do---	----do-----	550	---	
37	-24C4	---do---	----do-----	250	---	
	-24C3	---do---	----do-----	550	---	
	-25C1	None	----do-----	500	unknown	
38	-24C3	Cable and pipe.	----do-----	550	---	
	-24C7	---do---	----do-----	1,000	807–851 880–903	Changed from cable to pipe assembly in October 1973.
39	7S/1E-9D2	Cable	Recorder	605	unknown	
40	-16C5	Cable	---do---	908	unknown	Stress-strain plot for 708-ft interval.
41	7S/1E-16C6-11	Cable and pipe.	---do---	1,000	551–571 598–618 640–660	Stress-strain plot for 800-ft interval.
	-16C5	Cable	---do---	908	---	
42	-16C6-11	Cable and pipe.	---do---	1,000	---	Changed from cable to pipe assembly in April 1972.

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