EVALUATION OF SELECTED DATA TO ASSESS THE CAUSES OF SUBSIDENCE IN THE SACRAMENTO-SAN JOAQUIN DELTA, CALIFORNIA

By Stuart A. Rojstaczer, Rebecca E. Hamon, Steven J. Deverel, *and* Christine A. Massey

---

U.S. GEOLOGICAL SURVEY

Open-File Report 91-193

Prepared in cooperation with the

CALIFORNIA DEPARTMENT OF WATER RESOURCES

6217-15

Sacramento, California
1991

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

For sale by thc Books and
Open-File Reports Section,
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

For additional information write to:
District Chief
U.S. Geological Survey
Federal Building, Room W-2234
2800 Cottage Way
Sacramento, CA 95825

CONTENTS

FIGURES

Conversion Factors and Vertical Datum

Multiply	By	To obtain
feet (ft)	0.3048	meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per annum
pound per square inch (lb/in^2)	6.895	kilopascal

Vertical Datum

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

EVALUATION OF SELECTED DATA TO ASSESS THE CAUSES OF SUBSIDENCE IN THE SACRAMENTO-SAN JOAQUIN DELTA, CALIFORNIA

By Stuart A. Rojstaczer, Rebecca E. Hamon, Steven J. Deverel, *and* Christine A. Massey

Abstract

A preliminary study was done to evaluate selected data to assess the causes of subsidence in the Sacramento-San Joaquin Delta, California. Water-level and extensometer data indicate that ground-water withdrawal is not a major contributor to loss of elevation. Subsidence caused by ground-water withdrawal is temporary in the summer months, but the aquifer material rebounds during the winter months. The distribution of radioactivity of cesium-137 in sediments on undisturbed islands indicates that regional subsidence is less than 0.2 inch per year since 1963. Gas and ground-water withdrawals are not primary factors in determining subsidence rates in the delta.

Subsidence occurring in the peat layer was assessed using measurements of elevation loss near foundations of electrical transmission towers and land-surface elevation, and data from leveling surveys on three islands between 1922 and 1981. On the basis of these determinations, spatially variable subsidence rates range from 1 to 3 inches per year.

INTRODUCTION

The Sacramento-San Joaquin Delta lies at the confluence of the Sacramento and San Joaquin Rivers at the eastern end of San Francisco Bay, California. Prehistorically, the delta existed as a freshwater tule and reed marsh. Deposition of decayed plant material caused the marsh to maintain a constant elevation at sea level, in spite of the eustatic sea-level rise. The eustatic sea-level rise has been occurring at a rate of about 0.08 in/yr since the last ice age about 10,000 yrs ago (Atwater and others, 1977; Atwater, 1980). Under water-logged anaerobic conditions, decayed plant material accumulated faster than it decomposed, forming a peat layer which in some areas of the delta was more than 50 ft thick (Thompson, 1957). In the late 19th and early 20th centuries, the land was cleared and drained for farming purposes, halting the process of accumulation and eliminating the surface anaerobic conditions.

Reclamation and agricultural activities have caused land subsidence ranging from 1 to 3 in/yr. Such rates are nearly double the subsidence rates in comparable areas, including reclaimed sections of the Florida Everglades, where elevation loss averages 1 in/yr (Stephens and others, 1984). Subsidence has resulted in many of the delta islands' interiors lying substantially below sea level. Continuing subsidence poses a threat to the stability of the levees that are required to prevent the islands from flooding. As land surface subsides on the islands, the hydraulic gradient across the levees needs to be maintained to allow farming increases. The increased hydraulic gradient increases the stress on the levees, increasing the probability of failure.

This report presents the preliminary results of ongoing studies to determine what causes or contributes to subsidence in the Sacramento-San Joaquin Delta. Selected subsurface and land-use data were evaluated to provide information about subsidence occurring below and in the peat layer. Specifically, the causes of subsidence were assessed from extensometer and water-level data, cesium-137 determinations in sediment cores from undisturbed delta islands, soil loss measured against electrical transmission towers, and transect surveys.

This ongoing study is being done by the U.S. Geological Survey in cooperation with the California Department of Water Resources. Blueprints of the electrical transmission towers were provided by Pacific Gas and Electric Company. Christopher Fuller, U.S. Geological Survey, Menlo Park,

determined cesium-137 levels in sediment samples and Lisa Shepard, U.S. Geological Survey, Menlo Park, provided technical and field assistance.

EVALUATION OF SUBSURFACE DATA

GROUND-WATER WITHDRAWAL

Extensometers were installed and have been monitored continuously since October 1987 on Bacon Island and August 1988 on Bethel Island to measure ground-water related subsidence. Extensometers are attached and referenced to piers cemented below the peat layer and are not influenced by peat loss. The depths of the extensometers were selected to ensure that they were well below the primary aquifers on the islands. The extensometers were installed at depths of 440 and 540 ft at Bacon and Bethel Islands, respectively. Figure 1 shows the location of the Sacramento-San Joaquin Delta and the extensometer sites. The mechanical characteristics of extensometers were discussed by Riley (1986).

Depth to water in the primary aquifers used for ground-water withdrawal also is monitored continuously in observation wells. Observation wells with 5-foot screened intervals centered at depths of 300 and 440 ft were installed at the Bacon and Bethel Island sites, respectively. Figure 2 shows elevation loss and depth to water from September 1987 to December 1989 for the Bacon Island site. The Bacon Island data indicate that the monitoring well is not in direct contact with the surrounding aquifer, as the peaks and troughs in the depth-to-water data are offset from the extensometer data. The time lag between the responses in the two data sets is about 60 days. A slug test done on the well in July 1989 confirms this lag.

Figure 3 shows elevation loss and depth to water from July 1988 to November 1989 for the Bethel Island site. Data from Bethel Island show that elevation loss is about 0.005 ft during the summer months when the maximum quantity of ground water is pumped; however, the aquifer materials affected by pumping apparently still retain the capacity to rebound when pumping decreases, as indicated by a rise in elevation during the winter months. The October 17, 1989, earthquake at Loma Prieta is a prominent peak in the data; however, this peak is more likely the result of equipment disruption than a physical compaction process.

At both the Bethel Island and the Bacon Island sites, the depth to ground water is less than 5 ft. At Bethel Island, artesian conditions prevailed during the winter of 1989. The shallow depth to ground water indicates that ground water is not used extensively. The small changes in depth to water in the aquifers at these sites are consistent with a lack of ground-water related subsidence; therefore, ground-water withdrawal is not a major contributor to present-day elevation loss on Bacon and Bethel Islands.

NATURAL GAS WITHDRAWAL

Since the discovery of the Rio Vista gas field in the 1930's, many natural gas fields have been developed in the delta. The locations of the major gas fields adjacent to and in the delta are shown in figure 4. Natural gas is withdrawn from about 4,500 ft below land surface. Significant compaction of the rocks in the gas field could occur if the gas reservoirs were sufficiently depressurized (California Department of Water Resources, 1980), resulting in elevation loss. Examination of the historical gas field data from the files of the California Division of Oil and Gas indicates that the pressure in the Rio Vista gas field, the largest gas mining operation in the delta, has decreased more than 2,000 lb/in^2 since 1945. The effect of this decrease in pressure on surface subsidence depends on the compressibility and permeability of the reservoirs and surrounding rocks (Gertsma, 1973).

Dating of sediment cores at undisturbed sites provides an estimate of subsidence in the delta caused by ground-water and gas withdrawal. Small pockets of marshland were never reclaimed and remain at sea level. Soil accumulation still seems to be occurring in these areas, allowing the elevation to rise with the eustatic sea-level change. Concurrently, these sites also seem to accumulate enough material to offset any subsidence, which would tend to lower their elevation below sea level. Recent sedimentation rates can be measured by analyzing the vertical sediment core samples for cesium-137 (Delauney and others, 1978). Cesium-137 in sediment is predominately derived from atmospheric testing of atomic weaponry. Radioactive fallout containing high levels of cesium-137 began in 1954 with peak fallout in 1963, shortly before the nuclear weapons testing ban went into effect.

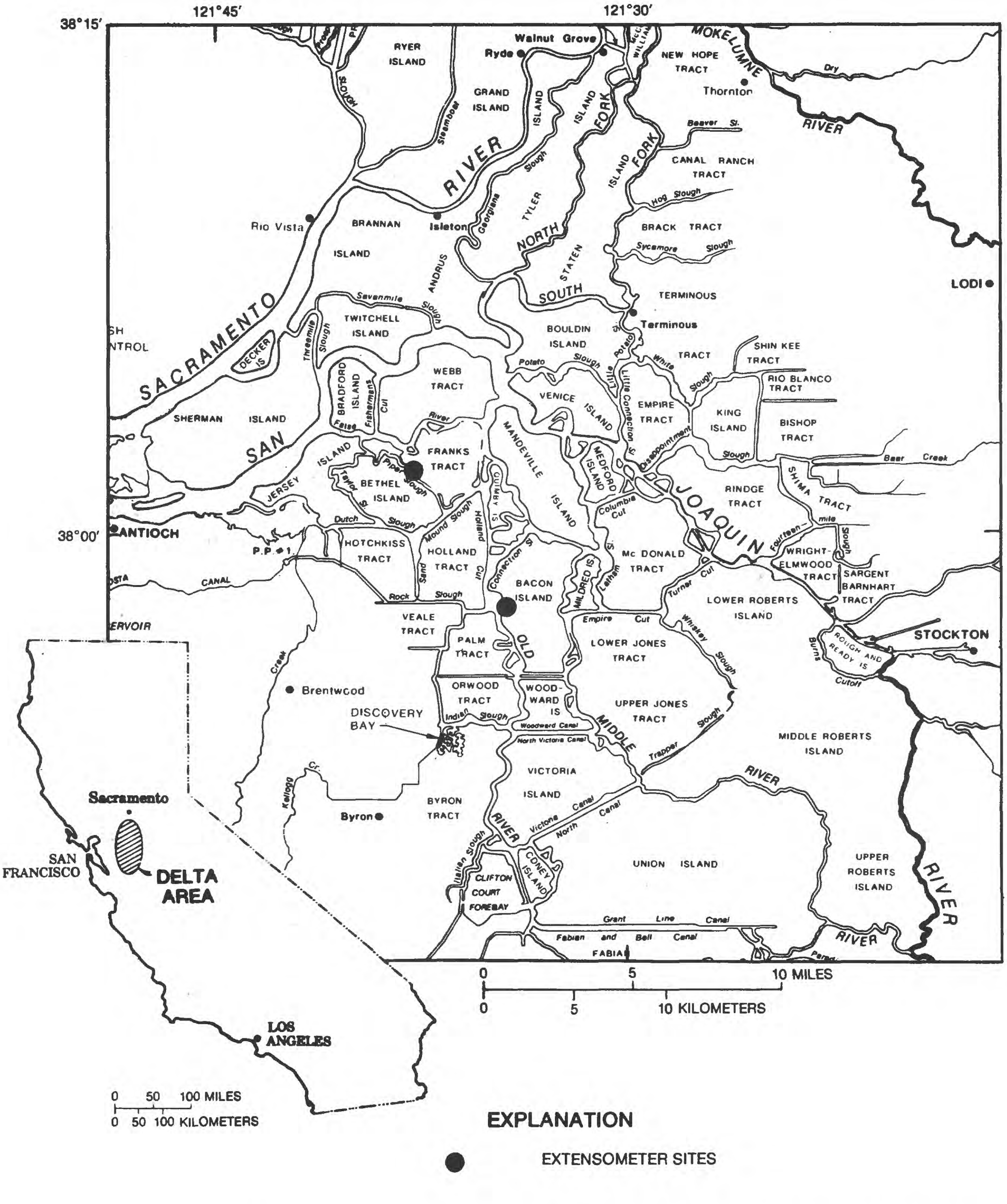


Figure 1. Location of Sacramento-San Joaquin Delta and extensometer sites. Modified from California Department of Water Resources (1980).

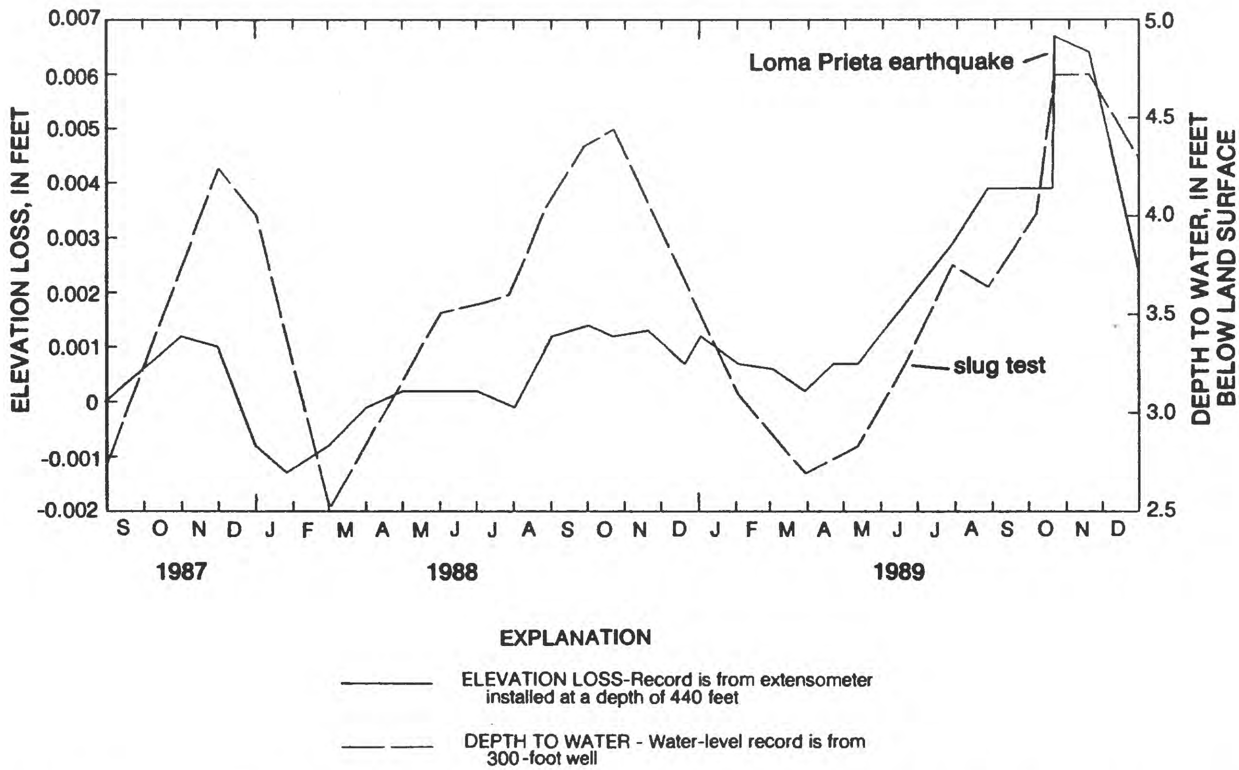


Figure 2. Extensometer record of elevation loss and depth to water from September 1987 to December 1989 for the Bacon Island site.

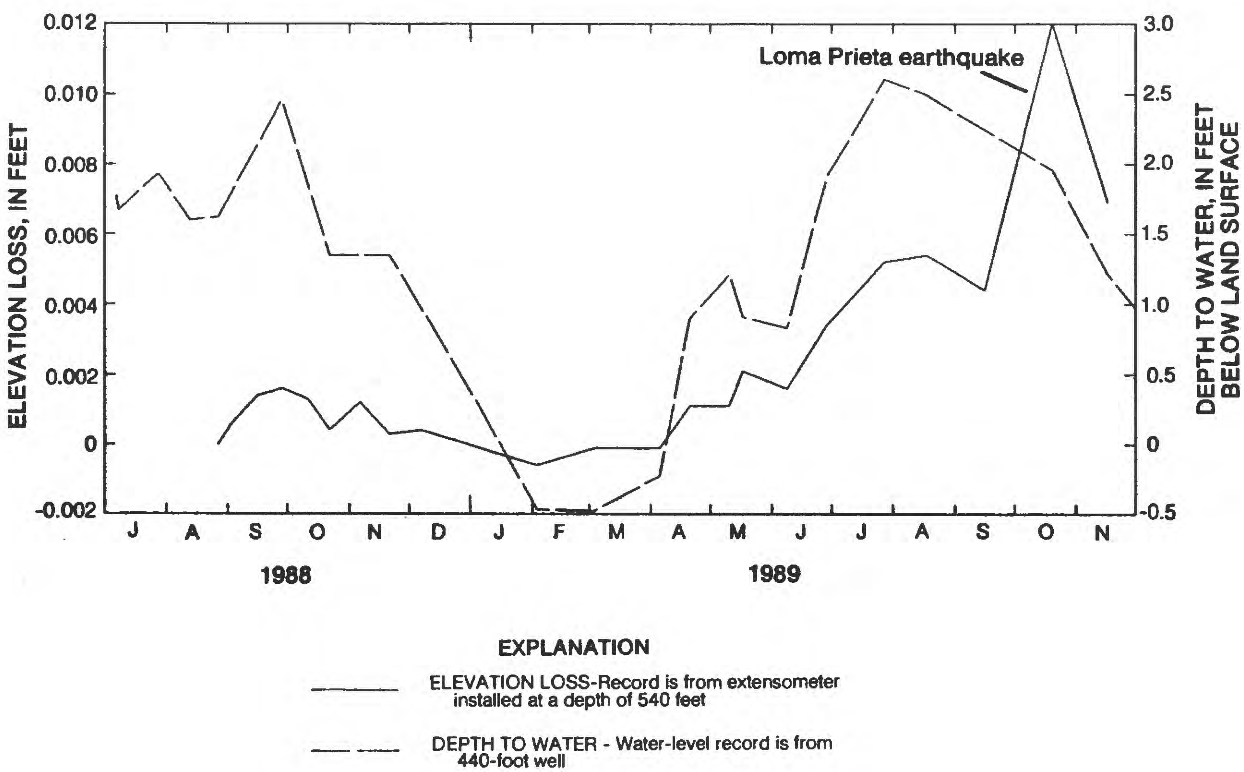


Figure 3. Extensometer record of elevation loss and depth to water from July 1988 to November 1989 for the Bethel Island site.

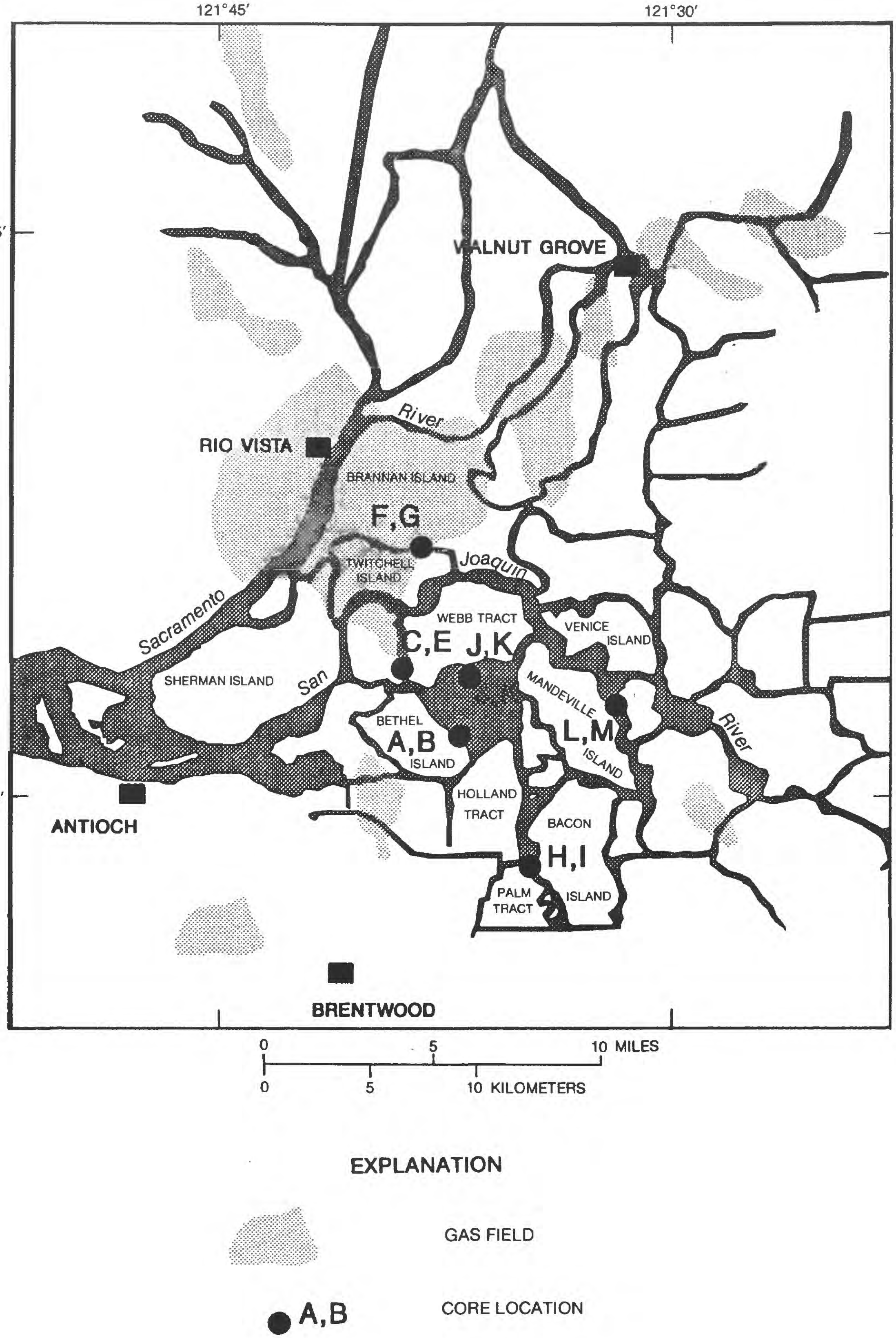


Figure 4. Locations of major gas fields and cores for cesium-137 sampling.

Twelve cores from six different sites were analyzed for radioactivity of cesium-137. Core samples were collected at 1-inch depth intervals at each of the sampling sites. The radioactivity of cesium-137 was determined by scintillation counting. The locations of the sites are shown in figure 4. Figure 5 shows the distribution of radioactivity associated with cesium-137 in the core samples. Five of the cores contain prominent peaks at variable depths. The rest of the cores (not shown) do not show prominent cesium-137 peaks, indicating that sampling took place in areas that experienced bioturbation, resulting in a mixing of the sediment histories. None of the cores had peaks below 7 in., indicating that the maximum possible subsidence in undisturbed areas (after the eustatic sea-level rise of 0.08 in/yr has been accounted for) has been less than 5 in., or 0.2 in/yr, since 1963. The rate is small relative to the subsidence on reclaimed islands. The subsidence in undisturbed areas probably is due to ground-water and gas withdrawal.

EVALUATION OF SURFACE DATA

Two types of data used to determine subsidence rates in the peat layer have been collected and analyzed. Loss of elevation relative to foundations of electrical transmission towers in three power lines installed across Sherman and Jersey Islands has been used to estimate time-averaged subsidence. The power line constructed in 1910 runs northeast-southwest across Sherman Island. Power lines installed in 1952 and 1965 traverse Jersey and Sherman Islands (fig. 6). Data from transect surveys by Weir (1950) and Broadbent (1960) also were analyzed to develop hypotheses about the causes of subsidence.

ELECTRICAL TRANSMISSION TOWERS

The foundations of electrical transmission towers serve as indicators of how much soil has subsided since the towers were erected because they are mounted on pilings which are driven to refusal, generally tens of feet below the peat layer. In the summer of 1988, tower foundation heights were measured using a level positioned in fields adjacent to each of the four foundations supporting the tower (fig. 7). The average of the four measurements was compared with the average foundation heights of the towers when they were first constructed.

At Sherman Island, the foundations were increasingly exposed toward the island center, showing a maximum soil loss of about 7 ft from 1910 to 1988. For the data from the towers constructed in 1910, the average soil loss on Sherman Island from 1910 to 1988 was about 1 in/yr (fig. 8). Data from the towers constructed in 1952 indicate a maximum soil loss of about 4 ft towards the center of Sherman Island, and an average rate of soil loss for Sherman Island of about 0.7 in/yr (fig. 9). Jersey Island has experienced less soil loss, with an average of about 1 ft (±0.75 ft) from 1952 to 1988 or 0.33 in/yr (fig. 8).

Some information is available to assess the accuracy of the 1910 and 1952 electrical transmission tower data. Historical foundation heights were obtained from blueprints, which showed how the foundations were designed, but specific installation details were unavailable. For the 1910 line, only a generalized blueprint applicable to all tower foundations was available. The foundations were intended to be installed with 2 ft of concrete exposed above land surface. Therefore, a maximum limit for subsidence rate can be established assuming the foundations were positioned, incorrectly, so that the tops of the foundations were at land surface. The subsidence rate then approaches 1.5 in/yr in areas where subsidence reaches its maximum on Sherman Island. Possible error with the 1952 data is minimal as the original foundation heights are based on detailed drawings that describe each of the tower foundations along the transmission line.

Data from the electrical transmission towers constructed in 1965 are problematic in that many of the points indicate an apparent rise in elevation from 1965 to 1988. This apparent elevation rise indicates that either elevation control was poor on the initial installation heights of the towers or possibly some of the pilings were not driven far enough and are sinking. This study indicates that since 1910, Sherman and Jersey Islands seem to be subsiding at a much slower rate than the islands along a transect survey (Weir, 1950) farther east, where there has been as much as 3 in/yr of soil loss.

TRANSECT SURVEYS

Twenty-one complete surveys following the route shown in figure 10 were conducted between 1922 and 1981 (Weir, 1950; Broadbent, 1960). These surveys

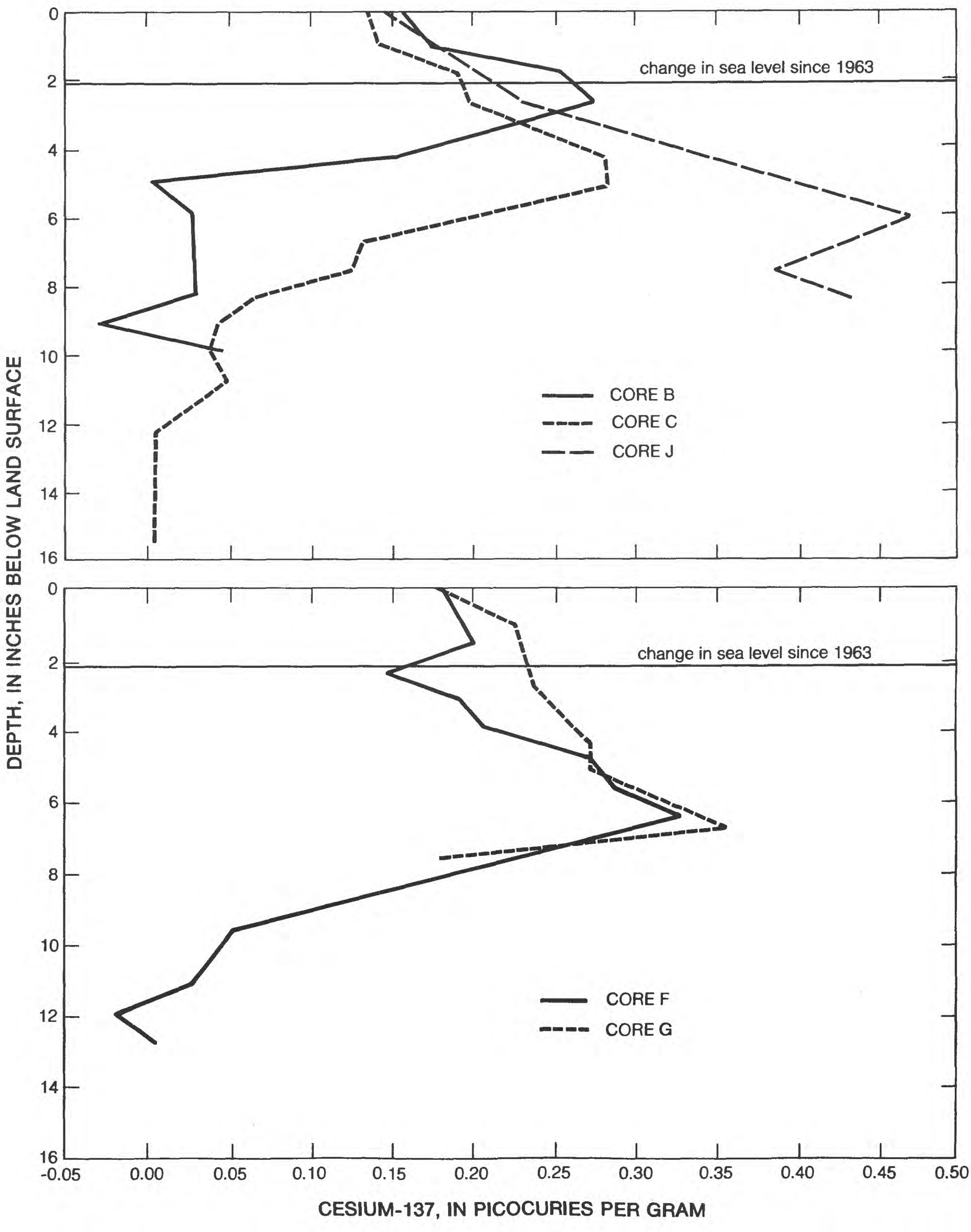


Figure 5. Distribution of radioactivity of cesium-137 in samples collected from cores B, C, and J, F, and G. Core locations shown in figure 4.

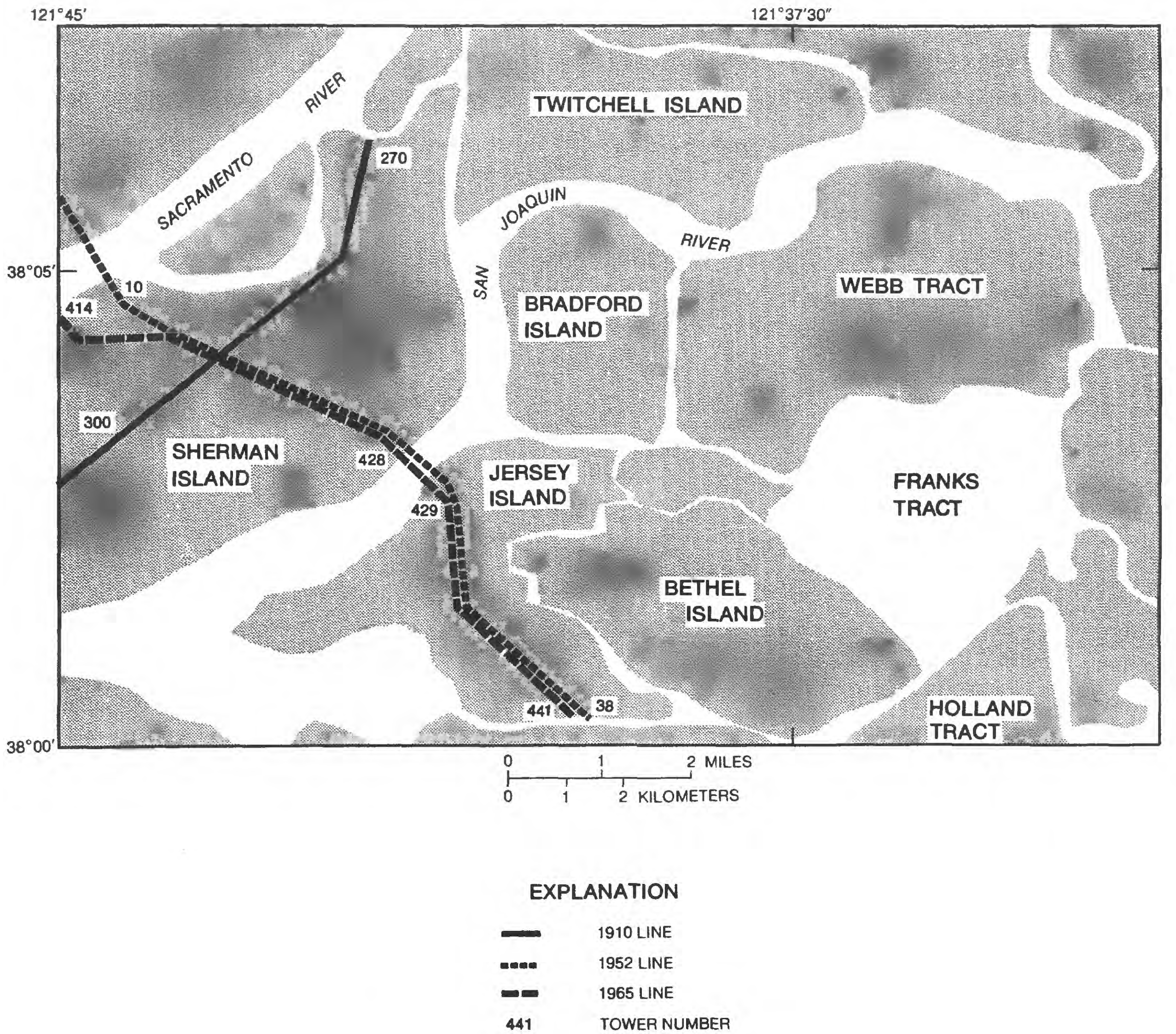
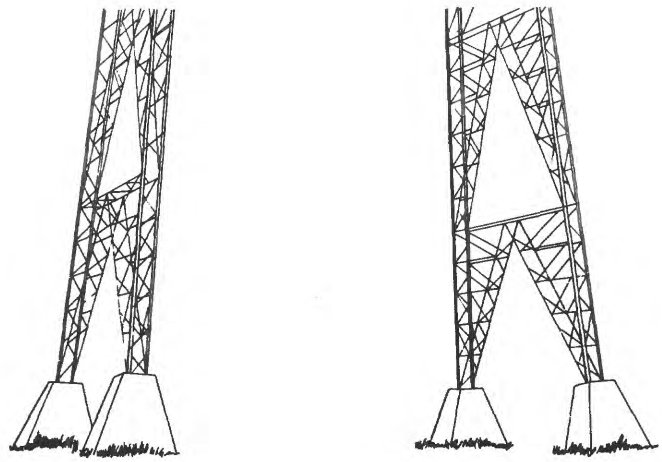


Figure 6. Locations of electrical transmission lines.

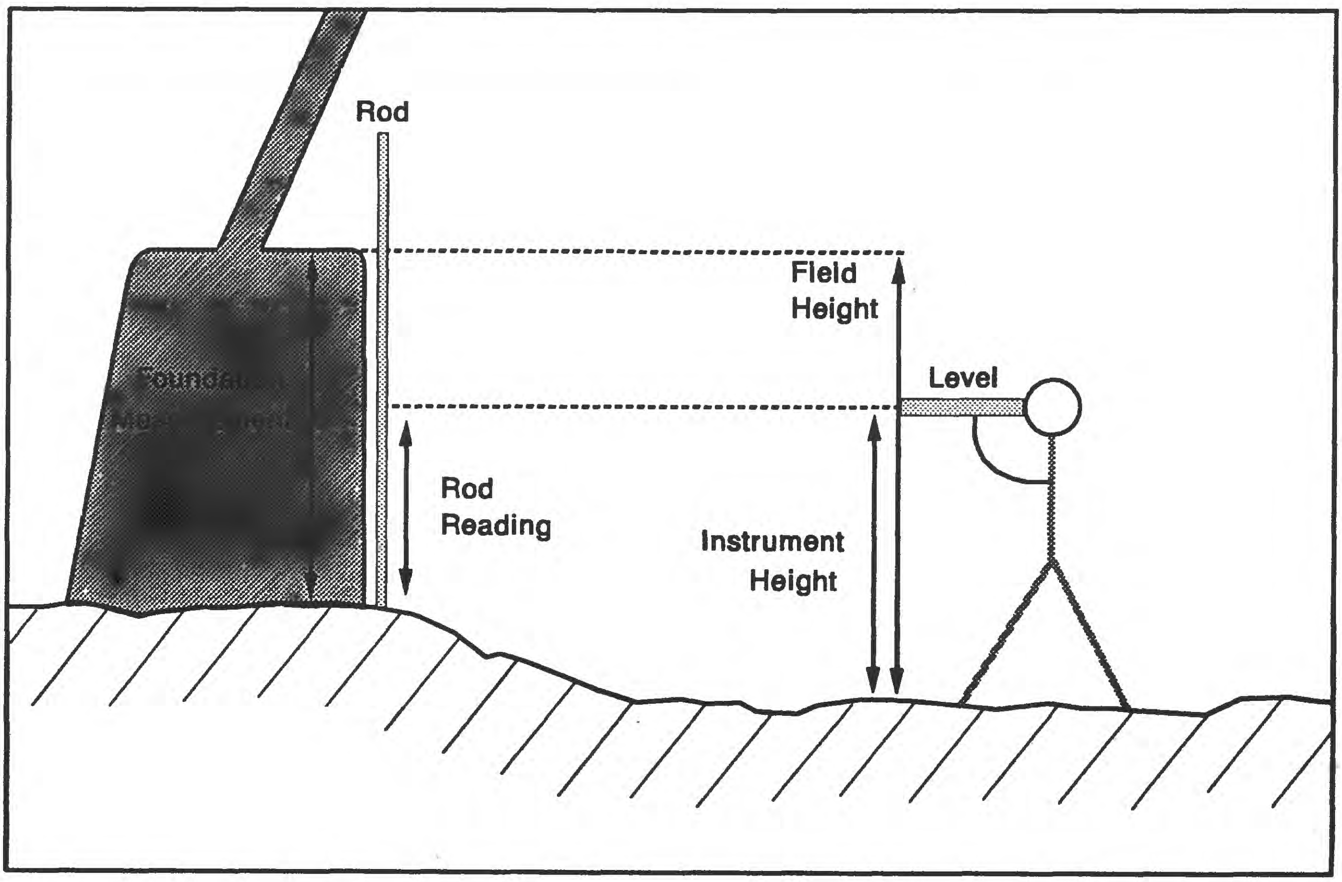
were referenced to a benchmark on the levee at the southwest corner of Lower Jones Tract. This benchmark is not anchored below the peat horizon; however, its position on the levee is apparently much more stable than the surrounding peat fields, as the surveys continue to show progressive subsidence each year.

The 18 surveys for which closure error information is available show that, in general, the surveys were conducted to the accuracy of an ordinary survey (Smirnoff, 1961). Closure differences ranged from 0.04 to 0.42 ft (average, 0.23 ft). Weir (1950) considered a closure error of 0.3 ft acceptable due to the difficult leveling conditions. Assuming that this closure error is random and distributed equally across the 8 mi of the transect, the leveling error is small relative to the rate of subsidence.

Information provided by the transect surveys was last analyzed in 1950 (Weir, 1950). These data provide a unique record of the history of subsidence on three islands in the delta. Thorough analysis of the data, including evaluation of subsidence trends, will help quantify the effects of variables such as land use and soil type on subsidence rates on Lower Jones Tract, Mildred Island, and Bacon Island.



A



Field Height = (Foundation measurement + instrument height) - rod reading

B

Figure 7. Foundation of electrical transmission tower (*A*) and technique for measuring soil loss relative to tower foundation (*B*).

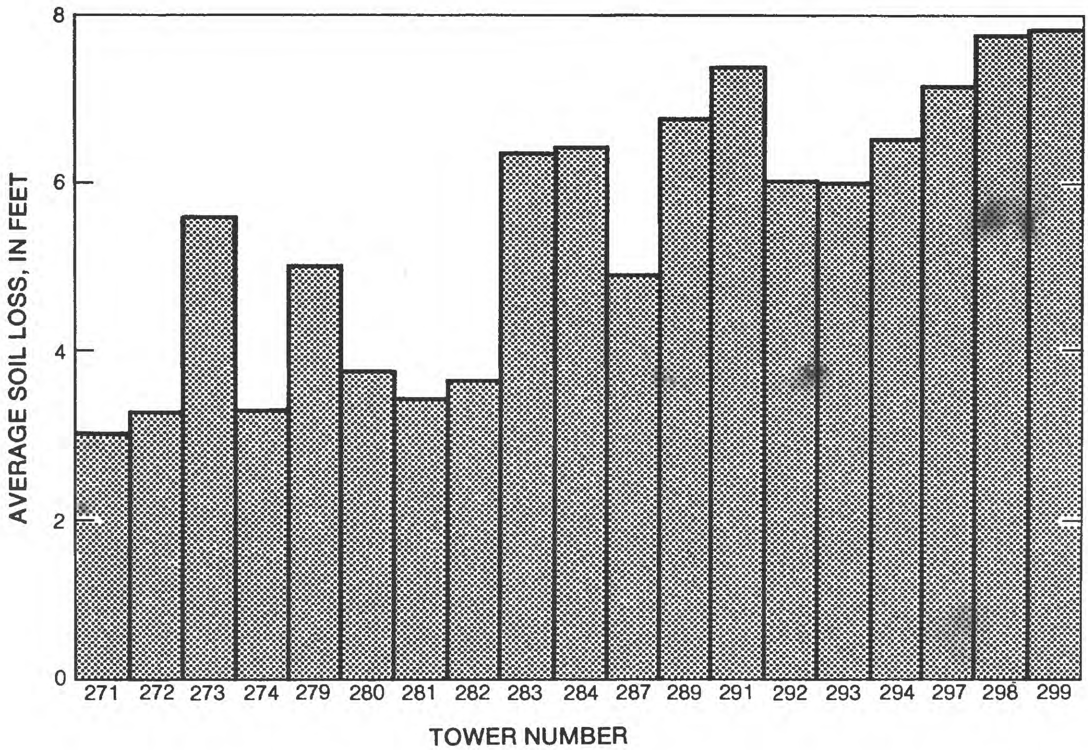


Figure 8. Average soil loss from 1910 to 1988 at electrical transmission towers installed on Sherman Island in 1910. Location of transmission line shown in figure 6.

The mean annual subsidence rates were calculated from the mean elevation histories for each island. To obtain elevation histories, the mean elevation of each island was calculated for every repeat survey, removing survey points which were taken on highly mineralized soil. The average annual subsidence rates are 2, 3, and 3 in. on Lower Jones Tract, Mildred Island, and Bacon Island, respectively.

The decreases in elevation over time were compared with two statistical regression models that predict linear and logarithmic decreases in elevation over time. Figure 11 shows the measured and predicted elevation changes for both models over time. The results of both models fit the data well, as indicated by the correlation coefficients. However, comparing the residuals of the predicted elevation losses for the two models with actual elevation losses indicates that the logarithmic model fits the data better than the linear model. For the logarithmic model, the residual values are normally distributed around zero over the range of the data. In contrast, for the linear model, the residuals are negatively skewed and not normally distributed. The better fit of the logarithmic model indicates that subsidence rates are slowing over time.

Subsidence histories were constructed for each of the islands along the transect. To construct subsidence histories, the 1925 survey (Weir, 1950) was used as the base elevation. Elevation data from subsequent surveys were subtracted from the base elevation to determine elevation changes since 1925. Figure 12 shows the spatial variations of subsidence and land-use histories during 1925-81 along sections of the transect on Lower Jones Tract, Mildred Island, and Bacon Island. The contours represent the cumulative elevation loss, in feet, for the years of

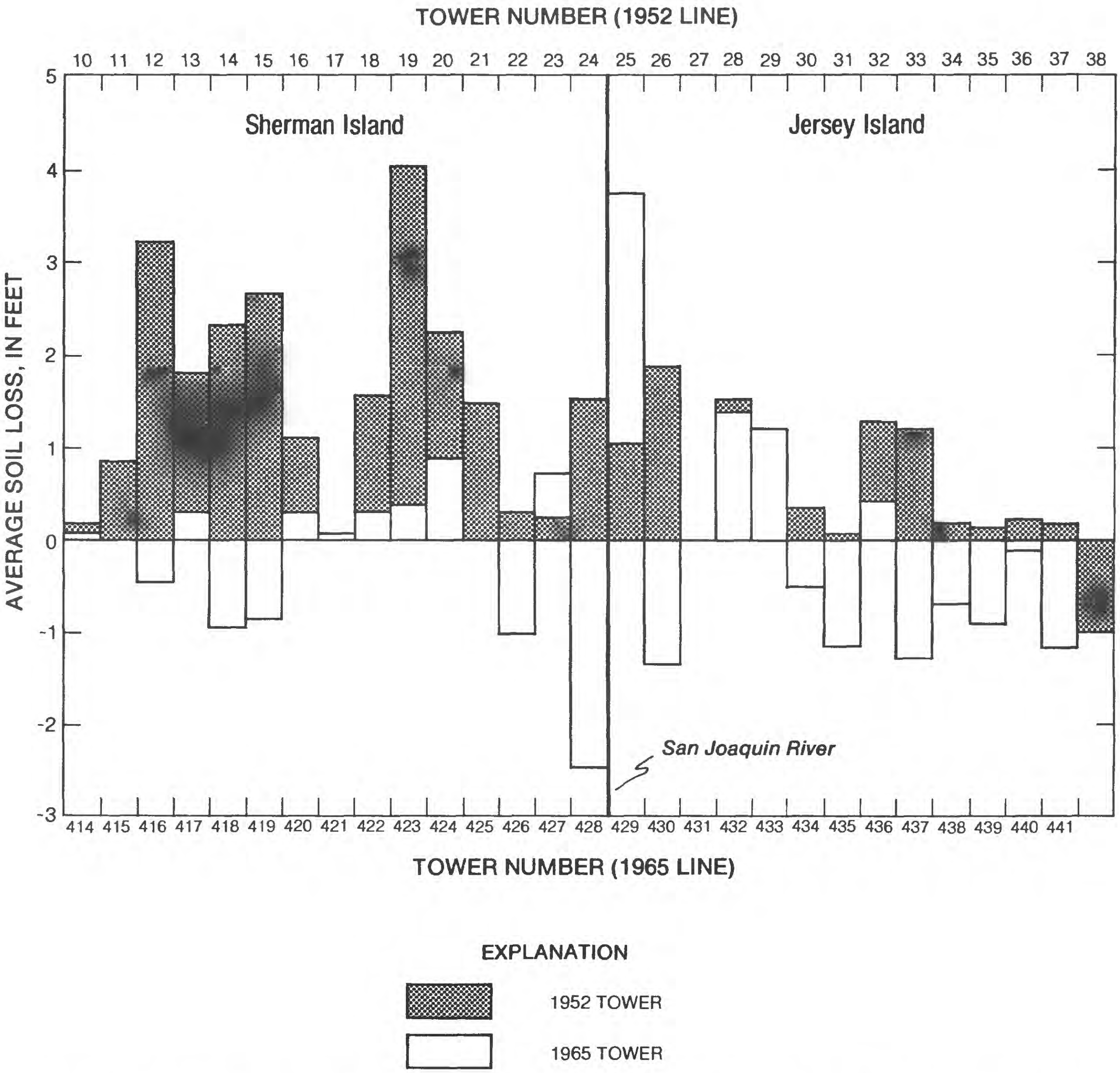


Figure 9. Average soil loss at electrical transmission towers installed on Sherman and Jersey Islands in 1952 and 1965. Locations of transmission lines shown in figure 6.

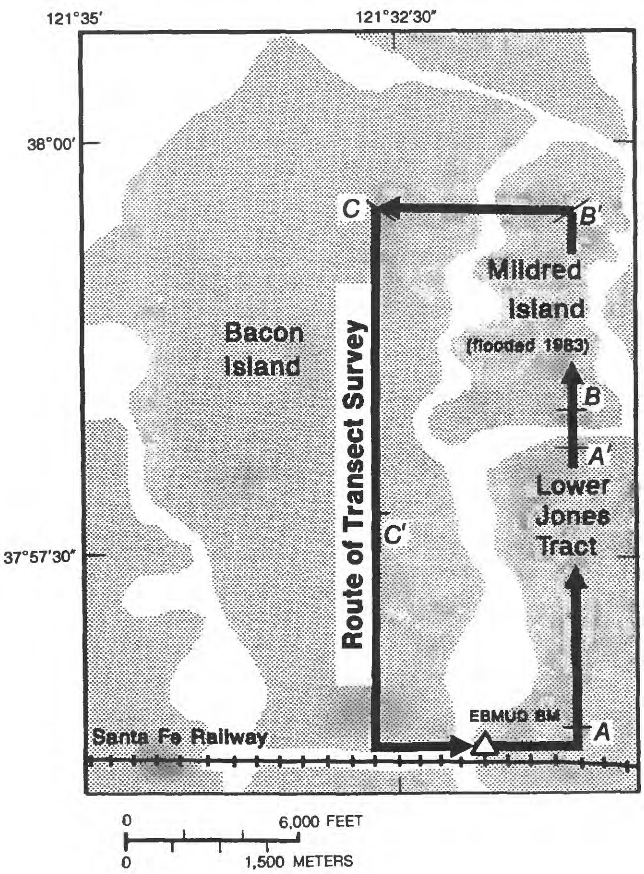


Figure 10. Location and route of transect survey (Weir, 1950) and location of sections shown in figure 12.

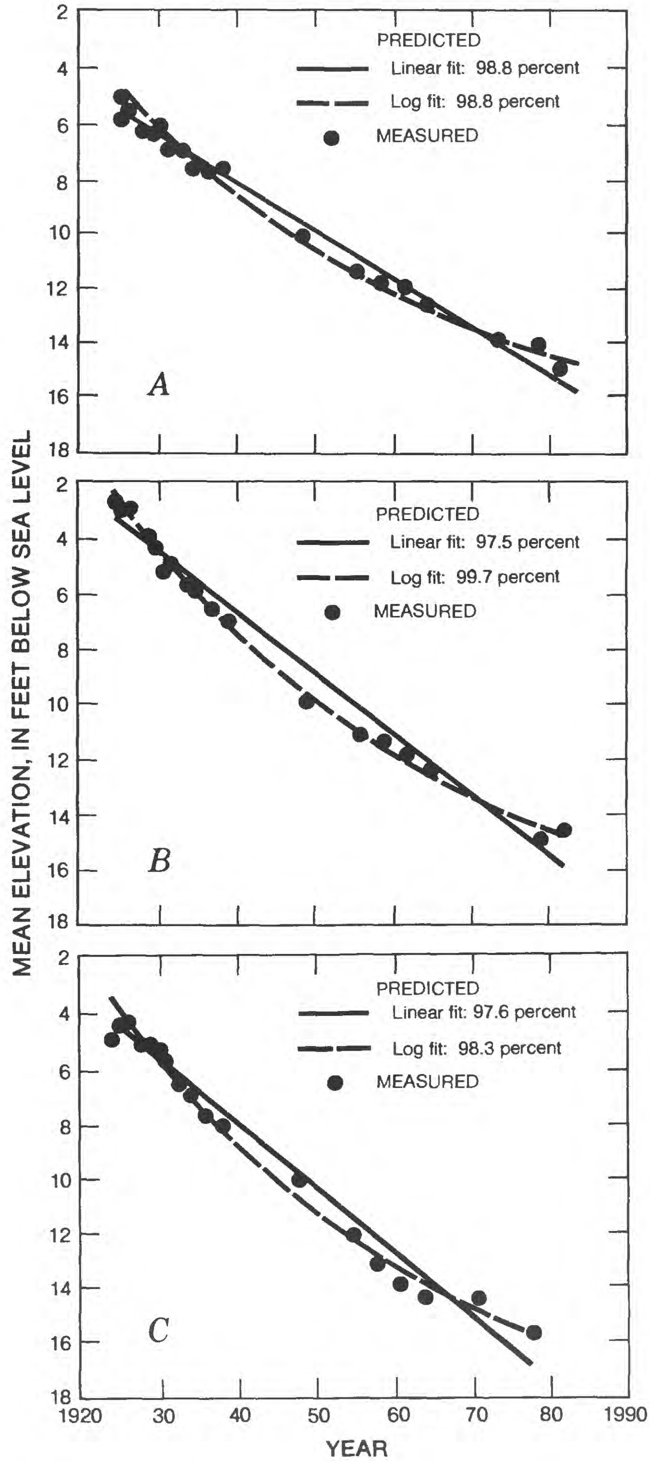


Figure 11. Measured and predicted mean elevation losses since the 1920's. *A*, Lower Jones Tract. *B*, Mildred Island. *C*, Bacon Island. Percentages reflect the correlation coefficients for a linear and logarithmic fit to the measured elevation data.

measurement. Areas with high subsidence rates appear as troughs, and areas with low subsidence rates appear as crests.

The California Department of Water Resources (1980) indicated that different farming techniques associated with different crop types could affect local subsidence rates, although they were not able to confirm this with available data. They did state that burning of peat fields has been localized and has diminished substantially in recent years. Where practiced, the California Department of Water Resources (1980) estimated that burning could result in 0.08 to 0.13 in/yr of subsidence. The types of crops growing along each leg of the transect were compared against the spatial contour and temporal subsidence data for each of the islands and time periods to assess the effects of farming techniques on subsidence.

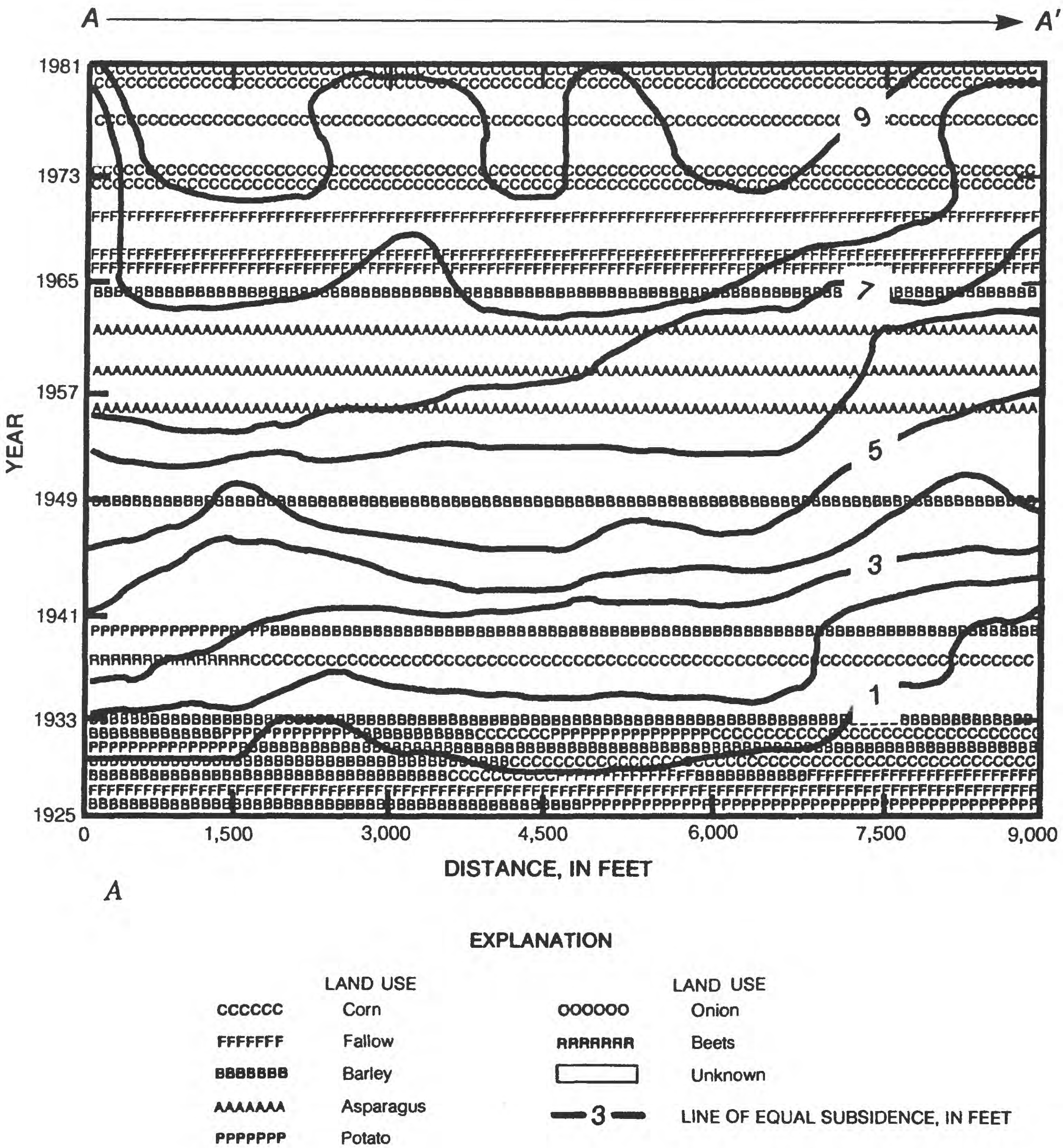


Figure 12. Spatial variation of subsidence and land-use histories along sections of the transect, 1925-81. *A*, Lower Jones Tract, section A-A′. *B*, Mildred Island, section B-B′. *C*, Bacon Island, section C-C′.

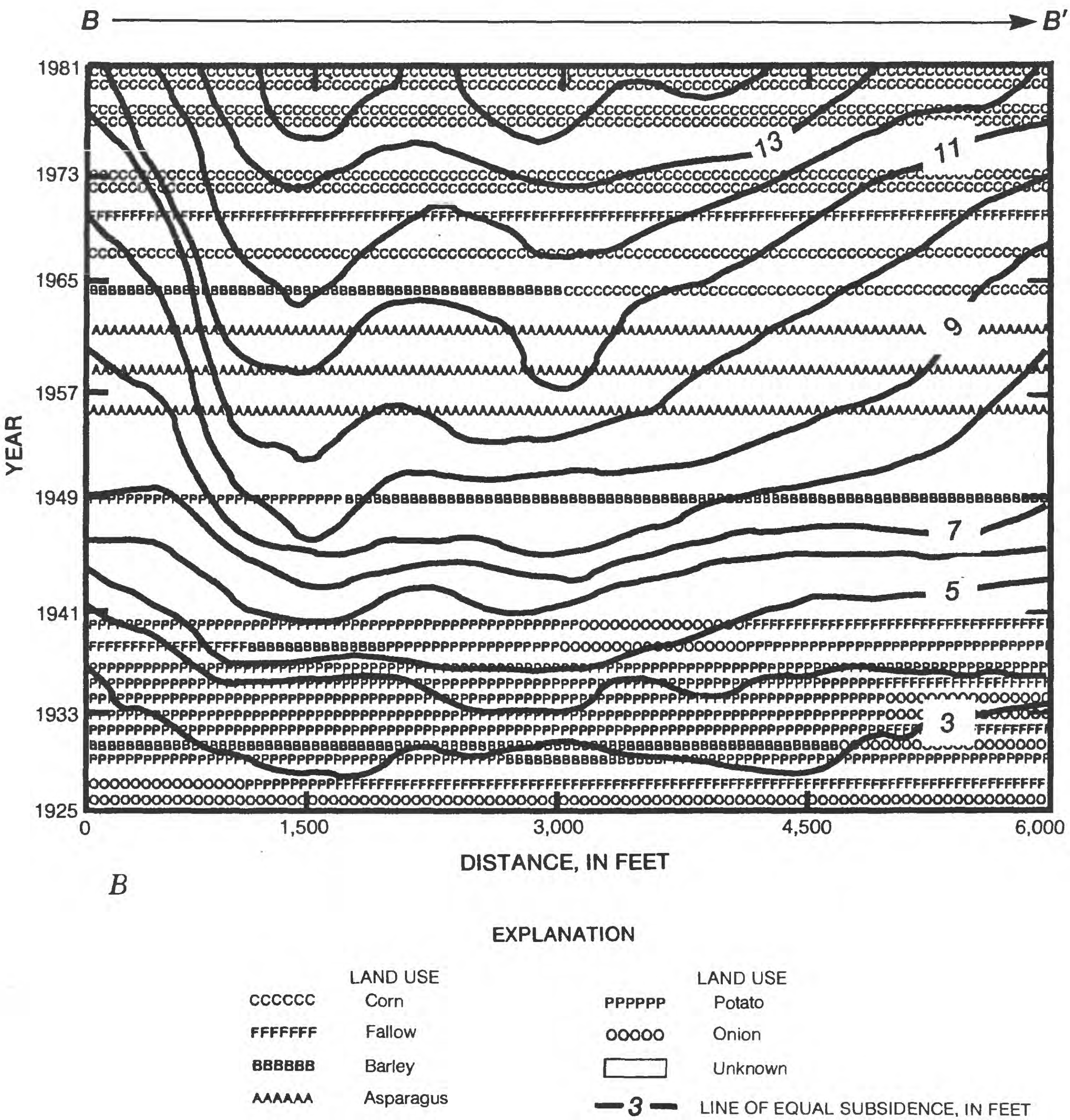


Figure 12. Continued.

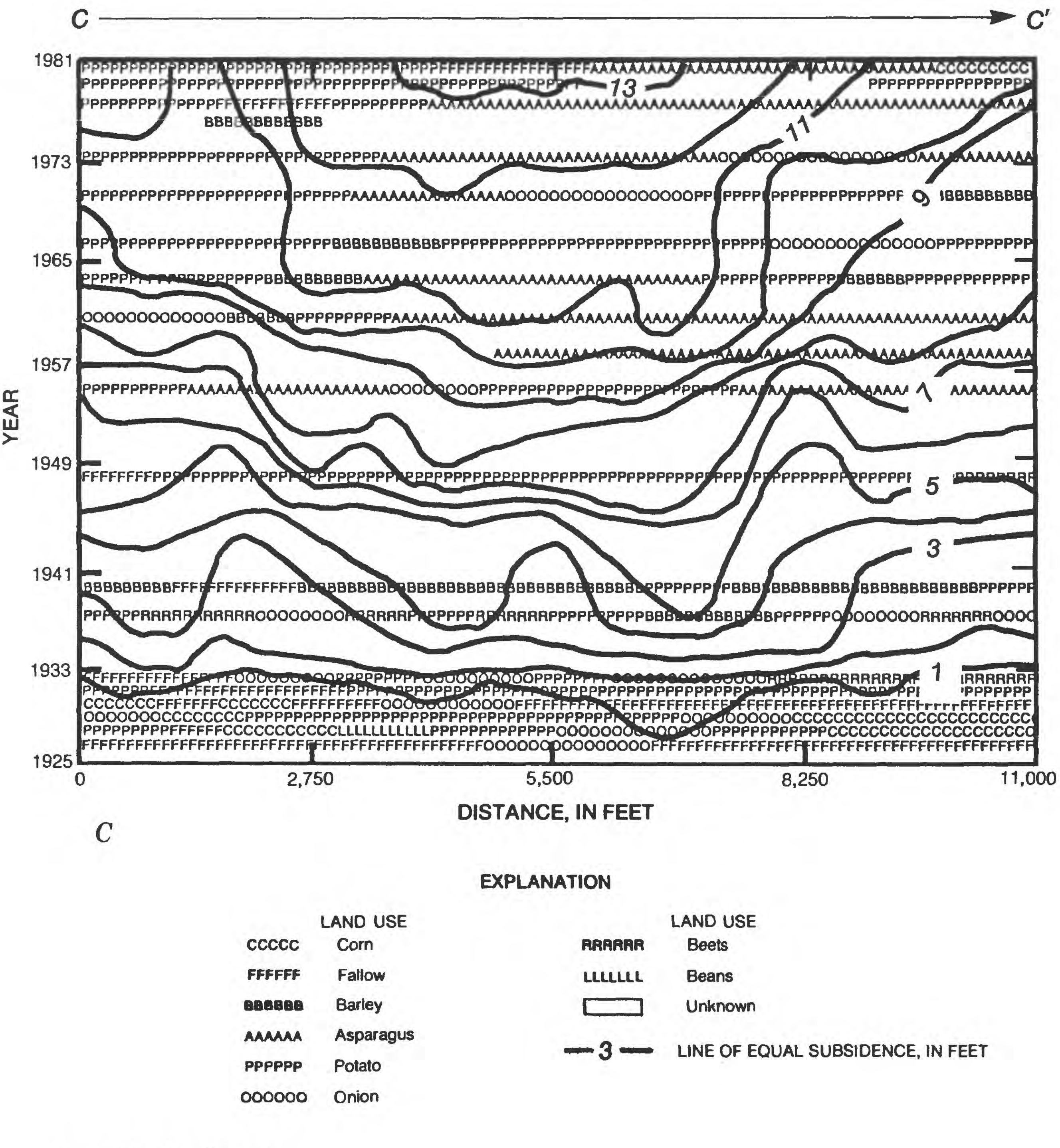


Figure 12. Continued.

Relatively evenly spaced contours in figure 12 indicate that temporal rates of subsidence have remained virtually constant on all three islands in spite of different types of crop cultivation. The one notable exception occurs between 1938 and 1948 where the contours, at least on Lower Jones Tract (fig. 12*A*) and Mildred Island (fig. 12*B*), are clustered, implying an increased rate of subsidence during this time. Data regarding land use are not available as the transect was not surveyed between 1938 and 1948. However, Thompson (1957) observed that sugar beets and potatoes were the predominant crops grown in the delta during World War II (1939-45) due to the war-time demand for these products. The production of potatoes and sugar beets benefit from the ash remaining after a peat field has been burned. Controlled burning was apparently done in the delta throughout the war years (Thompson, 1957). When a peat field is set alight, as much as the top 3 in. of soil can burn (Weir, 1950). The increased subsidence rates measured on Mildred Island and Lower Jones Tract between 1938 and 1948 could be the result of peat field burning if, indeed, farmers on these two islands shifted to the popular war-time cropping practices.

A historically persistent trough, indicating an area of increased subsidence, occurs toward the center of the transect along both Mildred and Bacon Islands. On Mildred Island, the subsidence trend cannot be correlated with a particular crop type as for any given year, crop type along the transect was virtually uniform. Also there was no apparent relation between crop type and subsidence for the Bacon Island data. With the possible exception of burning of the peat fields, cultivation and cropping practices do not seem to affect subsidence rates on these three islands.

SUMMARY AND CONCLUSIONS

Below the peat layer, extensometer data indicate that subsidence of 0.005 ft is temporary during the summer months when ground water is pumped, but that the aquifer materials rebound during the winter months. Distribution of radioactivity of cesium-137 in samples collected in undisturbed sediments indicates that the subsidence on undisturbed islands in the delta has been less than 0.2 in/yr since 1963. These data and the extensometer data indicate that ground-water and natural gas withdrawals occurring below the peat layer apparently do not contribute substantially to subsidence.

Data from measurements of decreases in elevation relative to foundations of electrical transmission towers and elevation measurements made from 1922 to 1981 provided information about subsidence occurring in the peat layer. These data indicate that subsidence rates range from about 1 to 3 in/yr. Data from a transect survey indicate that different cultivation and cropping practices do not substantially affect subsidence rates on Lower Jones Tract, Mildred Island, and Bacon Island.

REFERENCES CITED

Atwater, B.F., Hedel, C.W., and Helley, E.J., 1977, Late Quaternary depositional history, Holocene sea-level changes, and vertical crustal movement, southern San Francisco Bay, California: U.S. Geological Survey Professional Paper 1014, 15 p.

Atwater, B.F., 1980, Attempts to correlate Late Quaternary climatic records between San Francisco Bay, the Sacramento-San Joaquin Delta, and the Mokelumne River, California: Dover, Delaware, University of Delaware, Ph.D. dissertation, 215 p.

Broadbent, F.E., 1960, Factors influencing the decomposition of organic soil of the California delta: Hilgardia, v. 29, p. 825-830.

California Department of Water Resources, 1980, Subsidence of organic soils in the Sacramento-San Joaquin Delta: California Department of Water Resources.

Delauney, R.D., Patrick, W.H., and Buresh, R.J., 1978, Sedimentation rates determined by cesium-137 dating in a rapidly accumulating salt marsh: Nature, v. 275, p. 532-533.

Gertsma, J.E., 1973, Land subsidence above compacting oil and gas reservoirs: Journal of Petroleum Technology, v. 25, p. 734-744.

Riley, F.S., 1986, Developments of borehole extensometry: International Association of Hydrological Sciences, v. 151, p. 169-186.

Stephens, J.C., Allen, L.H., Jr., and Chen, E., 1984, Organic soil subsidence: Geological Society of America, Reviews in Engineering Geology, v. 6, p. 107-122.

Smirnoff, M.V., 1961, Measurements for engineering and other surveys: New York, Prentice Hall.

Thompson, John, 1957, The settlement geography of the Sacramento-San Joaquin Delta, California: Palo Alto, California, Stanford University, Ph.D. dissertation, 551 p.

Weir, W.W., 1950, Subsidence of peat lands of the Sacramento-San Joaquin Delta, California: Hilgardia, v. 20, 56 p.

☆U.S. GOVERNMENT PRINTING OFFICE: 1991 - 587-413/59228