Historical Surface Deformation near Oildale, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1245

Historical Surface Deformation near Oildale, California

By ROBERT O. CASTLE, JACK P. CHURCH, ROBERT F. YERKES, *and* JOHN C. MANNING

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1245

A description and analysis of continuing surface movements recognized along the east edge of the southern San Joaquin Valley

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1983

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

Castle, Robert O.
Historical surface deformation near Oildale, California

(Geological Survey Professional Paper 1245)
Includes bibliographical references.
Supt. of Docs. no.: I 19.16:1245.
1. Subsidences (Earth movements)—California—Oildale Region.
I. Castle, Robert O. II. Series: United States. Geological Survey. Professional Paper 1245.
QE600.3.U6H57 1983 551.3 83–600205

For sale by the Distribution Branch, U.S. Geological Survey,
604 South Pickett Street, Alexandria, VA 22304

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION DATA

1 mm	=	0.03937 inches
1 m	=	3.28083 feet
1 km	=	0.62137 mile
1 m^3	=	35.31338 $feet^3$
	=	6.28911 bbl
	=	0.03531 Mcf (10^3 $feet^3$)

HISTORICAL SURFACE DEFORMATION NEAR OILDALE, CALIFORNIA

By ROBERT O. CASTLE, JACK P. CHURCH, ROBERT F. YERKES, *and* JOHN C. MANNING[1]

ABSTRACT

Historical surface deformation recognized in the southern San Joaquin Valley and adjacent Sierra Nevada foothills near Oildale, Calif., includes: normal and apparently aseismic dip slip along four faults; subsidence within or adjacent to the Kern Front, Poso Creek, Mount Poso, and Fruitvale oil fields; and uplift of much of the area within and north of the Kern River oil field. As much as 0.34 m of vertical separation has been observed along a 5.2-km segment of the Kern Front fault, the structural barrier separating the Kern Front oil field on the west from the Kern River field to the east. Similar separations of as much as 0.15 m and 0.32 m, respectively, have also been identified along the surface traces of two en echelon faults between the Premier and Enas areas of the Poso Creek oil field and the fault that defines the southeast flank of the Premier area. The measured height changes are based on both unadjusted observed elevations and minimally constrained adjusted elevations developed from repeated control levelings referred to a relatively stable local bench mark; measurement error in the reported vertical movements probably is less than 0.05 m. Differential subsidence of at least 0.31 m (1903-68) and 0.05 m (1926/27/30/31-59) has occurred within the Kern Front and Fruitvale oil fields, respectively; subsidence of as much as 0.33 m (1903-53) and 0.19 m (1931-63) has also been measured along the north edge of the Premier area of the Poso Creek oil field and the south edge of the Main area of the Mount Poso field, respectively. Differential uplift of as much as 0.11 m and 0.13 m occurred within and immediately north of the Kern River oil field between 1903 and 1968, and similar uplift of as much as 0.19 m was measured along the north edge of the Dominion area of the Mount Poso field between 1931 and 1963.

Differential subsidence within the Kern Front and Fruitvale oil fields and along the edges of the Poso Creek and Mount Poso fields is attributable to subsurface compaction owing to fluid withdrawal; absence of subsidence within the much larger Kern River field probably is the result of either production from compaction-resistant materials or natural water flooding that has acted to preserve reservoir fluid pressures in the generally shallow producing beds. Contemporary displacements on the Kern Front fault and those along the faults within and adjacent to the Poso Creek oil field are attributable largely or entirely to changes in the subsurface stress regime associated with reservoir compaction; accumulated elastic strain of tectonic derivation conceivably contributed to the development of these displacements. The apparent uplift within and north of the Kern River oil field and along the north edge of the Mount Poso field probably is due in part to compaction of as much as 0.055 m beneath the reference bench mark; most of this apparent uplift, however, is interpreted as an effect of tectonic tilting.

[1]California State College, Bakersfield, 9001 Stockdale Highway, Bakersfield, Calif. 93309.

INTRODUCTION

Over the past half century parts of the southern San Joaquin Valley, California, have undergone various types of continuing surface deformation (Koch, 1933; Whitten, 1961, p. 318-319; Lofgren, 1966; Yerkes and Castle, 1969, p. 57-58). One such area, which lies generally north of the town of Oildale (fig. 1), has been characterized by both surficial faulting and differential subsidence. Contemporary faulting was recognized in this area at least as early as 1949 (Hill, 1954, p. 11), and recent releveling by the Geological Survey and the National Geodetic Survey has documented conspicuous vertical movements over parts of the area shown on plate 1.

The indicated surface movements probably are of complex derivation. The spatial associations with several oil fields suggest that the subsidence and faulting are attributable largely to the exploitation of these fields; it is likely, however, that the differential uplift recognized in the eastern part of this area is related in part to continuing tectonic activity.

We briefly describe here the nature, history, and magnitude of both the faulting and the height changes recognized in the Oildale area and present tentative explanations for their origins.

ACKNOWLEDGMENTS

We are indebted to M. L. Hill of the Atlantic Richfield Company and R. E. Bimat of the Westates Petroleum Company for early descriptions of the historical faulting along the east margins of the Kern Front and Poso Creek oil fields, respectively. G. M. Pittman of Getty Oil Company has provided valuable information on production from the Kern River and Kern Front oil fields (pl. 1). E. E. Glick of the Geological Survey assisted in the recovery of several bench marks critical to the measurement of locally developed vertical movements. The 1968 releveling was carried out under the direction of H. L. Stephens of the Geological Survey and Clarence

Symns of the National Geodetic Survey. Finally, we thank J. A. Bartow and T. L. Holzer of the Geological Survey for meticulous reviews of an earlier version of this report.

Our investigation has been supported in part by the Division of Reactor Development and Technology of the Atomic Energy Commission.

GEOLOGIC FRAMEWORK

The area shown on plate 1 is underlain by a more or less monoclinal series of Cenozoic clastic deposits dipping generally 4°-6° SW. toward the center of the flat, featureless San Joaquin Valley (Brooks, 1952a, b; Johnston, 1952; Albright and others, 1957, pl. III; Weddle, 1959, pl. IV; pl. 1, this report). These Cenozoic rocks in turn unconformably overlie crystalline basement at depths ranging from about 500 m (or a height of about −70 m) along the east edge of the Mount Poso oil field (Albright and others, 1957, pl. III) to about 3,200 m (or a height of about −3,100 m) beneath the Fruitvale oil field (Johnston, 1952, p. 122) on the southwest. The contact between Cenozoic and basement rocks, accordingly, dips nearly 8° SW.—or at a slightly greater inclination than does the onlapping homoclinal Cenozoic sequence; it emerges about 20 km east of Oildale, low on the western slope of the west-sloping Sierra Nevada block (Smith, 1964). The west-dipping Cenozoic deposits that make up the bulk of the unmetamorphosed section underlying this area are overlapped within the western and southwestern parts of the area by horizontally bedded, unconsolidated alluvial deposits that thicken generally westward to about 300-400 m (de Laveaga, 1952, p. 101).

Nearly all of Cenozoic time is represented by the deposits overlying the crystalline basement complex within the area of plate 1. The base of the sedimentary section is believed to consist of Eocene and Oligocene rocks (Brooks, 1952b, p. 156-157; Johnston, 1952, p. 122; Dibblee and Chesterman, 1953; Albright and others,

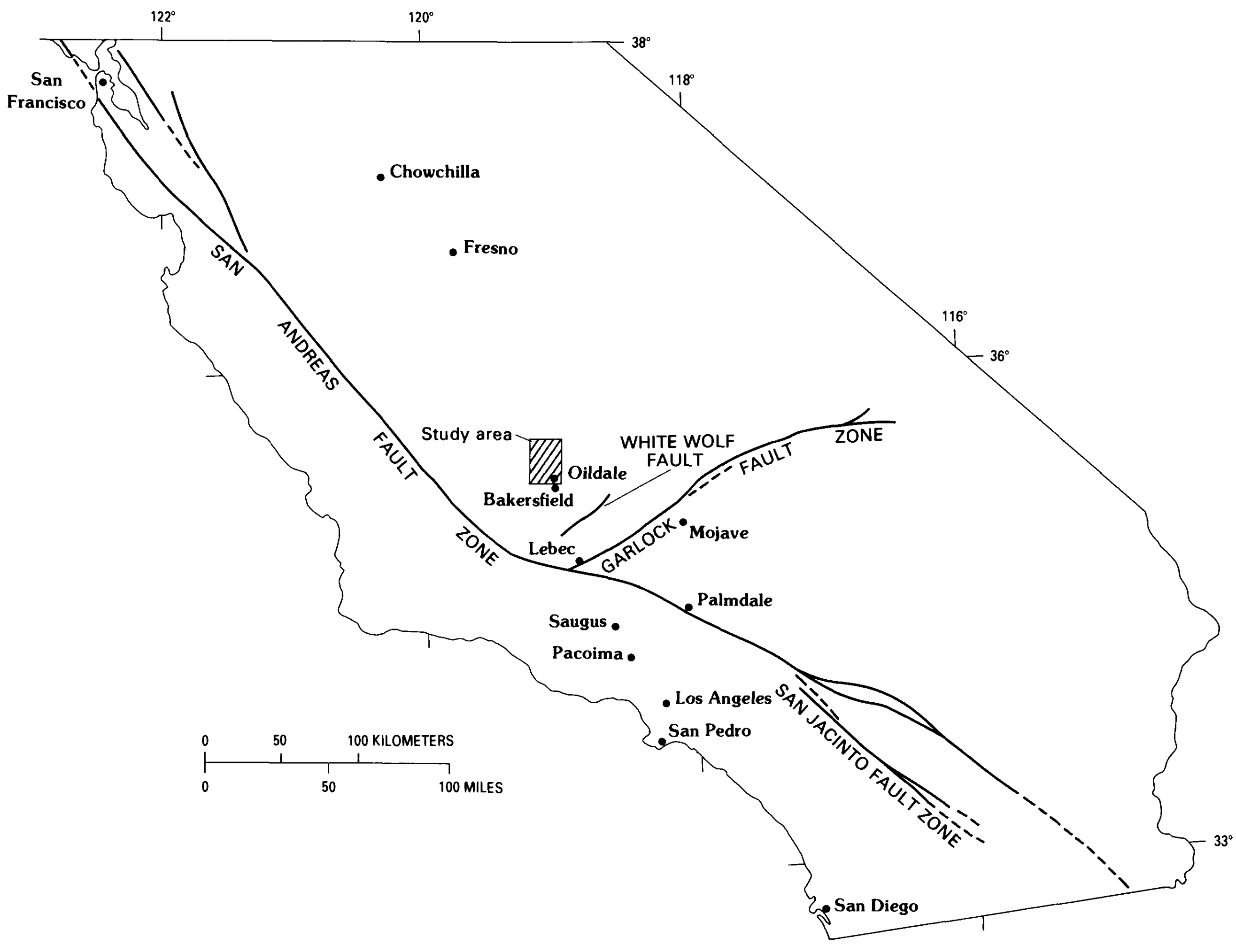

FIGURE 1.—Map of southern California showing location of study area and major faults.

1957, pl. III); these deposits, which probably are largely continental in the Mount Poso area (Pease, 1952, p. 150), grade into a marine sequence toward the southwest (Church and others, 1957). This Eocene and Oligocene section is in turn overlain unconformably by Miocene deposits that range in thickness from about 250 m on the east to more than 2,000 m beneath the Fruitvale oil field on the southwest (de Laveaga, 1952, p. 101; Johnston, 1952, p. 122; Albright and others, 1957, pl. III). This largely or entirely marine Miocene section apparently is conformably overlain by the marine or brackish-water upper Miocene sedimentary deposits that make up the Etchegoin Formation (Johnston, 1952, p. 122; Bartow and Pittman, 1983). The Etchegoin lenses out to the east, about midway through the area, from a maximum thickness of 100-200 m in the Fruitvale oil field (de Laveaga, 1952, p. 101; Johnston, 1952, p. 122). The nonmarine, upper Cenozoic Kern River Formation overlies the older Cenozoic rocks throughout the area generally north of Oildale (pl. 1) (Brooks, 1952a, b; Johnston, 1952, p. 122; Albright and others, 1957, pl. III). Although the Kern River Formation previously was thought to be largely of Pleistocene age, it is now believed to be of late Miocene, Pliocene, and Pleistocene(?) age (Bartow and Pittman, 1983). The Kern River Formation thins from about 800 m in the southwest to perhaps no more than 100 m along the east edge of the Mount Poso oil field; it crops out over most of the area north and east of Oildale, but it is generally overlapped in the lower elevations by younger Quaternary alluvium and the floodplain deposits of the Kern River.

A series of generally high-angle faults cuts much of the sedimentary section within the area of plate 1. These faults characteristically trend north to north-northwest; a less significant, apparently conjugate set trends generally north-northeast. Many of the faults extend to the surface, except within the southwestern part of the area, which is overlain by a 300- to 400-m veneer of alluvial deposits. Vertical separations along most of these faults are generally no more than a few meters or, locally, a few tens of meters (sections *A-A'*, *B-B'-B''-B'''*, *C-C'*, and *D-D'-D''-D'''-D''''*, pl. 1). An exception to this generalization seems to occur along the so-called "Mount Poso" fault, which virtually bisects the Main area of the Mount Poso oil field and shows vertical separations of as much as 100 m (Albright and others, 1957, p. 10, pl. III; section *D-D'-D''-D'''-D''''*, pl. 1, this report). None of the faults, except the Kern Front fault, which defines the east edge of the Kern Front oil field, and several discontinuous faults along the east margin of the Premier area of the Poso Creek field, are known to cut deposits younger than the Kern River Formation. We show here (pl. 1) both the surface traces (as mapped by us) and what we infer to be the subsurface traces (at depths of approximately 500 m and 700 m, respectively) of the Kern Front and Premier (Poso Creek) faults known to have sustained historical rupturing. The Kern Front fault dips about 60° W. at the north end of the Kern Front oil field, but it steepens to about 80° W. near its southern terminus (G. M. Pittman, oral commun., 1968). The dips along the historically active faults on the east side of the Premier area are less certain, but comparisons between their surface traces and their probable subsurface projections suggest that they too dip steeply to the west.

HISTORICAL SURFACE MOVEMENTS

FAULTING

Historical faulting along the Kern Front fault (pl. 1) was first recognized no later than 1949; its discovery is attributed to a geophysical crew employed by the Standard Oil Company (Hill, 1954, p. 11; M. L. Hill, written commun., 1967). According to M. L. Hill (written commun., 1967), the displacement(s) that caused the surface rupturing "probably occurred less than three months before the discovery date" late in 1949. Surface rupturing along the southeast side of the Premier area of the Poso Creek oil field (pl. 1) was first detected by R. E. Bimat (oral commun., 1974) of the Westates Petroleum Company shortly before the 1952 Kern County earthquakes. The faulting along the north margin of the Premier area was discovered by R. D. Nason (oral commun., 1974) in March 1971, and we have discovered no evidence suggesting that this faulting began before 1971.

Field observations by M. L. Hill and L. B. McMichael (Hill, 1954, p. 11; M. L. Hill, written commun., 1967), shortly after the discovery of the Kern Front surface rupturing, showed that a "continuous crack or zone of cracks" extended about 3 km along the surface trace of the Kern Front fault (pl. 1). Displacements were expressed as scarps as much as 200 mm high. Both the scarps and the mapped rupture trace indicate that faulting had occurred along a surface dipping 70°-90° W. and, hence, that the surficial rupturing was almost certainly the product of movement on the fault identified in the subsurface as forming the east closure of the Kern Front field. This initial inspection by Hill and McMichael also showed that the historical faulting was chiefly dip slip and normal, with downdropping on the west (or Kern Front oil field) side of the fault. Although Hill (written commun., 1967) suggests that subsidiary cracks, which he interprets as feather joints, imply a component of right-lateral slip along the fault, this component must have been no more than a small fraction of the dip-slip movement, for he recognized "no lateral offset of surface features."

Systematic reexamination of the surface trace of the Kern Front fault was carried out by the writers in March 1968. Insofar as we have been able to determine, this was the first detailed inspection of the trace since the original investigation of Hill and McMichael. Although our observations are largely consistent with those of Hill and McMichael, they differ in degree. The sense of displacement observed along the trace accords almost precisely with that described by these investigators (M. L. Hill, written commun., 1967); we could detect no evidence of lateral movement, nor did we discover any relative downdropping of the east block. The vertical separations measured in 1968 diminished generally, although unsystematically, both north and south from about midway along the rupture zone (pl. 1). Maximum vertical separations, which occur largely within the middle reaches of the rupture zone (figs. 2 and 3), had by 1968 increased to at least 340 mm (pl. 1). Moreover, if 230 mm of built-up grade along an oil-field service road that intersects the fault trace is correctly interpreted as a measure of the historical vertical separation that preceded resurfacing, the 180 mm of vertical movement since resurfacing suggest at least 410 mm of vertical separation by early 1968 (fig. 3).

The only obvious difference in the surface expression of the fault trace as it appeared in 1968 and as described by Hill and McMichael (Hill, 1954, p. 11; M. L. Hill, written commun., 1967) was the presence in 1968 of a large number of potholes along the trace. These potholes seemed to be concentrated on the downdropped side of the fault, but there were several places where their location relative to the trace was unclear. It is assumed that they developed through localization of drainage and resultant piping along the zone of surficial faulting.

Although we have little information on the rates of movement along the Kern Front fault since surficial displacements were first recognized in 1949, it is clear that these rates have been changing with time. Because about half the maximum vertical separations detected through the early part of 1968 had already been generated by the time that the trace was examined by Hill and McMichael, there must have been a general deceleration in the rate of movement since the initial recognition of historic rupturing; this is very nearly the only unambiguous generalization that can be made with respect to the displacement rate. It is virtually certain, in any case, that movement along the Kern Front fault must have continued beyond 1966. For example, Woody Road was resurfaced during October-November 1966 (R. P. Cooley, oral commun., 1968); yet by March 1968 this newly surfaced highway had cracked conspicuously and showed about 25 mm of vertical separation where it intersects the surface trace of the fault. Similarly, a tilt-beam creepmeter installed on October 19, 1968, about 2 km north of the James Road-Woody Road intersection,

FIGURE 2.—Typical scarp developed midway along recently ruptured trace of the Kern Front fault. View looking east. Photograph taken March 1968.

indicates that vertical separation across the Kern Front fault continued to accumulate through 1972 at an average rate of about 10 mm/year (fig. 4). Furthermore, although the record reproduced in figure 4 is based on visual readings (Nason and others, 1974, p. 261), it is fairly clear that movement on this fault has occurred as a series of discrete slip events.[2]

The first indication of any activity along the surface trace of the Premier fault (where it bounds the southeast margin of the Premier area of the Poso Creek oil field) was the discovery by R. E. Bimat (oral commun., 1975) in 1952(?) of approximately 150 mm of open fissuring about 1.7 km north of James Road. According to Bimat's best recollection, however, it was not until about 1965 that any vertical displacement across this fault became clearly defined. By the time we mapped the fault in April 1975, vertical separations, locally exceeding 300 mm, were developed over much of the 2.7 km of historical rupturing (pl. 1). The surface expression of the historical faulting that developed through 1975 (fig. 5) is virtually indistinguishable from that developed along the Kern Front fault (figs. 2 and 3). Not only has the Premier faulting been consistently down on the west toward the Poso Creek oil field, but it has been characterized as well by the generation of the same sort of ragged scarps and irregularly developed vertical separations, ranging between 0 and 320 mm (pl. 1), that occur along the Kern Front fault. Moreover, the historical faulting along the southeast margin of the Premier area seems to have controlled the development of potholes and drainageways similar to those associated with the Kern Front faulting. Whether movement is continuing along the Premier fault is uncertain, but at least some movement must have occurred after 1965. An oil-field

[2]We have one report of about 0.5 m of displacement (down on the west) during April 1967, where the Kern Front trace passes through a raceway immediately north of James Road (J. Moore, oral commun., 1968). However, the significance of this particular episode is equivocal; it closely followed a period of heavy rain, and it is very likely that the apparent displacement is the product of piping and resultant collapse along the line of faulting, rather than actual fault movement.

FIGURE 3.—Ruptured pavement along regraded and resurfaced section of oil field service road athwart the Kern Front fault immediately north of Woody Road. View looking north. Photograph taken March 1968.

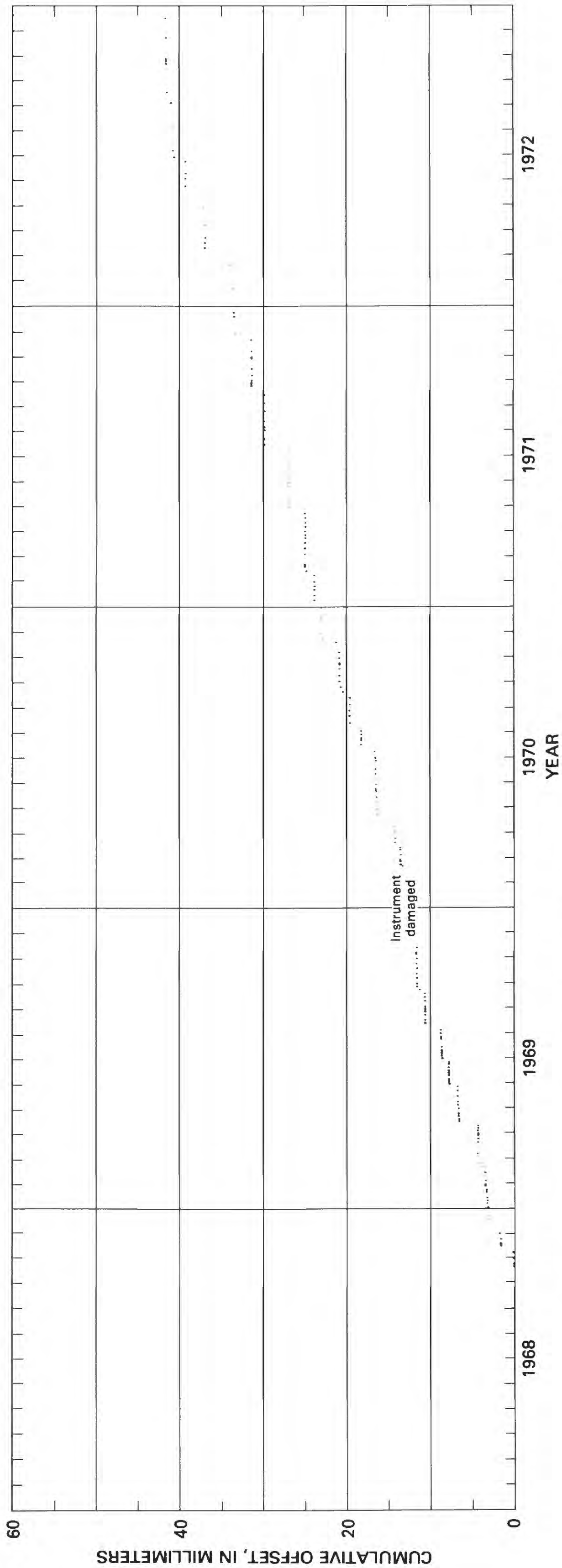

FIGURE 4.—Cumulative vertical separation recorded by creepmeter operating athwart the surface trace of the Kern Front fault 2.24 km north of Woody Road-James Road intersection (after Nason and others, 1974, p. 268).

FIGURE 5.—Typical scarps developed along recently ruptured trace of the Premier fault where it bounds the southeast margin of the Premier area of the Poso Creek oil field. *A*, 1.42 km north of James Road. *B*, 1.27 km north of James Road. Views looking north. Photographs taken April 1975.

service road athwart the main trace has continued to crack and warp since it was resurfaced in 1965 (R. E. Bimat, oral commun., 1975); because by 1975 this resurfaced road showed about 120-140 mm of vertical separation across the fault (fig. 6), as contrasted with roughly 270 mm defined by movement of the adjacent natural ground surface, the post-1965 displacement rates may have matched or even exceeded the pre-1965 rates.

According to R. D. Nason (oral commun., 1974), the active faulting along the north edge of the Premier area of the Poso Creek oil field was first identified on the basis of a warped and cracked pavement along State Highway 65 where it intersects the eastern of the two en echelon breaks recognized in this area (pl. 1). Nason also determined from his initial observations that the southeastern of the two strands was equally well defined by offsets of the ground surface. It was not until 1972, however, that this zone of active faulting was mapped in detail by students at California State College at Bakersfield. Our reexamination in 1974 showed only that the faulting probably extended a shorter distance to the north than originally mapped. Except for the clearly defined en echelon configuration and smaller displacements, which ranged up to a maximum of 150 mm (pl. 1), the faulting along the north end of the Premier area has been remarkably similar to that developed along the Kern Front fault and the southeast margin of the Premier area. It is, for example, consistently down on the west (toward the Premier area) and devoid of any evidence of strike-slip movement. Moreover, although the scarps are somewhat more subdued, this faulting has been associated with the development of sharply defined warping of the natural ground surface (fig. 7) similar to that found along the other historical traces described here. Movement has apparently continued along the trace of at least the eastern of the two en echelon breaks since they were first recognized. State Highway 65 was resurfaced in 1973, yet by the time that these faults were reexamined in November 1974, this newly paved road had already begun to crack and warp athwart its intersection with the eastern fault.

We have no evidence of movement on any of these faults associated with historical earthquake activity. According to Hill (1954, p. 11), for example, neither the Pasadena nor the Berkeley seismological stations recorded any seismic events in this area during the relatively short interval in which the initial movement on the Kern Front fault probably occurred. Furthermore, although much of this area must have undergone at least some strain adjustment during the Arvin-Tehachapi earthquake of July 21, 1952 (M 7.7) and the August 22 Bakersfield aftershock (M 5.8), there seems to have been little if any displacement on any of the historically active faults near Oildale associated with either of these events (Johnston, 1955). According to Johnston (1955, p. 225), "although investigations were made of all wells re-

FIGURE 6.—Differential movement across the Premier fault indicated by warped and cracked pavement of oil-field service road shown in left-hand half of figure 5*A*. View looking north. Photograph taken April 1975.

portedly affected by the [July 21] earthquake, no actual slippage or movement along a fault plane could be established. Knowing the very small amount of displacement necessary to cause a casing break (as has been demonstrated in the Ventura Avenue field), it seems surprising that there were not a considerable number of wells so affected." Even more specifically, although "150 wells were found to be sanded up [in the Kern Front-Kern River fields] as a result of the July 21 earthquake,...in no wells were the casings found to be collapsed or sheared," including, apparently, such wells as penetrate the Kern Front fault (Johnston, 1955, p. 222; Brooks, 1952a, p. 160).

HEIGHT CHANGES

Vertical control data for the bench marks shown on plate 1 date from 1902. Leveling surveys of third-order or higher accuracy have been run through this area by both the Geological Survey and the National Geodetic Survey (formerly the Coast and Geodetic Survey). Reconstruction of the results of levelings produced since 1903 has permitted comparisons of elevations among two or more of the bench marks shown on plate 1 for several intervals between 1903 and 1968.

The observed elevations (table 1) for the bench marks shown on plate 1 are referred to benchmark 448 B as invariant in height. This bench mark is peripheral to the area of major interest here and, hence, suitably located for the description of movements contained within the investigated system (see Castle and Youd, 1973, p. 91-93). It (or adjacent monument R 364) is, moreover, the only control point to which we can relate all the levelings referred to in this report. Bench mark 448 B apparently was destroyed sometime after 1947 (U.S. Coast and Geodetic Survey, 1966, p. 2; E. E. Glick, written commun., 1968); nevertheless, because observed elevation differences referred to bench mark R

FIGURE 7.—Warped surface athwart trace of the easternmost of the two active faults bounding the north end of the Premier area of the Poso Creek oil field. Locality adjacent to intersection between the fault and State Highway 65. Warped zone straddled by observer; vertical separation approximately equal to height of beer can. View looking northwest. Photograph taken November 1974.

364 (pl. 1) can be easily related to 448 B, and because R 364 lies no more than 200-300 m from 448 B and can be assumed to have remained unchanged with respect to 448 B, 448 B is retained here as our primary control point. Since R 364 and 448 B were never included in the same leveling, the tie between these two bench marks is necessarily indirect; it derives from an extrapolated 1953 height for 448 B, which is based, in turn, on measured regional subsidence at bench marks that straddle the positions of R 364 and 448 B (U.S. Coast and Geodetic Survey, 1966, p. 2-3). Thus, projected 1947-53 subsidence of 0.049 m at the site of 448 B produces a 1953 height difference between 448 B and R 364 of 0.615 m (U.S. Coast and Geodetic Survey, 1966, p. 2). The relative stability of 448 B can be shown through comparisons between the 1930-61 height change at this mark and 1926/30-61[3] height changes at bench marks else-

[3]Dates separated by slashes refer to surveys performed during the stated years. The convention "1926/30" indicates that leveling done during 1926 and leveling done during 1930 are combined and treated as a single survey.

TABLE 1.—*Orthometrically corrected observed elevations at selected bench marks in the Oildale area*

[Primary control point, 448 B, is fixed at 136.5440 m. Elevations in meters. Locations shown on pl. 1]

BENCH MARK	1903	1926/27/30/31	1931	1953	1957	1959	1963	1968
R 364------------	--	--	--	137.1588	137.1588	137.1588	137.1588	137.1588
C 747 Reset------	--	--	--	--	--	--	148.9732	148.9808
B-1 1931---------	--	--	183.9698	--	--	--	184.0716	184.0722
B 1931-----------	--	--	224.2065	--	--	--	224.1989	224.1650
768--------------	234.0759	--	--	--	--	--	--	234.1872
634 B------------	193.1653	--	--	--	--	--	--	193.1936
976 B------------	297.6528	--	--	--	--	--	--	297.7082
1133-------------	345.1974	--	--	--	--	--	--	345.3025
B-2 1931---------	--	--	319.0364	--	--	--	319.1482	319.1699
864--------------	263.2780	--	--	--	--	--	--	262.9686
B-0 1931 Reset---	--	--	138.6852	--	--	--	138.7218	--
Oil Hill Δ -------	--	--	--	--	--	--	367.5981	367.6426
1205-------------	367.3509	--	--	--	--	--	--	367.4457
E 747------------	--	--	--	--	--	--	157.1324	157.1211
29-0-------------	--	--	--	--	--	--	270.4033	270.4176
633 B------------	192.8952	--	192.9851	--	--	--	--	--
545 B------------	166.1255	--	--	165.7933	--	--	--	--
B-3 1931---------	--	--	233.7038	--	--	--	233.8339	--
884 B------------	269.3800	--	269.4693	--	--	--	269.2837	--
TBM 1266---------	--	--	386.1766	--	--	--	386.3354	--
B-7 1931---------	--	--	382.2581	--	--	--	382.4480	--
P 89-------------	--	133.5719	--	133.5871	133.5855	133.5845	--	--
Q 89-------------	--	133.3180	--	133.3298	133.3274	133.3257	--	--
F 55-------------	--	123.3134	--	123.3472	123.3474	--	--	--
Y 67-------------	--	121.7424	--	121.7737	121.7780	121.7852	--	--
X 67-------------	--	122.8151	--	122.8395	122.8398	122.8487	--	--
W 67-------------	--	120.9880	--	120.9483	120.9355	120.9339	--	--

where along the first-order line that includes 448 B. Examination of vertical movements recorded at distances of as much as 10 km, both northwest and southeast from 448 B, indicates that the maximum relative movement with respect to 448 B was −0.036 m, and that such movement was generally no more than a few millimeters (U.S. Coast and Geodetic Survey, 1966, p. 2-3, 7-8, 13).

The eight successive sets of orthometrically compatible observed elevations listed in table 1 are drawn from every vertical control line that is known to have been extended into the study area from the primary vertical control line along the Southern Pacific Railroad.[4] The 1903 leveling formed part of a regional network north of Bakersfield that was developed by the Geological Survey (Birdseye, 1925, p. 199, 107, and 209). The 1903 field measurements meet third-order standards and are tabulated in U.S. Geological Survey summary book A5837; the 1903 elevations (table 1) are based on a minimum constrained adjustment of orthometrically corrected field values in which bench mark 448 B has been held fixed. The 1926/27/30/31 elevations listed in table 1 consist of orthometrically corrected elevations reconstructed from National Geodetic Survey first-order lines 82598, 82727, and L-198. The 1931 measurements meet third-order standards and are given in U.S. Geological Survey summary book B4069; the 1931 figures (table 1) consist of orthometrically corrected observed elevations. Virtually all the 1953 elevations (table 1) were derived from first-order leveling and consist of orthometrically corrected values obtained from National Geodetic Survey lines L-14787, L-14799, and L-14781. The 1953 elevation of 545 B (table 1) is based on third-order leveling emanating from B-3 1931 and an assumption of stability between B-3 1931 and 448 B during the period 1953-63. The 1957 and 1959 elevations (table 1) are based on first-order leveling and derive from orthometrically corrected values listed in National Geodetic Survey lines L-16254, L-16280, and L-17160. The 1963 field measurements derive from third-order leveling and are recorded in U.S. Geological Survey summary book PV 492; the 1963 figures listed in table 1 consist of orthometrically corrected field values. The 1968 elevations are the result of a cooperative leveling effort between the National Geodetic Survey and the Geological Survey. Much of the 1968 leveling between bench marks E 747 and 1205 (pl. 1) meets first-order requirements, whereas that between 448 B and E 747 and in the general area of the Kern River oil field is based on third-order procedures. The 1968 elevation differences are listed in U.S. Geological Survey summary book PV 732; the 1968 elevations (table 1) derive from orthometrically corrected values and the proration of misclosures around several small loops.

Leveling precision is a function of the survey procedures and instrumentation. First-order procedures are so specified that expected random errors in measured elevation differences between two bench marks a distance L km apart are approximately normally distributed with a standard deviation of $\sigma_1 L^{1/2}$, where σ_1 is ordinarily about 1 mm/km$^{1/2}$ and probably never exceeds 3 mm/km$^{1/2}$. Thus in comparing elevation differences based on two successive first-order surveys of the same line, the standard deviation in the discrepancy between the measured elevation differences is $\sigma_{1d} L^{1/2}$, where σ_{1d} is generally about 1.4 mm/km$^{1/2}$ and probably never exceeds 4.2 mm/km$^{1/2}$. Hence over a distance of 14 km, approximately equal to that along the leveling route between 448 B and W 67 (pl. 1), one standard deviation in the difference between the measured elevation differences based on two successive surveys should be about 5 mm and should certainly be no greater than 16 mm. Similarly, third-order procedures of the Geological Survey are so prescribed that where random errors dominate, one standard deviation in the measured elevation difference between two bench marks a distance L km apart is $\sigma_3 L^{1/2}$, where σ_3 is generally about 4 mm/km$^{1/2}$ and may range up to 6 mm/km$^{1/2}$. Therefore, in comparing elevation differences based on two successive third-order levelings over the same line, the standard deviation in the discrepancy between the measured elevation difference is $\sigma_{3d} L^{1/2}$, where σ_{3d} is ordinarily about 5.7 mm/km$^{1/2}$ and seldom, if ever, greater than 8.5 mm/km$^{1/2}$. Accordingly, over a distance of 28 km, roughly that between 448 B and B-7 1931 (pl. 1), one standard deviation in the discrepancy between the measured elevation differences based on two successive third-order levelings should be about 30 mm and doubtfully will exceed 45 mm. Although several sets of measured elevation changes in the area north of Oildale involve comparisons between the results of third-order leveling with subsequent first-order surveys, the increased accuracy over comparisons based on two successive third-order surveys is relatively modest. For example, if the measured elevation difference based on a third-order leveling between 448 B and B-7 1931 (pl. 1) is compared with a first-order measurement between these two marks, the standard deviation in the difference between these two measurements is about 22 mm, or only 8 mm less than that based on two successive third-order surveys (where σ_3 and σ_1 are taken as 4 mm/km$^{1/2}$ and 1 mm/km$^{1/2}$, respectively). The chief source of systematic error, large elevation difference, is virtually absent in this area; hence it is unlikely that the elevation measurements

[4]Unless otherwise specified, all orthometric corrections are based on normal or theoretical gravity rather than on observed or interpolated gravity values (Vanicek and others, 1980, p. 510-513).

used here have been seriously contaminated by errors of this sort.

Any of the bench marks shown on plate 1 may be used as secondary control points. All of the orthometrically compatible elevation differences among the bench marks shown on this map are listed on plate 2. Relative height changes during successive periods can, with the aid of table 1, be calculated directly from comparisons among successive values listed in each of the boxes shown on plate 2.

Height changes measured with respect to bench mark 448 B are tabulated in table 2. Maximum measured subsidence is given as 0.3322 m; it occurred at bench mark 545 B (pl. 1) during the interval 1903-53. Maximum uplift of 0.1899 m occurred at bench mark B-7 1931 (pl. 1) during the interval 1931-63. Statistically significant subsidence has been measured at only five bench marks—B 1931, 864, 545 B, 884 B, and W 67 (table 2); all these marks occur within or immediately adjacent to operating oil fields (pl. 1). Moreover, had this subsidence been compared with nearby bench marks clearly outside the respective oil fields, it would have been increased by several hundredths to over a tenth of a meter in all but perhaps the case of 545 B—which is located 8-9 km from the nearest comparative mark (pl. 1). Significant uplift measured within the area of plate 1, except for that at bench mark 768, is well removed from areas of major petroleum production and increases more or less uniformly northeastward from 448 B. The vertical displacement histories of closely clustered bench marks are roughly consistent, provided that they are based on measurements over the same time interval. For example, bench marks 1133 and 1205 sustained nearly equal uplift during the period 1903-68 (table 2). However, B-2 1931, which lies no more than 0.1 km from 1133 (pl. 1), sustained even greater uplift than that at 1133 over the significantly shorter period 1931-68 (table 2). Measurement error in the 1903 leveling could, of course, account for part of this seeming discrepancy. In addition, apparent disturbance of both bench marks 1133 and 1205 may have further diminished the measured uplift at these marks; that is, the iron pipes supporting 1133 and 1205 were both reported to be leaning when recovered in 1968. The pipe supporting bench mark 1133 was clearly bent at ground level; thus the 1968 elevation, the 1968 elevation differences, and the height changes referred to this bench mark in tables 1 and 2, and plate 2 have been recalculated to provide for the reorientation of the supporting pipe into its undisturbed, vertical position. The calculated elevation correction applied to bench mark 1133, however, amounts to only about 12 mm. Moreover, the close agreement between the 1903-68 measured height changes at 1133 and 1205 (table 2) indicates that whatever disturbances these bench marks sustained must have had very little effect on the elevation difference between them. It is clear, nonetheless, that while the seemingly larger uplift generated at B-2 1931 might be traced to measurement problems or pre-1968 disturbance of bench marks 1133 and 1205, there exists a plausible alternative explanation: the rate and conceivably the sense of movement between 448 B and the general area of bench marks B-2 1931, 1133, and 1205, changed dramatically sometime between 1931 and 1968. However, outside of the southernmost part of the study area, we know little of variations in the rates of the described height changes, nor can we generally determine when these movements began.

The maximum differential movement recorded within the study area is 0.4207 m; it was measured between bench marks 768 and 864 in the Kern River and Kern Front fields, respectively, during the interval 1903-68 (table 2). This relative movement, however, was very nearly matched by movements of 0.4145 m and 0.4042 m between bench mark 864 and bench marks 1133 and 1205, respectively, during the same interval (table 2). Moreover, if the 1903-53 subsidence at bench mark 545 B is added to the 1931-63 uplift at B-7 1931 (table 2), and if it is assumed that there has been no reversal in the sense of movement at either mark, differential movement between 545 B and B-7 1931 during the full period 1903-63 must have been at least 0.5221 m. In any case, none of the vertical movements described here can be considered especially spectacular examples of historical height changes; their significance rests chiefly in their association with other phenomena.

PROBABLE NATURE OF THE SURFACE DEFORMATION

Surface movements of the sort recognized in the Oildale area have been attributed to a variety of processes, including changes in the ground-water regime, surface loading, oil-field operations, and tectonic activity (see, for example, Gilluly and Grant, 1949; Poland and Davis, 1969; and Castle and Yerkes, 1976). There has been very little development in the Oildale area involving major excavations or landfills; hence it is extremely unlikely that any of the recent surface movements in this area can be traced to changes in surface loading. Thus we are left with the probability that virtually all of the historical surface deformation described here is the result of ground-water withdrawals, oil-field operations, tectonic activity, or various combinations of all three.

TABLE 2.—*Height changes at selected bench marks in the Oildale area for various intervals between 1903 and 1968*

[Heights, in meters, measured with respect to 448 B. Locations shown on pl. 1]

BENCH MARK	1903-31	1903-53	1903-63	1903-68	1926/27/30/31-53	1926/27/30/31-57	1926/27/30/31-59	1931-63	1931-68	1953-59	1963-68
R 364-----------	--	--	--	--	--	--	--	--	--	0.0000	0.0000
C 747 Reset-----	--	--	--	--	--	--	--	--	--	--	+0.0076
B-1 1931--------	--	--	--	--	--	--	--	+0.1018	+0.1024	--	+0.0006
B 1931----------	--	--	--	--	--	--	--	-0.0076	-0.0415	--	-0.0339
768-------------	--	--	--	+0.1113	--	--	--	--	--	--	--
634 B-----------	--	--	--	+0.0283	--	--	--	--	--	--	--
976 B-----------	--	--	--	+0.0554	--	--	--	--	--	--	--
1133------------	--	--	--	+0.1051	--	--	--	--	--	--	--
B-2 1931--------	--	--	--	--	--	--	--	+0.1118	+0.1335	--	+0.0217
864-------------	--	--	--	-0.3094	--	--	--	--	--	--	--
B-0 1931 Reset--	--	--	--	--	--	--	--	+0.0366	--	--	--
Oil Hill▲ ------	--	--	--	--	--	--	--	--	--	--	+0.0445
1205------------	--	--	--	+0.0948	--	--	--	--	--	--	--
E 747-----------	--	--	--	--	--	--	--	--	--	--	-0.0113
29-0------------	--	--	--	--	--	--	--	--	--	--	+0.0143
633 B-----------	+0.0899	--	--	--	--	--	--	--	--	--	--
545 B-----------	--	-0.3322	--	--	--	--	--	--	--	--	--
B-3 1931--------	--	--	--	--	--	--	--	+0.1301	--	--	--
884 B-----------	+0.0893	--	-0.0963	--	--	--	--	-0.1856	--	--	--
TBM 1266--------	--	--	--	--	--	--	--	+0.1588	--	--	--
B-7 1931--------	--	--	--	--	--	--	--	+0.1899	--	--	--
P 89------------	--	--	--	--	+0.0152	+0.0136	+0.0126	--	--	-0.0026	--
Q 89------------	--	--	--	--	+0.0118	+0.0094	+0.0077	--	--	-0.0041	--
F 55------------	--	--	--	--	+0.0338	+0.0340	--	--	--	--	--
Y 67------------	--	--	--	--	+0.0313	+0.0356	+0.0428	--	--	+0.0072	--
X 67------------	--	--	--	--	+0.0244	+0.0247	+0.0336	--	--	+0.0092	--
W 67------------	--	--	--	--	-0.0397	-0.0525	-0.0541	--	--	-0.0144	--

SURFACE DEFORMATION ATTRIBUTABLE TO GROUND-WATER WITHDRAWALS

Various manifestations of surface deformation, including differential subsidence, elastic rebound, horizontal displacements and even faulting and fissuring, have been attributed to changes in the ground-water regime (Poland and Davis, 1969; Holzer, 1977; Morton, 1977). However, in the absence of compaction-induced subsidence clearly associated with ground-water withdrawals, it is very unlikely that any of these other expressions of surface deformation can be explained, whether directly or indirectly, as the products of ground-water extraction. Hence we begin this examination with an assessment of the subsidence, if any, that can be attributed to ground-water withdrawals within the area of plate 1.

SUBSIDENCE

Poland and Davis (1969) have concisely summarized the application of consolidation theory to the analysis of compaction-induced subsidence. Their summary, which provides a convenient point of departure for this discussion, begins with the acceptance of Terzaghi's principle of effective stress which states that within a porous, fluid-filled medium $p = p' + u$, where p = total stress or pressure, p' = effective stress or pressure, and u = fluid stress or pressure. In a confined water system in which the compressibility of the fluid is disregarded, unit head decline (which is proportional to fluid-pressure reduction) will produce a proportional increase in effective stress; in an unconfined water system any reduction in liquid level will produce an increase in effective pressure through loss of buoyancy, and the total pressure will decrease slightly owing to the loss of fluid mass (Poland and Davis, 1969, p. 193-196). Because the overburden is supported by both fluid pressure and effective stress, a decrease in fluid pressure to a point approaching zero will increase the effective pressure to a value approaching the lithostatic pressure, whereas an increase in fluid pressure to a value approaching the lithostatic pressure will decrease the effective pressure to a value approaching zero. Reservoir compaction thus becomes a function of both the magnitude of the increased effective stress and the compressibility of the materials, whereas any expansion of the reservoir skeleton is a function of the magnitude of the reduced effective stress and the elastic component of the compressibility.

Ground-water withdrawals from the semiconsolidated to unconsolidated deposits north of Oildale have been generally trivial (Poland and Davis, 1969, p. 241). Accordingly, it is unlikely that significant surface movements in this area can be traced to changes in the ground-water regime.

On the other hand, the unconsolidated deposits underlying the southwest quarter of the map area (pl. 1) could easily have sustained at least modest subsidence due to compaction accompanying ground-water withdrawals. For example, according to Dale and others (1966, figs. 6 and 7), water wells immediately adjacent to our primary reference mark, 448 B (pl. 1), penetrate several hundred meters of unconsolidated to poorly consolidated gravels and sands interbedded locally with fine sand and clay units. Between 1921 and 1944, water levels in the area of these wells declined by as much as 15 m (Lofgren, 1975, pl. 2A), and records obtained from wells adjacent to 448 B indicate that water levels in these wells dropped by as much as 50-60 m during the period 1937-68 (California Department of Water Resources, written commun., 1976). Hence there has certainly existed a potential for compaction and resultant surface subsidence attributable to ground-water extraction in the area extending northwestward from Bakersfield to 448 B.

In spite of the cited potential for subsidence associated with ground-water withdrawals, it is very unlikely that any such subsidence had occurred within the study area during the first third of the century and equally unlikely that more than about 0.05 m had occurred through at least 1968. Especially significant in this context is that about three-quarters of the San Joaquin Valley subsidence has occurred since 1950, and nearly all of the subsidence in the southern San Joaquin Valley has developed since about 1940 (Poland and Davis, 1969, p. 240, 252; Poland, 1972, p. 57). In addition, Poland (1972, p. 57) has indicated that subsidence in the area north of Oildale measured with respect to " 'stable' bedrock" bench marks was certainly less than 0.3 m (as contrasted with as much as 8.5 m elsewhere in the San Joaquin Valley) during the period 1926-69/70. Lofgren (1975, p. D11-D15), moreover, contends that while nearly the entire southern San Joaquin Valley has been subsiding, the peripheral subsidence is no more than apparent; that is, it derives not from the extraction of groundwater, but rather from tectonic uplift of the reference bench marks outside the area of heavy pumping. For example, Lofgren (1975, p. D36, pl. 3) shows on the basis of published, adjusted heights obtained from the results of repeated levelings of the Coast and Geodetic Survey, that bench marks C 55 (pl. 1) and K 54 (about 49 km south of Bakersfield and within the foothills of the Tehachapi Mountains) subsided about 0.30 m and 0.09 m, respectively, during the period 1926-68. However, this apparent subsidence, according to Lofgren (1975, p. D15), stems largely from the adjustment procedures that assumed stability within the surrounding mountains which may, in fact, have been rising at an average rate of as much as 18 mm/yr (with respect to an arbitrarily defined invariant datum). Thus, Lofgren (1975, p. D15) reasoned that the seeming 0.27-m subsidence of representative bench mark 421, Bakersfield, should be attributed to tectonic uplift of the reference marks rather than compaction of the generally unconsolidated section beneath 421 (see "Supplemental Data"). Lofgren's argument is certainly consistent with the displacement history of this mark. Specifically, based on comparisons between sequentially developed adjusted heights, 421 is represented as subsiding at an almost precisely uniform rate during the period 1931-65 (Lofgren, 1975, p. D15). For example, between 1931 and 1947 bench mark 421 supposedly subsided at almost exactly the same rate as the rate that obtained during the ensuing years. This characterization, however, as we have already indicated, is completely at variance with the generally recognized absence of subsidence in the southern San Joaquin Valley prior to 1940.

Although the evidence outlined in both the preceding paragraph and the "Supplemental Data" section shows that central Bakersfield, and specifically the area including bench marks F 55, Y 67, 421 B, and S 89, has undergone virtually no subsidence associated with ground-water withdrawals, permissive yet persuasive evidence indicates that subsidence associated with water-level declines has almost certainly occurred northwest of Bakersfield, yet still within the study area. Extrapolation of the apparent uplift of bench marks F 55 and Y 67 with respect to 448 B (table 2) indicates that the section beneath 448 B probably sustained about 0.055 m of compaction during the period 1926/27/30/31-68. Although we are uncertain whether 448 B underwent any compaction-induced subsidence prior to 1926/27/30/31, what little we know of the early hydrologic history of this area suggests that it must have been trivial. There is, of course, no way whereby we can prove that the differential subsidence of 448 B was nontectonic; nonetheless, the proclivity of the southern San Joaquin Valley toward compaction associated with ground-water withdrawals supports the conclusion that the subsidence beneath this mark is much more reasonably explained as a product of compaction.

We have labored the question of subsidence associated with ground-water withdrawals simply because an accurate appraisal of compaction-induced subsidence is critical to any interpretation of the vertical displacements referred to our primary control point, 448 B. The chronology and distribution of the levelings referred to in this report are such that they virtually compel that the computed vertical displacements be described with respect to a local control point (as opposed, for example, to the San Pedro tide station). Accordingly, in the absence of a good assessment of the compaction associated with water-level declines beneath 448 B (or, alternatively, one of the central Bakersfield bench marks), it would be virtually impossible to clearly distinguish between displacements of tectonic origin and those of nontectonic origin. Moreover, determinations of the magnitude of the various artificially generated vertical displacements would remain equivocal and might otherwise be very difficult to even recognize.

FAULTING

Because subsidence associated with ground-water withdrawals has been generally slight within the study area (see preceding section), it is very unlikely that any significant fraction of the historical faulting described here can be attributed to compaction produced in response to ground-water withdrawals.

SURFACE MOVEMENTS ATTRIBUTABLE TO OIL-FIELD OPERATIONS

The area considered here (pl. 1) contains five medium- to large-size oil fields: the Kern River, the Kern Front, the Poso Creek, the Mount Poso, and the Fruitvale. Several of these fields, moreover, include physically separable production "areas"; the distinction between a "field" and an "area," however, is apparently arbitrary and probably is a function of proprietary convenience.

DEVELOPMENT AND GENERAL CHARACTERISTICS OF THE KERN RIVER, KERN FRONT, POSO CREEK, MOUNT POSO, AND FRUITVALE OIL FIELDS

The Kern River oil field is both the oldest and most prolific of any of the five fields examined here. It was discovered in 1899 through the pick and shovel efforts of James and Jonathan Elwood (Brooks, 1952b, p. 156), and it has since produced prodigious volumes of oil but relatively little gas (table 3). Cumulative production from the Kern River field through 1968 (fig. 8) consisted of 437,230,993 barrels (bbls) (69.520×10^6 m^3) of oil, 2,581,322 Mcf (10^3 ft^3) (73.103×10^6 m^3) of gas, and 2,904,207,803 bbls (461.769×10^6 m^3) of water. Cumulative water disposal through 1968 reached 27,597,919 bbls (4.388×10^6 m^3) (table 3; California Division of Oil and Gas, 1968, p. 107), but it has been confined to the Santa Margarita Formation and the Vedder Sand, both of which lie well below the lowest producing zone (pl. 1). Steam and hot-water injection in the Kern River oil field were begun in 1961; cyclic injection through 1968 accounted for 155,717,139 bbls (23.759×10^6 m^3), whereas water-flood injection is given as 16,513,984 bbls (2.626×10^6 m^3) (table 3; California Division of Oil and Gas,

TABLE 3.—*Production figures for the Kern River oil field, 1903–68*

[Compiled chiefly from production figures given in the summary reports of the state oil and gas supervisor. 1903–1919 oil production from McLaughlin (1914) and Bradley (1917; 1918; 1920). Oil production from Premier and Enas areas during the period 1919–1934 deducted from published Kern River figures; pre-1942 oil, gas and water production for Kern Front field (see table 4) also deducted from published Kern River figures. One bbl = 5.615 ft^3 = 0.1590 m^3; 1 Mcf = 10^3 ft^3 = 28.32 m^3]

Year	Oil production (bbls)	Gas production (Mcf)	Water production (bbls)	Steam injection (bbls)	Cumulative gross liquid production (bbls)	Water disposal (bbls)	Cumulative net liquid production (bbls)
1899-1902	no records	-	-	-	-	-	-
1903	16,342,099	-	-	-	-	-	-
1904	17,226,240	-	-	-	-	-	-
1905	15,253,845	-	-	-	-	-	-
1906	12,825,166	-	-	-	-	-	-
1907	12,346,014	-	-	-	-	-	-
1908	13,803,579	-	-	-	-	-	-
1909	14,508,242	-	-	-	-	-	-
1910	14,776,435	-	-	-	-	-	-
1911	14,078,890	-	-	-	-	-	-
1912	12,446,445	-	-	-	-	-	-
1913	10,495,264	-	-	-	-	-	-
1914	7,214,372	-	-	-	-	-	-
1915	8,002,535	-	-	-	-	-	-
1916	8,382,570	-	-	-	-	-	-
1917	8,473,772	-	-	-	-	-	-
1918	7,903,648	-	-	-	-	-	-
1919	7,526,508	-	-	-	-	-	-
1920	7,048,401	-	26,382,167	-	33,430,568	-	33,430,568
1921	6,128,019	-	28,623,635	-	34,751,654	-	34,751,654
1922	6,749,262	-	34,489,661	-	41,238,923	-	41,238,923
1923	6,344,203	-	35,115,502	-	41,459,705	-	41,459,705
1924	6,243,218	-	35,362,932	-	41,606,150	-	41,606,150
1925	5,410,136	-	31,454,280	-	36,864,416	-	36,864,416
1926	3,617,511	-	23,513,150	-	27,130,661	-	27,130,661
1927	2,618,156	-	10,678,852	-	13,297,008	-	13,297,008
1928	2,183,792	-	12,395,541	-	14,579,333	-	14,579,333
1929	1,355,001	-	3,594,881	-	4,949,882	-	4,949,882
1930	930,942	-	835,438	-	1,766,380	-	1,766,380
1931	894,846	18,802	810,949	-	1,705,795	-	1,705,795
1932	850,258	18,983	923,391	-	1,773,649	-	1,773,649
1933	864,150	20,932	1,339,694	-	2,203,844	-	2,203,844

1934	1,296,637	19,559	2,571,779	-	3,868,416	-	3,868,416
1935	1,473,623	44,951	4,094,790	-	5,568,413	-	5,568,413
1936	1,066,821	17,867	2,728,056	-	3,794,877	-	3,794,877
1937	1,093,96Q	12,579	3,028,442	-	4,122,402	-	4,122,402
1938	1,084,391	9,349	4,123,099	-	5,207,490	-	5,207,490
1939	1,272,098	4,839	6,145,019	-	7,417,117	-	7,417,117
1940	1,578,958	6,416	9,861,812	-	11,440,770	-	11,440,770
1941	1,775,971	3,063	18,555,256	-	20,331,227	-	20,331,227
1942	2,691,361	3,068	65,252,150	-	67,943,511	-	67,943,511
1943	3,099,512	14,182	72,118,095	-	75,217,607	-	75,217,607
1944	3,511,399	14,965	71,942,462	-	75,453,861	-	75,453,861
1945	3,571,582	14,246	68,405,295	-	71,976,877	-	71,976,877
1946	3,592,108	9,975	61,611,120	-	65,203,228	-	65,203,228
1947	3,729,701	6,261	59,640,511	-	63,370,212	-	63,370,212
1948	4,513,544	10,442	55,227,468	-	59,741,012	-	59,741,012
1949	3,553,943	7,834	52,203,672	-	55,757,615	-	55,757,615
1950	3,416,783	2,217	50,861,451	-	54,278,234	-	54,278,234
1951	4,637,205	1,884	56,292,050	-	60,929,255	-	60,929,255
1952	4,609,480	1,962	56,540,670	-	61,150,150	-	61,150,150
1953	4,397,322	1,962	53,390,845	-	57,788,167	-	57,788,167
1954	2,875,832	2,524	45,676,364	-	48,552,196	-	48,552,196
1955	3,258,728	2,682	49,416,610	-	52,675,338	-	52,675,338
1956	4,695,239	3,572	55,206,426	-	59,901,665	-	59,901,665
1957	4,964,854	3,984	50,250,764	-	55,215,618	-	55,215,618
1958	4,339,658	5,101	37,050,537	-	41,390,195	-	41,390,195
1959	6,157,164	3,423	50,239,084	-	56,396,248	-	56,396,248
1960	7,008,265	15,792	49,374,678	-	56,382,943	-	56,382,943
1961	8,560,464	16,220	48,373,986	-	56,934,450	-	56,934,450 [1/]
1962	8,990,418	10,522	47,109,027	-	56,099,445	-	56,099,445 [1/]
1963	9,368,001	11,698	51,226,727	32,257,246 [2/]	60,594,728	-	60,594,728 [1/]
1964	9,874,961	23,761	54,558,489	-	64,433,450	791,569	63,641,881 [1/]
1965	13,978,869	25,248	57,946,677	-	71,925,546	1,803,299	37,865,001 [1/]
1966	19,467,647	13,623	68,330,985	44,329,746	87,798,632	2,657,962	40,810,924
1967	23,555,740	5,442	84,454,076	45,220,907	108,009,816	7,079,082	55,709,827
1968	25,132,549	5,395	98,722,568	50,423,224	123,855,117	15,266,007	58,165,886

1/ Does not provide for steam injection figure

2/ Cumulative figure, 1961-1965

1968, p. 103). Petroleum production, as is easily inferred from the produced gas:oil ratio (table 3), is overwhelmingly water drive. Both oil and gas have been drawn exclusively from the nonmarine Kern River Formation at average depths of from 275-400 m (Brooks, 1952b, p. 157; Crowder, 1952, p. 14; California Division of Oil and Gas, 1960, p. 139). The fluvial deposits that make up the reservoir beds of the Kern River Formation consist of poorly sorted sands interbedded irregularly with sandy siltstones and claystones (Brooks, 1952b, p. 157; Crowder, 1952, p. 14-15). Although several faults are mapped in the subsurface of the Kern River oil field, none are known to extend to the surface, and all are characterized by vertical separations of no more than a few meters (Brooks, 1952b, p. 156-157).

The Kern Front field, though a good deal smaller than the Kern River field, is nonetheless a major oil field. Although production statistics date from 1912 (table 4), the early production from the Kern Front field was considered trivial and noncommercial; it was not until 1915, the generally accepted discovery date, that significant production began (Park, 1965, p. 13, 20). Cumulative production from the Kern Front oil field through 1968 (fig. 9) consisted of 116,093,581 bbls (18.459 $\times$ 10^6 m^3) of oil, 13,725,637 Mcf (388.709 $\times$ 10^6 m^3) of gas, and 549,854,822 bbls (87.427 $\times$ 10^6 m^3) of water. Waste water produced from the Kern Front field has been distributed over the ground surface, and none had been injected through at least 1968 (Park, 1965, p. 19; California Division of Oil and Gas, 1968, p. 107). Steam- and hot-water injection began in the Kern Front field in 1964; cyclic injection through 1968 totaled 5,216,112 bbls (0.829 $\times$ 10^6 m^3), whereas water-flood injection accounted for only 99,587 bbls (15,834 m^3). The produced gas:oil ratio (table 4), though small in comparison with other California fields, suggests a partial gas drive. Petroleum produced from the Kern Front oil field has been drawn chiefly from the Miocene Chanac Formation (section *A-A'*, pl. 1) at average depths of 500-575 m (California Division of Oil and Gas, 1960, p. 137); a small amount of oil has also been drawn from the relatively clean marine sands of the Etchegoin Formation in the northeastern part of the field, and similarly small amounts have been produced from the Kern River Formation underlying the northern part of the field (Brooks, 1952a, p. 161; Park, 1965, p. 17-18). The producing beds of the Chanac Formation, which are lithologically similar to those of the Kern River Formation, consist of lenticular bodies of poorly sorted clayey sands interbedded with clays and silts (Park, 1965, p. 17-18). Several faults have been mapped in the subsurface of the Kern Front oil field, and the fault that forms the closure along the east margin of the field, the Kern Front fault, extends to the surface (pl. 1; Brooks, 1952a, p. 160). Vertical separations along these faults are generally less than 10 m, and even that on the Kern Front fault is only about 30 m.

The Poso Creek oil field is only about half the size of the Kern Front field; it is, nonetheless, divided into three separate parts—the Premier, Enas, and McVan

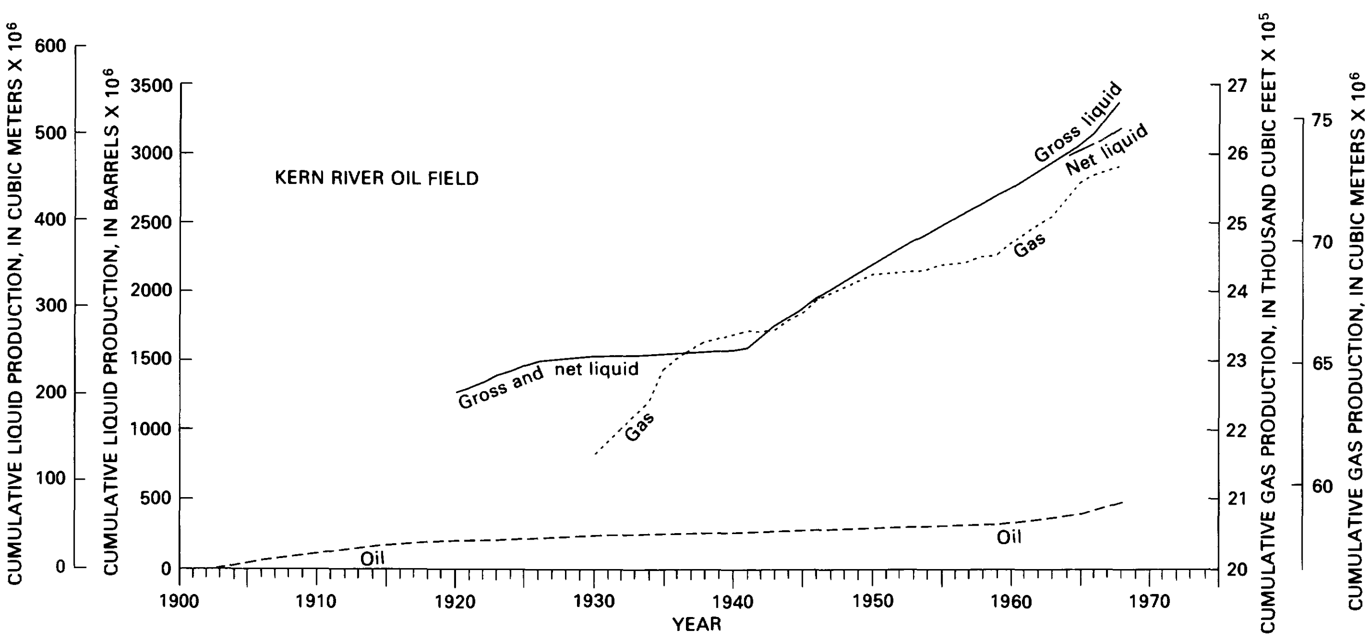

FIGURE 8.—Cumulative production from the Kern River oil field. Based on production figures given in table 3 and the 1968 cumulative production figures of the state oil and gas supervisor (California Division of Oil and Gas, 1968, p. 53, 77). Cumulative liquid production through 1919 derived through the application of the 1920-1928 produced oil:water ratio in the calculation of pre-1920 water production.

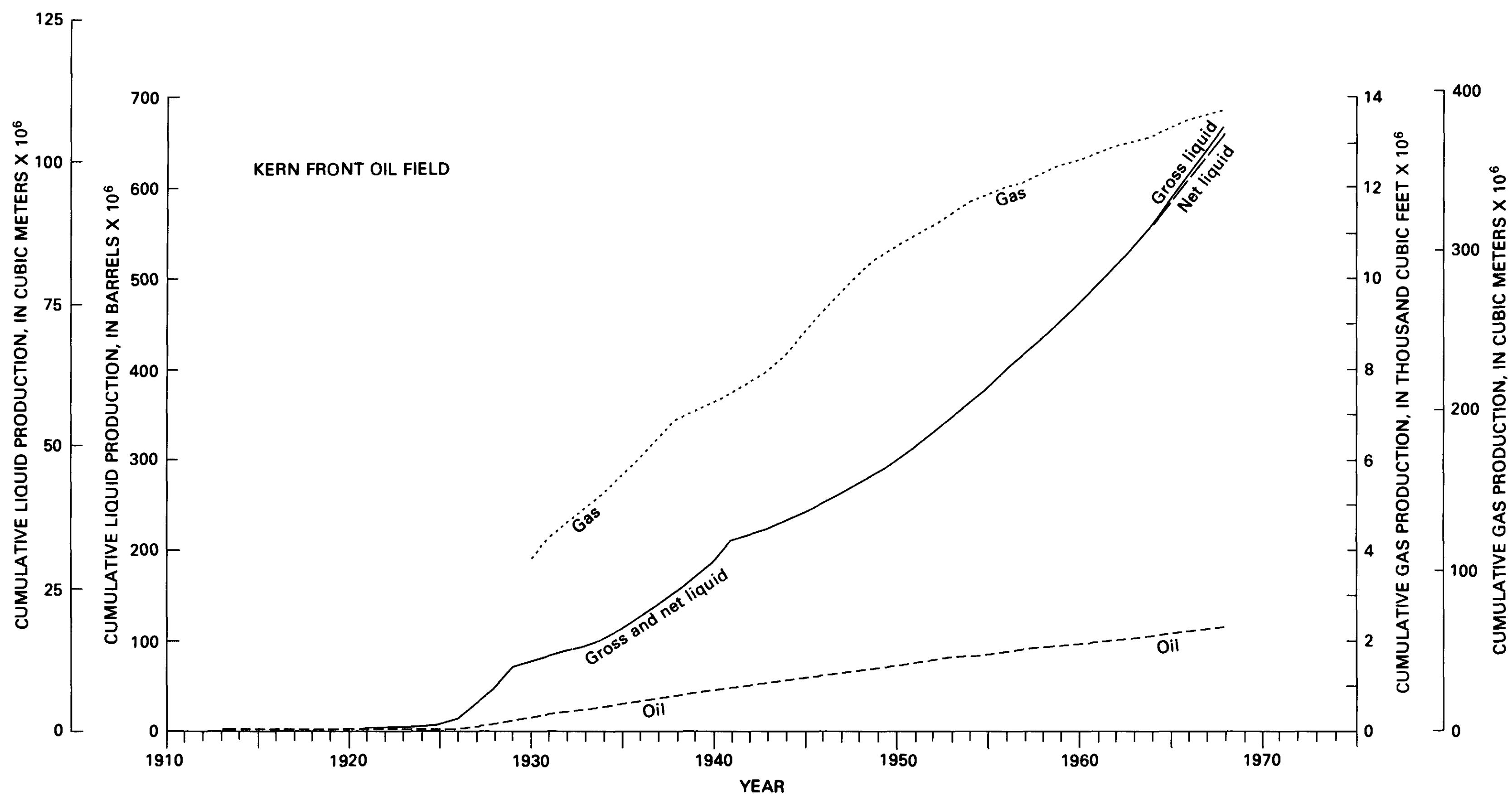

FIGURE 9.—Cumulative production from the Kern Front oil field. Based on production figures given in table 4 and the 1968 cumulative production figures of the state oil and gas supervisor (California Division of Oil and Gas, 1968, p. 53, 77). Cumulative liquid production through 1919 derived through the application of the 1920-1928 produced oil:water ratio in the calculation of pre-1920 water production.

TABLE 4.—*Production figures for the Kern Front oil field, 1912–68*

[Based chiefly on production figures given by Park (1965, p. 20). Production figures for 1964 and later years taken chiefly from annual summary reports of the state oil and gas supervisor. Water-production figures prior to 1942 determined through prorationing of the Kern River water production against oil production from the Kern Front and Kern River oil fields; production figures for the two fields were generally lumped prior to 1942. One bbl = 5.615 ft^3 = 0.1590 m^3; 1 Mcf = 10^3 ft^3 = 28.32 m^3]

Year	Oil production (bbls)	Gas production (Mcf)	Water production (bbls)	Cumulative gross liquid production (bbls)	Steam injection (bbls)	Cumulative net liquid production (bbls)
1912	No records	-	-	-	-	-
1913	4,245	-	-	-	-	-
1914	13,050	-	-	-	-	-
1915	32,439	-	-	-	-	-
1916	19,995	-	-	-	-	-
1917	21,838	-	-	-	-	-
1918	17,867	-	-	-	-	-
1919	36,452	-	-	-	-	-
1920	106,400	-	553,000	659,400	-	659,400
1921	288,356	-	1,345,000	1,633,356	-	1,633,356
1922	352,853	-	1,808,000	2,160,853	-	2,160,853
1923	226,637	-	1,250,000	1,476,637	-	1,476,637
1924	275,813	-	1,558,000	1,833,813	-	1,833,813
1925	318,065	-	1,850,000	2,168,065	-	2,168,065
1926	608,936	-	3,946,000	4,554,936	-	4,554,936
1927	3,230,335	-	13,200,000	16,430,335	-	16,430,335
1928	2,710,305	-	15,400,000	18,110,305	-	18,110,305
1929	4,535,059	-	16,550,000	21,085,059	-	21,085,059
1930	4,276,671	3,836,304 1/	3,838,000	8,114,671	-	8,114,671
1931	2,996,152	471,981	2,688,000	5,684,152	-	5,684,152
1932	2,540,348	350,563	2,744,000	5,284,348	-	5,284,348
1933	2,369,570	329,062	3,700,000	6,069,570	-	6,069,570
1934	2,381,228	343,465	4,740,000	7,121,228	-	7,121,228
1935	2,988,584	370,220	8,330,000	11,318,584	-	11,318,584
1936	3,555,297	368,096	9,101,000	12,656,297	-	12,656,297
1937	3,876,157	463,152	10,650,000	14,526,157	-	14,526,157
1938	3,093,025	367,933	11,700,000	14,793,025	-	14,793,025

1939	2,513,135	228,121	12,050,000	14,563,135	-	14,563,135
1940	2,197,236	200,080	13,760,000	15,957,236	-	15,957,236
1941	2,133,776	178,476	22,480,000	24,613,776	-	24,613,776
1942	2,442,379	206,924	4,185,186	6,627,565	-	6,627,565
1943	2,677,400	283,406	4,002,759	6,680,159	-	6,680,159
1944	3,224,744	392,398	4,950,057	8,174,801	-	8,174,801
1945	3,179,581	456,712	5,726,716	8,906,297	-	8,906,297
1946	3,228,376	478,758	6,968,983	10,197,359	-	10,197,359
1947	3,241,709	450,110	7,974,242	11,215,951	-	11,215,951
1948	3,243,276	441,155	9,013,052	12,256,328	-	12,256,328
1949	2,535,189	298,657	8,975,505	11,510,694	-	11,510,694
1950	2,422,423	233,676	9,742,610	12,165,033	-	12,165,033
1951	2,773,067	239,736	11,895,301	14,668,368	-	14,668,368
1952	2,737,880	256,722	13,319,878	16,057,758	-	16,057,758
1953	2,669,822	233,061	14,165,940	16,835,762	-	16,835,762
1954	2,248,232	214,667	13,858,855	16,107,087	-	16,107,087
1955	2,190,925	159,030	15,278,470	17,469,395	-	17,469,395
1956	2,302,904	167,246	16,374,761	18,677,665	-	18,677,665
1957	2,297,891	170,608	16,283,003	18,580,894	-	18,580,894
1958	2,166,030	161,949	15,625,461	17,791,491	-	17,791,491
1959	2,158,255	146,301	16,217,265	18,375,520	-	18,375,520
1960	2,027,629	134,128	16,263,209	18,290,838	-	18,290,838
1961	1,959,303	142,986	16,925,084	18,884,387	-	18,884,387
1962	2,162,826	139,044	19,082,738	21,245,564	-	21,245,564
1963	2,159,519	150,230	19,975,753	22,135,272	-	22,135,272
1964	2,265,650	145,707	20,740,735	23,006,385	-	23,006,385
1965	2,613,426	146,127	24,114,894	26,728,320	1,946,257[2/]	24,782,063
1966	2,543,400	136,564	25,085,940	27,629,340	1,517,876	26,111,464
1967	2,437,261	115,387	24,633,544	27,070,805	888,984	26,181,821
1968	2,464,519	116,895	24,431,510	26,896,029	962,582	25,933,447

[1/] Cumulative gas 1912-1930

[2/] Cumulative figure, 1964-1965

areas (pl. 1). Production from the Poso Creek oil field began in 1919 in the Premier area, but the "discovery" well was shut in in 1922 (Weddle, 1959, p. 41-42); significant production from the Premier, Enas, and McVan areas began in 1934, 1938, and 1936, respectively (table 5). Cumulative production from the Poso Creek oil field through 1972 by area consisted of: Premier area—52,024,136 bbls (8.272 × 10^6 m^3) of oil, 4,548,370 Mcf (128.810 × 10^6 m^3) of gas, and 424,798,125 bbls (67.543 × 10^6 m^3) of water (fig. 10*A*); Enas area—912,573 bbls (145,083 m^3) of oil, and 7,077,926 bbls (1.125 × 10^6 m^3) of water (fig. 10*B*); McVan area—2,534,959 bbls (403,058 m^3) of oil, and 9,027,802 bbls (1.435 × 10^6 m^3) of water (fig. 10*C*). Prior to 1972, wastewater was disposed of in sumps and stream channels; underground disposal, which was confined to the Premier area (table 5; Weddle, 1959, p. 47; California Division of Oil and Gas, 1972, p. 149), had by 1972 amounted to only 2,697,557 bbls (428,911 m^3). Although steam injection has been carried out in all the producing areas of the Poso Creek field, injection in the Enas area has been trivial, and cumulative injection over the field as a whole through 1972 consisted of 4,783,832 bbls (760,629 m^3) (table 5; California Division of Oil and Gas, 1972, p. 144).

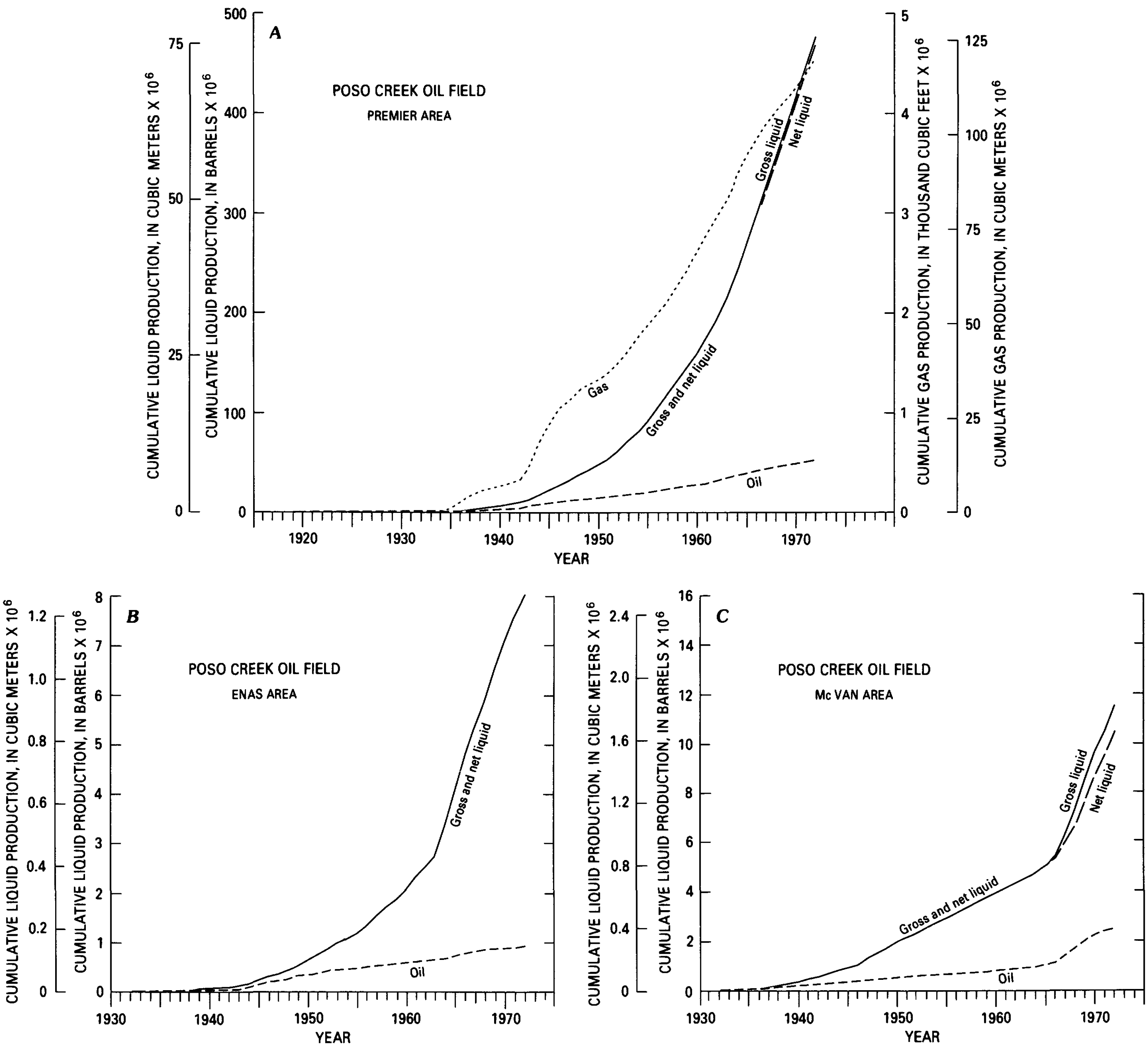

Figure 10.—Cumulative production from the Poso Creek oil field. Based on production figures given in table 5. *A*, Premier area. *B*, Enas area. *C*, McVan area.

TABLE 5.—*Production figures for the Poso Creek oil field, 1919–72*

[Premier and Enas areas: Based chiefly on production figures given by Weddle (1959, p. 50). Production figures for 1960 and later years taken from annual summary reports of the state oil and gas supervisor. McVan area: Based chiefly on production figures given by Mathews (1957, p. 27). Oil production for 1957 and 1958 and water production for 1957 deduced from Premier and Enas figures given by Weddle (1959, p. 50) and production figures for the full field given in the 1957 and 1958 summary reports of the state oil and gas supervisor. One bbl = 5.615 ft^3 = 0.1590 m^3; 1 Mcf = 10^3 ft^3 = 28.32 m^3]

	Premier area							
Year	Oil production (bbls)	Gas production (Mcf)	Water production (bbls)	Cumulative gross liquid production (bbls)	Water flooding (bbls)	Steam injection (bbls)	Water disposal (bbls)	Cumulative net liquid production (bbls)
1919-1929	16,632	-	-	16,632	-	-	-	16,632
1929	6,572	-	323	6,895	-	-	-	6,895
1930	-	-	-	-	-	-	-	-
1931	-	-	-	-	-	-	-	-
1932	-	-	-	-	-	-	-	-
1933	9,833	4,095	244	10,077	-	-	-	10,077
1934	75,571	7,300	4,816	80,387	-	-	-	80,387
1935	253,281	24,785	46,446	299,727	-	-	-	299,727
1936	570,431	65,746	198,400	768,831	-	-	-	768,831
1937	918,910	68,975	434,760	1,353,670	-	-	-	1,353,670
1938	599,927	40,412	574,232	1,174,159	-	-	-	1,174,159
1939	506,946	28,057	791,789	1,298,735	-	-	-	1,298,735
1940	427,717	25,065	961,314	1,389,031	-	-	-	1,389,031
1941	450,531	24,125	1,058,948	1,509,479	-	-	-	1,509,479
1942	570,366	34,385	1,440,514	2,010,880	-	-	-	2,010,880
1943	1,479,196	168,549	2,297,373	3,776,569	-	-	-	3,776,569
1944	1,618,733	210,499	2,440,292	4,059,025	-	-	-	4,059,025
1945	1,421,640	182,687	3,090,911	4,512,551	-	-	-	4,512,551
1946	1,239,974	150,862	3,348,420	4,588,394	-	-	-	4,588,394
1947	1,265,472	91,962	4,124,531	5,390,003	-	-	-	5,390,003
1948	1,216,436	101,849	4,616,777	5,833,213	-	-	-	5,833,213
1949	710,527	52,510	3,996,796	4,707,323	-	-	-	4,707,323
1950	770,139	59,300	4,541,427	5,311,566	-	-	-	5,311,566
1951	1,138,293	61,012	5,421,185	6,559,478	-	-	-	6,559,478
1952	1,352,793	101,071	6,466,360	7,819,153	-	-	-	7,819,153
1953	1,725,750	123,970	7,610,832	9,336,582	-	-	-	9,336,582
1954	1,275,342	130,985	7,198,829	8,474,171	-	-	-	8,474,171
1955	1,241,072	119,503	9,394,599	10,635,671	-	-	-	10,635,671
1956	1,465,415	122,607	13,023,014	14,488,429	-	-	-	14,488,429
1957	1,598,931	120,633	12,243,015	13,841,946	-	-	-	13,841,946
1958	1,288,507	144,484	11,530,583	12,819,090	-	-	-	12,819,090
1959	1,301,393	168,903	12,281,532	13,582,925	-	-	-	13,582,925
1960	1,294,230	192,170	12,703,673	13,997,903	-	-	-	13,997,903
1961	1,418,249	180,935	13,890,678	15,308,927	30,456	-	-	15,278,471
1962	2,091,727	151,481	16,974,611	19,066,338	90,058	-	-	18,976,280
1963	2,769,187	167,486	18,091,633	20,860,820	4,363	-	-	20,856,457
1964	2,810,751	231,998	22,081,266	24,892,017	-	-	-	24,892,017
1965	2,376,478	211,953	24,138,469	26,514,947	-	72,901	-	26,442,046
1966	2,234,539	175,581	29,403,950	31,638,489	-	276,342	-	31,362,147
1967	2,168,002	143,239	28,631,188	30,799,190	-	433,957	-	30,365,233
1968	1,949,108	145,311	27,605,579	29,554,687	-	402,496	-	29,152,191
1969	1,632,872	108,354	25,339,067	26,971,939	-	366,631	-	26,605,308
1970	1,595,335	103,503	27,904,413	29,499,748	-	478,062	-	29,021,686
1971	1,642,670	146,959	29,468,488	31,111,158	-	847,747	-	30,263,411
1972	1,524,658	155,069	29,426,848	30,951,506	-	696,522	2,697,557	27,557,427

TABLE 5.—*Production figures for the Poso Creek oil field, 1919-72*—Continued

Enas area						
Year	Oil production (bbls)	Gas production (Mcf)	Water production (bbls)	Cumulative gross liquid production (bbls)	Steam injection (bbls)	Cumulative net liquid production (bbls)
1929-1931	No records	-	-	-	-	-
1932	2,855	-	328	3,183	-	3,183
1933	2,255	-	321	2,576	-	2,576
1934	200	-	113	313	-	313
1935	168	-	112	280	-	280
1936	1,351	-	936	2,287	-	2,287
1937	1,855	-	1,332	3,187	-	3,187
1938	6,105	-	5,222	11,327	-	11,327
1939	12,629	-	37,741	50,370	-	50,370
1940	3,099	-	16,640	19,739	-	19,739
1941	-	-	-	-	-	-
1942	2,969	-	1,398	4,367	-	4,367
1943	18,358	-	4,049	22,407	-	22,407
1944	48,187	-	7,957	56,144	-	56,144
1945	52,536	-	15,865	68,401	-	68,401
1946	47,913	-	17,671	65,584	-	65,584
1947	42,817	-	26,456	69,273	-	69,273
1948	40,089	-	24,976	65,065	-	65,065
1949	37,453	-	44,200	81,653	-	81,653
1950	33,990	-	100,375	134,365	-	134,365
1951	30,512	-	90,117	120,629	-	120,629
1952	28,821	-	88,180	117,001	-	117,001
1953	25,348	-	81,553	106,901	-	106,901
1954	23,244	-	71,064	94,308	-	94,308
1955	23,652	-	77,347	100,999	-	100,999
1956	20,574	-	116,970	137,544	-	137,544
1957	22,992	-	166,709	189,701	-	189,701
1958	22,258	-	167,429	189,687	-	189,687
1959	20,213	-	145,074	165,287	-	165,287
1960	17,655	-	188,867	206,522	-	206,522
1961	17,604	-	232,995	250,599	-	250,599
1962	14,477	-	172,220	186,697	-	186,697
1963	14,510	-	197,743	212,253	-	212,253
1964	40,348	-	544,595	584,943	-	584,943
1965	53,268	-	677,226	730,494	-	730,494
1966	38,328	-	685,931	724,259	2,800	721,459
1967	36,894	-	502,425	539,319	-	539,319
1968	28,864	-	523,645	552,509	-	552,509
1969	25,083	-	591,765	616,848	-	616,848
1970	21,694	-	570,933	592,627	-	592,627
1971	14,837	-	492,349	507,186	-	507,186
1972	16,468	-	389,897	406,365	-	406,365

TABLE 5.—*Production figures for the Poso Creek oil field, 1919-72*—Continued

McVan area						
Year	Oil production (bbls)	Gas production (Mcf)	Water production (bbls)	Cumulative gross liquid production (bbls)	Steam injection (bbls)	Cumulative net liquid production (bbls)
1932	4,343	-	730	5,073	-	5,073
1933	8,999	-	1,187	10,186	-	10,186
1934	9,497	-	1,859	11,356	-	11,356
1935	3,701	-	1,208	4,909	-	4,909
1936	13,558	-	4,387	17,945	-	17,945
1937	53,758	-	31,017	84,775	-	84,775
1938	51,689	-	17,976	69,665	-	69,665
1939	35,072	-	41,563	76,635	-	76,635
1940	34,384	-	74,916	109,300	-	109,300
1941	28,507	-	77,332	105,839	-	105,839
1942	28,873	-	53,310	82,183	-	82,183
1943	30,721	-	70,566	101,287	-	101,287
1944	30,413	-	85,936	116,349	-	116,349
1945	30,511	-	62,626	93,137	-	93,137
1946	27,521	-	157,754	185,275	-	185,275
1947	32,062	-	192,648	224,710	-	224,710
1948	33,979	-	179,375	213,354	-	213,354
1949	37,713	-	181,763	219,476	-	219,476
1950	27,404	-	211,422	238,826	-	238,826
1951	26,100	-	154,625	180,725	-	180,725
1952	23,937	-	139,335	163,272	-	163,272
1953	24,105	-	150,036	174,141	-	174,141
1954	26,431	-	178,805	205,236	-	205,236
1955	21,814	-	161,833	183,647	-	183,647
1956	33,528	-	204,039	237,567	-	237,567
1957	36,212[1/]	-	170,865	203,347	-	203,347
1958	32,878[1/]	-	181,361[2/]	210,508	-	210,508
1959	28,988	-	191,856	220,844	-	220,844
1960	37,155	-	170,443	207,598	-	207,598
1961	40,335	-	175,583	215,918	-	215,918
1962	34,065	-	154,935	189,000	-	189,000
1963	40,246	-	153,090	193,336	-	193,336
1964	39,924	-	175,313	215,237	-	215,237
1965	41,766	-	226,172	267,938	6,228[3,4/]	261,710
1966	107,489	-	288,130	395,619	107,198[4/]	288,421
1967	290,327	-	532,536	822,863	233,660[4/]	589,203
1968	318,241	-	727,651	1,045,892	331,788[4/]	714,104
1969	311,768	-	957,782	1,269,550	213,879	1,055,671
1970	223,319	-	894,018	1,117,337	98,302	1,019,035
1971	139,979	-	748,506	888,485	94,191	794,294
1972	130,628	-	853,793	984,421	121,128	863,293

1/ Adjusted to agree with the 1959 cumulative figure.

2/ Average of 1957 and 1959 water production figures.

3/ Cumulative steam injection 1964 through 1965 (began Dec. 1964).

4/ Adjusted to agree with the 1968 corrected cumulative figure.

TABLE 6.—*Production figures for the Mount Poso oil field, 1926–63*

[Based chiefly on production figures given by Albright and others (1957, p. 19). Production figures for 1958 and later years taken from annual summary reports of the state oil and gas supervisor. One bbl = 5.615 ft^3 = 0.1590 m^3; 1 Mcf = 10^3 ft^3 = 28.32 m^3]

Year	Oil production (bbls)	Gas production (Mcf)	Water production (bbls)	Cumulative gross liquid production (bbls)	Water flooding (bbls)	Steam injection (bbls)	Cumulative net liquid production (bbls)
1926	52,124	1,720 1/	440	52,564	-	-	52,564
1927	42,944	1,417 1/	113	43,657	-	-	43,657
1928	56,344	1,859 1/	677	57,021	-	-	57,021
1929	1,826,201	24,286	124,105	1,950,306	-	-	1,950,306
1930	3,866,443	129,495	360,994	4,227,437	-	-	4,227,437
1931	3,017,175	71,806	1,262,044	4,279,219	-	-	4,279,219
1932	2,915,199	43,141	2,312,050	5,227,249	-	-	5,227,249
1933	3,043,262	17,502	2,461,016	5,504,278	-	-	5,504,278
1934	3,438,510	5,872	3,098,376	6,536,886	-	-	6,536,886
1935	5,375,637	39,776	4,177,093	9,552,730	-	-	9,552,730
1936	6,733,250	59,087	6,548,846	13,282,096	-	-	13,282,096
1937	6,574,928	40,050	10,989,122	17,564,050	-	-	17,564,050
1938	6,250,946	17,641	13,418,937	19,669,883	-	-	19,669,883
1939	4,262,235	12,998	13,830,332	18,092,567	-	-	18,092,567
1940	3,411,800	1,744	12,493,232	15,905,032	-	-	15,905,032
1941	4,102,032	575	14,033,745	18,135,777	-	-	18,135,777

1942	7,472,396	592	26,341,678	33,814,074	-	-	33,814,074
1943	8,427,304	63,110	37,177,639	45,604,943	-	-	45,604,943
1944	8,005,438	186,583	47,077,515	55,082,953	-	-	55,082,953
1945	6,712,104	194,614	55,619,576	62,331,680	-	-	62,331,680
1946	5,935,637	120,332	63,519,932	69,455,569	-	-	69,455,569
1947	5,157,837	77,428	69,566,885	74,724,722	-	-	74,724,722
1948	4,569,050	75,775	73,930,456	78,499,506	-	-	78,499,506
1949	4,202,066	83,591	77,659,629	81,861,695	-	-	81,861,695
1950	3,807,950	75,511	77,984,536	81,792,486	-	-	81,792,486
1951	3,450,576	61,028	81,171,519	84,622,095	-	-	84,622,095
1952	3,281,569	79,943	81,681,816	84,963,385	-	-	84,963,385 2/
1953	3,101,339	66,469	87,255,087	90,356,426	-	-	90,356,426 2/
1954	3,085,996	55,560	89,041,386	92,127,382	-	-	92,127,382 2/
1955	3,161,201	58,133	95,378,219	98,539,420	111,385 3,4/	-	98,428,035 4/
1956	3,379,734	51,617	99,582,612	102,962,346	54,398 4/	-	102,907,948
1957	3,315,953	33,411	105,112,491	108,428,444	52,338 4/	-	108,376,106
1958	3,393,644	44,796	109,867,717	113,261,361	47,716 4/	-	113,213,645
1959	3,175,586	56,212	110,359,421	113,535,007	56,704 4/	-	113,478,303
1960	2,847,895	49,282	111,182,315	114,030,210	49,892 4/	-	113,980,318
1961	2,473,243	40,762	108,070,351	110,543,594	-	-	110,543,594
1962	2,238,560	26,285	106,219,578	108,458,138	-	-	108,458,138
1963	2,163,317	730	104,155,602	106,318,919	-	No record	106,318,919

1/ Estimated figures.
2/ Does not reflect water flooding begun in 1952.
3/ Cumulative water flooding figure for 1952-1955.
4/ Adjusted to agree with 1963 corrected cumulative figure.

Cumulative Production by Area, 1963

	Main	Dorsey	Dominion	Baker-Grover	Granite Canyon	West
Oil (bbls)	133,378,777	3,761,832	4,550,013	3,491,350	716,941	2,428,512
Gas (Mcf)	1,970,733	-	-	-	-	-
Water (bbls)	1,670,553,304	63,519,185	77,660,853	60,797,505	4,106,359	26,429,868

Although a modest gas drive may have operated in the Premier area, the production is essentially water driven. Oil and gas produced from the Premier and Enas areas is drawn from the Chanac Formation and, to a much lesser extent, the basal sand of the Etchegoin (pl. 1); oil produced from the McVan area is drawn exclusively from the basal part of the Etchegoin (Mathews, 1957, p. 26; Weddle, 1959, p. 45). Production is from an average depth of 750 m in the Premier area, 550 m in the Enas area, and about 350 m in the McVan area (California Division of Oil and Gas, 1960, p. 213, 215). A number of faults, most of which roughly parallel this elongate field have been mapped in the subsurface, and at least two apparently extend to the surface (section *C-C'*, pl. 1; Weddle, 1959, pl. II).

Although areally expansive and broken into a number of producing areas (pl. 1), the Mount Poso oil field is, in fact, about the size of the Kern Front field. Production from the Main area of the Mount Poso oil field began in 1926 (table 6; Albright and others, 1957, p. 6). Discovery wells in the Dorsey, Dominion, Baker-Grover, Granite Canyon, and West areas were subsequently completed in 1928, 1928, 1935, 1938, and 1943, respectively (Albright and others, 1957, p. 8-9). Cumulative production from the entire Mount Poso oil field through 1963 consisted of 148,327,425 bbls (23.584 $\times 10^6$ m^3) of oil, 1,970,733 Mcf (55.811 $\times 10^6$ m^3) of gas, and 1,902,694,649 bbls (302.528 $\times 10^6$ m^3) of water (fig. 11). Production of both oil and water have been predominantly from the Main area; oil and water drawn from all

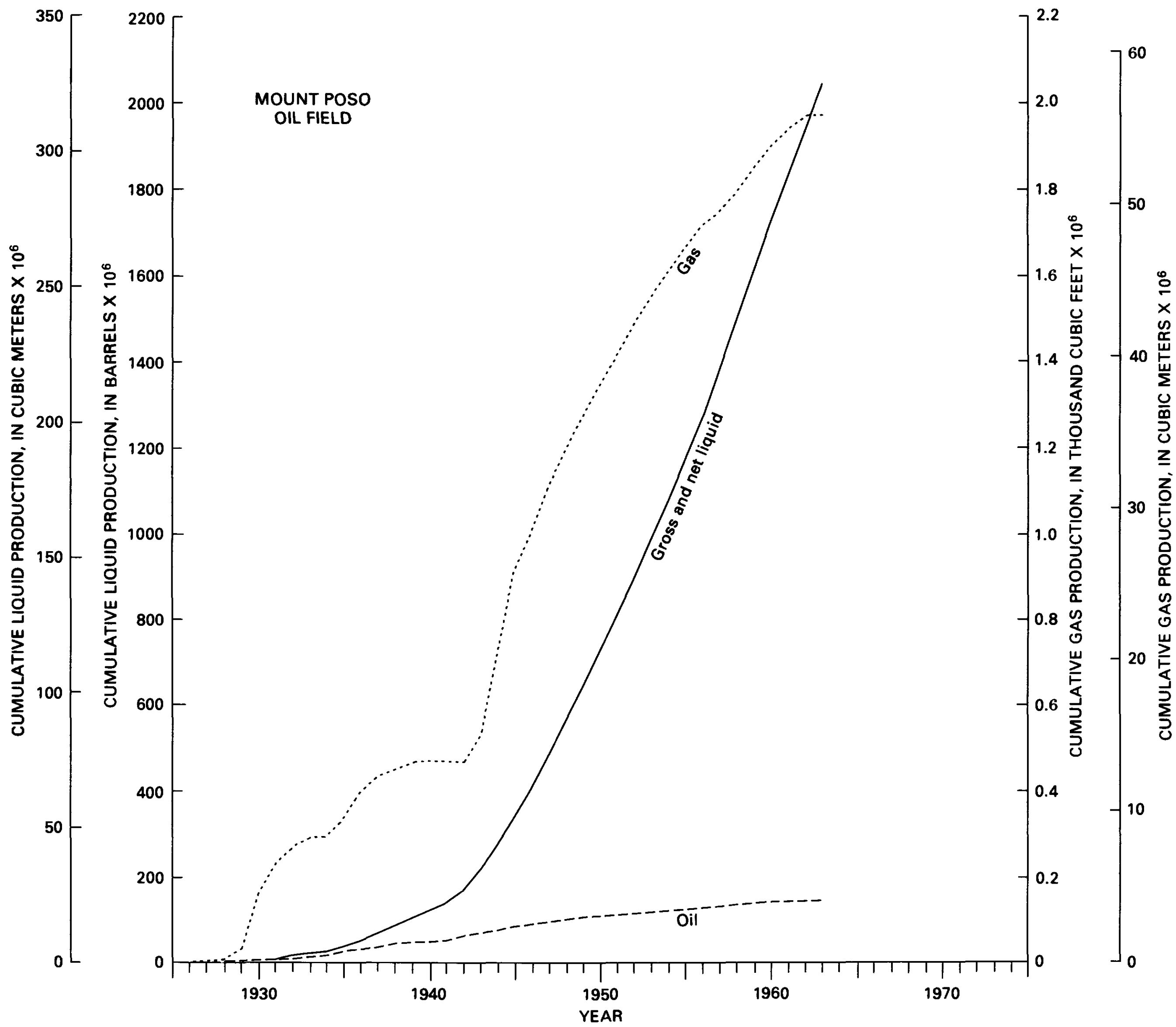

FIGURE 11.—Cumulative production from the Mount Poso oil field. Based on production figures given in table 6.

other areas combined is trivial by comparison (table 6). Water flooding, seemingly confined to the Main area, began in 1952; by 1963 it totaled only 372,433 bbls (50,217 m^3) (table 6). The gas:oil ratio in the Mount Poso oil field has been characteristically small (table 6; fig. 11), and the production clearly is water driven. Petroleum production in the Main area is principally from the various parts of the Vedder Sand (pl. 1) at an average depth of about 550 m (Albright and others, 1957, p. 14; California Division of Oil and Gas, 1960, p. 189). Production from the other areas of the Mount Poso field is nearly exclusively from the upper part of the Vedder at average depths that range between 425 and 800 m (California Division of Oil and Gas, 1960, p. 181, 183, 185, 187, 191). The entire Mount Poso oil field, according to Albright and others (1957, p. 10), is complexly faulted (section *D-D′-D″-D‴-D⁗*, pl. 1) and "all of the production areas within the field are fault closed reservoirs."

In terms of areal extent, the Fruitvale field is perhaps the smallest of all the oil fields considered here (pl. 1), but it has, nonetheless, been relatively productive. The field was discovered in 1928 (Johnston, 1952, p. 122), but it was not until the middle 1930's that production began to increase significantly (table 7). Cumulative production through 1959 consisted of 77,437,776 bbls (12.313 × 10^6 m^3) of oil, 22,731,949 Mcf (643.769 × 10^6 m^3) of gas, and 97,409,490 bbls (15.488 × 10^6 m^3) of water (fig. 12). Wastewater was not injected into the subsurface until 1958, and it amounted to only 2,535,763 bbls (403,186 m^3) through 1959 (table 7). Although the production from the Fruitvale oil field does not begin to compare with that from the Kern River field, the gas:oil ratio is more than an order of magnitude greater than the ratio that has characterized the Kern River production and about twice that of the Kern Front oil field (figs. 8, 9, and 12); hence we infer that gas drive in the Fruitvale field has been significantly greater than in any of the other fields shown on plate 1. Petroleum produced from the Fruitvale field has been almost exclusively from the Chanac Formation at an average depth of about 1,000 m (California Division of Oil

TABLE 7.—*Production figures for the Fruitvale oil field, 1928–59*

[Compiled from production figures given in annual summary reports of the state oil and gas supervisor. One bbl = 5.615 ft^3 = 0.1590 m^3; 1 Mcf = 10^3 ft^3 = 28.32 m^3]

Year	Oil production (bbls)	Gas production (Mcf)	Water production (bbls)	Cumulative gross liquid production (bbls)	Water disposal (bbls)	Cumulative net liquid production (bbls)
1928	151,596	-	-	151,596	-	151,596
1929	633,756	192,036	23,290	657,046	-	657,046
1930	915,897	404,317	28,855	944,752	-	944,752
1931	872,521	320,419	40,541	913,062	-	913,062
1932	1,626,378	594,163	104,877	1,731,255	-	1,731,255
1933	1,686,861	485,273	151,194	1,838,055	-	1,838,055
1934	1,360,849	330,590	166,208	1,527,057	-	1,527,057
1935	1,857,633	314,830	168,442	2,026,075	-	2,026,075
1936	2,864,106	442,137	257,231	3,121,337	-	3,121,337
1937	3,234,462	395,301	482,590	3,717,052	-	3,717,052
1938	3,087,265	323,583	847,290	3,934,555	-	3,934,555
1939	2,371,694	159,337	1,397,288	3,768,982	-	3,768,982
1940	2,061,009	85,901	1,312,938	3,373,947	-	3,373,947
1941	2,106,675	178,652	1,631,062	3,737,737	-	3,737,737
1942	2,343,320	514,061	1,566,440	3,909,760	-	3,909,760
1943	2,584,672	647,547	1,593,083	4,177,755	-	4,177,755
1944	3,107,735	538,524	2,624,474	5,732,209	-	5,732,209
1945	3,145,684	426,348	2,596,324	5,742,008	-	5,742,008
1946	2,865,318	358,325	3,315,850	6,181,168	-	6,181,168
1947	2,540,673	408,243	4,095,745	6,636,418	-	6,636,418
1948	2,510,580	433,429	5,400,324	7,910,904	-	7,910,904
1949	2,800,030	496,208	5,397,908	8,197,938	-	8,197,938
1950	2,879,778	598,438	4,978,029	7,857,807	-	7,857,807
1951	3,355,966	1,432,386	5,199,617	8,555,583	-	8,555,583
1952	3,413,106	1,653,180	4,403,574	7,816,680	-	7,816,680
1953	3,577,090	1,227,029	4,907,813	8,484,903	-	8,484,903
1954	3,580,703	1,450,330	5,723,608	9,304,311	-	9,304,311
1955	3,400,291	1,746,983	6,435,074	9,835,365	-	9,835,365
1956	3,203,696	1,741,083	7,538,478	10,742,174	-	10,742,174
1957	3,000,396	1,742,308	8,143,193	11,143,589	-	11,143,589
1958	2,718,723	1,653,561	8,488,380	11,207,103	13,993	11,193,110
1959	2,503,221	1,437,427	8,389,770	10,892,991	2,521,770	8,371,221

and Gas, 1960, p. 115). Although the subsurface is thought to be laced with faults and the east boundary of the field is clearly fault controlled (Johnston, 1952, p. 123), none of these faults is known to project to the surface.

DIFFERENTIAL SUBSIDENCE

Subsidence associated with producing oil fields is governed by the same general principles as those that control subsidence associated with ground-water withdrawals from a confined aquifer (see section on "Surface Deformation Attributable to Ground-water Withdrawals" and Poland and Davis, 1969). Moreover, because all five of the oil fields described in the preceding paragraphs meet at least two of the several criteria that render them susceptible to compaction-induced subsidence, the likelihood that these particular fields may have sustained measurably significant subsidence is greatly enhanced. Specifically, since all produce from relatively young deposits (none of which are older than Miocene or conceivably Oligocene) at relatively shallow depths of generally less than 1,000 m, we could expect to find at least modest subsidence centering on any of these fields (Yerkes and Castle, 1969).

Four of the five oil fields shown on plate 1 are characterized by differential subsidence of sufficient magnitude that it cannot be dismissed as the product of systematic or random error in geodetic leveling. Moreover, while this determination is in two out of four cases based on repeated surveys into a single mark, such that the measured signals are conceivably attributable to benchmark disturbance, this possibility would ask a good deal of chance coincidence. Similarly, even though the reported displacements are based largely on the results of single-run levelings, the differential subsidence identified with all but one of these examples is clearly an aberration on the regional tilt that persists through the oil fields (see section on "Surface Deformation Attributable to Tectonic Activity"). Hence it is very unlikely

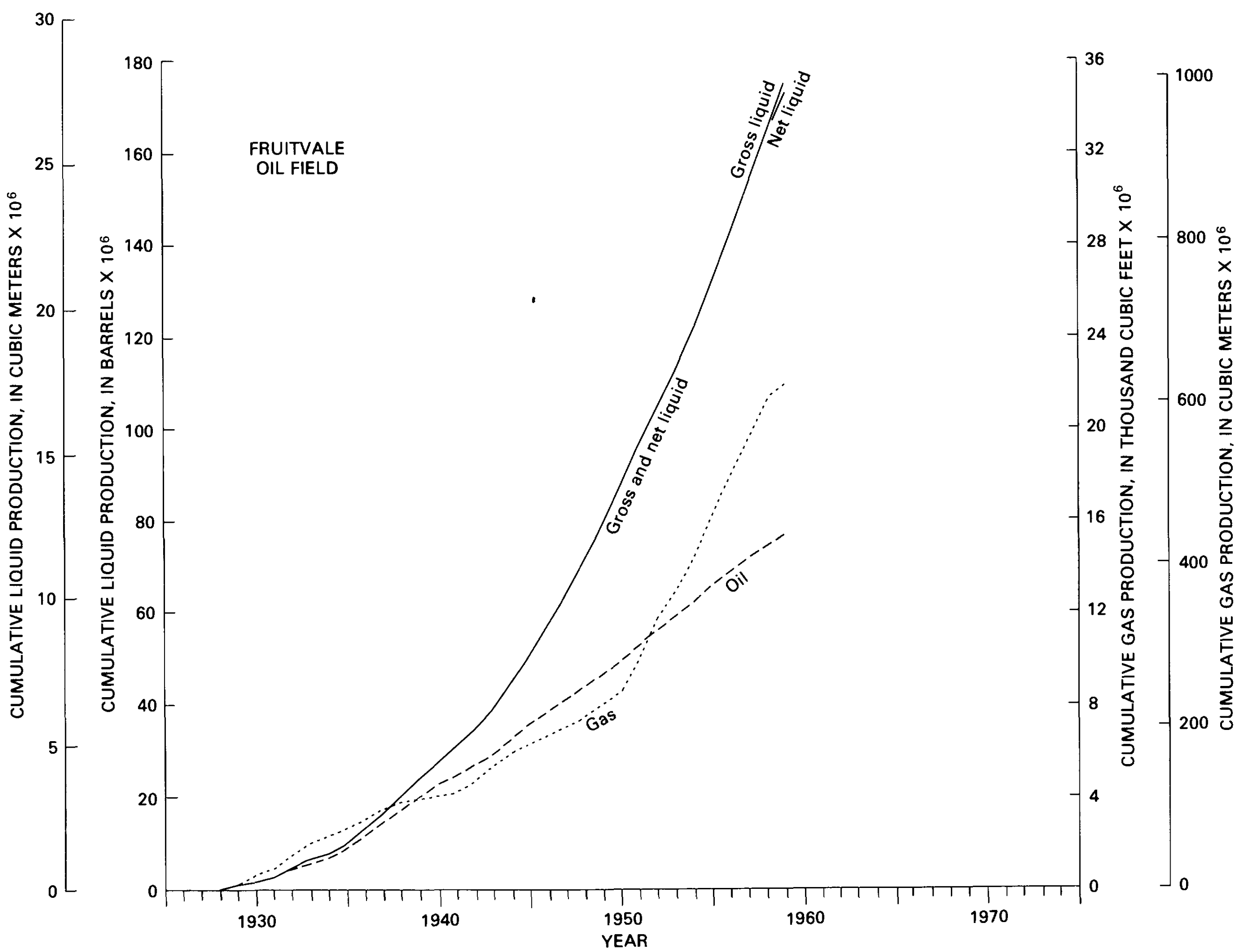

FIGURE 12.—Cumulative production from the Fruitvale oil field. Based on production figures given in table 7.

that the observed subsidence could be due to blunders in any of the levelings.

The maximum measured subsidence associated with operations in the Kern Front oil field has been recorded at bench mark 864 (pl. 1). Subsidence of this mark during the period 1903-68 is given as 0.3094 m with respect to 448 B (table 2). However, because significant production from this field did not begin until the middle or late 1920's (table 4, fig. 9), it is likely that nearly all this subsidence has occurred since about 1930. Similarly, because 448 B probably sustained about 0.055 m of compaction-induced subsidence during the period 1903-68 (see section on "Surface Deformation Attributable to Ground-water Withdrawals"), we infer that the Kern Front oil field could have undergone no less than 0.36 m of differential subsidence during the period 1925-68. Moreover, measurement with respect to either bench mark 1133 or 1205 (pl. 1), neither of which could have sustained significant compaction-induced subsidence, suggests that 864 subsided 0.4145 and 0.4042 m, respectively, during the period 1903-68 (table 2). Finally, because nearby bench mark B-1 1931 (pl. 1) apparently rose 0.1024 m with respect to 448 B during the period 1931-68 (table 2), subsidence in the Kern Front oil field with respect to any point adjacent to but well outside the producing area of the field clearly exceeded 0.4 or even 0.5 m during the period 1903-68.

The likelihood that the subsidence of bench mark 864 is due to oil-field operations is supported by the vertical displacement history of bench mark B 1931, which lies within but toward the edge of the Kern Front oil field (pl. 1). B 1931 subsided 0.0415 m with respect to 448 B and nearly 0.15 m with respect to B-1 1931 during the period 1931-68 (table 2). Nonetheless, a feature that challenges the likelihood that the subsidence in the Kern Front field is causally related to exploitation is the seeming absence of significant subsidence at B 1931 before 1963 (table 2). However, subsidence of B 1931 prior to 1963 could easily have been masked by comparable compaction-induced subsidence at 448 B or regional tilting between these marks during the period 1931-63. It is equally likely, moreover, that the recognition of subsidence at B 1931 since 1963 can be attributed to reduced pumpage or the achievement of near ultimate aquifer compaction in the area of 448 B. This interpretation is clearly consistent with the displacement history of B 1931 with respect to B-2 1931, a nearby bench mark that probably has undergone little if any compaction-induced subsidence. Specifically, roughly two thirds (or 0.1194 m) of the 0.1750 m of the subsidence of B 1931 with respect to B-2 1931 during the full period 1931-68 had occurred by 1963 (table 2).

The existence of subsidence identified with the operations in the Poso Creek oil field is based on a single comparison; it is, as a result, the most equivocal of any of the examples of oil-field subsidence described here. Subsidence of bench mark 545 B (pl. 1) during the interval 1903-53 is given as 0.3322 m with respect to 448 B (table 2). If allowance is made for the probable compaction beneath 448 B, differential subsidence of this mark could easily increase to 0.36-0.37 m. Computation of the reported subsidence of 545 B is based on an assumption of vertical invariance between 448 B and B-3 1931 during the period 1953-63, a period that bracketed the inception and first major deformational episode associated with the evolution of the southern California uplift (Castle and others, 1976). Because B-3 1931 sustained an up-to-the-east tilt of 0.1301 m with respect to 448 B during the period 1931-63 (table 2), it is likely that at least a fraction of this relative uplift, and conceivably as much as 0.07-0.08 m, occurred between 1953 and 1963. Accordingly, the actual 1953 height of 545 B with respect to 448 B may have been 0.07-0.08 m less than the computed value, and the actual 1903-53 subsidence may have been enhanced by a like amount. Thus, while a measure of uncertainty pervades this entire reconstruction, differential subsidence of bench mark 545 B probably was about 0.4 m—roughly comparable with that measured in the Kern Front oil field. Moreover, a subjective argument (see below) indicates that the maximum subsidence centering on the Poso Creek oil field probably was several times that measured at this peripheral mark.

The results of repeated surveys through the Mount Poso oil field indicate that the Main area (pl. 1) has sustained significant subsidence clearly associated with oil-field operations. Specifically, bench mark 884 B (pl. 1) rose 0.0893 m with respect to 448 B during the interval 1903-31 (table 2), a period preceding significant production from this field (table 6, fig. 11), whereas this same mark subsided 0.1856 m with respect to 448 B during the interval 1931-63 (table 2). The magnitude of the differential subsidence of 884 B is easily obtained through comparisons with the displacement histories of B-3 1931 and B-7 1931 (pl. 1). Accordingly, depending on the comparison, differential subsidence of bench mark 884 B ranged between 0.3157 and 0.3755 m during the interval 1931-63 (table 2). Regrettably, because this mark is located along the southeast edge of the field, we can only speculate on the maximum differential subsidence that occurred within the Mount Poso field. However, the production statistics (table 6, fig. 11) indicate that the liquid production from this field has been three and four times that in the Kern Front and Poso Creek oil fields, respectively. Thus it is likely that differential subsidence centering on the Mount Poso field may have approached 1.0 m. Finally, because this is the only one of the five fields described here in which two or more surveys preceded significant production, it is also the only one in which we can document an association between subsidence and production in both space and time.

The vertical displacement histories of bench marks W 67 and X 67 (pl. 1) together indicate that the subsidence centering on the Fruitvale oil field is almost certainly due to the exploitation of this field. Subsidence of W 67 with respect to 448 B during the period 1926/27/30/31-59 was only 0.0541 m (table 2). However, because bench marks F 55 and Y 67 (pl. 1) rose 0.0340 and 0.0428 m with respect to 448 B during the periods 1926/27/30/31-57 and 1926/27/30/31-59, respectively (table 2), differential subsidence centering on the Fruitvale field probably approached 0.1 m between the initiation of significant production in 1929 (table 7, fig. 12) and the 1959 survey. Because the marginally positioned bench mark X 67 sustained measurably significant subsidence with respect to F 55 and Y 67 during the periods 1926/27/30/31-57 and 1926/27/30/31-59 (table 2), there is virtually no possibility that the modest subsidence centering on the Fruitvale oil field can be due to other than oil-field operations. Specifically, had X 67 shown no tendency toward differential movement consistent with the subsidence of W 67, it could be reasonably argued that the apparent subsidence of W 67 is the product of nothing more than bench-mark disturbance or some aberration in the measurements.

Because production from all four of the subsiding oil fields cited above is essentially water drive, associated with varying but generally trivial gas drive, the magnitude of the measured subsidence seems surprisingly large in all but perhaps the Fruitvale field. That is, the better known examples of oil-field subsidence in California are clearly identified with gas-drive production (see, for example, Castle and Yerkes, 1976). Hence we infer that the observed subsidence in these fields can be traced in large measure to heavy pumpage and resultant compaction drive that simply outpaced edge-water migration.

Although significant differential subsidence can be identified with production from all of the other oil fields considered in this report, the Kern River oil field seems to have been virtually devoid of subsidence. Comparisons with 448 B suggest, in fact, that the centrally located marks 768 and 634 B (pl. 1) actually rose during the period 1903-68 (table 2). Although a fraction of this apparent uplift certainly is due to compaction-induced subsidence of 448 B, comparisons with several nearby bench marks well outside the field are equally supportive of a general absence of subsidence within the Kern River field. Specifically, during the period 1903-68 and with respect to bench mark 976 B (pl. 1), 768 rose 0.0559 m and 634 B subsided only 0.0271 m (table 2). Similarly, during the same period and with respect to bench mark 1133, 768 rose 0.0062 m and 634 B subsided 0.0768 m (table 2). Therefore, although the subsidence of 634 B with respect to 1133 cannot be dismissed as negligible, it is nonetheless evident that exploitation-induced subsidence within the Kern River oil field has been nonexistent to trivial. This observation, accordingly, suggests a seeming paradox: the occurrence of subsidence in all of the other oil fields considered here is much more easily explained than is the absence of subsidence in the Kern River field. In other words, by virtually every standard used to evaluate the susceptibility of producing oil fields to extraction-induced subsidence, it is the Kern River rather than any of these other oil fields that should have sustained major subsidence. In comparing it only with the adjacent Kern Front oil field, the Kern River field is characterized by: (1) about four times the production; (2) production from significantly younger units; and (3) production from a median depth that is only slightly more than half that of the Kern Front oil field. In fact, the only feature of the Kern Front field that favors its subsidence over that of the Kern River oil field is the higher, but still relatively minor gas drive associated with the Kern Front production.

The absence of significant subsidence in the Kern River oil field probably can be attributed to several factors. The most obvious, although not necessarily the most valid possibility, is that the compressibilities of the reservoir beds included with the Kern River Formation are generally very low. This possibility, moreover, is clearly supported by the inferred depositional environment of the productive facies at the head of the Kern River fan, where the relatively fine-grained and generally more compressible sediments would tend to be winnowed out. Hence, even with the enormous liquid production from the Kern River field (table 3, fig. 8), the compression index of these deposits may have simply precluded significant subsidence, however great the increased effective stress. Alternatively, the absence of subsidence within the Kern River oil field may be related to its close association with the Kern River drainage. That is, we assume that recharge through the Kern River may be introduced into the gently dipping producing beds of this oil field through the spreading grounds of the Kern River flood plain, at least within the area where these beds are neatly truncated by the Kern River (pl. 1). This postulated recharge, in effect, comprises a natural water flood that has acted to preserve reservoir fluid pressures at the near normal hydrostatic levels that characterize pre-exploitation reservoir conditions in most California oil fields. In other words, though Crowder (1952, p. 17) has indicated that water drive in the Kern River oil field is generated by edge-water encroachment from the south and west, it is not unlikely that encroachment from along the south edge and, perhaps latterly, the east edge of the oil field (pl. 1) has dominated the production drive throughout most of the history of this field. Significant fault offset athwart the line of natural fluid flow would, of course, operate to inhibit this presumed natural water flooding. However, the trends of the major faults in the Kern River field roughly parallel the direction of maximum dip and are localized in the northern part of the field (pl. 1).

The likelihood that natural water flooding has preserved reservoir fluid pressures within the Kern River oil field is supported by the salinities obtained from the produced waters. Zone-water salinities in the Kern River field are given as 3-16 grains/gallon (California Division of Oil and Gas, 1960, p. 139); this contrasts markedly with other southern San Joaquin Valley oil fields which are identified with salinities that range up to 2,700 grains/gallon and probably average over 1,000 grains/gallon (California Division of Oil and Gas, 1960, p. 10-295). Although very low zone-water salinities have been reported from several oil fields north and east of Bakersfield, including the Kern Front (17 grains/gallon—California Division of Oil and Gas, 1960, p. 137), the Kern River field holds the fresh-water purity record among those southern San Joaquin Valley oil fields for which zone-water analyses are given by the California Division of Oil and Gas (1960, p. 10-295).

FAULTING

The historical faulting along the east margins of the Kern Front and Poso Creek oil fields (pl. 1) is strikingly similar in its general characteristics to that associated with oil-field operations elsewhere in the United States. Of the eleven other recognized examples of surficial faulting around various California and Texas oil fields, seven closely resemble the Kern Front and Poso Creek faulting in that they are high angle, normal, downthrown on the oil-field side, and generally associated with measured differential subsidence (Yerkes and Castle, 1969). The Kern Front and Poso Creek faulting probably is similar to these seven examples in yet another respect, for it parallels the oil-field boundaries and, hence, probably parallels the inferred isobases of subsidence that ordinarily are more or less concentrically distributed around these oil fields (Yerkes and Castle, 1969, p. 55). Castle and Yerkes (1976, p. 70-72) describe, in addition, three examples of subsurface faulting that accompanied oil-field exploitation in the Los Angeles basin; these examples lend support to a general cause-and-effect relation between oil-field operations and associated faulting, whether such faulting has propagated to the surface or not.

Castle and others (1973) show that faulting along the east margin of the Inglewood oil field in the Baldwin Hills of southern California not only developed but should have developed as a result of differential compaction of the producing oil measures. Differential compaction in the Inglewood field, as in the general case, created an annulus of centripetally directed extensional horizontal strain surrounding the subsidence bowl centering on the field; it is this extensional strain, coupled with rebound of the elastically compressed, downwarped section along the edge of the subsidence bowl, that led directly to rupturing and faulting (fig. 13*A*).

The Baldwin Hills faulting, which is probably the best studied example of surficial rupturing associated with oil-field operations in the world (California Department of Water Resources, 1964; Hudson and Scott, 1965; Jansen and others, 1967; Hamilton and Meehan, 1971; Casagrande and others, 1972; Leps, 1972; Castle and others, 1973; Castle and Youd, 1973; Castle and Yerkes, 1976), is similar to the faulting along the margins of the Kern Front and Poso Creek oil fields in the following ways: (1) both were preceded by several decades of production; (2) both were confined essentially to the oil-field periphery; (3) both were accompanied by oil-field subsidence; (4) both were unassociated with local seismic activity; (5) movement occurred largely or entirely on preexisting faults in both the Baldwin Hills and Oildale areas; and (6) faulting in both cases was high angle, normal, and characterized by relative downward movement on the oil-field side. The faulting in the Baldwin Hills and Oildale areas are dissimilar in that: (1) rupturing on the Kern Front fault has extended about 5.2 km and that on the Premier fault more than about 2.7 km—or about six and three times, respectively, the length of the longest rupture recognized in the Baldwin Hills (Castle and Yerkes, 1976, pl. 2); and (2) maximum fault displacement with respect to maximum subsidence

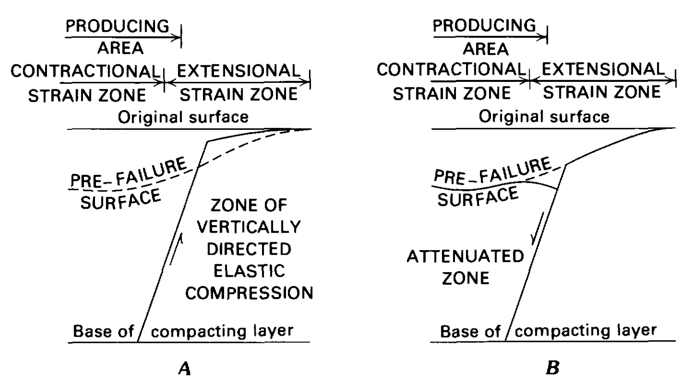

FIGURE 13.—Schematic diagrams illustrating possible modes of failure (faulting) around the periphery of a subsiding oil field. *A*, the Baldwin Hills model (Castle and Yerkes, 1976, p. 72-74). *B*, postulated model designed to explain the faulting along the east margins of the Kern Front and Poso Creek oil fields.

is far less in the Baldwin Hills than in either the Kern Front or Poso Creek oil fields—displacements of 0.15-0.18 m associated with 1.73 m of subsidence compared with displacements of more than 0.3 m associated with 0.6-0.9 m of subsidence in at least the Kern Front field and probably the Poso Creek field as well. Cumulative displacements on the Baldwin Hills faults reached a maximum of one-quarter to one-half the theoretical limit; this limit is based on the assumption that subsidence along the trace of the fault was the product of strictly elastic compression of the underlying section (fig. 13*A*). On the other hand, if we assume the operation of a similar model along the Kern Front fault, the maxiumum displacement measured since 1949 probably closely approaches—if it does not actually exceed—the theoretical limit that can be attributed to elastic rebound. That is, because the maximum differential subsidence in the Kern Front oil field is estimated to have been no more than about 0.6-0.9 m, it seems unlikely that subsidence along the trace of the fault could anywhere have exceeded more than 0.30-0.45 m; hence, for example, measured displacement on the Kern Front fault of at least 0.3 m (pl. 1) suggests either that downwarping of the section along the trace of the fault was nearly entirely elastic, or that simple elastic compaction can account for no more than a fraction of the historical faulting.

Alternatively, the observed faulting may be the product of nothing more than differential compaction across the hydrologic (or fluid-pressure) barriers defined by the faults that bound the east margins of both the Kern Front oil field and the Premier area of the Poso Creek oil field. This postulated mechanism is analogous to the one proposed by Holzer (1980) to explain the historical displacements along the Pond-Poso Creek fault near Delano, Calif. Although the simplicity of this model is especially appealing, several general observations suggest that the actual mechanism may be somewhat more complex. Specifically, radially oriented horizontal strain has been recognized in every subsiding oil field where the appropriate measurements have been made (Castle and Yerkes, 1976), such that any explanation, it seems to us, must be able to explain the relation between the presumed presence of this horizontal strain (as well, of course, as the differential subsidence) and the faulting. Moreover, if simple differential compaction across the faults accounted for both the subsidence and the measured vertical separations across the faults, we should expect to find a fairly good correspondence between the two. However, the displacement opposite bench mark B 1931 was significantly greater than the subsidence of this mark, whether referred to 448 B or B-1 1931 (pl. 1; table 2), whereas the displacement opposite 864 was much less than the 1903-68 subsidence of this mark (pl. 1; table 2), most of which probably occurred after 1930 (table 4, fig. 9). Moreover, the general strain pattern described here probably differs from that in the area of the Pond-Poso Creek faulting in several significant ways. For example, though the data do not permit a clear determination, the subsidence gradients across the Kern Front and Poso Creek oil fields probably are much steeper than those in the area of the Pond-Poso Creek faulting. In addition, we infer that the faulting in this area roughly parallels the isobases of equal elevation change, whereas it lies nearly athwart the isobases in the area described by Holzer (1980, p. 1066). There is clearly no way we can exclude simple differential compaction as the source of the faulting in this area, but we doubt that it can fully explain the observed faulting if only because the dips on these faults (toward the centers of the respective fields) would tend to inhibit any vertical separation in the absence of at least modest extensional strain across these faults.

Finally, the faulting along the margins of the Kern Front and Poso Creek oil fields may be explained by a "roll back" or "collapse" model based on a presumed attenuation of the hanging-wall block (fig. 13*B*). Specifically, if we assume that the radially oriented extensional strain characteristically developed around subsiding oil fields is linearly related to the subsidence gradient, we can calculate approximate values for both the extensional strain and the maximum likely horizontal displacement that could have been generated athwart a fault paralleling the subsidence isobases in at least the Kern Front field, by simple comparison with actually measured values in the Baldwin Hills. Thus, on the one hand, by 1958 (when faulting was first clearly recognized in the Baldwin Hills) the average subsidence gradient developed across the Inglewood oil field was about 700 mm/km (Castle and Yerkes, 1976, p. 19-20, pl. 4), whereas on the other hand, the average gradient across the Kern Front field probably has been no more than about 400 mm/km—a figure based on maximum probable subsidence through 1968 of about 0.9 m. Because the maximum extensional strain around the margin of the Baldwin Hills subsidence bowl could have been as much as (but probably was less than) 0.10 percent (Castle and Yerkes, 1976, p. 27-29), it is conceivable that the radially oriented extensional strain surrounding the Kern Front oil field may have been as great as 0.057 percent—and, hence, that the average extensional strain was about 0.028 percent. Thus, in the extreme case, if the radially oriented extensional strain within an hypothesized 1,000-m annulus was taken up entirely through slip along the Kern Front fault, extensional strain of 0.028 percent could have been associated with centripetally directed horizontal displacements athwart the fault of as much as 0.3 m. Accordingly, if the average dip on the Kern Front fault is about 70° W., we could anticipate a maximum vertical separation of about 0.8 m associated with a postulated horizontal displacement of 0.3 m. Because the actually measured vertical separation on the Kern Front was only about one-half this figure, the "roll back" model (fig. 13*B*) may account for at least a part of the historical faulting observed along the edges of both the Kern Front and Poso Creek oil fields.

Analogies with the several examples cited by Yerkes and Castle (1969), and especially that of the Baldwin Hills (Castle and others, 1973; Castle and Yerkes, 1976), strongly support the conclusion that the historical faulting measured along the edges of the Kern Front and Poso Creek oil fields is also attributable to oil-field operations. Although historical movement on these faults may have involved other processes as well, the nature of this movement has been such that it is very unlikely that it could have occurred in the absence of oil-field operations.

SURFACE MOVEMENTS ATTRIBUTABLE TO TECTONIC ACTIVITY

Because southern California is recognized as an area of continuing tectonic activity, all the surface movements described here could be interpreted as products of this activity. However, we are inclined to concur with Gilluly and Grant (1949, p. 488) who observed that "causes of tectonic movements are so obscure that it is always possible to assert their effectiveness without the possibility of direct disproof; in the nature of the case, the demonstrated adequacy of another mechanism known to be operative and competent to produce the observed effects can only make it unnecessary to appeal to the unknown tectonic forces."

HEIGHT CHANGES

Studies of differential subsidence centering on oil fields around the world have shown repeatedly that this subsidence can be attributed to fluid extraction and resultant compaction of the petroleum reservoir beds (Gilluly and Grant, 1949; Poland and Davis, 1969; Yerkes and Castle, 1969; Poland, 1972; Castle and Yerkes, 1976); hence we need not "appeal to unknown tectonic forces" in order to explain the differential subsidence within or around the Kern Front, Poso Creek, Mount Poso, and Fruitvale oil fields. We insist, in fact, that the burden of proof lies with those who choose to attribute this subsidence to tectonic activity. Accordingly, it seems inescapable that the subsidence we describe here (pl. 1; table 2) can, at best, be only incidentally associated with tectonic activity.

Clearly tectonic deformation in the Oildale area is suggested especially by the history of movement at bench marks B-2 1931, B-3 1931, and B-7 1931 (pl. 1). Specifically, northeastward from Oildale these marks rose by progressively increasing amounts during the interval 1931-63, reaching a maximum of +0.1899 m at B-7 1931 (table 2). This is the largest positive signal revealed through comparisons of any of the vertical control data incorporated in this report, and it is unlikely that more than about 0.05 m of this displacement can be dismissed as the product of compaction beneath 448 B. Indeed, since compaction-induced subsidence of bench mark B-0 1931 (pl. 1) probably has been trivial (see section on "Surface Deformation Attributable to Groundwater Withdrawals"), referencing these movements to B-0 1931 indicates that relative tectonic uplift through the period 1931-63 probably reached a maximum (at B-7 1931) of about 0.1533 m (table 2). Owing to the relative stability between bench marks B-1 1931 and B-2 1931 (table 2), a minor element of ambiguity attaches to the interpretation of these displacements as tectonic. That is, although there is certainly no necessity that what we interpret as a generally up-to-the northeast tilt need be expressed as a uniformly smooth feature, the 1931-63 uplift of B-1 1931 seems an unexpectedly large aberration on a regionally developed tectonic tilt. In fact, however, a significant fraction of the differential uplift of B-1 1931 could be the product of artificially-induced rebound of the eastern or footwall block of the Kern Front fault (see section on "Surface Movements Attributable to Oil-field Operations"). Because the interval 1931-63 includes both the 1952 Kern County earthquake and the inception of the southern California uplift (and perhaps still other unrecognized tectonic events), the nature of this apparent tectonic tilting remains uncertain. However, because the 1931-63 uplift seems to have increased significantly to the northeast (away from the White Wolf fault), it seems unlikely that this tilting could have been a coseismic effect associated with the 1952 shock.

FAULTING

Two independent lines of evidence suggest a tectonic contribution to the historical displacements recognized along the faults bordering the Kern Front and Poso Creek oil fields. (1) Movement, insofar as we are aware, has been confined to the traces of throughgoing faults that show clearly defined evidence of prehistoric Quaternary activity which certainly had its origins in the tectonic evolution of this region. Thus there exists an inverse uniformitarian basis for assuming that any contemporary movement on these faults must be attributable to the same tectonic forces that were responsible for the prehistoric displacements. (2) The largest, cumulative historical displacements measured along the surface trace of at least the Kern Front fault (pl. 1) cannot, as we have already observed, be completely and unambiguously explained as the product of oil-field exploitation. Accordingly, tectonic activity could account for an undetermined and otherwise doubtfully explained fraction of this movement. The occurrence of any normal faulting and the size of any associated displacements on the Kern Front and Poso Creek faults are functions of both the orthogonally directed extensional horizontal strain across these faults and any differential uplift to the east—of whatever origin. Because tectonically generated uplift east of these faults, even if only of trivial dimensions, would tend to increase both the extensional strain and any resultant displacements on the fault, the differential uplift of bench mark B-2 1931 (table 2) suggests a tectonic basis for a part of the historical movement on at least the Kern Front fault.

CONCLUSION

Historical surface movements in the Oildale area, though in some ways small in comparison with similar movements elsewhere, are significant if only because they demonstrate the complex interaction among various natural and artificial processes. Height changes described in this paper probably can be explained largely as a result of subsurface compaction associated with fluid extraction and resultant reservoir pressure decline, coupled with modest up-to-the-east tectonic tilting. The historical rupturing along the surface traces of the Kern Front and Premier faults, which are among the longest examples recognized in the United States of both movement on historically aseismic faults and faulting associated with oil-field operations (Bonilla, 1967, p. 17-18, table 1; Yerkes and Castle, 1969, p. 61), can also be explained largely as the product of exploitation and resultant subsurface compaction. However, even though it is very unlikely that the observed faulting could have occurred in the absence of operations in the Kern Front and Poso Creek oil fields, a small, undetermined fraction of this historical movement is conceivably attributable to continuing tectonic activity along the west ramp of the Sierra Nevada.

SUPPLEMENTAL DATA: AN APPRAISAL OF COMPACTION-INDUCED SUBSIDENCE IN THE CENTRAL BAKERSFIELD AREA

Rigorous analysis of the available geodetic data, coupled with a limited assessment of the local hydrologic history, strongly support Lofgren's (1975, p. D15) basic thesis: namely, that the apparent (and, by inference, compaction-induced) subsidence of those bench marks around the edge of the southern San Joaquin Valley in general and those in central Bakersfield in particular is actually due to the generally positive movement of the control points to which the various adjustments have been referred. This analysis, however, is significantly complicated by the occurrence of at least four and perhaps five major tectonic displacements of Bakersfield during the period 1901-65 (see below).

The vertical displacement history of a representative mark in central Bakersfield, 421 B (pl. 1, fig. 14), indicates that Bakersfield was actually rising with respect to San Pedro during the period 1930/31-72/74 in which compaction-induced subsidence should have been accelerating. Moreover, height changes referred to Tidal 8, San Pedro, are biased toward the recognition of subsidence, such that the significance of at least a part of the subsidence shown by 421 B should be discounted. Specifically, bench mark Tidal 8 is located adjacent to an automatic tide gauge identified with a history of relatively positive movement that has exceeded the rise in eustatic sea level and probably has been rising at something less than 2 mm/yr with respect to an invariant datum (Hicks, 1972, p. 23; Hicks and Crosby, 1975). Alternatively, if we assume that the San Diego tide station has remained more or less invariant during the full period of its occupation—as suggested by geologic studies (McCrory and Lajoie, 1979)—we would be forced to conclude as a corollary that the San Pedro station has been rising at about 1.3 mm/yr with respect to a fixed datum. The acceptance of either of these estimates indicates, for example, that about 0.039-0.058 m of the 1926-53/55 subsidence of 421 B (fig. 14) should be attributed to relative uplift of Tidal 8. In addition, although 421 B subsided 0.1770 m during the period 1914-26, this subsidence accumulated (albeit irregularly) over virtually the entire line extending northward from Pacoima (fig. 1); hence the subsidence that occurred at 421 B must have been largely if not entirely tectonic. Similarly, although 421 B apparently subsided 0.3-0.4 m between 1926 and 1930/31, because this subsidence increased smoothly southward from Chowchilla (fig. 1), it is very unlikely that the 1926-30/31 (or 1901-30/31) subsidence of 421 B was other than tectonic. Again, although the available geodetic evidence neither confirms nor refutes either possibility, the 1930/31-53/55 uplift could have been chiefly aseismic and may have closely followed the 1926-30/31 collapse. Alternatively, of course, it may have accompanied the 1952 M 7.7 Arvin-Tehachapi earthquake, the product of a major left-lateral thrust event on the White Wolf fault (Oakeshott and others, 1955).

The geodetic evidence (fig. 14) convincingly supports the idea that central Bakersfield sustained signifi-

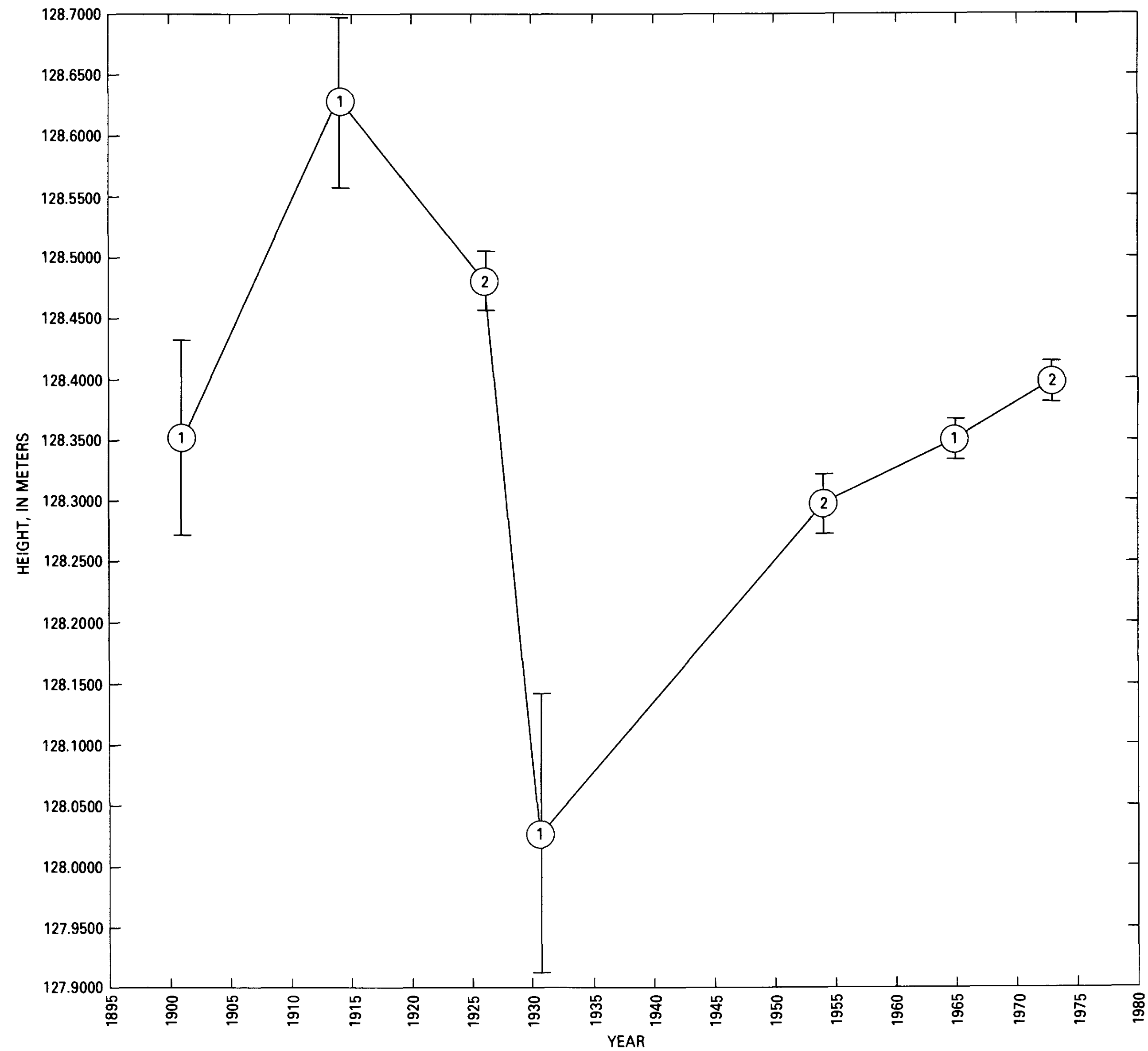

FIGURE 14.—Changes in orthometric height at bench mark 421 B, Bakersfield, Calif., with respect to Tidal 8 (or nearby equivalents, bench marks A or I 33), San Pedro (fig. 1). (1) Based on leveling via Saugus, Palmdale, and Mojave (fig. 1). (2) Based on leveling via Saugus and Lebec (fig. 1).The "1901" height is based on the results of 1897 third-order, double-rodded leveling between San Pedro and Pacoima (fig. 1) and 1902 second-order, double-rodded leveling between Pacoima and Bakersfield. The 1914 height is based on the results of second-order, double-run leveling. The 1930/31 height is based on the results of 1897/1902 third- and second-order leveling between San Pedro and Chowchilla (fig. 1), an assumption of invariance at bench mark 241 B, Chowchilla, during the interval 1897/1902-1930/31, and 1930/31 first-order leveling between Chowchilla and Bakersfield. Although it is unlikely that 241 B subsided in response to groundwater withdrawals during this period (Poland and Davis, 1969, p. 240-247), the location of Chowchilla along the south edge of a large reentrant of older rocks into the central valley (Jennings, 1977) that sustained rapidly accelerating arching during late Quaternary time (Marchand, 1977; D. G. Herd, oral commun., 1979) suggests that 241 B may have experienced modest uplift during the period 1897/1902-1930/31; hence the 1930/31 height probably is underestimated. All other heights are based exclusively on the results of first-order surveys. Orthometric corrections based on observed or interpolated gravity. Error bars show conventionally estimated random error only. Observed elevation data from U.S. Geological Survey field books 5718-5749, U.S. Geological Survey summary books 9114 and 9679, and National Geodetic Survey lines 82466, 82583, 82598, L-198, L-14778, L-14799, L-15577, L-19752, L-20130, L-20145, L-20169, L-20279, L-20298, L-22757, L-23611, L-23614, L-23644, L-23673, L-23675, L-23677, and L-23691.

cant subsidence during the periods 1914-26 and 1926-30/31, whereas it sustained net uplift during the periods 1897/1902-1914, 1897/1902-1926, 1930/31-72/73/74, and 1953/55-72/73/74. It is entirely conceivable, of course, that any compaction-induced subsidence associated with ground-water withdrawals may have been masked by overwhelming tectonic signals even during those periods of net uplift. Nonetheless, the surface and subsurface hydrologic history, various geologic considerations and the local geodetic record combine in such a way that compaction-induced subsidence in the central Bakersfield area during the full interval 1901-73 must have been trivial (measurably insignificant) to nonexistent.

Although we have no knowledge of the hydrologic history of this area prior to 1894, what we know of the post-1894 history indicates that Bakersfield remained free of subsidence attributable to ground-water withdrawals through at least 1930. Discharge from the Kern River increased steadily from about 1905 through 1918 and declined somewhat between 1919 and 1926 (Lofgren, 1975, p. D17). Because this increased discharge would tend to inhibit any contemporary depletion of the ground-water reservoir (or recharge any earlier depletion owing to percolation through and into the sediments that form the head of the Kern River fan in the Bakersfield-Oildale area), water levels probably remained unchanged or even rose during the period 1905-26 (or 1901-26). In fact, comparisons between 1915 and 1925 ground-water levels in central Bakersfield indicate that they remained virtually static during this decade (Mendenhall and others, 1916, pl. 1; Harding, 1927, map 1). Nonetheless, Harding's (1927, map 3) studies indicate that water levels declined about 2 m (a figure that probably roughly approximates the seasonal variation) in the area of 421 B during the period 1920-25. Water-level measurements from one of the few observation wells in the Bakersfield area for which we have a pre-1941 history, 29S/27E-26D (pl. 1), show that there was no decline in ground-water levels in this relatively shallow (~15-m) well between 1924 and 1946 and no more than 4-6 m between 1946 and 1959 (California Department of Water Resources, written commun., 1976). Similarly, hydrographs for wells about 6 km southeast of Bakersfield (30S/28E-10N3) and 4 km west-southwest of Bakersfield (29S/27E-34N1) indicate that water levels within the shallow aquifers (perforated at depths of 65 m) declined by no more than 4 m during the intervals 1952-68 and 1952-59, respectively (Lofgren, 1975, pl. 2F). Although these very modest changes followed the period of immediate interest here, they occurred within a period of clearly declining recharge of the producing ground-water reservoir. Because the period 1924-52 was one of generally balanced changes in the Kern River discharge (which, in fact, increased significantly during the decade 1935-45), ground-water declines in the shallow aquifers during the interval 1924-52 must have been significantly less than even the very small declines recognized (in wells 30S/28E-10N3 and 29S/27E-34N1) during subsequent periods and can thus be dismissed as negligible.

Although water-level records for the deeper aquifers underlying Bakersfield indicate generally greater declines than those measured at 29S/27E-26D, it is unlikely that even these more precipitous declines could have provoked significant compaction of the reservoir skeleton, particularly during the period 1924-52. Specifically, very few deep-water wells (in excess of 100 m) had been drilled in the Bakersfield area prior to about 1940 (B. E. Lofgren, oral commun., 1976), such that it is unlikely that large water-level declines had occurred within the deeper, confined, or semiconfined aquifers before 1940. However, the hydrograph for well 29S/28E-20B1 (pl. 1), which reached a depth of 200 m, shows that water levels in this well declined at an average rate of about 1.3 m/yr between 1940 and 1949 and at about 2.0 m/yr during the period 1950-68 (Lofgren, 1975, pl. 2F). Records obtained from well 29S/28E-19J2 (pl. 1), which bottoms at about 180 m, show that water levels in this well declined at an average rate of about 1.25 m/yr during the period 1941-59 and at a slightly greater rate during succeeding years (California Department of Water Resources, written commun., 1976), and hence roughly corroborate the declines shown by well 29S/28E-20B1. However, even given these head declines, it is unlikely that they would have induced significant compaction, for they occurred within a section characterized by coarse clastic deposits identified with the head of the Kern River fan. Both pre- and post-war production in the Bakersfield-Oildale area has been drawn from the semiconsolidated, relatively young and presumably fresh alluvial deposits of the Kern River Formation and, to a lesser extent, a thin veneer of overlying gravels (Smith, 1964; Dale and others, 1966, p. 22, figs. 10 and 29). Because these deposits are much less susceptible to compaction than those distributed around the periphery of the fan, it is unlikely that the shallower aquifers in particular could have sustained more than trivial compaction through 1968, even in the absence of continuing recharge. Moreover, the deeper aquifers penetrated by wells 29S/28E-20B1 and 29S/28E-19J2 are contained within the same formation (the Kern River Formation) that produced massive volumes of oil and water (3.5×10^9 bbls through 1968) from the nearby Kern River oil field (pl. 1), yet at the same time (and for whatever reason) generated little (if any) differential subsidence within this field during the period 1903-68 (see section on "Surface Movements Attributable to Oil-field Operations").

Perhaps the clearest evidence of an absence of compaction associated with ground-water withdrawals from the surficial deposits underlying the Bakersfield-Oildale area during the period 1924-52 derives from the results of local leveling, coupled with a skeletal knowledge of the subsurface hydrologic history around the southeast margin of the southern San Joaquin Valley. Leveling between X 67 and both Y 67 and F 55 (pl. 1) indicates that Y 67 and F 55 rose 7 and 9 mm, respectively, with respect to X 67 during the interval 1926/30-53 (table 2). Yet, as shown by the water-level records for 29S/27E-26D, water-table reductions in this well were no more than 1 or 2 m during this same period and probably even less during the period 1921-44 (Lofgren, 1975, pl. 2A), whereas water-table declines beneath F 55 during the interval 1921-44 were 5-6 m (Lofgren, 1975, pl. 2A). Thus, other things being equal, because most of the pre-1946 ground-water withdrawals were from relatively shallow aquifers, any differential subsidence between these marks attributable to ground-water extraction should have been in a sense opposite to that actually observed. In fact, however, other things have not been equal and the very limited subsidence of X 67 with respect to either Y 67 or F 55 (table 2) is almost certainly due to its proximity to the Fruitvale oil field (pl. 1), a field that may have been associated with as much as 0.1 m of differential subsidence during the period 1926/30-59 (see section on "Surface Movements Attributable to Oil-field Operations"). Similarly, comparisons between observed elevation differences based on first-order leveling between F 55 and a series of marks extending 12 km southward from bench mark P 54 (about 1 km south of the White Wolf fault, fig. 1) to K 54, show that height changes with respect to F 55 during the interval 1926-47 ranged from about −2 mm at P 54 to a maximum of +27 mm at K 54 (NGS lines 82598, L-12137, and L-12152). Through 1958 none but the northern part of the area between P 54 and K 54 was under irrigation, and a long-term hydrograph for a well (11N/19W-24R1) about 10 km east of P 54 and 8 km south of the White Wolf fault (and, hence, centering on the subsidiary ground-water basin south of the White Wolf), shows that water levels in this area remained essentially unchanged between 1925 and 1946 (Wood and Dale, 1964, p. 71, pls. 5 and 9). Because all the available information indicates that the water-bearing section beneath P 54 sustained little (if any) extraction-induced compaction through at least 1946 and probably through 1958, the stability of F 55 with respect to P 54 suggests that the central Bakersfield area remained equally free of compaction-induced subsidence between 1926 and 1947. Although this analysis is somewhat questionable owing to the 1926-30/31 tectonic subsidence that occurred at Bakersfield (fig. 14), the preservation of these elevation differences throughout this period of collapse actually enhances the likelihood that the Bakersfield-Oildale area underwent little compaction-induced subsidence during the period 1926-47. That is, because it is much more likely that the Bakersfield marks experienced subsidence associated with ground-water withdrawals during the interval 1926-47 than did those bench marks south of the White Wolf fault, it follows either that the Bakersfield-Oildale area could not have sustained any significant subsurface compaction between 1926 and 1947 or, alternatively (and much more unlikely in our judgment), that the 1926-30/31 tectonic subsidence south of the White Wolf was markedly greater than that at Bakersfield. Indeed, we strongly suspect that tectonic activity during the interval 1926-47 accounts for the modest (27 mm) uplift of K 54, a mark that lies well within the Tehachapi Range.

Subsidence associated with ground-water withdrawals in the central Bakersfield area during the post-1952 (post-earthquake) period is, in some ways, much more easily assessed than any that might have occurred prior to 1953. Specifically, the results of first-order levelings between bench mark 421 B, Bakersfield, and Tidal 8, San Pedro, show that 421 B rose 0.0514 m and 0.0989 m during the periods 1953/55-65 and 1953/55-72/74, respectively (fig. 14). Nevertheless, even if we accept the observation that 421 B rose with respect to Tidal 8 during the period 1953/55-72/74, we are again left with the possibility that tectonic uplift of 421 B may have masked measurably significant compaction-induced subsidence beneath this mark. However, a variety of arguments indicate that there was virtually no subsidence of central Bakersfield associated with ground-water withdrawals during the period 1953-59. For example, comparisons among observed elevation differences based on first-order levelings (NGS lines L-14778 and L-17166) between bench mark S 89 (pl. 1) and several representative marks along the southeast edge of the San Joaquin Valley suggest that any subsidence of S 89 accompanying water-level declines beneath this mark during the interval 1953-59 must have been trivial. On the one hand, bench mark Bank AZ, situated about 20 km east-southeast of S 89 and about 5 km east of the east edge of the Edison oil field, subsided about 20 mm with respect to S 89 during the interval 1953-59. Bank AZ overlies a generally coarse, clastic ± 100 m section of the Kern River Formation and older fan deposits; this section in turn overlies indurated Miocene rocks (J. A. Bartow, oral commun., 1980) that crop out less than 2 km to the north and in apparently normal (or unconformable) contact with the Kern River Formation (Smith, 1964). On the other hand, bench mark S 55, situated about 35 km east-southeast of central Bakersfield, rose by a similarly small amount (23 mm) with respect to S 89 during the period 1953-59. S 55 lies directly over or immediately adjacent to granitic basement about 5 km northwest of the main trace of the White Wolf fault (Smith, 1964). Although we have no evidence of water-level declines beneath Bank AZ, this does not, of course, preclude their occurrences. Nevertheless, because the semiconsolidated Kern River Formation is three or four times thicker beneath central Bakersfield than it is beneath Bank AZ (J. A. Bartow, oral commun., 1980), there is a much greater likelihood (other things remaining equal) that S 89 would have subsided with respect to Bank AZ rather than vice versa. Moreover, not only did S 89 actually rise with respect to Bank AZ during the interval 1953-59, this uplift occurred during a period in which the subsidence within the unambiguously defined Arvin-Maricopa subsidence basin was actually accelerating (Lofgren, 1975, p. D35-D38). Hence we infer that the surficial deposits that characterize the head of the Kern River fan in the Bakersfield-Oildale area are virtually incompressible, even in the presence of major water-level declines. Owing to the clearly incompressible nature of the natural foundation underlying bench mark S 55, the subsidence of S 89 with respect to S 55 is a seemingly more reliable index of the actual compaction beneath S 89 than is the uplift of this mark with respect to Bank AZ. However, the proximity of S 55 to the White Wolf fault mitigates against the tectonic invariance of this mark during the 1953-59 period of postseismic adjustment. Accordingly, we are finally left with the near certainty that bench marks in the central Bakersfield area could have sustained little if any subsidence associated with ground-water withdrawals during the period 1953-59. Because this 6-year period is especially critical in this context, owing to the generally diminishing discharge of the Kern River and the accelerating subsidence throughout much of the southernmost San Joaquin Valley, it is equally unlikely that the central Bakersfield area could have sustained significant subsidence associated with ground-water withdrawals during any subsequent years through at least 1968.

REFERENCES CITED

Albright, M. B., Hluza, A. G., and Sullivan, J. C., 1957, Mount Poso oil field, *in* Summary of operations, California oil fields, forty-third annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 43, no. 2, p. 5-20.

Bartow, J. A., and Pittman, G. M., 1983, The Kern River Formation, southeastern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1529-D [in press].

Birdseye, C. H., 1925, Spirit leveling in California, 1896-1923: U.S. Geological Survey Bulletin 766, 748 p.

Bonilla, M. G., 1967, Historic surface faulting in continental United States and adjacent parts of Mexico: U.S. Geological Survey open-file report, 36 p.; also U.S. Atomic Energy Commission Report TID-24124, 36 p.

Bradley, W. W., 1917, California mineral production for 1916: California State Mining Bureau Bulletin 74, 179 p.

———1918, California mineral production for 1917: California State Mining Bureau Bulletin 83, 179 p.

———1920, California mineral production for 1919: California State Mining Bureau Bulletin 88, 204 p.

Brooks, T. J., 1952a, Kern Front oil field, *in* AAPG, SEPM, SEG field trip routes, oil fields, geology: American Association of Petroleum Geologists Annual Meeting, Los Angeles, California, March 1952, p. 159-161.

———1952b, Kern River oil field, *in* AAPG, SEPM, SEG field trip routes, oil fields, geology: American Association of Petroleum Geologists Annual Meeting, Los Angeles, California, March 1952, p. 156-158.

California Department of Water Resources, 1964, Investigation of failure, Baldwin Hills Reservoir: California Department of Water Resources, 64 p.

California Division of Oil and Gas, 1960, California oil and gas fields—part 1, San Joaquin-Sacramento Valleys and northern coastal regions: California Division of Oil and Gas, San Francisco, 493 p.

———1968, Production statistics 1968, *in* Summary of operations, California oil fields, fifty-fourth annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 54, no. 2, part 1, 128 p.

———1972, Oil and gas statistics, *in* Summary of operations, oil, gas and geothermal production statistics, fifty-eighth annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 58, no. 2, p. 61-166.

Casagrande, Arthur, Wilson, S. D., and Schwantes, E. D., Jr., 1972, The Baldwin Hills Reservoir failure in retrospect: Proceedings of Specialty Conference on Performance of Earth and Earth-Supported Structures, Purdue University, June 12-14, 1972, American Society of Civil Engineers, New York: v. I, pt. 1, p. 551-588.

Castle, R. O., Church, J. P., and Elliott, M. R., 1976, Aseismic uplift in southern California: Science, v. 192, p. 251-253.

Castle, R. O., and Yerkes, R. F., 1976, Recent surface movements in the Baldwin Hills, Los Angeles County, California: U.S. Geological Survey Professional Paper 882, 125 p.

Castle, R. O., Yerkes, R. F., and Youd, T. L., 1973, Ground rupture in the Baldwin Hills—an alternative explanation: Association of Engineering Geologists Bulletin, v. 10, p. 21-46.

Castle, R. O., and Youd, T. L., 1973, The Baldwin Hills Reservoir failure: Discussion: Proceedings of Specialty Conference on Performance of Earth and Earth-Supported Structures, Purdue University, June 12-14, 1972, American Society of Civil Engineers, New York, v. III, p. 91-99.

Church, H. V., Jr., and Krammes, Kenneth (chm.), and others, 1957, Cenozoic correlation section across south San Joaquin Valley from San Andreas fault to Sierra Nevada foothills, California: American Association of Petroleum Geologists, Geologic Names and Correlations Committee, San Joaquin Valley Subcommittee on the Cenozoic, scale about 1 inch to 1-1/2 miles.

Crowder, R. E., 1952, Kern River oil field, *in* Summary of operations, California oil fields, thirty-eighth annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 38, no. 2, p. 11-18.

Dale, R. H., French, J. J., and Gordon, G. V., 1966, Ground-water geology and hydrology of the Kern River alluvial-fan area, California: U.S. Geological Survey open-file report, 92 p.

de Laveaga, M., 1952, Oil fields of central San Joaquin Valley province, *in* AAPG, SEPM, SEG field trip routes, oil fields, geology; American Association of Petroleum Geologists Annual Meeting, Los Angeles, California, March 1952, p. 99-105

Dibblee, T. W., Jr., and Chesterman, C. W., 1953, Geology of the Breckenridge Mountain quadrangle, California: California Division of Mines Bulletin 168, 56 p.

Gilluly, James, and Grant, U. S., 4th, 1949, Subsidence in the Long Beach Harbor area, California: Geological Society of America Bulletin, v. 60, p. 461-529.

Hamilton, D. H., and Meehan, R. L., 1971, Ground rupture in the Baldwin Hills: Science, v. 172, p. 333-344.

Harding, S. T., 1927, Ground water resources of the southern San Joaquin Valley: California Department of Water Resources, Bulletin 11, 146 p.

Hicks, S. D., 1972, On the classification and trends of long period sea level series: Shore and Beach, v. 40, no. 1, p. 20-23.

Hicks, S. D., and Crosby, J. E., 1975, An average long-period, sea-level series for the United States: National Oceanic and Atmospheric Administration, Technical Memorandum NOS 15, 6 p.

Hill, M. L., 1954, Tectonics of faulting in southern California, chap. 4, *in* Jahns, R. H., ed., Geology of southern California: California Division of Mines Bulletin 170, p. 5-13.

Hilton, G. S., McClelland, E. J., Klausing, R. L., and Kunkel, Fred, 1963, Geology, hydrology, and quality of water in the Terra Bella-Lost Hills area, San Joaquin Valley, California: U.S. Geological Survey open-file report, 158 p.

Holzer, T. L., 1977, Ground failure in areas of subsidence due to ground-water decline in the United States, *in* Land subsidence symposium: Proceedings of the Second International Symposium on Land Subsidence, Anaheim, California, December 1976, International Association Hydrological Sciences Pub. 121, p. 423-433.

———1980, Faulting caused by groundwater level declines, San Joaquin Valley, California: Water Resources Research, v. 16, p. 1065-1070.

Hudson, D. E., and Scott, R. F., 1965, Fault motions at the Baldwin Hills Reservoir site: Seismological Society of America Bulletin, v. 55, p. 165-180.

Jansen, R. B., Dukleth, G. W., Gordon, B. B., James, L. B., and Shields, C. E., 1967, Earth movement at Baldwin Hills Reservoir: Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers, v. 93, SM4, p. 551-575.

Jennings, C. W., 1977, Geologic map of California: California Division of Mines and Geology, Geologic Data Map series, scale 1:750,000.

Johnston, R. L., 1955, Earthquake damage to oil fields and to Paloma Cycling Plant in the San Joaquin Valley, *in* Oakeshott, G. B., ed., Earthquakes in Kern County, California, during 1952: California Division of Mines Bulletin 171, p. 221-225.

Johnston, Robert, 1952, Fruitvale oil field, *in* AAPG, SEPM, SEG field trip routes, oil fields, geology: American Association of Petroleum Geologists Annual Meeting, Los Angeles, California, March 1952, p. 122-123.

Koch, T. W., 1933, Analysis and effects of current movement on an active fault in Buena Vista Hills oil field, Kern County, California: American Association of Petroleum Geologists Bulletin, v. 17, p. 694-712.

Leps, T. M., 1972, Analysis of failure of Baldwin Hills Reservoir: Proceedings of Specialty Conference on Performance of Earth and Earth-supported Structures, Purdue University, June 12-14, 1972, American Society of Civil Engineers, New York: v. 1, pt. 1, p. 507-550.

Lofgren, B. E., 1966, Tectonic movement in the Grapevine area, Kern County, California, *in* Geological Survey research 1966: U.S. Geological Survey Professional Paper 550-B, p. B6-B11.

———1975, Land subsidence due to ground-water withdrawal, Arvin-Maricopa area, California: U.S. Geological Survey Professional Paper 437-D, 55 p.

Marchand, D. E., 1977, The Cenozoic history of the San Joaquin Valley and adjacent Sierra Nevada as inferred from the geology and soils of the eastern San Joaquin Valley, *in* Singer, M. J., ed., Soil development, geomorphology, and Cenozoic history of the northeastern San Joaquin Valley and adjacent areas, California: Guidebook for the Joint Field Session of the American Society of Agronomy, Soil Science Society of America and the Geological Society of America, Modesto, California, November 10-13, 1977, p. 39-50.

Mathews, J. F., Jr., 1957, McVan area of Poso Creek oil field, *in* Summary of operations, California oil fields, forty-third annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 43, no. 1, p. 24-28.

McCrory, P. A., and Lajoie, K. R., 1979, Marine terrace deformation, San Diego County, California [abs.]: Tectonophysics, v. 52, p. 407-408.

McLaughlin, R. P., 1914, Kern River field, chap. V, *in* Petroleum industry of California: California State Mining Bureau Bulletin 69, p. 195-216.

Mendenhall, W. C., Dale, R. B., and Stabler, Herman, 1916, Ground water in San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 398, 310 p.

Morton, D. M., 1977, Surface deformation in part of the San Jacinto Valley, southern California: U.S. Geological Survey Journal of Research, v. 51, p. 117-124.

Nason, R. D., Philippsborn, F. R., and Yamashita, P. A., 1974, Catalog of creepmeter measurements in central California from 1968 to 1972: U.S. Geological Survey Open-File Report 74-31, 287 p.

Oakeshott, G. B., and others, ed., 1955, Earthquakes in Kern County, California during 1952: California Division of Mines Bulletin 171, 283 p.

Park, W. H., 1965, Kern Front oil field, *in* Summary of operations, California oil fields, fifty-first annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 51, no. 1, p. 13-22.

Pease, E. W., 1952, Mount Poso group oil fields, *in* AAPG, SEPM, SEG field trip routes, oil fields, geology: American Association of Petroleum Geologists Annual Meeting, Los Angles, California, March 1952, p. 150-151

Poland, J. F., 1972, Subsidence and its control, *in* Underground waste management and environmental implications: American Association of Petroleum Geologists Memoir 18, p. 50-71.

Poland, J. F., and Davis, G. H., 1969, Land subsidence due to withdrawal of fluids, *in* Varnes, D. J., and Kiersch, George, eds., Reviews in engineering geology, vol. II: Boulder, Colorado, The Geological Society of America, p. 187-269.

Smith, A. R., compiler, 1964, Geologic map of California, Olaf P. Jenkins edition, Bakersfield sheet: California Division of Mines and Geology, scale 1:250,000.

U.S. Coast and Geodetic Survey, 1966, Vertical control data: U.S. Coast and Geodetic Survey Quadrangle 351192, 113 p.

Vanicek, P., Castle, R. O., and Balazs, E. I., 1980, Geodetic leveling and its applications: Reviews of Geophysics and Space Physics, v. 18, p. 505-524.

Weddle, J. R., 1959, Premier and Enas areas of Poso Creek oil field, *in* Summary of operations, California oil fields, forty-fifth annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 45, no. 2, p. 41-50.

Welge, E. A., 1973, Poso Creek oil field, McVan area, *in* Summary of operations, fifty-ninth annual report of the state oil and gas supervisor: California Division of Oil and Gas, v. 59, no. 1, p. 59-68.

Whitten, C. A., 1961, Measurement of small movements in the earth's crust: Annales Academiae Scientiarum Fennicae, Ser. A, III. Geologica-Geographica Suomalainen Tiedeakatemia, p. 315-320.

Wood, P. R., and Dale, R. H., 1964, Geology and ground-water features of the Edison-Maricopa area, Kern County, California: U.S. Geological Survey Water-Supply Paper 1656, 108 p.

Yerkes, R. F., and Castle, R. O., 1969, Surface deformation associated with oil and gas field operations in the United States, *in* Land subsidence: International Association of Science Hydrology-UNESCO, pub. no. 88, v. 1, p. 55-66.